

Behaviour and inspection of novel non-crimp dry thick reinforcement fabrics

by

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Abstract

Aerospace structural components made from polymer matrix composites (PMCs) offer numerous advantages. Their high stiffness and high strength combined with low densities enable lower fuel consumption coupled with higher payloads. As a result, PMCs provide an important economic advantage over typical metallic airframes. Textile reinforcements for PMCs are made by assembling reinforcement fibres, typically carbon. Then, the textile reinforcements are typically cut into smaller pieces, stacked, draped and assembled into a dry assembly called a preform, the shape of which generally approaches that of the PMC part to be made. This manufacturing process is labour intensive and expensive.

Novel thick, net-shape, drapable, high v_f textile reinforcements used toward manufacturing aerospace PMCs are being developed at the University of Ottawa. The technology enables the manufacturing of flat, drapable multilayered near net-shape preforms. The bending and in-plane shear behaviours of such novel thick reinforcement textiles was investigated to understand and define the behaviour of such thick fabric reinforcements when formed into required shapes. A bending apparatus was developed for investigating the bending behaviour of these novel thick reinforcement fabrics and an articulated frame shear rig was used for investigating the in-plane shear behaviour. A non-destructive inspection method using infrared imaging was used for investigating and identifying flaws and defects in these thick, dry textile reinforcements, aiming at increasing the quality and reproducibility of the final PMC parts made from these reinforcements.

Dedication

This dissertation is lovingly dedicated to my mother. Her support, encouragement, and constant love have sustained me throughout my life.

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Above all, I would like to thank Allah (subhanahu wa taala) for endowing me with health, patience, and knowledge to complete this work. It would not have been possible to write this doctoral thesis without the help and support of the kind people around me, to only some of whom it is possible to give particular mention here.

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Symbols

Roman Letters		Units
a	Distance between bending force and sample support	mm
b	Distance between bending force and sample free end	mm
$\hat{C}$	Contrast	
C_p	Specific heat capacity	J.kg ⁻¹ .K ⁻¹
D	Displacement	mm
E	Fibres Young's modulus	GPa
E_b	Energy radiated by an ideal black body	W.m ⁻²
E_f	Fraction of energy radiated by a real body	W.m ⁻²
f	Correction factor	mm
F_A	Horizontal component of axial force acting on link AB	N
F_{AB}	Axial force acting on link AB	N
F_M	Machine force	N
F_O	Force acting on BR at support O	N
F_s	Shear force	N
H'	Bending rig initial height	mm
H	Bending rig instant height	mm
I_{CM}	Moment of inertia obtained from cantilever model	mm ⁴
I_{fibre}	Moment of inertia of a single fibre	mm ⁴
I_{FM}	Moment of inertia obtained from fibre model	mm ⁴
I_{sample}	Moment of inertia of sample	mm ⁴
I_{yarn}	Moment of inertia of a single yarn	mm ⁴
I_{yarn}^{Row}	Moment of inertia of a single row of yarns around its own axis	mm ⁴

$I_{S\ Axis}^{Row1}$	Moment of inertia of a single row 1 of yarns around sample axis	mm ⁴
$I_{S\ Axis}^{Row2}$	Moment of inertia of a single row 2 of yarns around sample axis	mm ⁴
I_0^{Row}	Moment of inertia of fibres at row 0 around its own axis	mm ⁴
I_1^{Row}	Moment of inertia of fibres at row 1 around its own axis	mm ⁴
I_n^{Row}	Moment of inertia of fibres at row n around its own axis	mm ⁴
L	Length of upper bending rig link	mm
k	Thermal conductivity	W.m ⁻¹ .K ⁻¹
L_o	Span length of a single yarn	mm
L_{fabric}	Fabric length	mm
L_{frame}	Frame length	mm
L_s	Span length of sample	mm
M	Analytical bending moment	N.mm
M_B	Experimental bending moment	N.mm
M_{CF-ICM}	Analytical bending moment obtained from curvature formula using cantilever model moment of inertia	N
M_{CF-IFM}	Analytical bending moment obtained from curvature formula using fibre model moment of inertia	N
M_{DF-ICM}	Analytical bending moment obtained from deflection formula using cantilever model moment of inertia	N
M_{DF-IFM}	Analytical bending moment obtained from deflection formula using fibre model moment of inertia	N
m	Sample mass at 100% v_f	g
MM	Measured mass of the sample	g
MSW	Mean square within for all data	
NL	Number of layers containing yarns normal to sample cross-section	

NY	Number of yarns normal to sample cross-section	
R	Bending radius	mm
r	Roller radius	mm
r_f	Radius of a single fibre	μm
RR	Bending rig radius	mm
SPR	Spacer size	mm
STD	Standard deviation value	
$SS(C)$	Sum of squares for contrast	
T	Absolute temperature	K
t	Time	s
T_{min}	Minimum recorded temperature at sample surface	$^{\circ}\text{C}$
T_{cen}	Center region recorded temperature at sample surface	$^{\circ}\text{C}$
T_{max}	Maximum recorded temperature at sample surface	$^{\circ}\text{C}$
V	Sample volume	mm^3
v_f	Fibre volume fraction	%
w_o	Distributed load of yarn span subjected to its own weight	N/m
z	Depth of sub-surface defect	mm

Greek Letters

Units

α		
β	Inner shear rig half angle	rad
γ	Shear angle	rad
γ_L	Shear locking angle	$^{\circ}$
ε	Emissivity of surface	
θ	Angle between rig radius and vertical	$^{\circ}$

κ	Curvature radius of the neutral axis of sample	mm
λ	Thermal diffusivity	$\text{m}^2.\text{s}^{-1}$
ρ	Density	g/cc
σ	Stefan-Boltzmann constant	$\text{W}.\text{m}^{-2}.\text{K}^{-4}$
τ	Maximum time limit for observation	s
ν	Deflection at the free end of sample	mm
ν_{max}	Maximum deflection	mm
φ	Angle between rig link and vertical	°
Φ	Angle between rig radius and rig link	°

Acronyms

<i>ANOVA</i>	Analysis of variance
<i>AVG</i>	Average
<i>ASTM</i>	American Society for Testing and Materials
<i>BES-FY</i>	Kawabata bending evaluation system for fabrics and yarns
<i>CF</i>	Curvature formula
<i>CNC-device</i>	Computer controlled cutting device
<i>CSM</i>	Contour stitching machine
<i>DF</i>	Deflection formula
<i>IR</i>	Infrared
<i>IRT</i>	Infrared thermography
<i>KES-FB</i>	Kawabata evaluation system for fabric bending

<i>LAVG</i>	Line average
<i>LCM</i>	Liquid composites moulding
<i>LSTD</i>	Line standard deviation
<i>NCF</i>	Non-crimp fabric
<i>PAN</i>	Polyacrylonitrile
<i>PMMA</i>	Polymethyl metacrylate
<i>PMC</i>	Polymer matrix composite
<i>RFI</i>	Resin film infusion
<i>RTM</i>	Resin transfer moulding
<i>UO-APT</i>	University of Ottawa advanced preforming technology
<i>VARI</i>	Vacuum-assisted resin infusion
<i>VARTM</i>	Vacuum-assisted transfer moulding
<i>VI</i>	Vacuum infusion
<i>YLM</i>	Yarn laydown machine

Chapter 1

Introduction

1.1 Composites manufacturing

Advanced aerospace structural components and sub-assemblies are increasingly made from carbon fibre reinforcements embedded in a polymer resin matrix, often a thermosetting epoxy. Polymer matrix composites (PMCs) offer numerous advantages, foremost amongst which are their high stiffness and high strength combined with the low densities of the constituent fibre and matrix materials. As a result, PMCs enable lower fuel consumption coupled with higher payloads, providing an important economic advantage over typical metallic airframes [1].

The manufacturing process most often used for building PMC primary structural airframe components relies on the consolidation of thin, laminated pre-impregnated tapes made of collimated fibres embedded in a partially cured resin [2]. Such pre-impregnated tapes, known as prepreg, are referred to as a semi-product in the sense that whilst they are manufactured from fibres and resin, they must undergo a further manufacturing operation whereby they are transformed into a PMC part or structure. Consolidation is ideally conducted in an autoclave, where stacks of uncured prepreg tapes under vacuum are subjected to strictly prescribed profiles of applied positive pressure and temperature; prepreg stack consolidation and cure typically last from 3 to 6 hours depending on the materials. Structural PMC laminates typically feature fibers oriented along different directions to endow the laminated component with the stiffness and strength needed along load paths expected in service.

Manufacturing PMC components from pre-impregnated tapes, or prepreg, leads to components that may be specified with relatively tight dimensional tolerances and offer reproducible performance. However, this manufacturing route is labour intensive and expensive, with limited throughput. Prepreg is produced as rolled stock; inhibiting resin cure requires that it be stored in freezers. Consequently, manufacturing PMC parts requires that prepreg rolled stock first be thawed whilst bagged under vacuum to preserve it from water condensation. Once prepreg is thawed and unrolled, numerous pieces of different shapes must be cut and carefully laid at set positions and along prescribed orientations on a moulding tool. Whilst cutting is typically automated, laydown often remains a manual operation. Furthermore, vacuum pre-consolidation must be conducted every 3 to 4 plies to

ensure the removal of any entrapped air in an operation known as de-bulking. Prepreg stacking operations are labour intensive and costly [3], with autoclave manufacturing further adding to costs [4]. As a result, the aerospace industry is seeking PMC manufacturing processes that may enable the production of PMC parts and structures offering dimensional accuracy and performance reproducibility similar to those obtained from prepreg-based processes, at reduced cost.

The expression liquid composites moulding (LCM) designates a group of PMC manufacturing processes [5-6] alternative to prepreg-based consolidation, that can enable the manufacturing of high quality, reproducible high performance PMC parts near net-shape in a series of operations that are less labour intensive and significantly more flexible. Fundamentally, in LCM processes a dry reinforcement is contained in a closed cavity and infused with a liquid polymer resin, with resin cure occurring mostly after infusion has completed. LCM processes enable the manufacturing of near net-shape PMC parts, or parts that require only limited trimming as LCM moulded PMC parts take the shape defined by the volume of the closed cavity into which they are manufactured. They can be made less labour intensive as the need for laying a large number of cut pieces of thin prepreg tape is avoided. Finally, LCM processes are significantly more flexible in the sense that contrary to prepreg-based manufacturing routes where in practice the nature of fibres and resins are largely dictated by prepreg suppliers and prepreg availability, with LCM the process engineer may select his or her fibres and resin at will. Cure issues prior to PMC manufacturing are avoided along with concerns over semi-product shelf-life or the need for cold storage.

Different variations to LCM exist. Resin transfer moulding (RTM) uses a rigid mould made of two or more pieces, and the resin is injected under positive pressure at one or more inlets. Vacuum-assisted resin transfer moulding (VARTM), also known as RTM-light or vacuum-assisted resin infusion (VARI), uses a lighter, more flexible shell typically made of 2 pieces. Resin is infused under vacuum applied at the outlet, from one or more point or line inlets where resin is at or slightly above atmospheric pressure. Vacuum infusion (VI) use a single-sided rigid mould referred to as a half mould. The textile reinforcement is laid on the half mould and enclosed under a sealed film. Resin is infused under vacuum applied at the outlet, from one or more inlets where resin is at atmospheric pressure. In all cases manufacturing starts with laying up a number of layered pieces of textile reinforcement most often made from carbon fibres. Carbon fibres are currently the best known and most widely used continuous reinforcement fibres for manufacturing high performance PMC parts and structures [7]. Their high specific properties, good overall mechanical performance and availability in many different textile forms make them ideally suited to aerospace applications where mass reduction plays a critical role towards more favourable aircraft operating costs [8].

Several aerospace application examples exist of PMC parts and subassemblies manufactured using different LCM processes such as the manufacturing of a main landing gear prototype using RTM for infusing a complex, net-shape assembly of thick pieces of carbon fibre textiles, Figure 1-1 [9]. Other examples include the manufacturing of the upper deck of a production helicopter using VARTM for infusing a single complex textile preform assembled from layered textiles and featuring integral stringers, Figure 1-2 [10]; of rear

pressure bulkheads using resin film infusion (RFI) for infusing net-shape assemblies of thin pieces of carbon fibre textiles with integrated stitched stiffeners, Figure 1-3 [11]; of jet engine fan blades using RTM for infusing dedicated net-shape 3D woven preforms featuring interlacing and yarn shedding, Figure 1-4 [12]; and of control surfaces using RTM for infusing complex, net-shape assemblies of thin pieces of carbon fibre textiles, Figure 1-5 [13].

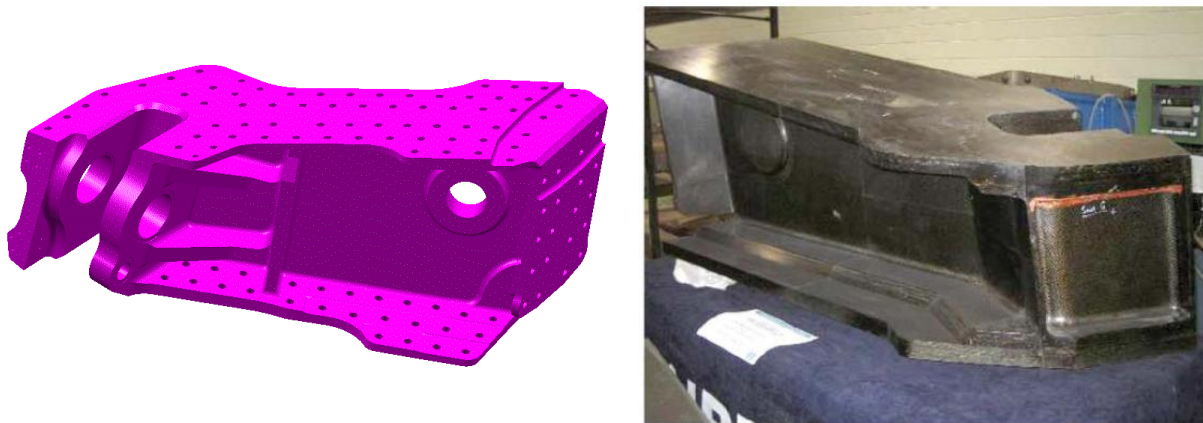


Figure 1-1: Main landing gear prototype manufactured using RTM [9].

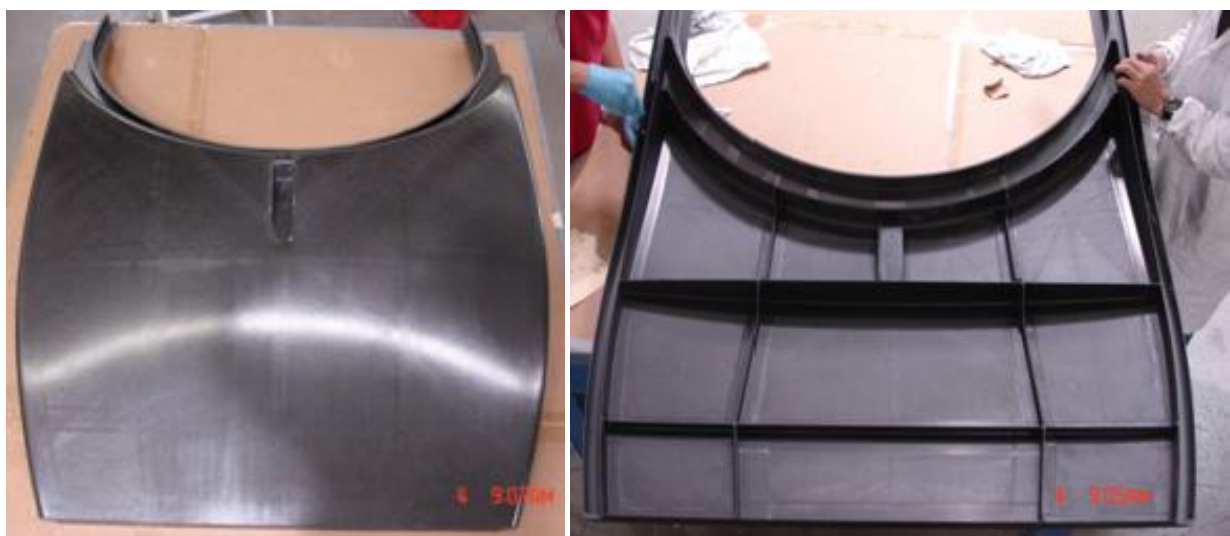


Figure 1-2: Helicopter upper deck manufactured using VARTM [10].

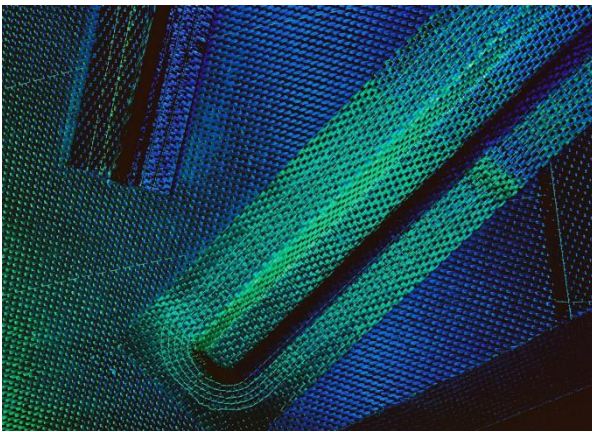
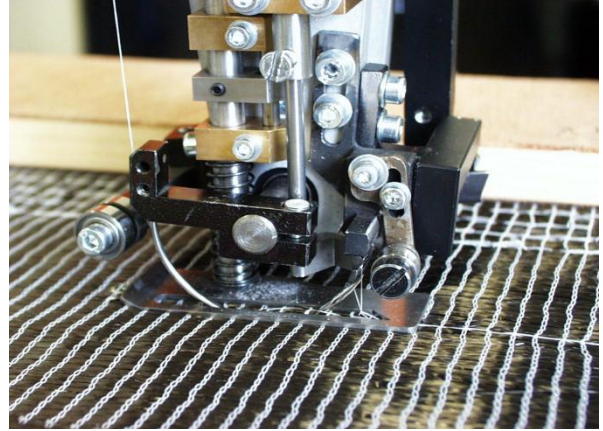
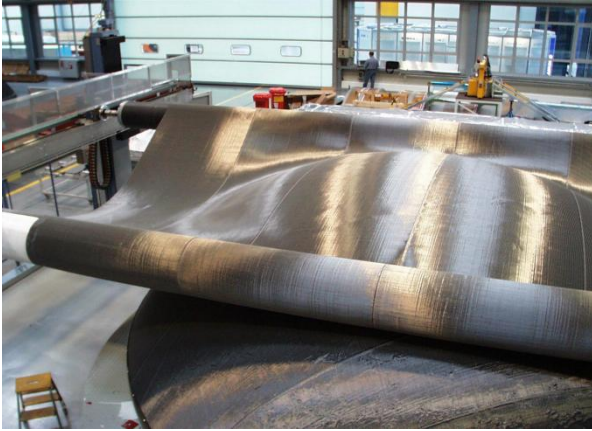


Figure 1-3: Rear pressure bulkhead manufactured using RFI [11].



Figure 1-4: Jet engine fan blade manufactured using RTM [12].



Figure 1-5: Control surface manufactured using RTM [13].

Textile reinforcements for PMCs are made by assembling reinforcement fibres, typically carbon, first into yarns featuring a few hundred to a few thousands individual fibres, and then into diverse textile forms through various textile processes including weaving, braiding, stitching and others [14, 15]. Textile reinforcements are typically cut into smaller pieces, stacked, draped and assembled into a dry assembly called a preform, the shape of which generally approaching that of the PMC part to be made. The type of textiles selected for making a preform and part will depend on many factors including part geometry, fibre orientations required for withstanding applied loads, and availability of reinforcements made from fibres that are certified for airworthiness. Most reinforcements are available as thin fabrics and most PMC parts are designed primarily as thin shells, hence PMCs have been used for decades in making relatively simple thin components that behave predictably as structural elements.

Manufacturing PMCs using LCM as opposed to a prepreg-based route provides more freedom in terms of reinforcement construction and possible fibre orientations. It also enables advanced reinforcement techniques, such as through-the-thickness fibres in the textile preform, much more readily. However, cutting and tailoring layers of reinforcement fabrics into smaller pieces, and then laying and stitching these textile pieces on moulds that may feature complex geometry with the accuracy and reproducibility required for aerospace applications remains a highly manual, time-consuming and expensive process that largely negates the competitive advantage associated with PMCs in general and LCM PMCs in particular [3]. Furthermore, the variability associated with preforms made through manual handling of many pieces of fabric is such [16-18] that in practice PMC parts must be over-designed, leaving designers to struggle in outperforming parts made of aluminium alloys which can be manufactured predictably, quickly and economically. Consequently, the aerospace industry has expressed strong and sustained interest towards obtaining textile reinforcements that are thick, manufactured near net-shape, and drapable to complex geometries. Such textile reinforcements are referred to as 3D preforms in this thesis; they should be designed individually for parts of specific geometries, manufactured in automated processes, and draped onto LCM moulds in a single, reproducible operation. They should also enable PMC consistency, reproducibility and high fibre volume fractions (v_f) as required of high performance PMC parts and structures, comparable to those obtained through autoclave prepreg-based manufacturing but achieved at lower cost [19].

1.2 Novel carbon fibre preforms

Manufacturing processes for advanced textile reinforcements that feature novel characteristics such as yarns oriented along the thickness, higher thicknesses that correspond to those needed for producing PMC parts from a single piece or layer of reinforcement, as well as complex shapes and near net-shape contours that correspond more or less closely to those of the PMC parts to be produced, are evolving very rapidly. Different textile solutions are being devised depending on the structural performance needed of each final PMC part, on the composite manufacturing process used for making a given PMC part, and most fundamentally on the shape of the specific part to be produced. Textile manufacturing processes are reviewed in this thesis. 3D weaving and stitching appear to offer the greatest potential amongst the more established and available 3D textile manufacturing processes, although yarn interlacing in the thickness reduces in-plane structural properties of PMC parts made from the former whilst the latter may lead to weaker interlaminar performance in PMC parts [19]. On this aspect, as with many others such as flexibility offered by different textile processes over in-plane yarn orientations, often the best compromise must be found.

A novel, patented textile reinforcement manufacturing technology aiming at producing thick, net-shape, drapable, high v_f textile reinforcements used toward manufacturing aerospace PMCs is being developed at the University of Ottawa. The technology, referred to in this thesis as University of Ottawa advanced preforming technology (uO-APT), enables the manufacturing of flat, drapable multilayered near net-shape preforms featuring steered yarns assembled by directional stitching, Figure 1-6 [20, 21].

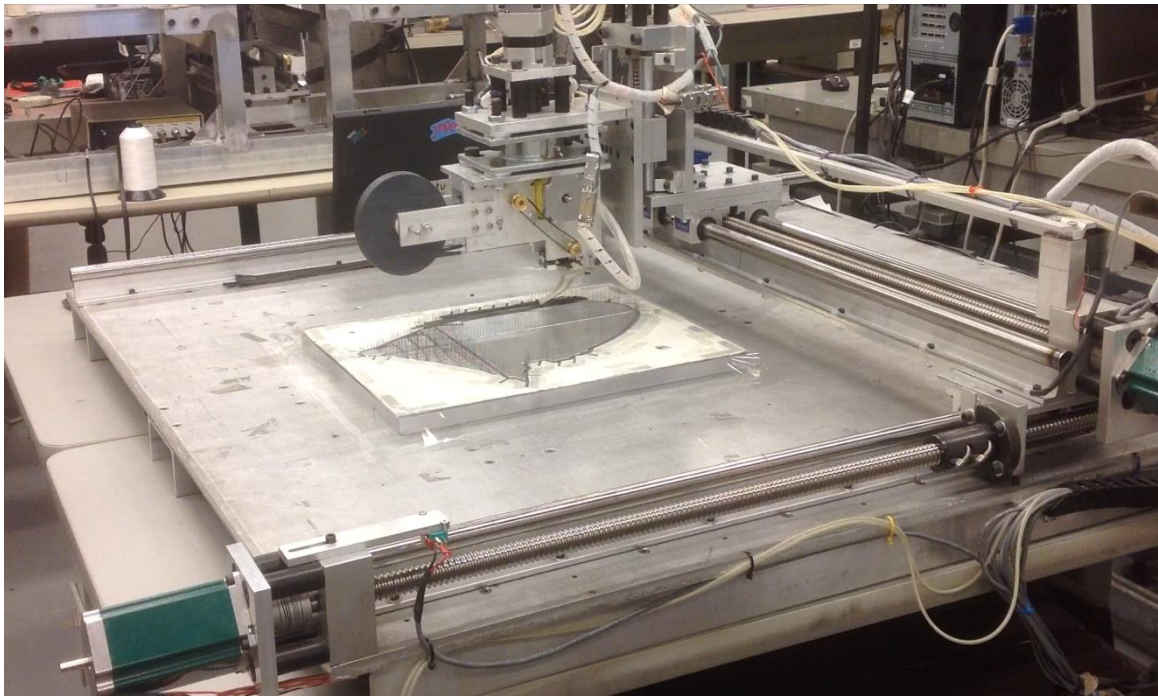


Figure 1-6: u0-APT prototype manufacturing equipment for laydown (top) and stitching (bottom) [21].

Preform manufacturing consists of two main operations, namely yarn laydown and stitching. The target part geometry for uO-APT preforms is shells of varying thickness and complex geometry featuring double curvatures and tight bending radii. Preforms for such parts typically involve the manual assembly of many small, stacked pieces of fabrics; uO-APT enables the manufacturing of preforms made from a single or few, generally net-shape and final thickness textile pieces designed and made specifically towards a PMC part of known geometry. uO-APT preforms are manufactured flat and drapable, enabling straightforward adaptation of the manufacturing equipment for producing preforms for parts of different geometries. Construction makes the preforms capable of undergoing large in-plane shear strains where this is mandated by double curvatures in the PMC part geometry. Yarns in a flat preform can be oriented locally to optimize drapability, processing properties such as the permeability, or the structural behaviour of the PMC part.

The above characteristics of uO-APT preforms are achieved by constructing the preforms as layers of yarns that are mostly parallel but not necessarily straight, and stitching all layers along the yarn paths in a single operation, Figure 1-7. It should be noted that the process does enable some level of inter-layer, interlaminar yarn interlacing. Limitations to yarn paths within a layer are twofold: first, inter-yarn spacing can only vary between set bounds to avoid resin-rich zones in the PMC part; second, yarns can only steer around relatively large radii to avoid buckling. Yarns in uO-APT preforms are not straight hence they cannot be tensioned as in usual textile processes; this makes uO-APT very distinct with fundamental work needed towards quantifying dry yarn and fabric behaviour.

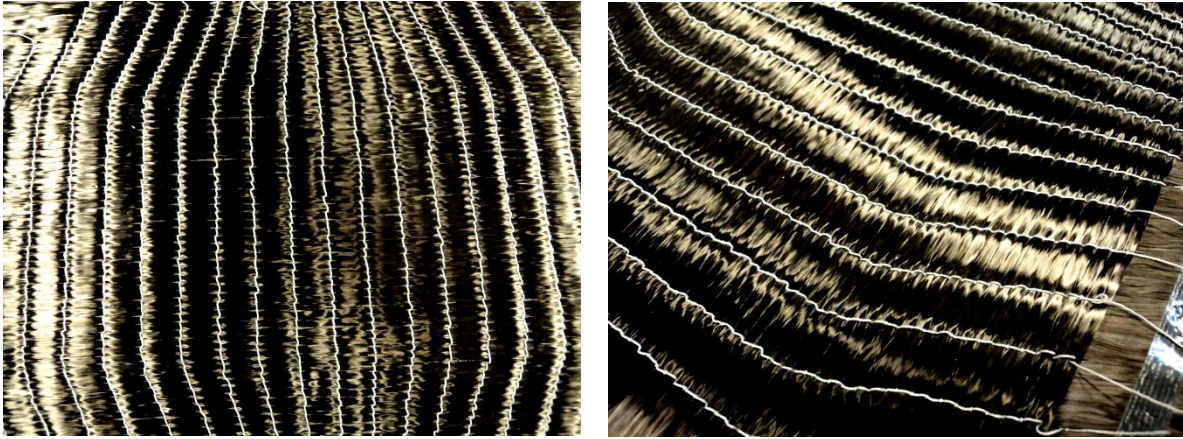


Figure 1-7: Early carbon preforms made using the uO-APT manufacturing process.

Once a first layer of yarns is laid it is followed by a second layer featuring different yarn orientations and paths. Preform thickness is built by laying successive layers. Whilst a uO-APT preform should feature at least 2 yarn orientations at every point for cohesion, only these 2 yarn orientations may be repeated in the different layers over zones of the preform that are to be draped onto doubly curved zones of the part, as draping from a flat configuration requires large in-plane shear deformation of the preform. On the other hand, yarns and stitches may follow any number of orientations over zones where the preform will stay flat or undergo single-curvature bending only. The unique capabilities for adapting yarn orientations to part geometry and draping requirements and for producing a multi-axis structure where appropriate, coupled with the possibility for through-thickness yarn interlacing and yarn drop-off anywhere in the preform, makes uO-APT preforms more flexible and closer to industrial needs than say 3D woven textiles, especially in terms of yarn orientations.

Typical reinforcement textiles or stacks of reinforcement textile layers thicker generally than one millimetre tend to show different behaviour when subjected to in-plane shear and bending, restricting their ability towards forming and draping and so limiting the range of PMC part geometries that may be manufactured from such textiles. Furthermore, the bending behaviour of thick, dry reinforcements is poorly documented in the open literature, adding an additional roadblock for designers wishing to introduce such reinforcements in actual PMC structures. Therefore, advances in preforming technologies in general, and in the understanding of the mechanical behaviour of thick textile reinforcements upon bending and shearing are critically needed towards reliable, efficient and economical production of PMC parts using LCM processes [19]. This thesis addresses this critical requirement through extensive testing and analysis of uO-APT textiles, and by comparing the results with those obtained using commercially available carbon fibre textile sourced from a leading supplier of dry reinforcement to the aerospace industry, in configurations directly comparable to those used in testing uO-APT textiles.

As reinforcement textiles are bent and sheared, buckling and wrinkling must be avoided as such deformation modes are highly likely to impact negatively the structural load-bearing properties of the finished PMC part. Contrary to thin fabrics, 3D preforms cannot be assessed and verified reliably through visual inspection of their external surfaces because of the thickness of the reinforcements and opacity of the fibres. Therefore, non-destructive inspection methods must be devised for enabling the detection of defects within preforms that may be induced upon bending and shearing. Alterations in textile architecture and general yarn configuration must be documented through means that can be used in actual

practice over complete preforms. Non-destructive inspection methods for PMCs were the subject of much research work conducted over decades. However, no such work has been published in the open literature, dedicated to the use of such methods for inspecting dry carbon fibre textile reinforcements and preforms devoid of a polymeric matrix. This thesis addresses this issue by investigating a pragmatic infrared-based technique that may be developed towards use in industrial production.

1.3 Contributions of the thesis

Several original contributions are made and embodied in this thesis. The most outstanding contributions can be summarized as follows.

- The behaviour of novel 3D carbon fibre textile reinforcements was investigated and defined by comparing its most critical elements upon draping, namely the bending behaviour and in-plane shear behaviour, with those of equivalent stacks of 2D industrial carbon fibre textile reinforcements commonly used in aerospace PMC manufacturing.
- The bending behaviour of such novel 3D reinforcement textiles is of great importance towards manufacturing advanced aerospace composites parts of complex geometry and it must be investigated to understand and define the behaviour of such thick fabric reinforcements when formed into required shapes. A bending apparatus was devised and developed to investigate the bending behaviour

of these novel thick reinforcement fabrics. Then, numerous bending tests were conducted through systematic variation of testing parameters, analysed, and compared.

- The in-plane shear behaviour of the novel 3D reinforcement fabrics is similarly of great importance towards manufacturing advanced aerospace composites parts of complex geometry. In-plane shear testing of thick fabric reinforcements using an articulated frame shear rig was investigated, as further development to tests typically conducted on thin fabrics only. Numerous in-plane shear tests were conducted through systematic variation of testing parameters, analysed, and compared.
- The non-destructive inspection of thick, dry textile reinforcements using infra-red imaging was investigated and used for identifying flaws and defects in thick, dry carbon fibre textile reinforcements, which may be used in increasing the quality and reproducibility of the final PMC parts made from these reinforcements. Imaging results generated using comparable stacks of 2D industrial fabric reinforcements commonly used in aerospace PMC construction were compared against the results generated using uO-APT reinforcements.

1.4 Thesis overview

The aforementioned subjects are developed and documented in this thesis as separate chapters, where each chapter features a literature review that covers the relevant subject matter. References appear as a unified list at the end of the thesis.

Chapter 2 provides a review of general background literature covering the different types of 3D reinforcement textiles, along with current developments being made regarding 3D reinforcement textiles.

Chapter 3 opens with a literature review on the bending behaviour of thick, dry textile reinforcements and covers aspects related to the bending apparatus devised in this work along with bending tests conducted. Numerous uO-APT and industrial reinforcement stack samples were tested using the bending apparatus purposely built, with results compared with those obtained using industrial reinforcement fabric stacks that featured similar fibre volume fractions and surface densities as well as yarn and stitch orientations. Results are analysed using selected metrics defined in the chapter.

Chapter 4 covers the topic of the in-plane shear behaviour of the uO-APT and industrial reinforcement fabrics. The chapter opens with a literature review on in-plane shear and covers all tests that were conducted on the novel 3D reinforcement and stacks of 2D industrial reinforcement textiles. Results obtained from characterising both sets of reinforcements are compared. Results are analysed using selected metrics defined in the chapter.

Chapter 5 opens with a review of selected literature pertaining to non-destructive inspection methods and inspection methods for textiles. The chapter introduces the innovative use of infrared thermal imaging for identifying defects in thick, dry carbon fibre reinforcements. The method is highly innovative, in that it applies to dry reinforcements as opposed to consolidated PMC parts. Furthermore, it uses simple equipment and as such it is highly portable and transferable to an industrial context. The chapter discusses the need for such a non-destructive method to be used on thick reinforcements prior to the production of final PMC parts of reproducible quality and behaviour.

Chapter 6 provides a synthesis, discussion and conclusion pertaining to the topics covered in the thesis, along with guidance regarding work that should be considered afterwards.

Chapter 2

Literature review on advanced textile reinforcements and preforms

2.1 Textile reinforcements

The architectures of textile reinforcements and preforms made from continuous fibres vary from basic unidirectional 1D yarns to very complex, intricate 3D assemblies of different types of textiles [3, 22, 23]. Wambua *et al.* [14] reviewed research work conducted on advanced textile preforms for PMC applications. The authors classified reinforcements for composites into 1D, 2D, 2.5D and 3D preforms, whereby 2.5D preforms identified planar thick reinforcements featuring yarns running in the plane of the fabric only, whilst 3D reinforcements preforms identified reinforcements taking more complex shapes and/or featuring yarns extending out of a plane defined by the orientations of a majority of yarns in the preform. Fukuta *et al.* [24] classified textile reinforcements based on significant

dimensions of the materials and their specific geometries, whilst Scardino [25] classified textile reinforcements into 4 groups as discrete reinforcements, continuous reinforcements, reinforcements with planar geometry and reinforcements with spatial geometry. Beyond 1D reinforcements i.e. yarns and rovings, most reinforcement were found to be manufactured through weaving processes although 3D performs may be manufactured using various forms of weaving, braiding, knitting, stitching and combinations thereof [12, 22, 23, 26]. Understanding the structure and configuration of a dry textile and its effects on the constitutive behaviour of the dry reinforcement is of great importance [27] as they have major influences on PMC manufacturing operations, and thus on the properties, performance and cost of the final PMC parts made from these reinforcements.

Thin 2D textile reinforcements are available in continuous rolls as weaves featuring diverse yarn interlacing patterns; the most common are plain weaves, twills, and 4-harness, 5-harness and 8-harness satins. Unbalanced unidirectional woven fabrics are also available where load-bearing weft yarns interlace with light warp yarns, typically made of thermoplastic fibres and used for assembly only. Such construction reduces crimp in the load-bearing yarns and improves overall in-plane stiffness and strength of the composite. Thin 2D textile reinforcements can also be made by superimposing 2 or more layers of parallel non-interlaced load-bearing yarns and assembling them using either warp-knitting or stitching. Straight load-bearing yarns devoid of crimp impart superior in-plane properties to the composite but penetration of knitting or stitching needles through yarns can induce gaps or damage in the textiles. Reinforcements available as continuous rolls are

well adapted to the construction of simple shells, either flat or gently curved, as they drape and bend well. On the other hand, bi-axial and tri-axial 2D continuous braids are better suited to the production of tubes; continuous tubular braids can also be collapsed into diverse profiles such as hat sections, L-beams or I-beams. In the case of thin parts, geometry largely dictates the best suited textile type.

Constructing textile preforms for more complex or realistic parts featuring thick sections, integral ribs or flanges and/or assemblies of intersecting shells or other similar features requires 3D and/or net-shape textiles. Designing and manufacturing such textiles demands thorough consideration of the shape of the part, and eventual alterations to the shape aiming at better accommodating preform construction. Mouritz *et al.* [22] reviewed applications of three-dimensional preforms for PMCs made by weaving as discussed in forthcoming Section 2.2, braiding as discussed in forthcoming Section 2.3, as well as stitching and knitting as discussed in forthcoming Section 2.4. The review shows that 3D woven composites have largely failed to replace laminates in most aerospace structures. One main issue is the inability of producing 3D woven fabrics containing in-plane yarns aligned along orientations other than 0° and 90° . According to the authors, this limitation restricts 3D woven fabrics to configurations leading to orthotropic properties in PMCs, which are unsuitable for many aircraft structures where either quasi-isotropic material properties remain sought, or yarns oriented at $+45^\circ$ or -45° are required along with yarns oriented along 0° and 90° . In general, the authors observed that 3D woven composites must overcome a number of technical, scientific and economic challenges before becoming acceptable to the aerospace industry. It should be noted that very recent industrial

developments were made that claim to remove partially this restriction on orientations for profiles produced by 3D weaving [29].

With regards to 3D braided composites, the same review [22] found that applications of such preforms and their composites have also been limited. One major reason is limitations in preform size that may be realistically manufactured, determined by the dimensions of typical braiding machines. For typical aerospace structures, extremely large and expensive machines are needed for producing preforms that are sufficiently large for justifying the use of 3D fabrics as opposed to regular fabrics. Another limitation of 3D braided preforms and PMCs is that many 3D braiding machines are slow and have very long set-up times. The review also mentions that stiffness and strength of 3D braided PMCs are generally low as most braided tows are off-axis from loading directions, and they are heavily crimped. However, the review indicated that engineers at NASA Langley deemed it worthwhile to assess the potential use of braided composites in stiffeners and stringers for aircraft wings, and in circumferential frames for aircraft fuselages.

Highly complex preforms are often made by assembling different types of textiles prior to liquid resin infusion using techniques such as stitching, as specific textile forms will be best suited to specific geometries and desired fibre orientations. For example, the reinforcement for a tube which is to be subjected to torsion may be best realised using simple 2D braiding. If a plate or shell geometry is adjacent to said tube within a more complex PMC part, this second section may be realised using traditional woven textiles with stitching and overlaying used for assembling the tubular and planar sections into a complete, complex

dry preform to be injected with liquid resin in a single PMC manufacturing operation, Figure 2-1 [30].

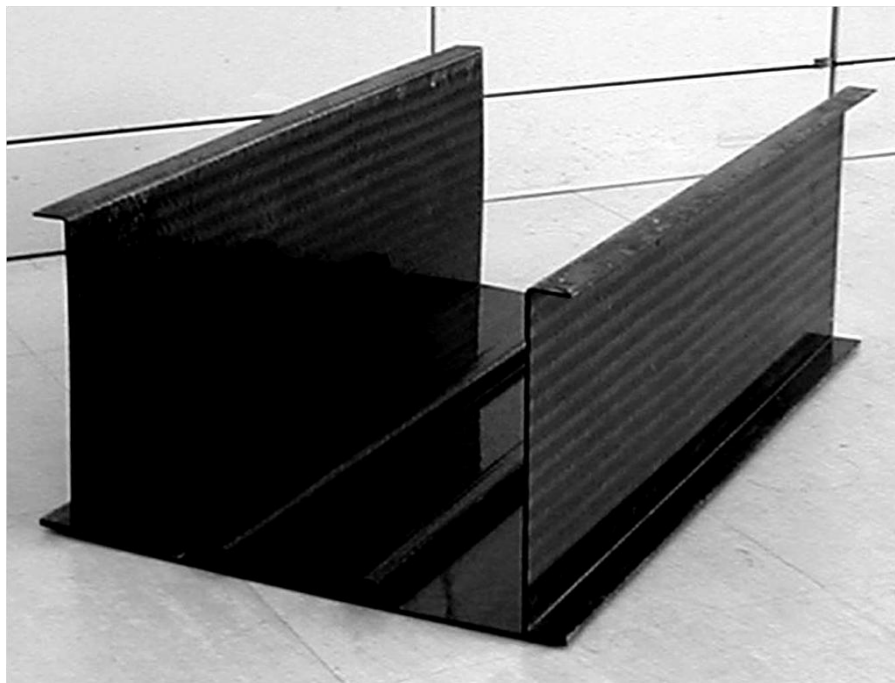
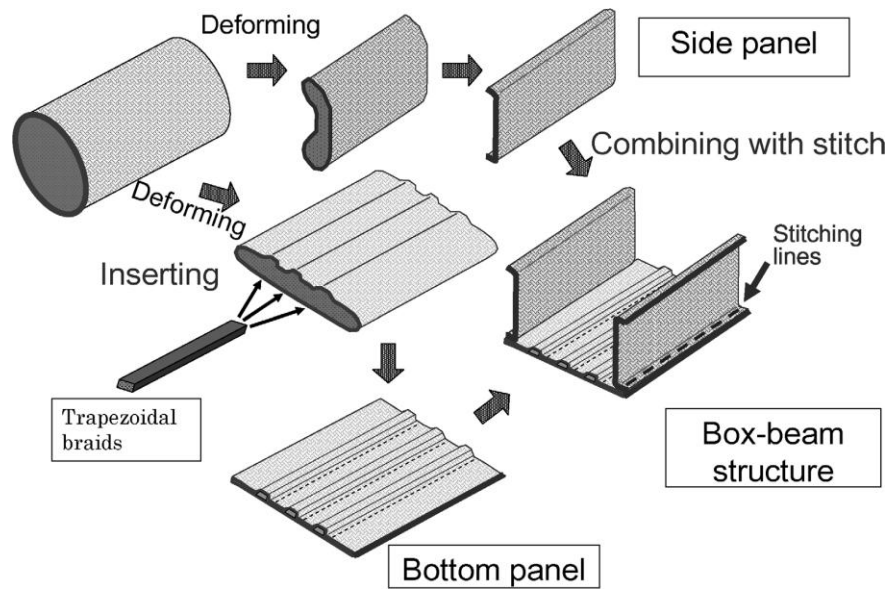


Figure 2-1: Complex preform assembled by stitching; preform assembly process (top) and final part (bottom) [30].

2.2 3D woven reinforcements

Woven reinforcements are fabricated by interlacing warp yarns in the textile direction with weft yarns running typically at 90° from the textile direction. The terminology 2D weaves typically refers to relatively thin reinforcements where one layer of parallel warp yarns interlaces with one layer of parallel weft yarns, whilst 3D weaves feature more yarn layers with more or less extensive interlacing. Typical types of 2D woven architectures are shown in Figure 2-2.

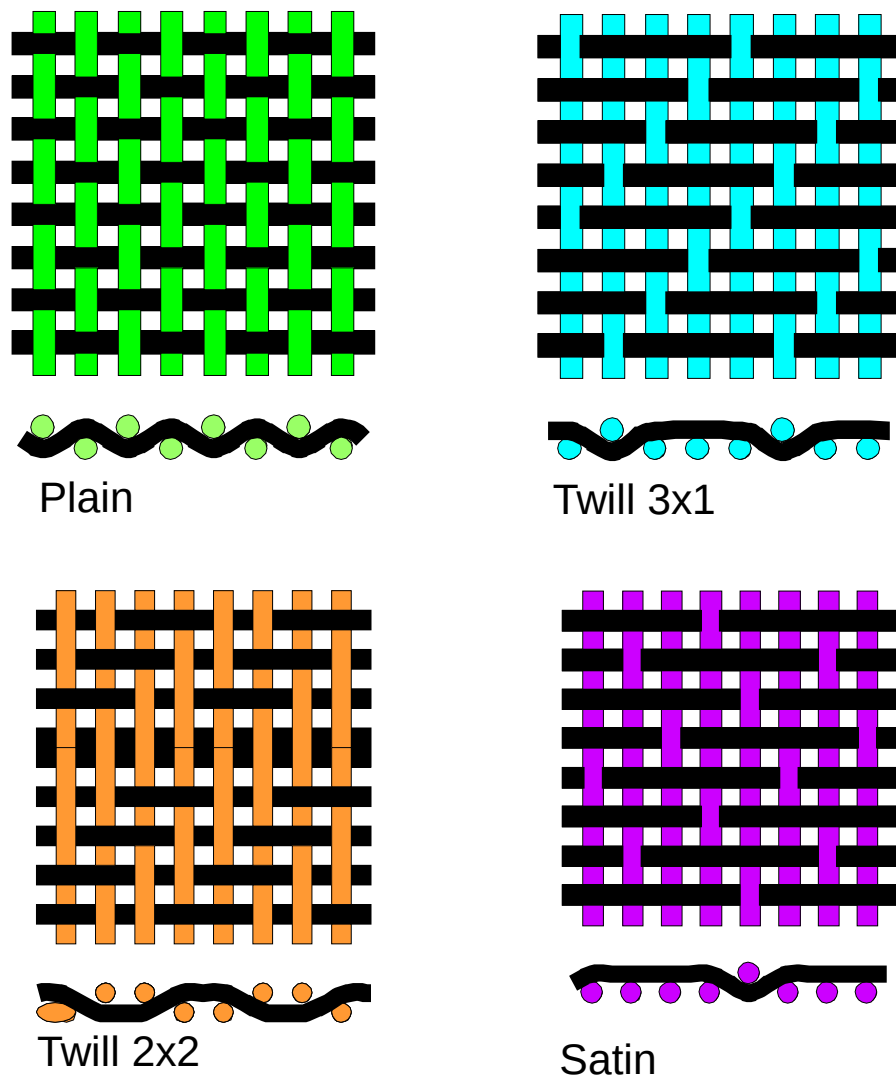


Figure 2-2: 2D woven architectures.

3D weaving extends the 2D process by integrating superimposed layers of yarns with diverse degrees of interlacing with yarns extending along the thickness, known as z-yarns [31-40]. Z-yarns are typically used as binders [41] or structural in warp-interlock structures [37]. The reinforcements are mostly woven as thick slivers or wider sheets where machinery capability is available; however, specific geometries such as domes were also made [42-45]. The availability of further complex shapes enabled by mechanisms such as yarn shedding is sustained through ongoing developments in weaving machinery [46-54] with some attention given to fibre damage [55, 56]. The processes aim at producing thick fabrics with high fibre volume fractions (v_f) or fabrics that can be compressed to high values of v_f [57-59]. As 3D weaves are mostly produced flat, their deformability through bending and shear is also important to preforming [60-62]. PMCs made from 3D weaves are the most studied of composites featuring advanced textile reinforcements, with a good body of data on the mechanical properties of the composite materials [63-75] including compression [76], through-thickness [77], high rate [78] and fatigue [79] behaviour. Whilst z-yarns can represent less than 10% of fibre mass, PMC inter-laminar shear strength (ILSS) and impact properties tend to be superior to those of traditional laminates, at the expense of in-plane stiffness.

Multilayer woven fabrics, generally known as 3D woven fabrics, are fabricated by interlacing several series of warp yarns and weft yarns to assemble layers that extend one above the other [80]. The fabrics produced can be woven as thick textiles with a fibre density that is essentially constant along the thickness, or they can feature horizontal gaps between some layers. The layers may be bound together by interlacing warp yarns with the

weft yarns of adjacent layers. Such interlacing is referred to as angle interlock 3D weaving as shown in Figure 2-3, left. When warp ends interlace with the face and back filling layers, the textile is referred to as a warp interlock 3D weave as shown in Figure 2-3, right [81].

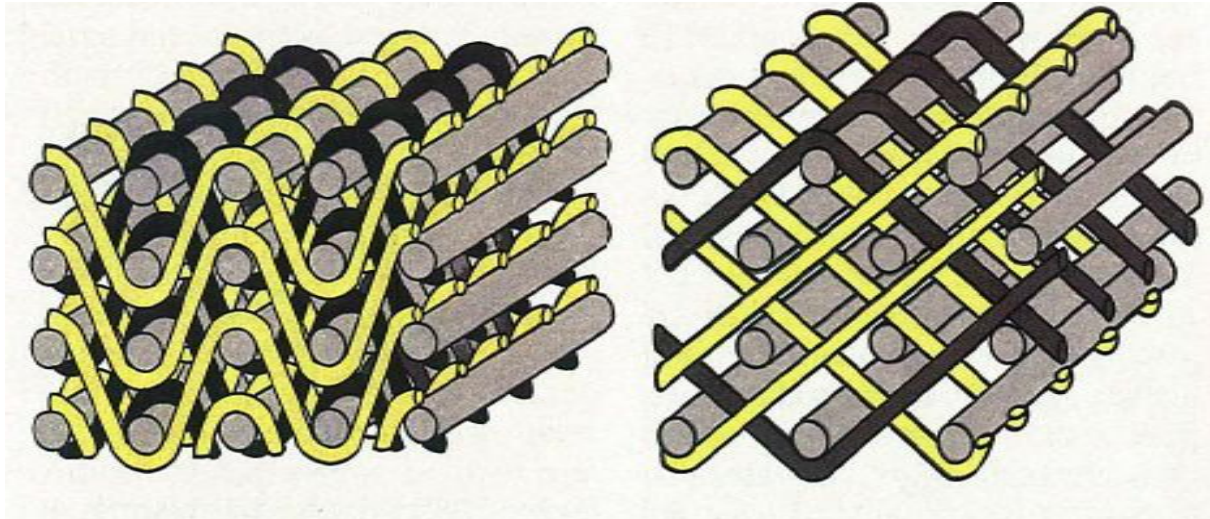


Figure 2-3: 3D interlock woven architectures: angle interlock (left), warp interlock (right) [81].

Another type of 3D woven fabric produced by interlacing wrap yarns or binder yarns in the through-thickness direction is illustrated in Figure 2-4 [82]. Orthogonal 3D weaving can be done using machines designed specifically for that purpose but such machines are usually very costly and proprietary. Generally, more work is required towards innovative 3D preforms to achieve greater availability and use. As seen in the figures, the architectures produced by such 3D weaving leads to substantial levels of interlacing and yarn crimp [81].

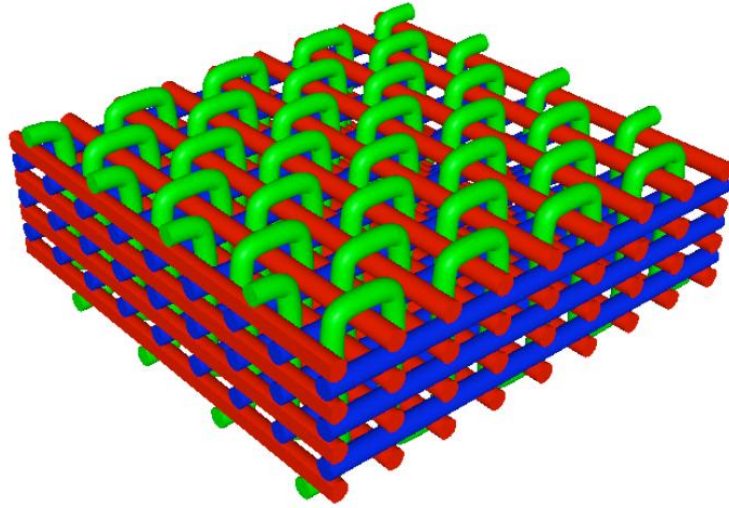


Figure 2-4: Orthogonal interlock woven fabric used in 3D woven composites [81].

Chen *et al.* [83] provided a comprehensive overview of fabrication methods for 3D woven preforms. Their study shows that 3D woven fabrics may be made through two main groups of methods. The first group of methods uses conventional weaving technology. The second group of methods involves special weaving devices. The availability of such devices, which are diverse in nature, is very limited due to cost. The authors noted that all warp and weft yarns in woven preforms are crimped, leading to relatively low initial moduli in PMC parts subjected to tensile loading along the warp and weft directions.

Mohamed *et al.* [84] conducted a comparative study on the fibre architectures and mechanical properties of 3D woven preforms manufactured using different processes and machines. The study concluded that different textile processes and machines may lead to very different 3D woven preforms with very different fabric architectures, resulting in composite parts featuring vastly different properties. This was validated in a comparative experimental study of 3D interlock weave and 3D non-crimp weave composites [85, 86].

Bilisik [87, 88] developed multi-axial 3D woven preforms made from five yarn sets. It was found that additional sets of yarns increased the modulus and in-plane shear strength of the resulting PMC structure, but decreased its bending and inter-laminar shear strengths when compared to a PMC structure made from 3D orthogonal woven reinforcement. The author showed that yarn orientations in 3D woven reinforcements greatly influence the mechanical properties of the resulting PMCs, and that the structure of such textiles must be optimised based on the intended use of the PMC part.

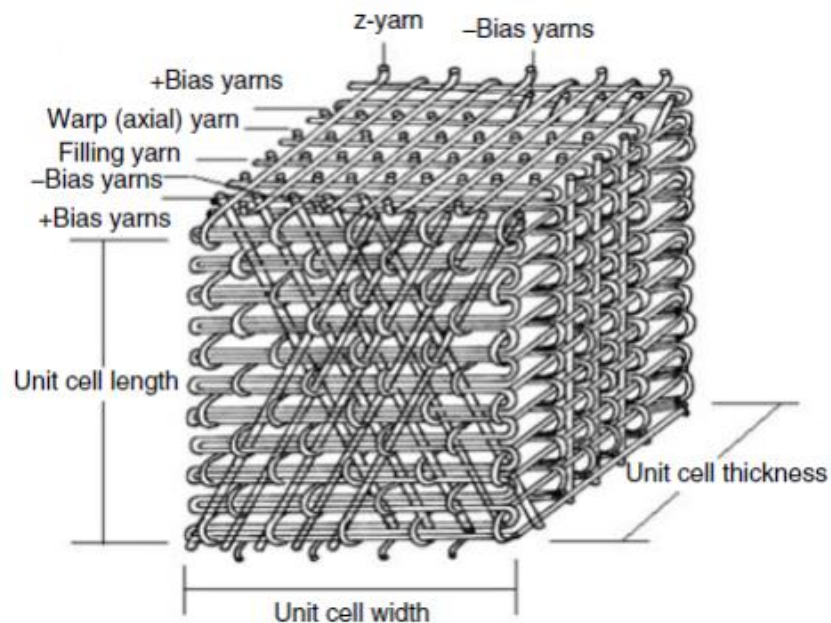


Figure 2-5: Multi-axial 3D woven preform unit cell [87].

Although 3D weaving has the potential to reduce lay-up and assembly costs in PMC fabrication there are major limitations preventing 3D woven preforms from replacing 2D laminates in most composite components. The high cost of production and certifying of such 3D woven textile reinforcements, and PMC parts made from them, impede them from being used widely in primary load-bearing structures in the aerospace industry.

2.3 3D braided reinforcements

2D braiding is a method of interlacing yarns into fabrics which features many similarities to weaving in terms of the textile structures produced. The most common version is biaxial 2D braiding, where two sets of yarns move along intersecting circular paths in opposite directions to form a tubular interlaced fabric. As shown in Figure 2-6, 2D axial braids are classified as diamond braids (left), regular braids (center), and Hercules braids (right) depending on the yarn interlacing patterns corresponding to plain, 2/2 twill and 3/3 twill weaves respectively. If a third group of axial yarns is inserted through the centers of bobbins carrying the interlacing yarns of biaxial 2D braids, a triaxial 2D braid is created as shown in Figure 2-7 [89].

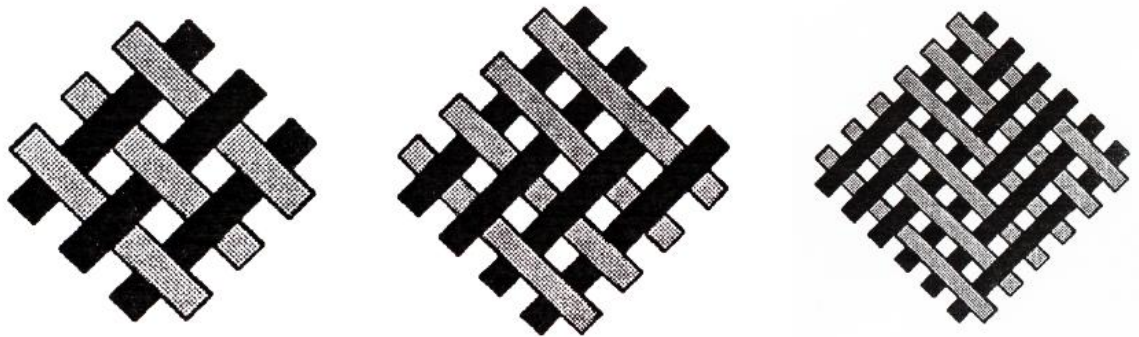


Figure 2-6: 2D axial braid types: diamond (left), regular (center) and Hercules (right).



Figure 2-7: Triaxial 2D braid [38].

Advanced preforms made from braided reinforcements often consist of relatively involved assemblies of simpler tubular or circular braids used as profiles or on cores on one hand [30, 90-93], or of flat braided preforms made to final shape in more complex processes [94]. The latter enable stronger departures from structural properties [95-97] typical of thin reinforcements [98] through more extensive interlacing through the thickness of parts.

3D braiding is very different from 2D braiding. In this process many yarns interlace in a much more extensive way, typically creating a specific cross-sectional shape [22, 28, 30]. Whereas traditional 2D braiding techniques cannot make thick-walled structures, this advanced braiding technique was developed in order to manufacture profiled, thick-walled 3D braided preforms [22]. Bogdanovich *et al.* [89, 99] introduced a novel 3D rotary braiding process which can produce different types of thick cross-sections such as rectangles, I profiles, T profiles, L profiles and other similar constant sections as shown in Figure 2-8.

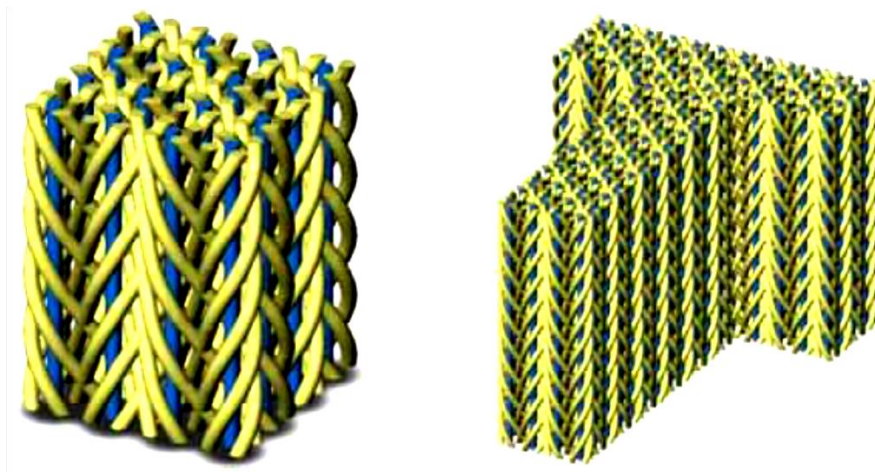


Figure 2-8: 3D braided square profile and T- shape profile [89].

Branscomb *et al.* [100] provided a general review on the history and evolution of braiding [101-105]. The work also reviewed braiding machinery and engineering developments related to braiding design and manufacturing, and revealed several new developments such as a machine vision system to control conventional braiding and a machine that is capable of producing true triaxial braided fabric architectures. Usually, machines used in 3D braiding processes are slow and very expensive to manufacture, and so they are often designed for producing very specific aerospace parts where cost is not an issue, Figures 2-9 and 2-10 [106-108].

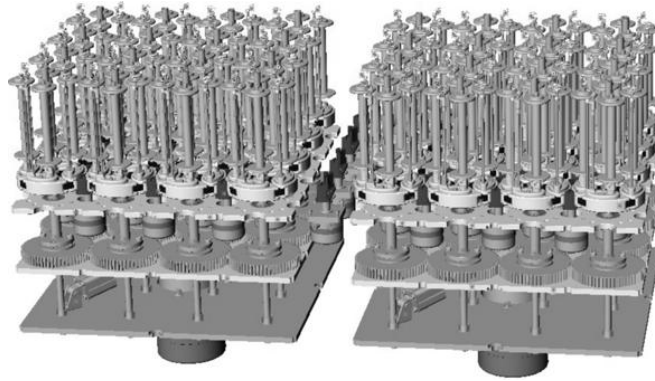


Figure 2-9: 3D braider devised by D. Mungalov and A. Bogdanovich [99].



Figure 2-10: An example of a 3D braiding machine [108].

2.4 3D knitted reinforcements

Mentions in the literature of knitted reinforcements pertaining to PMC parts most often refer to thick non-structural knits with in-laid load-bearing yarns [109-111], generally known as non-crimp knitted fabrics (NCFs). These are essentially thicker versions of 2D knits or stitched fabrics with in-laid straight load-bearing yarns, often labelled 2.5D fabrics in the literature. Work on spacer fabrics with or without load-carrying yarns [112, 113] and on actual knitted fabrics – warp-knits, weft-knits or circular knits – where the knitted yarns carry loads is also reported. Examples of applications of such fabrics to net-shape composite parts appear in [114]. The main advantage of knits resides in their very high conformability [115]; however, their limited maximum v_f and low structural properties [116] make them largely unsuitable as reinforcements for structural composites.

Knitting may not at first appear to be a manufacturing technique best suited to the production of reinforcements for structural composite components, and it is arguably the least used and understood of the classes of textile processes described in this chapter. However, knitted carbon fabrics that can be produced on standard industrial knitting machines have particular properties that potentially make them ideally suited for certain composite components [22].

Knitted preforms where load-bearing carbon yarns are actually knitted have good formability, but PMC parts made from such reinforcements are characterised by low fibre volume fraction (v_f) as well as low strength and stiffness compared with PMCs made from woven reinforcements. Traditional warp-knitting and weft-knitting process are available

for manufacturing reinforcements for composite structures; this can be achieved using standard industrial knitting machines. In such cases a more flexible fabric is produced using either warp-knitting where yarns extend along fabric length and multiple yarns cover the full width of the fabric, or weft-knitting where yarns extend along fabric width and one yarn covers the full width of the fabric as shown in Figure 2-11.

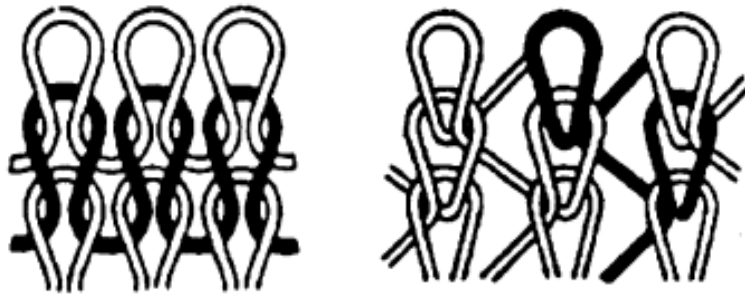


Figure 2-11: Weft-knitting process (left); wrap-knitting process (right) [22].

Alternatively, these same types of knitting processes may be used for knitting lightweight, non structural yarns used for assembling superimposed and non-interlacing layers of straight and parallel load bearing yarns, enabling high fibre volume fractions in these non-crimp, load-bearing yarns leading to 2D non-crimp fabrics.

The potential, manufacturing and mechanical properties of structural composites made from such knitted fabrics were reviewed in the literature [111, 114, 117-120]. Leong *et al.* [114] provided a review on the current state of knitting technology for manufacturing advanced reinforcement, fully knitted composites. The review concludes that most efforts towards applications remain conceptual with more investigation needed for improving the correlation between theoretical and experimental measurements. On the other hand, NCFs

have become increasingly popular as PMC parts made from such reinforcements exhibit better in-plane mechanical properties than those made from comparable weaves due to the absence of crimp. However, NCFs remain 2D reinforcements and suffer from the associated limitations.

3D knitted fabrics are basically produced using processes that derive from warp-knitting or weft-knitting, interlocking of one or more yarns through a series of loops. They are considered 3D due to the non-planar configuration of loops in the structure.

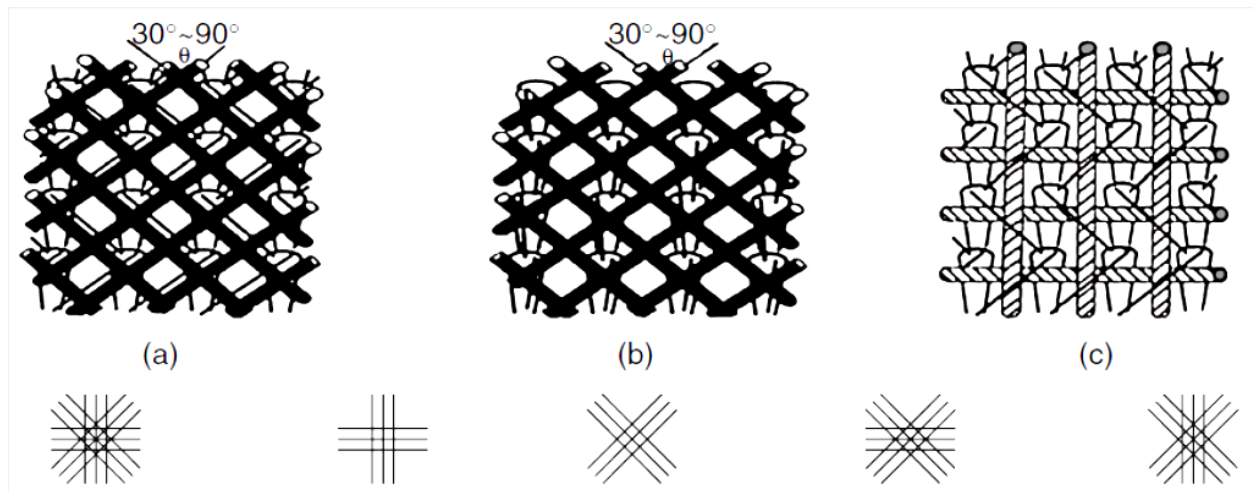


Figure 2-12: Knitting with insertions [121].

3D weft-knitted structures feature some characteristics undesirable for composites such as low packing density and low fibre volume fractions compared to 3D wrap-knits. Generally, both types are at laboratory development stage and the mechanical properties of PMCs made from these 3D knitted fabrics are low with some of them remaining unpredictable due to the complexity of such fabrics [121]. Also, upon infusion the non-linearity of knitting loops and severe bending of yarns during the knitting process lead to the formation of resin

pockets within knitting loops in PMC [122]. For these reasons, neither 2D nor 3D knitting can be seen as alternative processes for producing advanced structural reinforcement performs aimed at composite parts for structural applications.

2.5 Non-crimp fabrics

PMCs are made by assembling reinforcement fibres into textile forms. PMCs have been used for decades to make simple components which are efficient and reliable [123-125]. However, manufacturing remains highly manual, time-consuming and expensive, most notably for textile preforming aspects [126]. The aerospace industry has expressed interest towards thick, net-shape, drapable textile reinforcements herein referred to as 3D preforms that can be used in manufacturing aerospace composite parts using one of the liquid composite moulding processes. Non-crimp fabrics NCFs have the potential to be used in manufacturing next generations of composite materials [127]. Non-crimp fabrics are manufactured by laying one or more layers of parallel crimp-free fibres that are assembled by means of stitching, knitting or bonding.

Knitted NCFs can be made by warp knitting or weft knitting and may be uniaxial, biaxial or multiaxial as shown in Figure 2-13.

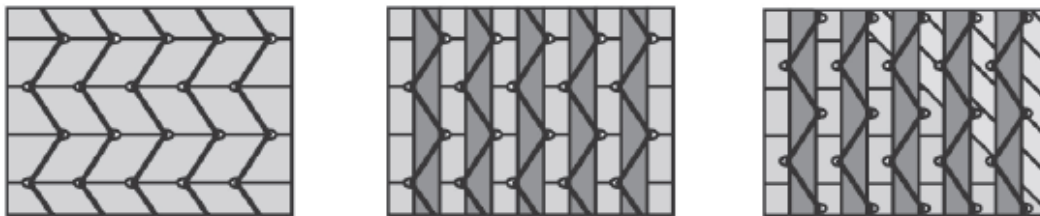


Figure 2-13: Types of non-crimp fabrics [128].

In warp-knitted NCFs, loop formation in the warp direction is used for binding layers of yarns [129]. There are two types of fixation in biaxial and multiaxial warp-knitted NCFs depending on the length of knitting threads, coursewise and non-coursewise weft insertions. In coursewise weft insertion, each warp and weft yarn is bonded with a single knitting loop without penetrating the yarns, Figure 2-14 (left). In non-coursewise weft insertion the knitting threads can penetrate the yarns, Figure 2-14 (right).

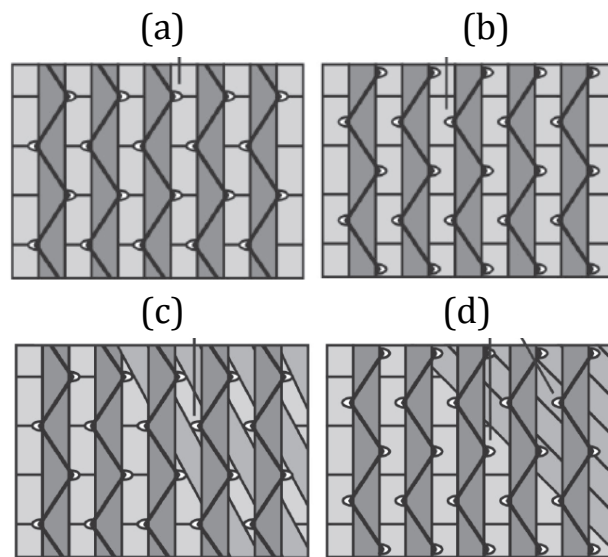


Figure 2-14: Coursewise warp-knitted NCFs for biaxial (a), multiaxial (C) and non-coursewise warp-knitted NCFs for biaxial (b), multiaxial (d) [128].

Warp-knitted NCFs can also be used in manufacturing so-called spacer warp-knitted NCF which is consists of two surfaces connected with pile threads as shown in Figure 2-15.

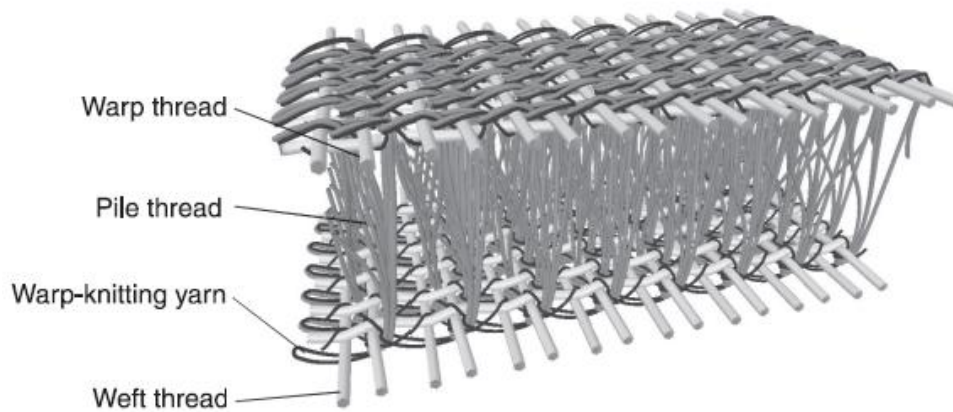


Figure 2-15: Spacer warp-knitted NCF [128].

In weft-knitted NCFs loop formation in the weft direction is used for binding yarns together [130, 131]. There is one type of fixation in weft-knitted NCFs which is used to manufacture biaxial and multiaxial fabrics, Figure 2-16.

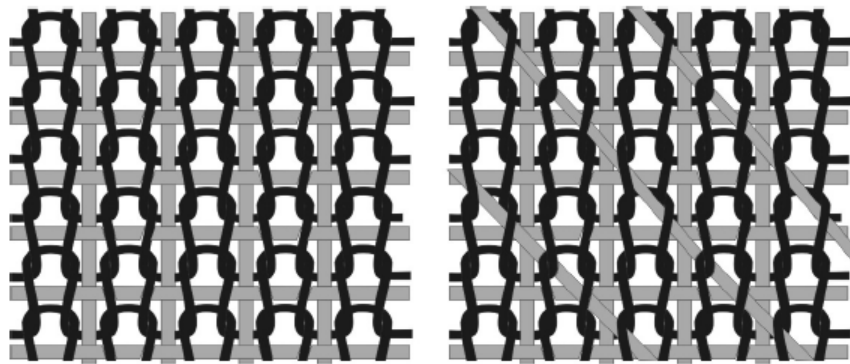


Figure 2-16: Biaxial weft-knitted NCF (left) and multiaxial weft-knitted NCF (right) [128].

Bonding can be used in manufacturing biaxial and multiaxial NCFs by using adhesion fixation where warp and weft yarns are bonded without knitting or interlacing, to produce an open net-like structure, Figure 2-17.

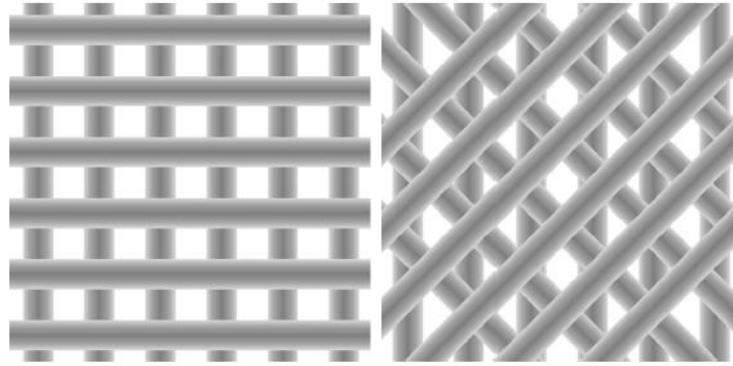


Figure 2-17: Biaxial bonded NCF (left) and multiaxial bonded NCF (right) [128].

Different thicknesses can be built up by laying down different numbers of layers and the fibers in each layer can be oriented in different directions, which gives more flexibility to such manufacturing technique and enables producing multiaxial multiply non-crimp near net-shape fabrics [132, 133] for the aerospace industry.

Stitching technology went through many developments in the clothing industry and offers a wide range of variations that can be used in the manufacturing of NFCs. Stitching can be used for fixation or positioning, for assembly or as structural stitching [134, 135]. Stitching technology is discussed in more details in the next section.

2.6 Embroidery, textile assembly and automation

An identified need for net-shape preforms with high and potentially variable thickness, enabling gains through orienting load-bearing yarns for increased conformability of the preform, resin flow and structural properties of the composite parts, prompted the development of techniques whereby load-bearing yarns are laid individually on a light

textile support and held in place using embroidery [136-142]. Similar techniques based on binders were also proposed [143]. The potential automated production of net-shape preforms with control over yarn orientations is very appealing; process speed, yarn damage and undulation, and the presence of inter-yarn gaps are concerns at this point.

Beyond the production of self-contained pieces of textile reinforcement by 3D weaving, 3D braiding, knitting, embroidery or other processes [144], preforms that are adapted to specific complex shapes may be produced by assembling a small number of textile piece of different types. The advantages of reduced labour and increased consistency are largely maintained without need for overly complex or dedicated textile processes. However, the design of appropriate jointing techniques is crucial to preform handling, for its processing, and for the structural properties of PMC parts [145]. Stitched, tufted and z-pinned joints are discussed in the literature.

Robotised single-side stitching [146-149] was developed as an alternative to traditional double-side stitching [150, 151] allowing major simplifications in handling as stitches can be made directly on preforming tools. Work on various double-side, single- and double-threaded stitches is reported in the literature, focusing on local preform compression and increases in v_f induced by stitch tension [151]. Thread selection was reported as being critical [152] with further development work done using commercially available carbon fibre stitching thread [153, 154]. Tufting [155, 156] and blind stitching [148] were also used for preform assembly. The presence of stitching holes associated with stitching and tufting is a concern and was probed [157], as well as the deformability in bending of

reinforcements assembled by stitching [158]. The effect of stitching [159-171] and tufting [172-174] on diverse structural properties of the composite parts was also investigated.

Z-pinning is an alternative assembly technique whereby an array of rigid rods with diameters of a few tens of microns is inserted in a fabric stack, prior to resin infusion. Proprietary trade name Z-pinning is widespread in the literature, along with the less frequent Z-anchor [175] and Z-fiber [176]. Carbon nanotubes were also used for a similar purpose [177]. Although Z-pinning can enable preform assembly, the literature focuses solely on improving the structural behaviour at the joint in the composite part with results available for loading in tension [178-180], compression [181, 182], bending [183] and for fatigue [184-186], delamination [187-189], impact [190] and damage resistance [191].

Efforts were directed towards developing automated manufacturing for advanced reinforcement preforms [192-197]; however, these have not resulted in significant transfer of any automated means of production of net-shape preforms towards industrial practice; to this day, preforming and assembly operations involving dry reinforcement textiles remain largely manual, limiting their growth.

2.7 University of Ottawa Advanced Preforming Technology

The evolution of the uO-APT process can be traced to Master's theses completed at the University of Ottawa by Nicholas Burnford [20], Andrew Stewart [198], Aymen Sakka [199], Scott Audette [200] and Thanos Drivas [21]. Important contributions were made by

undergraduate students Alex Maclure, Helene Fortier, Khadijah Ahmad, Yue Heng 'Jack' Xu, Cedric Eveleigh and also by Master's student Lucas West and to the completed PhD thesis of Reza Samadi.

The uO-APT pre-production process enables the design and manufacturing of thick, net-shape, flat drapable reinforcements featuring variable spacings between adjacent yarns, allowing them to be steered in their initial manufacturing plane. Local alterations to yarn spacings enable local tailoring of the forming behaviour of the reinforcement, and eventually of its processing properties and of the structural properties of the resulting PMC part. By tailoring tow spacings in a targeted manner it is possible to produce a final-thickness reinforcement that is uniquely suited for forming on a precise geometry.

uO-APT preform manufacturing proceeds in two distinct operations, currently implemented in two distinct machines: the yarn laydown machine (YLM) and the contour stitching machine (CSM), Figure 1-6. The YLM is a 6-axes CNC-device: 4 axes enable linear and rotational motions, 1 axis is for yarn payout and 1 axis is for yarn cutout. The YLM tracks above a needle plate whilst it deposits yarn at a synchronized rate. The needle plate, further described below, is a flat plate equipped with protruding flexible pins that guide and keep the deposited yarn segments in their intended positions. Deposition is done in successive layers until the required thickness is reached. Then yarns are transferred to the CSM where stitching thread is used for assembling the stacked layers of yarns into a reinforcement or preform. Mechanizing the preforming processes improves repeatability;

automating it removes much human involvement, further increasing repeatability and efficiency.

A set of major parameters must be quantified initially towards preform design. The first parameters are the maximum and minimum allowable yarn spacings, which define the range of spacings permitted for a specific preform. Increased yarn spacings increase the in-plane distance available to each yarn and enables further in-plane shear, but it may also reduce the fibre volume fraction v_f . Conversely, closer yarns may buckle out-of-plane upon shearing if forced to occupy a volume that is too constrained. In this thesis, bending, shearing and inspection are performed on preforms featuring exclusively straight yarns; as such, yarn spacing took a constant value of 4.0 mm in all yarn layers. The spacing value was defined from characteristics of the yarns used as detailed below. Another major parameter is the number of yarn layers in the preform. The numbers of yarn layers in preforms manufactured towards testing in the context of this thesis were chosen based primarily on target fibre volume fractions as defined in the relevant chapters. Furthermore, as results from tests conducted using uO-APT preforms are compared systematically with those of tests conducted using industrial reinforcements, numbers of layers in all cases had to be selected so as to allow directly comparable values of both v_f and total thickness. This point is discussed specifically in Chapter 3 of the thesis.

uO-APT preforms manufactured towards testing and inspection in the context of this thesis were made from Tenax®-J HTS carbon fibre yarns from Toho-Tenax America, Inc (Rockwood, TN, USA). The fibres are manufactured from PAN precursor and feature a

polyurethane-based sizing. The fibres were available as flat yarns containing nominally 12000 carbon fibres corresponding to an equivalent solid yarn cross-section of 0.462 mm². Owing to their flat, ribbon-like arrangement the yarns showed some propensity to spread between pins on the needle plate, contributing to preforms that showed limited inter-yarn gaps. Yarn linear density was measured by Sakka [199] at 805.5 tex with a standard deviation of 0.47 tex; carbon fibre diameter [201, 202], size levels [199], yarn linear density [202] fibre density [199] were documented by the supplier at 5 µm, 1.3%, 810 tex, and 1.76 g/cc respectively.

All uO-APT preforms tested in the context of this thesis featured bi-axial lay-ups of straight, orthogonal yarns that were realised using the needle plate and frame shown in Figure 2-18. The 13 mm polymethyl metacrylate (PMMA) plate featured CNC-machined holes used for locating 0.6 mm diameter flexible pins with an accurate spacing of 4 mm between centres; pins extended approximately 19 mm outside of the plate. Pins were located along two intersecting groups of parallel lines spaced by 40 mm. A first 3 mm thick aluminium frame with 330 mm by 330 mm opening, shown in Figure 2-18, was positioned around the pins beforehand. Its function, along with a similar frame laid above the yarns and first frame upon completion of laydown, was to hold the carbon fibre yarns in place. As such, yarn segment extended 25 to 50 mm beyond the outer edges of the pin lines and between the two aluminium frames, sometimes further, Figure 2-19. The frames were assembled using 36 #6 flat head machine screws and nuts. Upon laydown, the head actually went between the needles, and so the laydown operation did not introduce defects in yarns, Figure 2-20. 80 yarns were laid next to each other for covering a single layer. A subsequent layer was

laid with yarns oriented at 90° from those of the previous layer, except for the two central layers which were laid parallel to maintain symmetry in case of even numbers of layers.

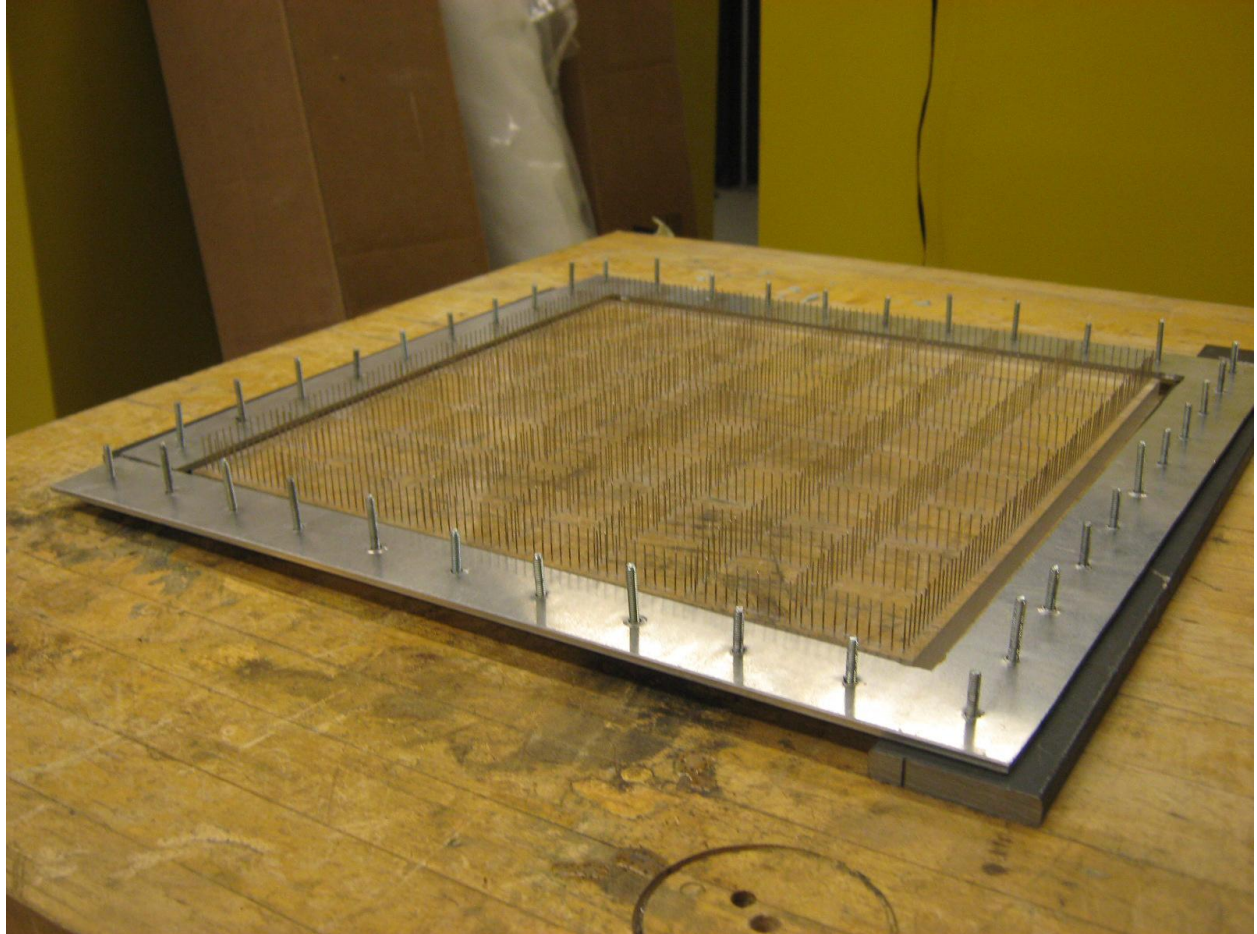


Figure 2-18: Needle plate and lower aluminium frame [200].

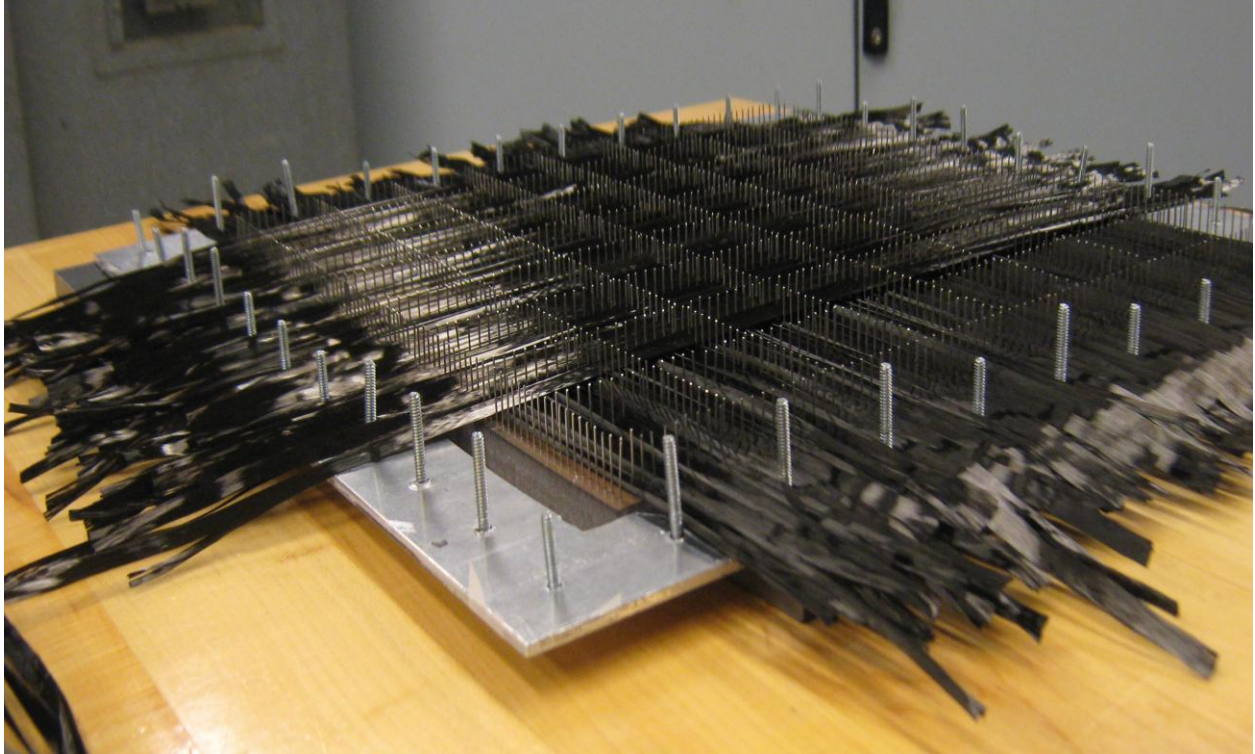


Figure 2-19: Needle plate, lower aluminium frame and layers of yarns [200].



Figure 2-20: Carbon fibre yarn being laid between needle plate pins by YLM.

After laydown, each yarn layer was subjected to a light compaction force exerted by a 300 mm x 300 mm PMMA assembly featuring grooves for protruding pins, Figure 2-21. Light pressure was applied on the yarns, from gravity only. This compaction settled the yarns, removed any out-of-plane waviness, further improved surface coverage, and made the laydown of the following yarn layer more robust.

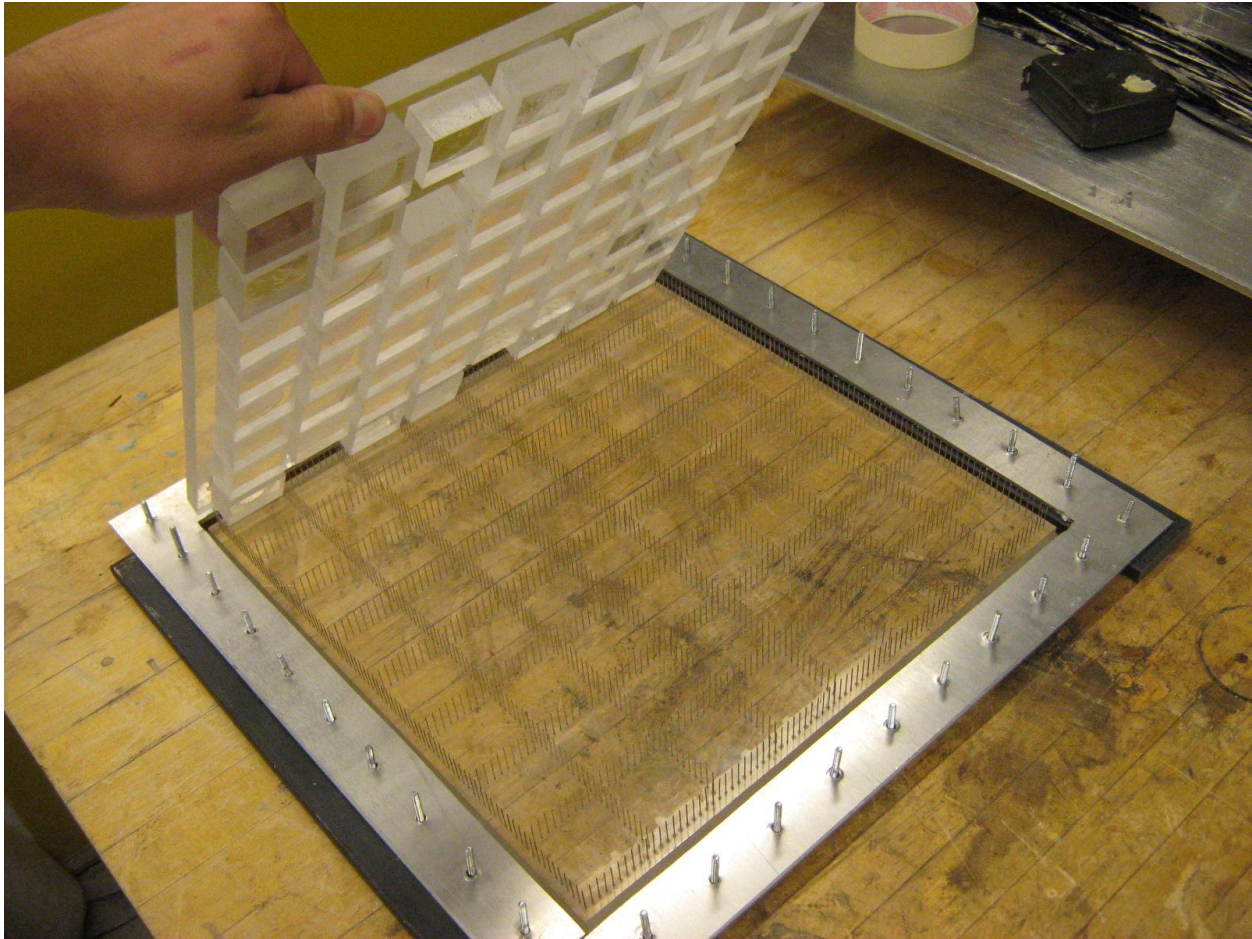


Figure 2-21: PMMA assembly used for compacting yarn layers [200].

Clamping the yarns provided mechanical fastening which helped in reducing tow warpage during the removal of the stack from the needle plate, prior to stitching, and also during stitching. Removal was done with great care and handling of the stacked and clamped yarns prior to stitching was minimized.

Assembly was performed using the CSM using lock stitches made from commercial grade 100% polyester white thread in both the needle and bobbin. The CSM uses a single needle, Figure 2-22; a stitching knot is created, needle motion stops, the preform is displaced in its plane following the intended path for the stitch line, and the next stitching knot is created.

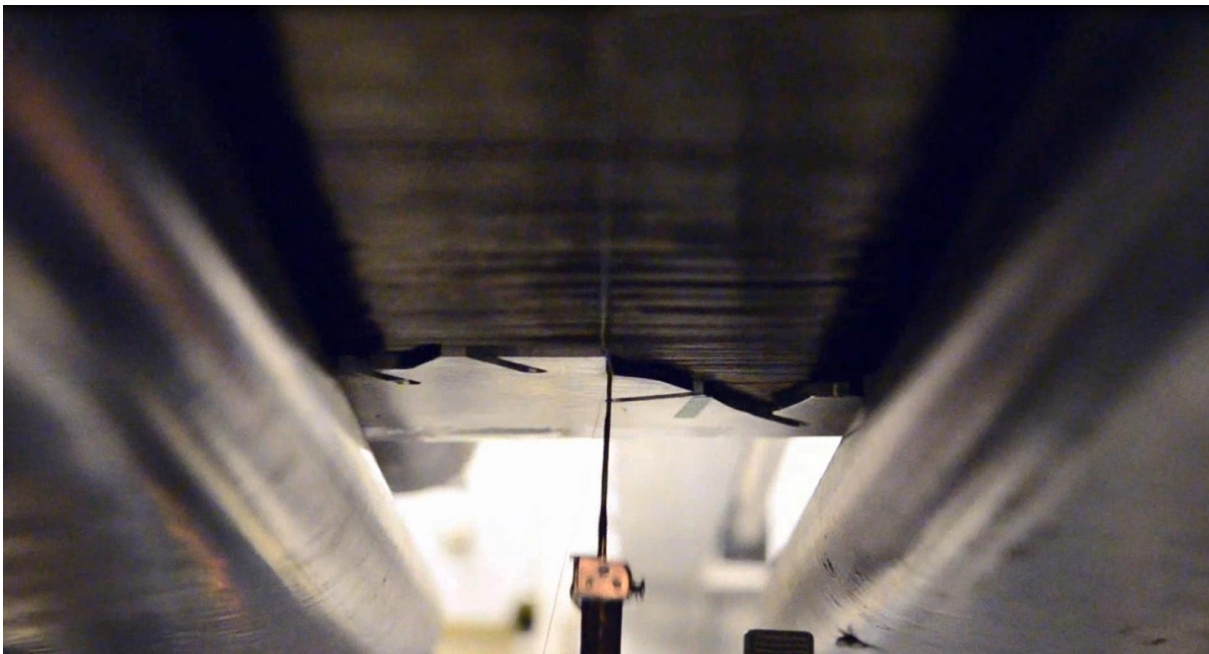
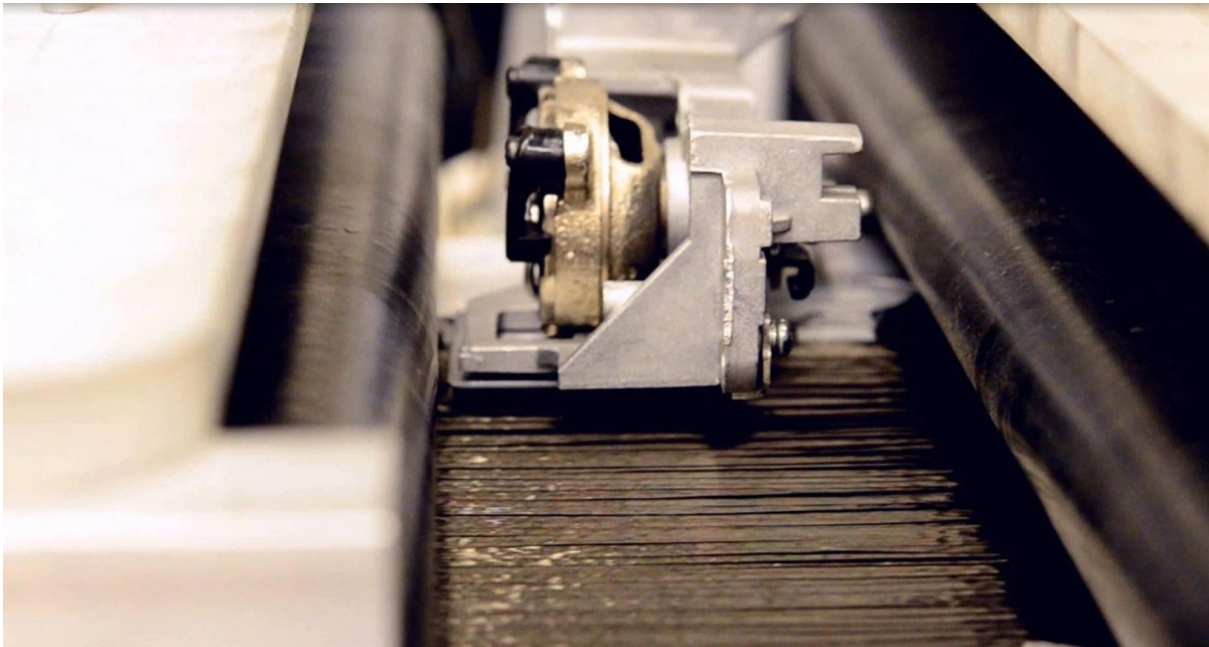


Figure 2-22: CSM in operation, above (top) and underneath (below) the carbon yarns.

Knot interspacing was set to 4 mm for manufacturing preforms tested in the context of the thesis. All stitching lines were straight and parallel, extending along a single direction only. The stitch lines were oriented in an orientation differing from that of both outer yarn layers to ensure that these layers, and then all yarn layers in between, were properly secured within the preform. Stitch line interspacing was generally set at 20 mm.

Displacements of individual yarns are avoided in the uO-APT process as yarns remain secured between the frames during stitching. However, stitching compresses the yarns locally under the stitching loops. The bobbin thread tension was monitored and adjusted manually to produce a modified lock-stitch geometry whereby knots were located on the back surface of the preform. After stitching, the preforms were trimmed using a manual cutter. With the clamping frame removed a preform could be gently handled with fibre orientation remaining intact, towards sample cutting as discussed in the following chapters.

Chapter 3

Single curvature bending of structural stitched textile reinforcements

3.1 Introduction

The bending behaviour of thick structural textile reinforcement plays a central role in preforming operations involving such textiles, and so it is crucial to probe and document it towards understanding reinforcement forming and the eventual onset of buckling. In the present work the bending behaviour of both 3D reinforcements produced at the University of Ottawa using the uO-APT process, and of stacks of industrial fabrics commonly used in manufacturing load-bearing aerospace PMC parts, was investigated using a bending rig designed for this purpose as part of the work. The novel 3D uO-APT reinforcements required testing towards defining and understanding their material properties and

constitutive behaviour. The bending behaviour of such thick structural textiles was the subject of very limited investigation work with virtually no results available in the open literature.

3.2 Literature review on fabric bending testing methods

The process of forming thick, dry textile reinforcements to complex shapes must be engineered robustly through predictive design. To this end the axial, shear and bending behaviour of reinforcement textiles must be investigated. The axial behaviour of a textile subjected to tension can be quantified using axial or biaxial tensile tests, and the shear behaviour can be quantified using bias extension or picture-frame tests. The bending behaviour can be quantified using the ASTM D1388 cantilever bending test or the Kawabata evaluation system for fabric bending (KES-FB), but both suffer from restrictions in using them on thick reinforcement textiles.

Boisse *et al.* [203] investigated the influence of tensile, in-plane shear and bending stiffnesses on the onset of wrinkling during textile forming. Wrinkling is a major defect that can occur upon forming textile reinforcements. The onset of wrinkles will happen readily in unfavourable forming scenarios as the bending and shear stiffnesses of fabrics are low.

Two main test configurations were used for measuring textile bending properties. First is the ASTM cantilever bending test initially developed by Peirce, as reported by de Bilbao *et al.* [204]. In this test the textile is cantilevered and the bending moment resulting from the overhanging textile mass is related to the curvature calculated from the geometry of the

bent specimen. The instrument shown in Figure 3-1 is based on a design described in a number of internationally recognized test standards comparable with ASTM D1388. For stiff and thick reinforcement textiles, significant curvature calculated from the geometry of the bent specimen will not be realised hence quantifying it meaningfully will be fraught with difficulty.

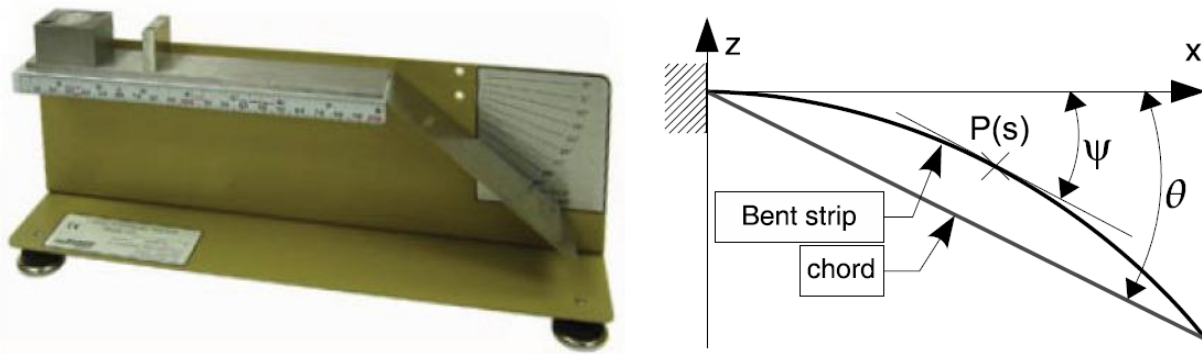


Figure 3-1: TABER® fabric stiffness tester model 112 (left); Peirce's test geometry (right) [204].

The second test configuration is embodied in the Kawabata evaluation system for fabric bending (KES-FB). Kawabata's evaluation system includes multiple devices that were designed for measuring numerous basic mechanical properties of fabrics. The bending test quantifies properties in pure bending and enables the direct recording of the bending moment as a function of sample curvature. The fabric sample is held between a fixed clamp (A) and a moving clamp (B), Figure 3-2. The setting of the sample within clamps ensures pure bending during the test as the moving clamp rotates around the fixed one resulting in curvature that is constant through the sample length at any given time [205]. While KES-FB does enable the measurement of bending properties it is not suitable for stiff, thick reinforcements. Sample dimensions are 1 cm length in the bending direction by 20 cm

width. The apparatus was developed for low stiffness fabrics such as those aimed at garment applications. Testing stiff and thick reinforcements may be accommodated by a reduction in sample width; still, measurements may be impossible altogether as the system is designed for very low bending moments [204].

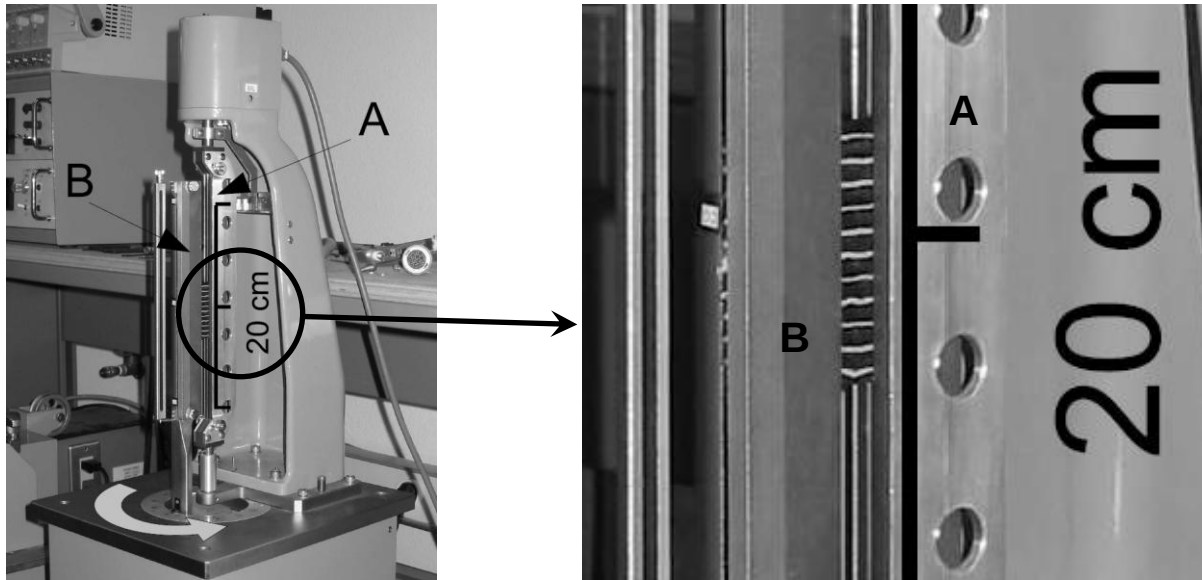


Figure 3-2: Kawabata bending apparatus [205].

Yu *et al.* [206] studied the bending behaviour of fabrics and yarns using another device, the Kawabata bending evaluation system for fabrics and yarns (BES-FY). The fundamental configuration of BES-FY appears in Figure 3-3 along with diagrams detailing each step involved in a measurement. The authors investigated mainly the effect of BES-FY system parameters such as the distance between u-shaped pins, length of the sample mounted on the two jaws, and diameter and speed of upward motion of the u-shaped pins, on the bending stiffness measured. Their work showed that bending stiffness of fabrics and yarns is best calculated at curvatures within 1.5 to 2.5 cm^{-1} in the BES-FY apparatus, and that the

relationship between bending moment or bending stiffness and curvature can be divided into distinct zones that may be represented using constant, linear and quadratic functions.

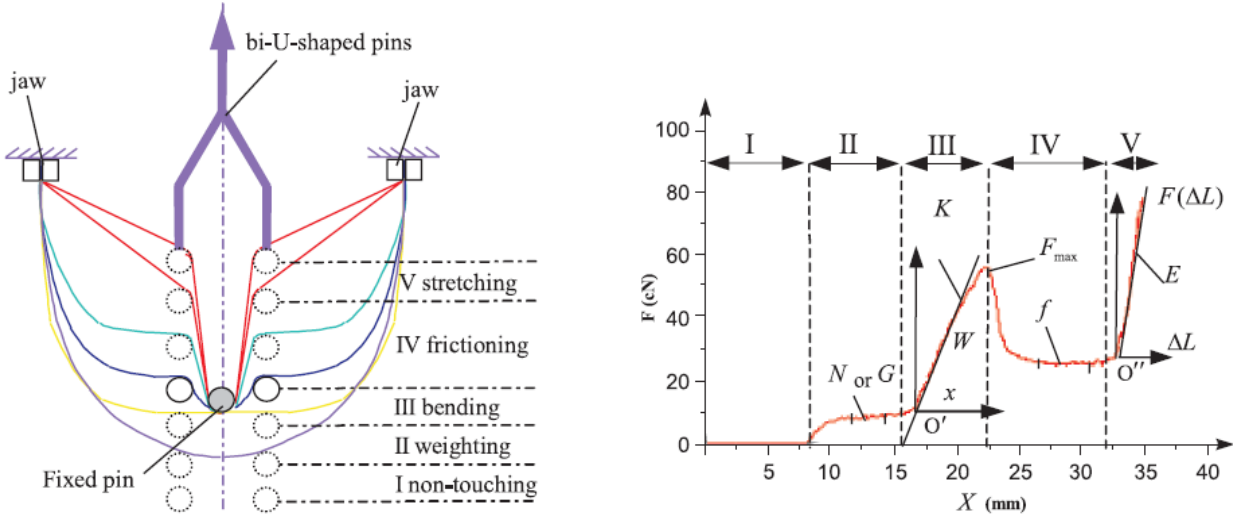


Figure 3-3: Steps in BES-FY bending test (left); typical force–maximum deflection curve (right) [206].

Bilbao *et al.* [205] introduced a cantilever beam fabric bending test coupled with optical curvature measurement. The optical module takes images of the bent sample, which are processed to extract the shape of the bent sample. A preliminary step of pixel calibration is required so that pixel measurements may be translated into accurate dimensions through scaling. The authors observed that the standard cantilever test is limited because of its reliance on the elastic linear model, and that the bending behaviour of fabrics cannot be predicted accurately only from its yarns properties.

Investigations conducted in the context of this thesis quickly revealed that the two main devices that have been used for measuring fabric bending properties, the KES-FB system [205] and the ASTM cantilever bending device [204] are unsuitable for testing stiff, thick fabrics where significant forces are applied and small curvature radii must be imposed. An

additional important objective of the work undertaken here was to replicate the way in which such textile reinforcements are bent in actual PMC manufacturing operations, as closely and reproducibly as possible. Therefore, an apparatus was designed and manufactured for testing thick and stiff textile reinforcements; this apparatus is referred to as the bending rig (BR) henceforth.

3.3 Experimental

Two types of carbon fibre reinforcements were characterized in this work, using a purposely designed bending rig that aimed at reproducing industrial preforming operations as closely as possible whilst obtaining documented and reproducible data. An experimental plan was devised towards quantifying the effect of textile reinforcement thickness, yarn and stitch orientations as well as fibre volume fraction v_f on the bending behaviour. Results obtained with different textile constructions are compared. Figure 3-4 shows a flow chart of the tests conducted to investigate the bending behaviour.

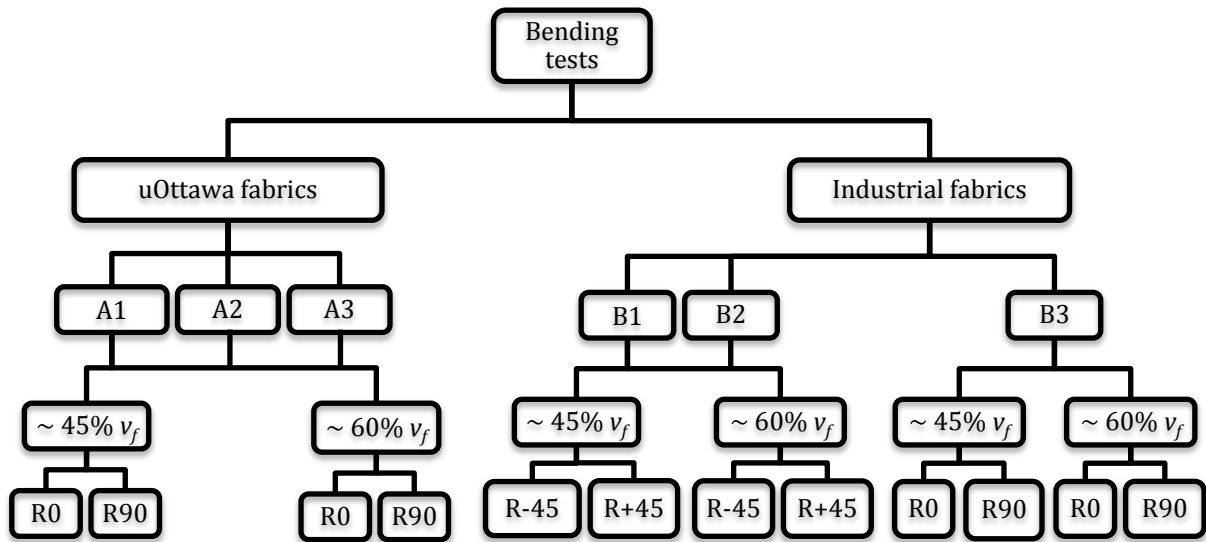


Figure 3-4: Bending tests flow chart.

3.3.1 Reinforcement fabrics

Two types of carbon fibre reinforcements were tested in bending, labeled types A and B. Type A reinforcements consisted of a single, thick bidirectional textile layer made of superimposed arrays of parallel carbon fibre yarns assembled by stitching in a final operation using the uO-APT process, Figure 3-5, left. Conversely, type B reinforcements consisted of stacks of thin individual bidirectional textile layers, each layer being individually assembled by stitching prior to stacking, Figure 3-5, right. Type A reinforcements are thick, monolithic single layer textiles whilst type B reinforcements are stacks of thin textile layers that can be separated readily one from another.

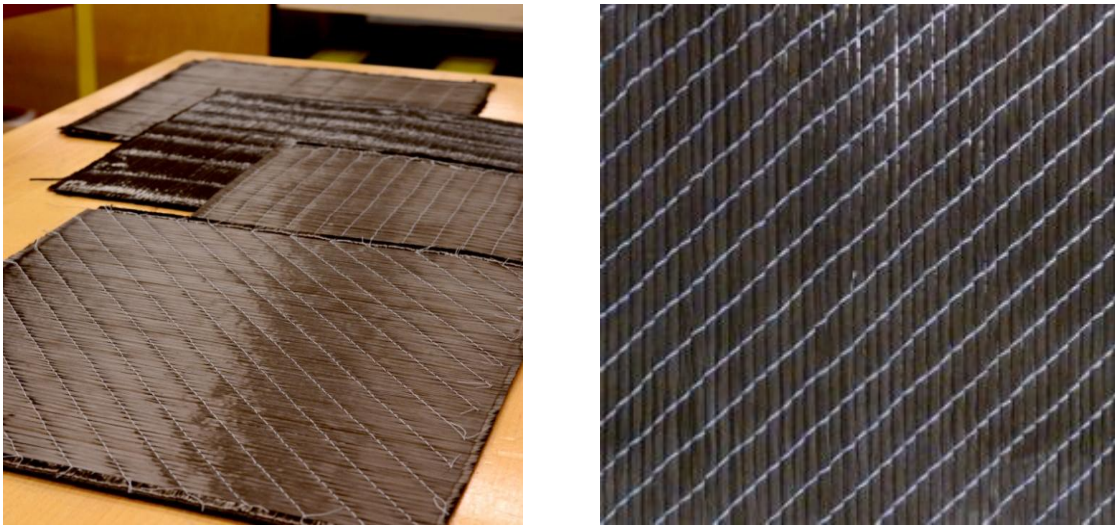


Figure 3-5: Carbon fibre reinforcements made using the uO-APT process (left); sourced from Saertex (right).

Type A reinforcements were made from Tenax-J grade HTS40 E13 12K, 800 tex carbon fibre yarns. Nominal yarn centre-to-centre in-plane distance within each array of parallel yarns was set to 4.0 mm leading to a surface density of 200 g/m² per unidirectional array of parallel yarns. The reinforcements were stitched using Cansew PF 68/2 16 tex lock stitch

lines with 20 mm centre-to-centre in-plane spacing. All type A reinforcements were bidirectional, symmetrical and featured even numbers of yarn arrays; numbers of arrays and their orientations in each reinforcement tested are specified in Section 3.3.3. Each type A reinforcement was stitched in one direction only; stitch lines ran parallel to one carbon yarn direction in some samples, and they ran between both carbon yarn directions in other samples as specified in Section 3.3.3. All type A reinforcements were manufactured at the University of Ottawa using dedicated equipment and a patented process.

Type B reinforcements consisted of stacked layers of Saertex 534 g/m² [+45°/-45°] bidirectional non-crimp stitched carbon textiles made from Tenax HTS40 12K yarns assembled using parallel lines of unspecified non-structural stitch. Stitch lines ran along the 0° direction with 5.0 mm centre-to-centre in-plane spacing. Numbers of textile layers within each type B reinforcement stack tested in bending are specified in Section 3.3.3.

Type A reinforcements were stitched along one direction only. Yarns in the outermost arrays on both external faces had to run in the same direction to ensure that these yarns and all those from arrays in between remain assembled in the reinforcement layer. Furthermore, and again to ensure the integrity of the reinforcement, stitch line direction in type A reinforcements had to differ from the direction of yarns in the outermost arrays. Contrary to type A reinforcements, each distinct layer within type B reinforcement stacks featured yarns in different orientations on each face. In this case, the need to ensure the integrity of the reinforcement dictates that stitch lines in type B reinforcements cannot run parallel to either yarn direction, hence the construction and orientations specified above.

As explained in the following sections, carbon yarn orientations relative to bending orientation in tests were similar for reinforcement types A and B with yarns running either parallel and perpendicular to the bending plane, or at $+45^\circ$ and -45° to the bending plane, in all cases. Considering tests performed on reinforcements where carbon yarns ran parallel and perpendicular to the bending plane, in the case of type A reinforcements stitch lines also ran parallel or perpendicular to the bending plane, whilst in the case of type B reinforcements stitch lines ran at $+45^\circ$ or -45° from the bending plane. However, considering tests performed on reinforcements where carbon yarns ran at $+45^\circ$ and -45° to the bending plane, it should be noted that stitch lines ran parallel or perpendicular from the bending plane for both types of reinforcements; all yarns and stitch lines orientations are stated explicitly in Section 3.3.3, for all reinforcements. Beyond stitching, all reinforcements and reinforcement stacks tested were directly comparable in terms of thickness, v_f , carbon yarn orientations and how they may be used in building composite structures.

3.3.2 Apparatus

The objective in designing the bending apparatus used in this work was to enable bending of reinforcements of varied thickness and v_f over a single curvature surface of constant radius, in a process similar to that induced by preforming ancillaries used in forming reinforcements in actual manufacturing of PMC parts and structures. Another central aim was to measure the evolution of the force required to do so whilst enabling direct observation of the reinforcements as they bent. The magnitude of the bending force is immaterial in most practical manufacturing situations; however, it is insightful in

identifying and understanding the behaviour of the reinforcements as they are bent, in making comparisons between tests, and in enabling the detection of any instability occurring during bending tests say from fibre, yarn or textile buckling. The apparatus appears in Figure 3-6. Design dimensions of the bending apparatus are provided in Appendix A.

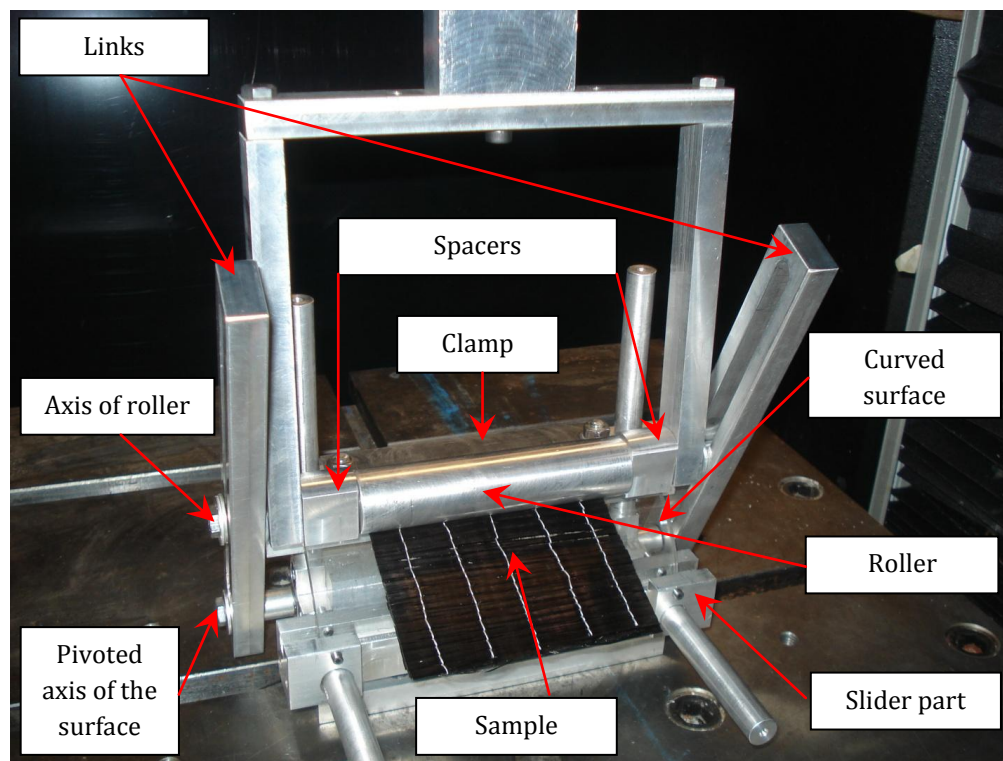


Figure 3-6: Bending apparatus.

The apparatus was mounted on an Instron 4482 universal testing frame equipped with a 100N load cell. Forces and displacements measured by the testing frame were used directly; no correction to the latter was required given the small forces involved. The apparatus was designed for bending cantilevered samples over a constant radius surface to a 60° angle. In an approach similar to industrial practice reinforcement samples were bent

by a low-friction roller rotated and pivoted over the sample. A thick, translucent curved surface was used enabling some visual observation of the inner side of the reinforcement during bending. Flat-sided circular spacers mounted on both sides of the roller ensured accurate fibre volume fractions in samples under the roller, during testing. The spacers were used upon rig preparation and sample mounting, before testing; then they were rotated prior to actual testing to ensure that no friction with the curved surface occurred. The curved surface and base were attached to the lower platen of the Instron frame, whilst the roller axis was connected to the frame's cross-head through a sturdy upper linkage. The rotation axis of the lower linkage and the axis of the curved surface were coincident. Limited friction pivots were used throughout; the apparatus installed in the frame appears in Figure 3-7.

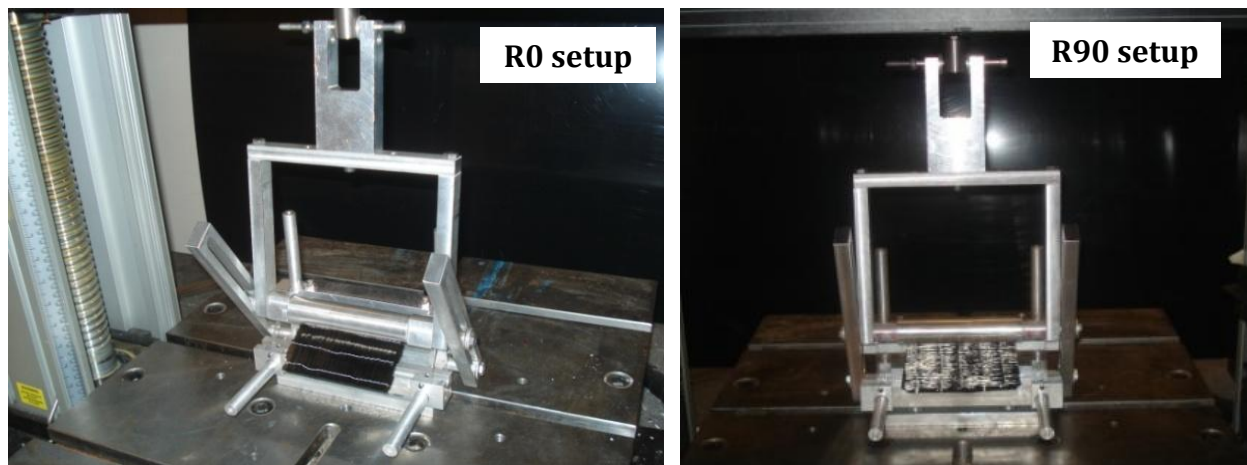


Figure 3-7: Bending apparatus installed in Instron 4482 testing frame; stitch lines along R0 (top) and R90 (bottom).

Figures 3-7 and 3-8 identify reference directions R0 and R90 for the apparatus, used for identifying bending orientations. Stitch lines extend along R0 and R90 in the upper and

lower parts of the figure, respectively. Equations for converting vertical displacements to bending angles are summarized in Section 3.5, along with a discussion of the theory used in analyzing the data.

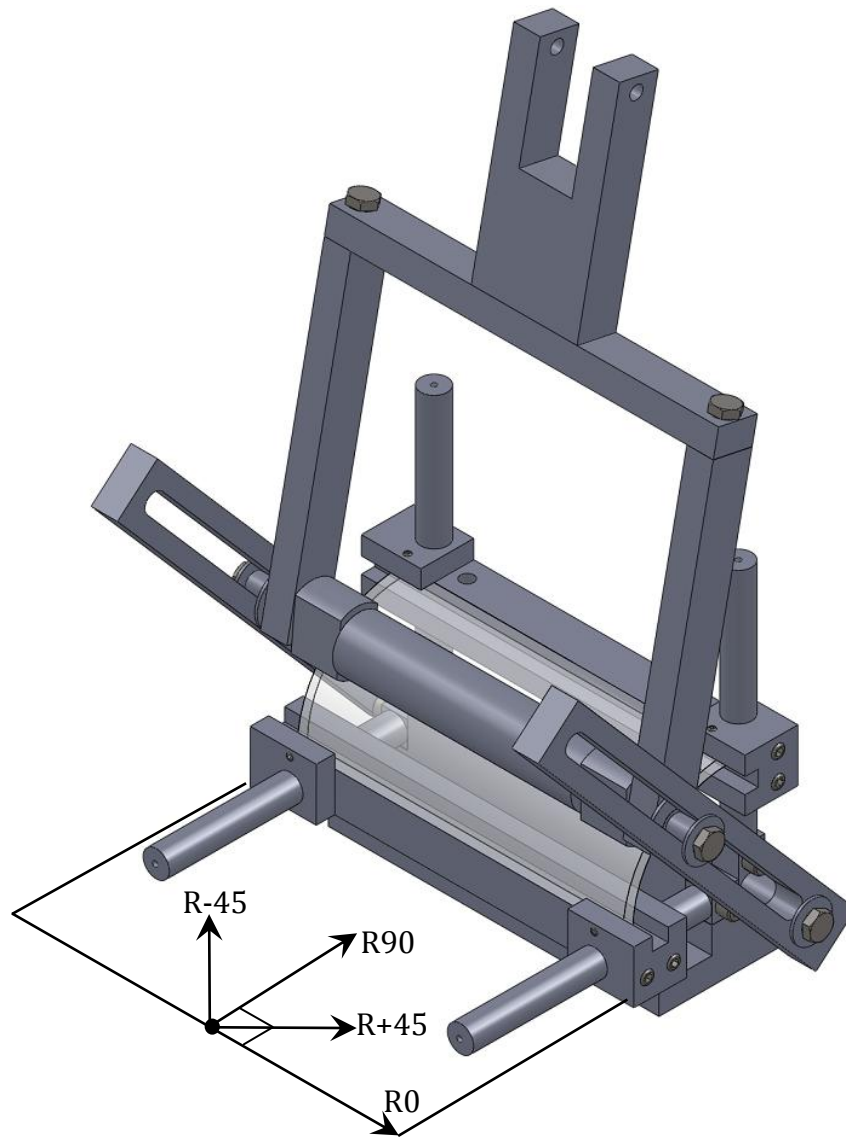


Figure 3-8: Orthogonal reference directions used for the apparatus.

3.3.3 Type A reinforcement experimental plan

Samples featuring different numbers of layers, v_f , yarn directions and stitch line orientations were tested for both reinforcements type A and type B. All sample and testing configurations are summarized in Table 3-1 through Table 3-3 for type A reinforcements, and Table 3-4 to Table 3-6 for type B reinforcements. All tests were conducted using a 50.8 mm curved surface radius.

Tests conducted using type A reinforcements were classified into test groups A1, A2 and A3 where samples used in test groups A1, A2 and A3 featured 8, 12 and 8 superimposed arrays of parallel yarns respectively. Stitch lines ran at 0° and 90° from yarns in test groups A1 and A2, and at 45° from yarns in test group A3. Test groups A1, A2 and A3 were further classified into sub-groups based on v_f and thickness; 2 values of thickness and corresponding v_f under the roller were used. For groups A1 and A3, thicknesses of 2.0 mm and 1.5 mm were used leading to nominal v_f values of approximately 45% for sub-groups A1/45 and A3/45, and approximately 60% for sub-groups A1/60 and A3/60. For group A2 thicknesses of 3.0 mm and 2.0 mm were used leading to nominal v_f values of approximately 45% for sub-group A2/45 and approximately 66% for sub-group A2/66. It should be noted that nominal v_f is the same for sub-groups A1/45, A2/45 and A3/45 enabling a direct evaluation of the effect of the number of layers at constant v_f , whilst targeted thickness is the same for sub-groups A1/45, A2/66 and A3/45 enabling the direct comparison of the effect of v_f at constant thickness.

As stated above, type A tests were classified into sub-groups based on the way samples were mounted into the bending apparatus, using the orientation of stitch lines as reference. All samples were symmetrical balanced bidirectional with yarns running at 0° and 90° from stitch lines in groups A1 and A2, and at -45° and $+45^\circ$ from stitch lines in group A3. Tests were conducted with stitch lines running along apparatus reference directions R0 and R90 for groups A1, A2 and A3 leading to 12 type A reinforcement sub-groups A1/45/R0, A1/45/R90, A1/60/R0, A1/60/R90, A2/45/R0, A2/45/R90, A2/66/R0, A2/66/R90, A3/45/R0, A3/45/R90, A3/60/R0 and A3/60/R90. It is worth noting again that in type A reinforcements, stitch lines are not parallel to the outer yarns; in this work they can extend perpendicularly or at $\pm 45^\circ$ from the outer yarn direction.

Lastly for type A reinforcements, 3 different physical samples were used for every testing configuration and sub-group, with each sample bent for 3 consecutive cycles leading to 108 bending tests performed for these reinforcements. Sample and cycle are identified by appending to the above sub-group numbers, labels such as S1-C2 for sample 1 and cycle 2 for example. Sample data appear in Tables 3-1, 3-2 and 3-3 including number of superimposed arrays of parallel yarns; yarn stacking sequence expressed relatively to a 0° orientation local to the reinforcement only; stitching orientation expressed relatively to a 0° orientation local to the orientation only; set-up of the sample into the apparatus expressed using the direction of the stitch lines and apparatus reference orientations R0 and R90; reinforcement thickness imposed under the roller through spacers (*SPR*); measured sample mass; measured in-plane sample dimensions; and calculated reinforcement fibre volume fraction under the roller (v_f).

Table 3-1: Characteristics of group A1 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	RR (mm)	SPR (mm)	Sample	MM (g)	Dimensions (mm)	v_f
uO-APT	A1	8 parallel yarn arrays - [90/0/90/0/0] _s	Along 0° in reinforcement	A1/45	R0	50.8	2.0	S1	16.36	105 x 100	0.44
								S2	15.79	100 x 100	0.45
								S3	15.27	100 x 100	0.43
							1.5	S1	16.02	100 x 102	0.60
								S2	17.08	101 x 102	0.63
								S3	16.05	100 x 102	0.60
				A1/60	R90	50.8	2.0	S1	17.22	102 x 105	0.46
								S2	17.19	102 x 108	0.44
								S3	16.63	100 x 110	0.43
							1.5	S1	16.33	100 x 103	0.60
								S2	16.05	100 x 100	0.61
								S3	16.93	100 x 101	0.64

3.3.4 Fibre volume fraction

Different spacer sizes (SPR) were used for enforcing nominal v_f values of 45%, 60% and 66% under the roller in samples being bent. The v_f calculations for sample A1/45/R90/S1 are detailed here as an example. Sample dimensions were 102 mm by 105 mm with a measured mass (MM) of the sample of 17.22 g. For a spacer size of 2 mm, sample thickness of 0.2 cm leads to a v_f nearing 0.45 as shown. Assuming an even thickness throughout the sample for calculations only, the volume of the sample V expressed in mm³ is:

Table 3-2: Characteristics of group A2 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	RR (mm)	SPR (mm)	Sample	MM (g)	Dimensions (mm)	v_f
uO-APT	A2	12 parallel yarn arrays – [90/0/90/0/90/0] _s	Along 0° in reinforcement	A2/45	R0	50.8	3.0	S1	24.68	100 x 103	0.45
								S2	24.07	100 x 101	0.45
								S3	23.66	100 x 99	0.45
				A2/66			2.0	S1	23.83	100 x 100	0.66
								S2	23.21	101 x 101	0.65
								S3	24.12	100 x 102	0.67
				A2/45	R90	50.8	3.0	S1	24.66	100 x 103	0.45
								S2	23.78	100 x 98	0.46
								S3	23.29	102 x 98	0.44
				A2/66			2.0	S1	24.40	100 x 102	0.68
								S2	24.31	100 x 102	0.68
								S3	24.01	100 x 102	0.67

$$V = 102 \cdot 105 \cdot 2 = 21\,420 \quad (3.1)$$

Knowing the density of HTS40 carbon fibres as 1.76 g/cm³ [202] the mass m expressed in g that the volume would have if it was occupied entirely from carbon (100% v_f) is:

$$m = V \cdot \rho = 21.42 \cdot 1.76 = 37.70 \text{ g} \quad (3.2)$$

The value of v_f is the ratio of measured mass MM to theoretical mass m at $v_f = 100\%$:

Table 3-3: Characteristics of group A3 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	RR (mm)	SPR (mm)	Sample	MM (g)	Dimensions (mm)	v_f
uO-APT	A3	8 parallel yarn arrays - [90/0/90/0] _s	Along 45° in reinforcement	A3/45	R0	50.8	2.0	S1	13.55	90 x 95	0.45
								S2	15.74	100 x 95	0.47
								S3	15.58	100 x 95	0.47
				A3/60			1.5	S1	16.20	101 x 101	0.60
								S2	15.92	100 x 103	0.59
								S3	15.95	100 x 102	0.59
				A3/45	R90	50.8	2.0	S1	16.35	104 x 97	0.46
								S2	16.48	104 x 100	0.45
								S3	15.55	102 x 96	0.45
				A3/60			1.5	S1	15.97	99 x 104	0.59
								S2	16.20	99 x 105	0.59
								S3	16.47	100 x 104	0.60

$$v_f = \frac{MM}{m} = \frac{17.22}{37.70} = 0.4568 \quad (3.3)$$

A spacer *SPR* and corresponding sample thickness of 1.5 mm lead to a v_f nearing 0.60 as shown below. In this case, sample volume V expressed in mm³ is:

$$V = 102 \cdot 105 \cdot 1.5 = 16\,070 \quad (3.4)$$

Theoretical sample mass m expressed in g assuming a theoretical 100% v_f becomes:

$$m = V \cdot \rho = 16.07 \cdot 1.76 = 28.27 \quad (3.5)$$

The fibre volume fraction of the sample is:

$$v_f = \frac{MM}{m} = \frac{17.22}{28.27} = 0.6090 \quad (3.6)$$

3.3.5 Type B reinforcement experimental plan

Tests conducted on type B reinforcements were designed for being directly comparable with the above tests conducted on type A reinforcements. They are classified into groups B1, B2 and B3. Samples used in test groups B1 and B3 featured 3 layers of 534 g/m² Saertex HTS40 12K fabric for a total surface density of 1602 g/m². Yarns aligned at [90°/0°], bonded together by pillar stitching at 45°, very closely matching the 8 arrays of parallel yarns in groups A1 and A3 reinforcements at 200g/m² per array and 1600 g/m² in total. Samples used in group B2 featured 4 layers of Saertex HTS40 12K fabric for a total surface density of 2136 g/m², compared with the 12 arrays of yarns in group A2 reinforcements at 2400 g/m² in total.

Type B tests were classified into sub-groups based on v_f and thickness, similarly to type A tests described above. For groups B1 and B3, thicknesses of 2.0 mm and 1.5 mm lead to nominal v_f values of approximately 45% for sub-groups B1/45 and B3/45, and approximately 58% for sub-groups B1/58 and B3/58. For group B2, different thicknesses of 2.7 mm and 1.8 mm lead to nominal v_f values of approximately 45% for sub-group B2/45 and approximately 63% for sub-group B2/63, enabling the same comparisons as above. Detailed information appears in Tables 3-4 to 3-6.

Type B tests were further classified into sub-groups based on stitch line orientations. All samples were balanced bidirectional with yarns running at -45° and $+45^\circ$ from stitch lines in all groups to guarantee reinforcement integrity as per Saertex construction. Tests were conducted with stitch lines running along apparatus reference directions R-45 and R+45 for groups B1 and B2 as shown in Figures 3-8 and 3-9, and along apparatus reference directions R0 and R90 for group B3 leading to 12 type B reinforcement sub-groups B1/45/R-45, B1/45/R+45, B1/58/R-45, B1/58/R+45, B2/45/R-45, B2/45/R+45, B2/63/R-45, B2/63/R+45, B3/45/R0, B3/45/R90, B3/58/R0 and B3/58/R90. Type B reinforcement stacks were balanced but not symmetrical, as a result of textile construction.

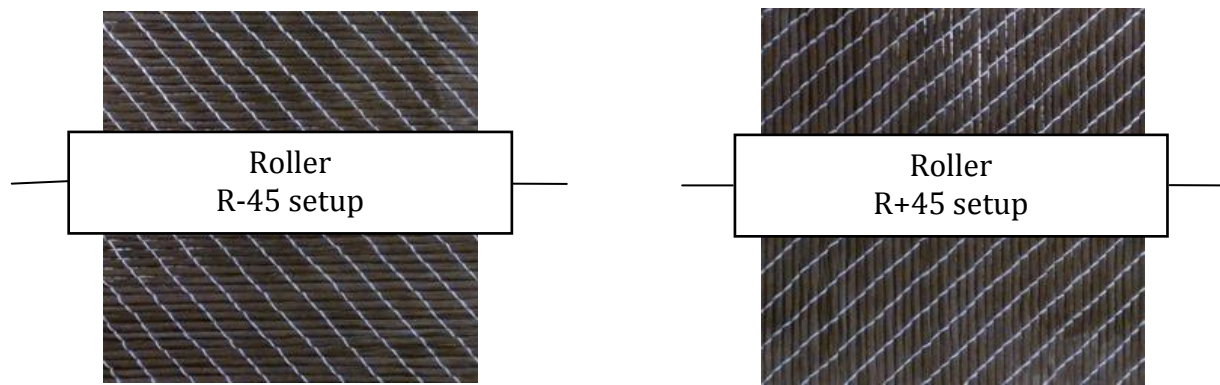


Figure 3-9: Stitching direction setup with respect to roller.

Three different physical samples were used for every type B testing configuration with each sample bent 3 in consecutive cycles leading to an additional 108 bending tests for type B reinforcements, bringing the total to 216 tests.

Table 3-4: Characteristics of group B1 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	RR (mm)	SPR (mm)	Sample	MM (g)	Dimensions (mm)	v_f
Saertex industrial reinforcement	B1	3 layers - [(0/90)] ₃	Along 45° in reinforcement	B1/45	R-45	50.8	2.0	S1	15.99	100 x 103	0.44
								S2	15.94	102 x 102	0.44
								S3	15.98	102 x 102	0.44
				B1/58			1.5	S1	16.36	101 x 103	0.60
								S2	16.40	102 x 103	0.59
								S3	15.17	100x103	0.56
				B1/45	R+45	50.8	2.0	S1	16.17	102 x 104	0.43
								S2	15.68	101 x 103	0.43
								S3	15.67	101 x 102	0.43
				B1/58			1.5	S1	16.26	103 x 103	0.58
								S2	15.37	100 x 102	0.57
								S3	15.98	102 x 104	0.57

Using sample B1/45/R+45/S1/T3 as an example, the following information can be read from the tables. The sample is made from Saertex fabric and is from group B1, featuring 3 layers. The test was conducted as R+45, where stitch lines are at $+45^\circ$ to the roller. A nominal fibre volume fraction of 45% was enforced by the use of 2 mm spacers. S1 means that this sample was the first to be tested in its sub-group and C3 indicates that this was the third cycle in testing the same sample. Sample groups constituted from stacks of Saertex reinforcements were labelled B1, B2, and B3 to indicate that they are directly comparable with samples from groups A1, A2 and A3 made from the uO-APT process, respectively.

Table 3-5: Characteristics of group B2 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	<i>RR</i> (mm)	<i>SPR</i> (mm)	Sample	MM (g)	Dimensions (mm)	v_f
Saertex industrial reinforcement	B2	4 layers - [(0/90)] ₄	Along 45° in reinforcement	B2/45	R-45	50.8	2.7	S1	21.33	103 x 105	0.42
								S2	21.36	104 x 104	0.42
								S3	21.50	104 x 105	0.42
				B2/63			1.8	S1	21.11	103 x 105	0.62
								S2	21.33	103 x 104	0.63
								S3	21.29	103 x 105	0.63
				B2/45	R+45	50.8	2.7	S1	20.66	100 x 103	0.43
								S2	21.55	103 x 104	0.43
								S3	21.55	103 x 105	0.42
				B2/63			1.8	S1	20.73	103 x 105	0.61
								S2	21.56	105 x 105	0.62
								S3	20.97	103 x 105	0.62

It should be noted that the numbers of layers in samples made from stacked industrial reinforcements differed from the number of arrays of parallel yarns in u0-APT samples, due to the difference in density per array or layer between the two reinforcements. As an example, samples from group A1 featured 8 arrays of parallel yarns, which compares closely to samples from group B1 in terms of total surface density. The equivalent number of layers for group B1 which gives the same fibre volume fraction at the same thickness can be calculated as follows.

Table 3-6: Characteristics of group B3 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	<i>RR</i> (mm)	<i>SPR</i> (mm)	Sample	MM (g)	Dimensions (mm)	<i>v_f</i>
Saertex industrial reinforcement	B3	3 layers - [(0/90)] ₃	Along 45° in reinforcement	B3/45	R0	50.8	2.0	S1	15.71	100 x 105	0.43
								S2	15.88	104 x 104	0.42
								S3	16.03	100 x 105	0.43
				B3/58			1.5	S1	15.87	100 x 100	0.60
								S2	16.50	102 x 105	0.58
								S3	14.90	100 x 100	0.56
				B3/45	R90	50.8	2.0	S1	15.83	100 x 105	0.43
								S2	16.13	100 x 105	0.44
								S3	15.76	100 x 105	0.43
				B3/58			1.5	S1	15.53	100 x 100	0.59
								S2	16.38	104 x 104	0.57
								S3	16.30	104 x 104	0.57

Considering for example reinforcements from group B1 with a spacer thickness *SPR* of 2.0 mm, and knowing that the density of carbon fibres is 1.76 g/cm³ [202] and that the surface density of the industrial fabric is 534 g/m², assuming in-plane sample dimensions of 100 mm by 100 mm or 100 cm² and a measured mass (*MM*) of the sample as follows:

$$MM = 534 \cdot 0.1 \cdot 0.1 = 5.34 \text{ g} \quad (3.7)$$

The volume *V* of the sample expressed in cm³ is:

$$V = 100 \cdot 0.2 = 20 \text{ cm}^3 \quad (3.8)$$

The theoretical sample mass m expressed in g assuming a theoretical 100% v_f is:

$$m = V \cdot \rho = 20 \cdot 1.76 = 35.2 \text{ g} \quad (3.9)$$

Targeting a fibre volume fraction of 0.45 in the sample under the roller, the number of layers NL of Saertex reinforcement required for testing samples from group B1 is:

$$NL = \frac{0.45 \cdot 35.2}{5.34} = 2.966 \cong 3 \quad (3.10)$$

The same number of layers is required for reaching a target fibre volume fraction of 0.45 for samples from group B3. Considering reinforcements from group B2 with a spacer thickness SPR of 2.7 mm with other quantities unchanged, assuming again in-plane sample dimensions of 100 mm by 100 mm and a measured mass (MM) of the sample as follows:

$$MM = 534 \cdot 0.1 \cdot 0.1 = 5.34 \text{ g} \quad (3.11)$$

The volume V of the sample expressed in cm^3 is:

$$V = 100 \cdot 0.27 = 27 \text{ cm}^3 \quad (3.12)$$

The theoretical sample mass m expressed in g assuming a theoretical 100% v_f is:

$$m = V \cdot \rho = 27 \cdot 1.76 = 47.52 \text{ g} \quad (3.13)$$

Again targeting a fibre volume fraction of 0.45 in the sample under the roller, the number of layers NL of Saertex reinforcement required for testing samples from group B2 is:

$$NL = \frac{0.45 \cdot 47.52}{5.34} = 4.004 \cong 4 \quad (3.14)$$

Similar calculations conducted for samples from groups B1 and B3 made from 3 layers of Saertex reinforcement bent with a spacer thickness SPR of 1.5 mm can be conducted, leading to a fibre volume fraction v_f of 0.58 under the roller for these samples. Further calculations conducted for samples from group B2 made from 4 layers of Saertex reinforcement bent with a spacer thickness SPR of 1.8 mm lead to a fibre volume fraction v_f of 0.63 under the roller for these samples.

3.4 Bending tests procedures

The bending apparatus was designed for testing samples fixed as a cantilever beam and bent over a single curvature surface of specified radius, made of translucent polyacrylonitrile (PAN). Ends of the curved surface were mounted into two slider parts which may be adjusted to fit curved surfaces of different radii in future work. Reinforcement samples were bent using a roller pivoted over the sample, above the curved surface with a predefined spacing. Spacers assembled on both sides of the roller ensured a specific fibre volume fraction in samples under the roller during testing. All apparatus parts were assembled on a base that was attached to the lower platen of an Instron 4482 universal testing frame. The cross-head of the testing frame was connected to the roller via

two rigid links. As the cross-head moves downward, it pushes down on the roller, which rotates on its axis but also around the central pivot of the apparatus, coincident with the axis of the curved surface, enforcing the sample into bending over the surface and replicating an industrial preforming operation.

The actual test procedure is described step by step in the following pages using sample A1/45/R0/S1/C3 as an example. From the sample name, the following information can be gathered:

- Sample is from group A1 hence made from uO-APT reinforcement with 8 superimposed arrays of parallel yarns;
- Fibre volume fraction of 45% is enforced through the use of 2.0 mm spacers;
- Test is conducted using setup R0 hence stitch lines are parallel to roller;
- S1 indicates that sample is the first tested within its sub-group;
- C3 indicates the third cycle in testing the same sample.

The first step towards testing was to cut samples from larger reinforcement layers with specific dimensions compatible with the bending apparatus. A photograph of uO-APT reinforcement layers ready for cutting into smaller samples appears on the left side of Figure 3-4.

The bending has an opening of 125 mm widthwise. Along their length, samples were cut so that they may cover a 90° angle on the curved surface once bent; curved surface radius RR

on the apparatus was 50.8 mm for all tests. Typical sample dimensions were 100 mm by 100 mm. Figure 3-10 shows a sample from group A1 after being cut and prepared for testing. Cutting uO-APT reinforcements was done manually using a sharp blade. The operation was somewhat difficult to conduct whilst maintaining relatively accurate dimensions for all samples; this caused some scattering in fibre volume fraction values of the samples as reported in the above tables.

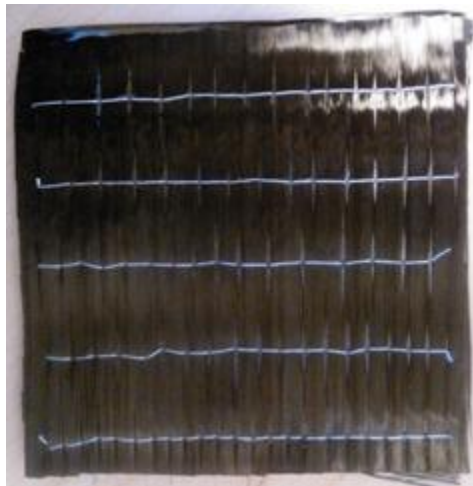


Figure 3-10: A bending test sample from group A after being cut.

The second step consisted in installing spacers that induced the required fibre volume fraction v_f under the roller during bending. In this case and for group A1, an *SPR* value of 2.0 mm translates to a nominal v_f of 45%. The third step consisted in attaching the apparatus to the Instron 4482 universal testing frame. The fourth step was to set the sample in the upper clamp of the bending apparatus so that the stitch direction would be parallel (R0) or perpendicular (R90) to roller as shown in Figure 3-11.

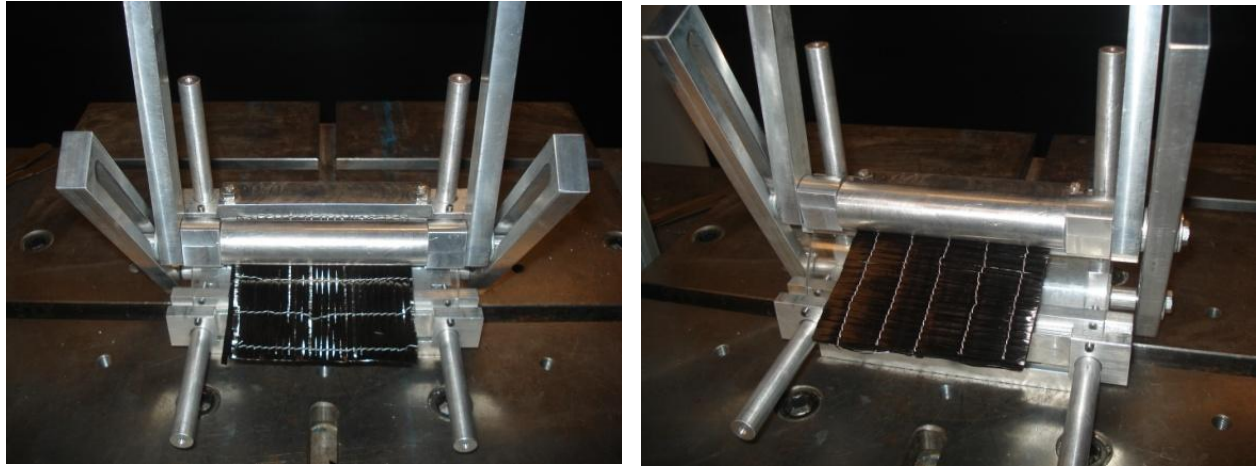


Figure 3-11: Bending tests samples mounted in apparatus; R0 test set-up (left) and R90 test set-up (right).

The fifth step was to move the cross-head to its starting position, link it to the apparatus and calibrate the load cell. The sixth step was to start the bending test and record both the force and displacement with the help of data acquisition software Bluehill 2.0 from Instron that controls the testing frame, until the end position was reached, Figure 3-12.

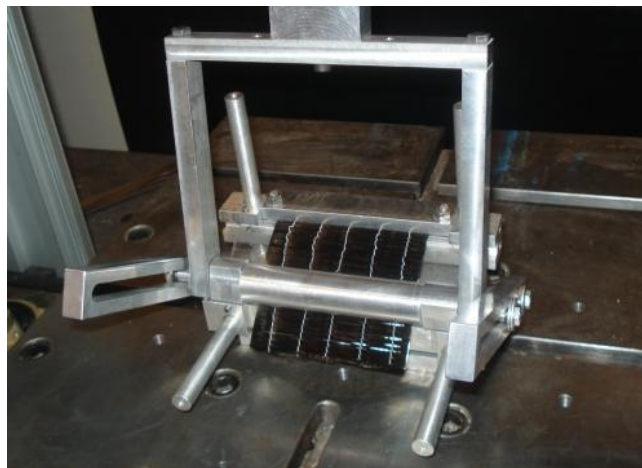


Figure 3-12: End position of the roller.

The seventh and final step was to return the cross-head to its starting position and repeat the procedure for the same sample, without removing the sample.

3.5 Results

In this section the apparatus and sample geometries are quantified, and the system of forces is reviewed leading to curves of the bending moment (M_B) as a function of the bending angle (θ). Typical curves are introduced along with quantities used in summarizing them for analysis. The effects of parameters mentioned in Section 3.3 are quantified.

3.5.1 Geometry and forces

The vertical force F_M is the recorded experimental machine force that generates bending of the sample. Analyzing the force system requires that all apparatus angles be determined. The geometry and angles of the apparatus and linkage appear in Figure 3-13.

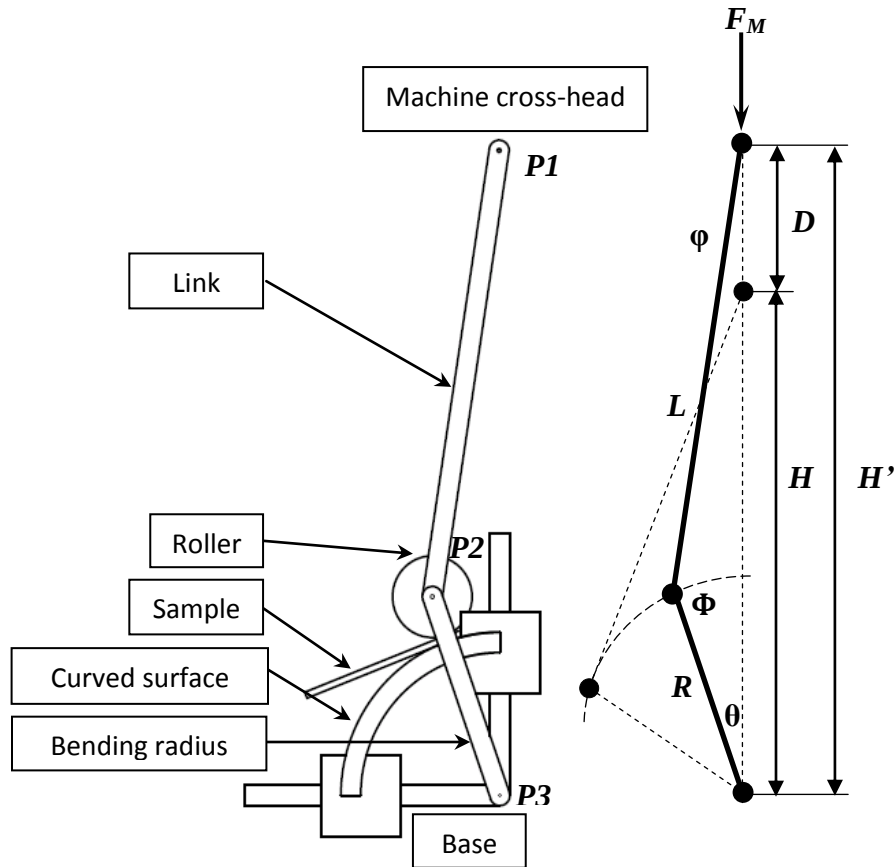


Figure 3-13: Side view of the bending apparatus setup.

In the figure, $P1$ identifies the attachment of the rotation axis of the upper linkage to the load cell, $P2$ identifies the rotation axis of the roller and $P3$ identifies the rotation axis of the lower linkage. The distance between the roller axis $P2$ and load cell attachment point $P1$ is labeled L , and the distance between the roller axis $P2$ and lower linkage axis $P3$ is labeled R . The distance between the rotation axis of the lower linkage $P3$ and load cell attachment point $P1$ is labeled H and its initial, maximum value is labelled H' . Figure 3-12 shows the apparatus in the configuration corresponding to the starting position of a test. Length L is constant at 255 mm for all test setups. Roller radius r is constant at 12.7 mm. Bending radius R depends on 3 quantities: 1) rig radius RR which is the radius of the curved surface around which the sample is bent, equal to 50.8 mm, 2) spacer thickness SPR , which defines v_f in the bent sample under the roller, and 3) roller radius r equal to 12.7 mm. As an example, for a 2 mm spacer thickness SPR , 50.8 mm rig radius RR and 12.7 mm roller radius r , the bending radius R is:

$$R = RR + SPR + r = 65.5 \text{ mm} \quad (3.15)$$

Force F_M is the vertical force applied by the machine cross-head on the bending apparatus. Initial vertical distance H' between the cross-head and base makes an angle φ with the link, and an angle θ with the bending radius. Vertical displacement D is recorded as the machine cross-head displacement and has a value of zero at starting position. The angle between the link and bending radius is Φ . Values of φ , θ and Φ evolve during a test.

Upon starting the test, distance D is provided by the Instron 4482 testing frame readout and saved to file. Angles Φ , φ and the bending angle θ are calculated as follows:

$$H^2 = L^2 + R^2 - 2LR\cos\phi \quad (3.16)$$

$$\phi = \cos^{-1} \left(\frac{L^2 + R^2 - H^2}{2LR} \right) \quad (3.17)$$

$$\frac{\sin \theta}{L} = \frac{\sin \phi}{H} \quad (3.18)$$

$$\theta = \sin^{-1} \left(\frac{L}{H} \cdot \sin \phi \right) \quad (3.19)$$

$$\varphi = \pi - (\phi + \theta) \quad (3.20)$$

By conducting the above calculations all angles may be determined for all recorded displacements D during a bending test, and compiled along with the corresponding bending force. Values of Φ , θ and φ for all spacer thicknesses and corresponding values of R and H' are available in Appendix B.

Analysis of the bending moment starts by considering the forces acting on the bending system. Figure 3-14 (a) shows the force applied on the system by the machine.

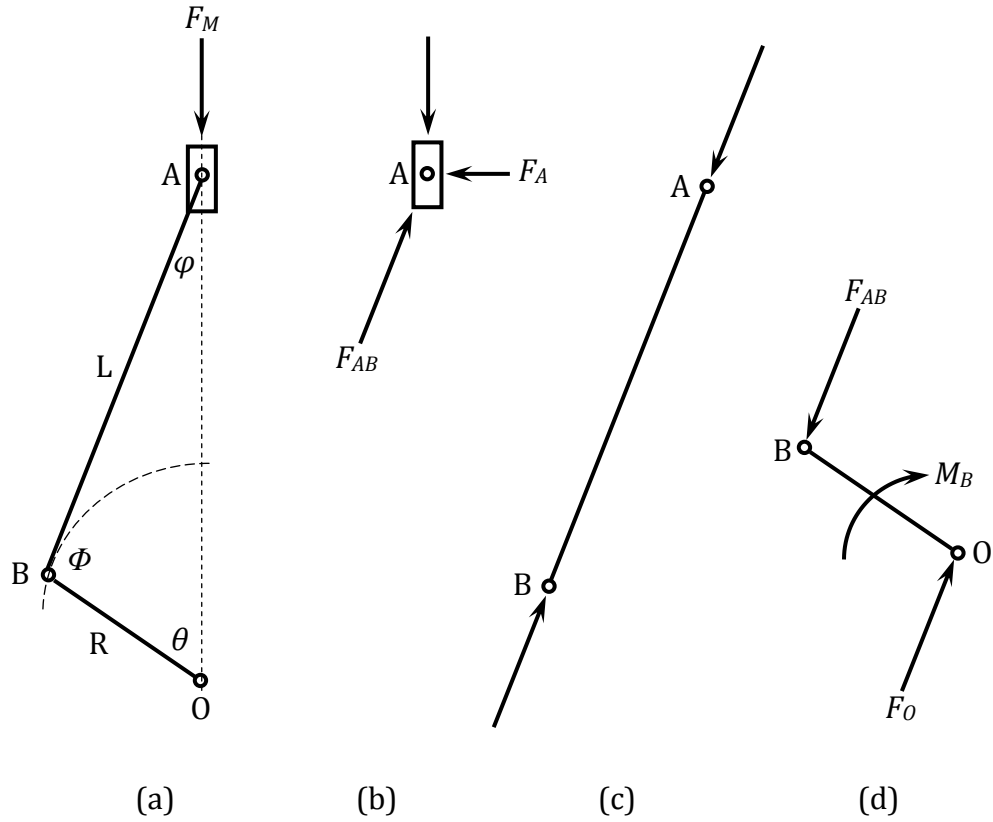


Figure 3-14: The forces acting on the bending system.

The free body diagram at point A appears in Figure 3-14 (b). Forces F_M and F_A are the vertical and horizontal components of force F_{AB} acting in the upper linkage, respectively. The free body diagram of this linkage appears in Figure 3-14 (c). The amplitude and direction of F_M are known, hence F_A and F_{AB} can be calculated as:

$$F_{AB} = \frac{F_M}{\cos\varphi} \quad (3.21)$$

$$F_A = F_{AB} \sin\varphi \quad (3.22)$$

Considering the free body diagram of the lower linkage, member OB shown in Figure 3-14 (d), the member is subjected to the forces F_{AB} and F_O which are not collinear. These two forces must be equal and opposite for the member to be in equilibrium.

$$F_{AB} = F_O \quad (3.23)$$

Additionally, for equilibrium to be maintained a moment M_B of the same magnitude must be applied in the clockwise direction on the diagram as shown in Figure 3-14 (d). This moment, defined herein as the experimental bending moment, can be calculated through the following equations:

$$\overrightarrow{F_{AB}} = -F_{AB}\sin\varphi \bar{i} - F_{AB}\cos\varphi \bar{j} \quad (3.24)$$

$$\overrightarrow{OB} = -R\sin\theta \bar{i} + R\cos\theta \bar{j} \quad (3.25)$$

$$\overrightarrow{M_B} = -(\overrightarrow{OB} \times \overrightarrow{F_{AB}}) = -[(R\sin\theta \cdot F_{AB}\cos\varphi) + (R\cos\theta \cdot F_{AB}\sin\varphi)]\bar{k} \quad (3.26)$$

3.5.2 Curves and analysis of experimental results

Curves of the bending moment as a function of the bending angle are presented in Appendix C for all tests. Selected curves appear in Figure 3-15 to 3-18. The magnitude of M_B varies up to 500 Nmm for bending angles θ ranging from 23° to approximately 60° for all samples. The angle 23° represents the value of the bending angle θ of the apparatus in its

starting position. Figure 3-15 shows a set of curves representative of many results obtained in this work. The bending moment increases quickly from zero to values that generally fluctuate smoothly around an average value from a bending angle of about 25° towards final bending values of about 55°. Figure 3-15 shows 3 curves corresponding to 3 successive loading cycles applies successively on the same sample. Values of the bending moment decrease through the cycles, as they do for the vast majority of the results presented.

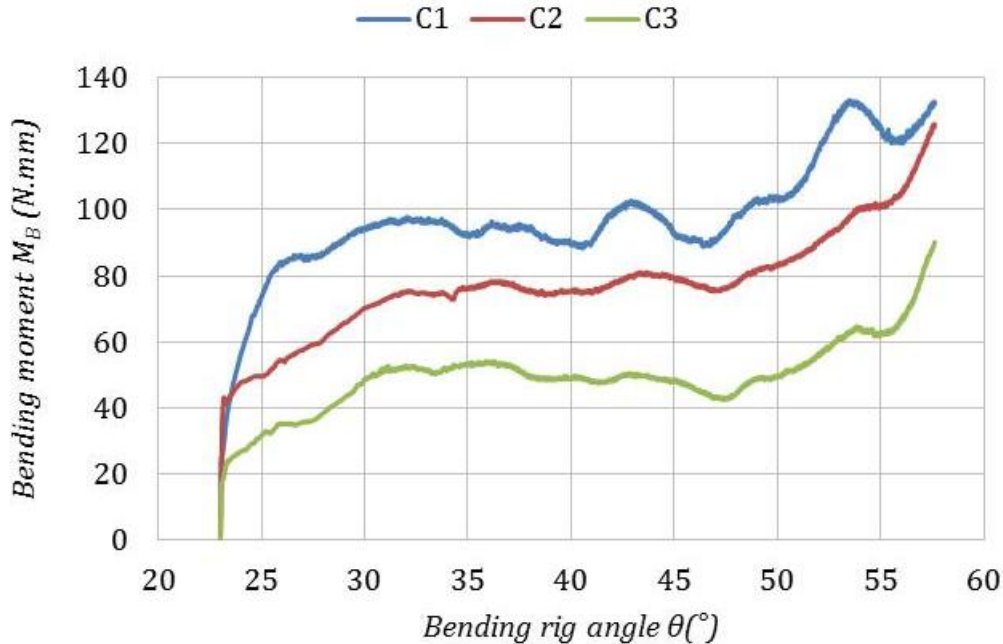


Figure 3-15: Curves of the bending moment as a function of the bending angle for sample A3/45/R90/S3, cycles C1, C2 and C3, representative of the results of many bending tests.

Some curves featured specific elements of behaviour. Curves on Figure 3-16 feature large pikes; these pikes can be associated directly to the passage of the roller over stitch lines in some cases where uO-APT preforms were bent in a configuration where these stitch lines

were parallel to the roller axis; such pikes are not present in cases where stitch lines were perpendicular to the roller.

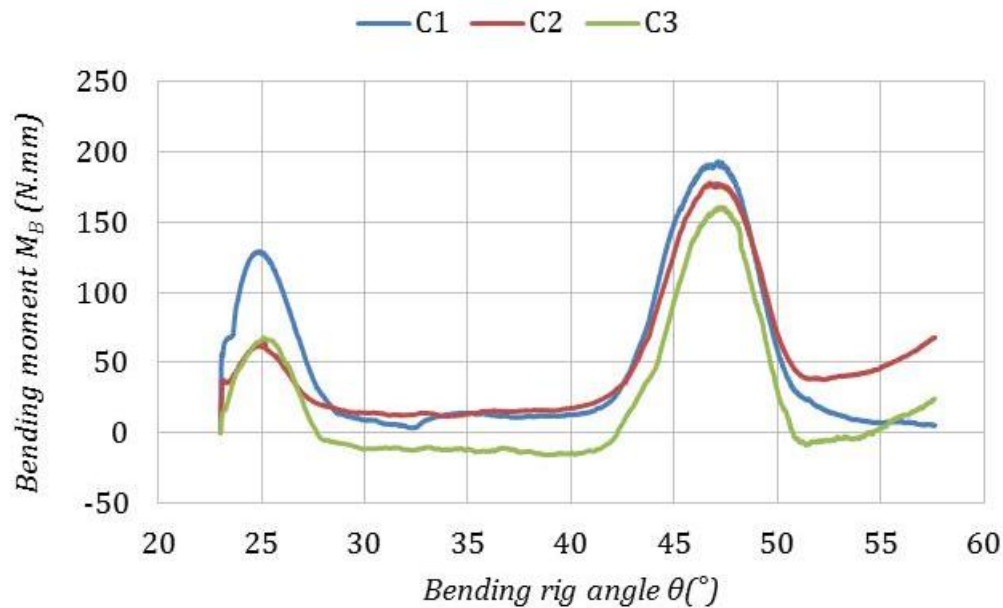


Figure 3-16: Curves of the bending moment as a function of the bending angle for sample A3/45/R0/S2, cycles C1, C2 and C3, featuring large pikes that can be related to stitch lines.

Curves on Figure 3-17 featured smaller pikes and troughs that could not readily be associated with precise features of the textile reinforcements, although the distance may correspond more or less closely to the nominal distance between yarns or between stitch lines in industrial Saertex reinforcements; such behaviour was observed only in a limited number of cases. In many cases such as this one, a 4th bending cycle was performed on the sample aiming at confirming observed behaviour.

Curves on Figure 3-18 features small-amplitude noise, or roughness; a number of curves showed such behaviour. Such qualitative observations are revisited in Section 3.5.3, after

the quantitative analysis of the results. Again in the case presented in Figure 3-17, 4 bending cycles were performed.

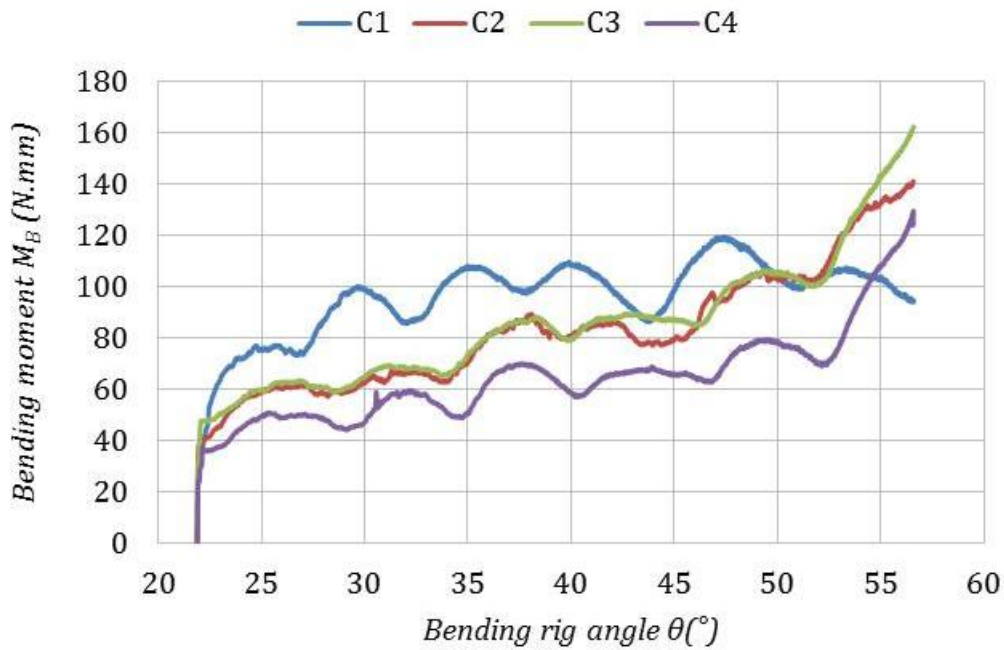


Figure 3-17: Curves of the bending moment as a function of the bending angle for sample A2/45/R0/S3, cycles C1, C2 and C3, featuring smaller pikes that cannot be related directly to precise features.

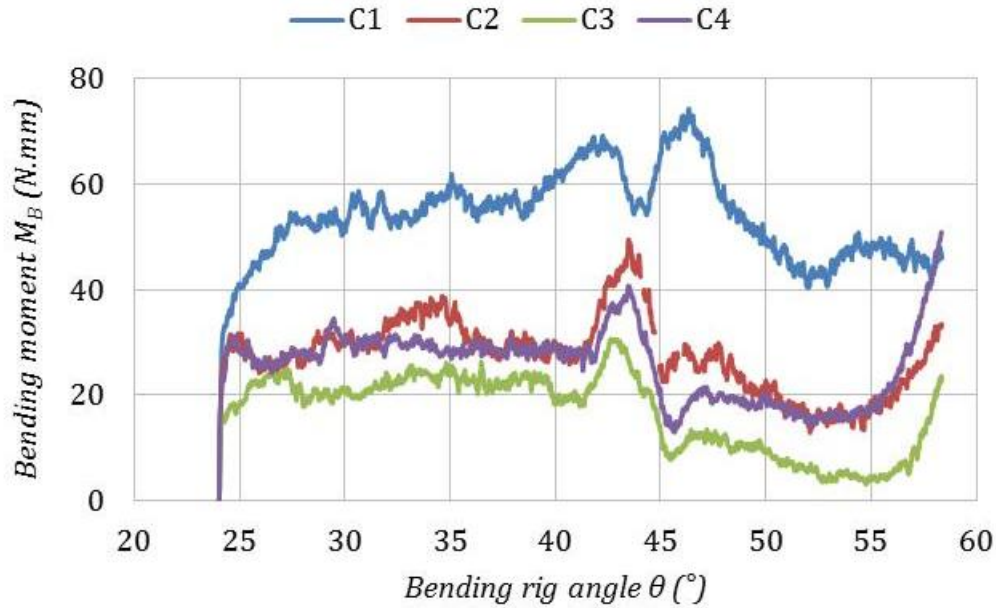


Figure 3-18: Curves of the bending moment as a function of the bending angle for sample A3/60/R0/S1, cycles C1, C2 and C3, featuring roughness.

The quantitative analysis of bending results was performed as follows. Results were structured into two 2-level, 5-parameter Taguchi [207] plans for analysis. The first plan compared the effect of the 5 following parameters and their interactions, for two modalities represented as (-) and (+) in the plans, on 2 quantitative responses that are discussed after the introduction of the parameters:

- Parameter *A*: smaller number of layers (-) vs. larger number of layers (+);
- Parameter *B*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *C*: low v_f (-) vs. high v_f (+);
- Parameter *D*: setup in rig 1 (-) vs. setup in rig 2 (+);
- Parameter *E*: bending cycle 1 (-) vs. bending cycle 3 (+).

The second plan compared the effect of the 5 following parameters and their interactions on the same 2 quantitative responses that are discussed further on:

- Parameter *A*: rovings bent at $0^\circ/90^\circ$ (-) vs. rovings bent at $-45^\circ/+45^\circ$ (+);
- Parameter *B*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *C*: low v_f (-) vs. high v_f (+);
- Parameter *D*: setup in rig 1 (-) vs. setup in rig 2 (+);
- Parameter *E*: bending cycle 1 (-) vs. bending cycle 3 (+).

The first plan focuses on the effect of the number of layers along with other parameters on the response in bending. Data analysed in this plan was generated from tests listed in

Tables 3-1, 3-2, 3-4 and 3-5. The second plan focuses on the effect of the orientation of the yarns along with other parameters on the response in bending. It aimed more specifically at quantifying the effect of bending the fabrics along the bisector to yarn directions in the samples. Data analysed in this plan was generated from tests listed in Tables 3-1, 3-3, 3-4 and 3-6. Whilst the structure of the data precluded it from being all analysed within a single plan, the two distinct plans featuring mostly common parameters and sharing 50% of common experimental results enable a clear comparison of the effect of reinforcement thickness and yarn orientations, which are two important preform parameters.

The plans are fully factorial hence each plan quantifies independently the main effects of parameters *A*, *B*, *C*, *D* and *E*, as well as all the effects of all 10 interactions of two parameters *AB*, *AC*, *AD*, *AE*, *BC*, *BD*, *BE*, *CD*, *CE* and *DE*, of all 10 interactions of 3 parameters *ABC*, *ABD*, *ABE*, *ACD*, *ACE*, *ADE*, *BCD*, *BCE*, *BDE* and *CDE*, of all 5 interactions of 4 parameters *ABCD*, *ABCE*, *ABDE*, *ACDE* and *BCDE*, and of interaction of 5 parameters *ABCDE*. All tests were replicated on 3 samples which enabled the quantitative evaluation of inner-group variability and comparison with between-group variability; the statistical significance of the effects of parameters could be assessed through multi-factorial analyses of variances and calculation of F-ratios [207].

The modalities taken by each parameter for each test in both plans are listed in Table 3-7. Actual parameters corresponding to labels *A* to *E* along with the modalities corresponding to labels + and – in each case appear in the previous page for both plans; one should note that only parameter *A* changes between the plans whilst parameters *B* to *E* stay the same.

Table 3-7: Modalities taken by all parameters and interactions for both plans.

Run	A	B	C	D	E	AB	AC	AD	AE	BC	BD	BE	CD	CE	DE	ABC	ABD	ABE	ACD	ACE	ADE	BCD	BCE	BDE	CDE	ABCD	ABCE	ABDE	ACDE	BCDE	ABCDE	
1		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
2		+	+	+	+	-	+	+	+	-	+	+	-	+	-	-	+	+	-	+	-	-	+	-	-	-	+	-	-	-	-	-
3		+	+	+	-	+	+	+	-	+	+	-	+	-	+	-	+	-	+	-	+	-	-	+	-	-	+	-	-	-	-	-
4		+	+	+	-	-	+	+	-	-	+	-	-	-	-	+	+	-	-	-	-	+	-	-	+	+	-	-	+	+	+	+
5		+	+	-	+	+	+	-	+	+	-	+	+	-	-	+	-	+	+	-	-	+	-	-	+	-	-	-	+	-	-	-
6		+	+	-	+	-	+	-	+	-	-	+	-	-	+	-	-	+	-	+	-	-	-	+	-	+	-	+	-	+	+	+
7		+	+	-	-	+	+	-	-	+	-	-	+	+	-	-	-	-	+	+	-	-	+	-	-	+	+	-	-	+	+	+
8		+	+	-	-	-	+	-	-	-	-	-	-	+	+	+	-	-	-	+	+	+	+	+	+	-	+	+	+	-	-	-
9		+	-	+	+	+	-	+	+	+	-	-	-	+	+	+	-	-	-	+	+	+	-	-	-	+	-	-	-	+	-	-
10		+	-	+	+	-	-	+	+	-	-	-	+	+	-	-	-	-	+	+	-	-	-	+	+	-	-	+	+	-	+	+
11		+	-	+	-	+	-	+	-	+	-	+	-	-	+	-	-	+	-	+	-	-	+	-	+	-	+	-	+	-	+	+
12		+	-	+	-	-	-	+	-	-	-	+	+	-	-	+	-	+	+	-	-	+	+	+	-	+	+	+	-	+	-	-
13		+	-	-	+	+	-	-	+	+	+	-	-	-	-	+	+	-	-	-	-	+	+	+	-	-	+	+	-	-	+	+
14		+	-	-	+	-	-	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	+	+	-	+	+	+	-
15		+	-	-	-	+	-	-	-	+	+	+	-	+	-	-	+	+	-	+	-	-	-	+	+	+	-	+	+	+	+	-
16		+	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	+	+
17		-	+	+	+	+	-	-	-	-	+	+	+	+	+	+	-	-	-	-	-	-	+	+	+	+	-	-	-	-	+	-
18		-	+	+	+	-	-	-	-	+	+	+	-	+	-	-	-	-	+	-	+	+	+	-	-	-	-	+	+	+	+	+
19		-	+	+	-	+	-	-	+	-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	-	-	+	-	+	+	-	+
20		-	+	+	-	-	-	-	+	+	+	-	-	-	-	+	-	+	+	+	+	-	-	-	+	+	+	+	-	-	+	-
21		-	+	-	+	+	-	+	-	-	-	+	+	-	-	+	+	-	-	+	+	-	-	-	+	-	+	+	-	+	-	+
22		-	+	-	+	-	-	+	-	+	-	+	-	-	+	-	+	-	+	+	-	+	-	+	-	+	+	-	+	-	+	-
23		-	+	-	-	+	-	+	+	-	-	-	+	+	-	-	+	+	-	-	+	+	+	-	-	+	-	+	+	-	+	-
24		-	+	-	-	-	-	+	+	+	-	-	-	+	+	+	+	+	+	-	-	-	+	+	+	-	-	-	-	+	-	+
25		-	-	+	+	+	+	-	-	-	-	-	-	+	+	+	+	+	+	-	-	-	-	-	-	+	+	+	+	-	-	+
26		-	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	-	-	+	+	-	+	+	-	+	-	-	+	+	-
27		-	-	+	-	+	+	-	+	-	-	+	-	-	+	-	+	-	+	+	-	+	+	-	+	-	-	+	-	+	+	-
28		-	-	+	-	-	+	-	+	+	-	+	+	-	-	+	+	-	-	+	+	-	+	+	-	+	-	-	+	-	-	+
29		-	-	-	+	+	+	+	-	-	+	-	-	-	-	+	-	+	+	+	+	-	+	+	-	-	-	-	+	+	+	-
30		-	-	-	+	-	+	+	-	+	+	-	+	-	+	-	-	+	-	+	-	+	+	-	+	+	-	+	-	-	-	+
31		-	-	-	-	+	+	+	+	-	+	+	-	+	-	-	-	-	+	-	+	+	-	+	+	+	+	-	-	-	-	+
32		-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	-

The responses analysed with both plans are the average and standard deviation of the values of bending moments M_B measured between bending angles of 25° and 55°. The first value characterises the general resistance to bending shown by a sample during a given test, whilst the second value characterises the extent to which this resistance fluctuates. More specific behaviour such as the larger pikes shown in Figure 3-15 is analysed qualitatively after the presentation of the results of the quantitative analysis. Values of the average and standard deviation appear in Table 3-8 for the first plan evaluating the effect of the number of layers along with other parameters, and in Table 3-9 for the second plan evaluating the effect of the orientation of yarns along with other parameters. In these tables, the labels *AVG* and *STD* represent the average and the standard deviation of the values of bending moment M_B respectively, whilst the labels S1, S2 and S3 identify the sample number as mentioned previously. Therefore, one value of the average *AVG* of M_B and one value of the standard deviation *STD* of M_B is reported for each specific bending test, cycle number and sample number.

Tables 3-8 and 3-9 also state explicitly the correspondence between the run numbers as introduced in Table 3-7 along with the systematic variation of parameters *A* to *E* and their interactions. It should be noted that modalities taken by each interaction at each run, as presented by + and – labels in Table 3-7, are the product of modalities taken by the corresponding individual parameter on the same line and therefore, all evaluations of the effects of main parameters and interactions are independent [207].

Table 3-8: Responses for the first plan (Nmm).

Run	Sub-group	S1 <i>AVG</i>	S1 <i>STD</i>	S2 <i>AVG</i>	S2 <i>STD</i>	S3 <i>AVG</i>	S3 <i>STD</i>
1	B2/63/R+45/C3	28.79	13.47	20.93	10.17	50.52	5.43
2	B2/63/R+45/C1	112.02	14.67	143.27	14.17	129.68	6.98
3	B2/63/R-45/C3	62.26	8.26	57.86	11.88	67.89	6.42
4	B2/63/R-45/C1	128.18	20.60	134.05	11.61	122.37	17.76
5	B2/45/R+45/C3	12.54	9.49	19.52	5.67	46.57	2.51
6	B2/45/R+45/C1	40.23	8.03	45.35	4.17	22.17	11.88
7	B2/45/R-45/ C3	37.94	3.33	0.11	10.72	32.42	4.65
8	B2/45/R-45/C1	57.91	8.55	57.07	4.33	51.74	9.35
9	A2/66/R90/ C3	115.25	22.49	149.47	22.65	177.54	25.96
10	A2/66/R90/C1	183.43	47.26	211.56	33.30	174.06	49.61
11	A2/66/R0/C3	67.08	17.73	41.17	7.56	59.43	21.52
12	A2/66/R0/C1	110.73	15.40	144.42	21.46	139.17	20.26
13	A2/45/R90/C3	59.68	7.60	50.40	10.27	85.12	16.93
14	A2/45/R90/C1	140.46	25.64	109.88	7.43	99.67	10.98
15	A2/45/R0/C3	42.34	19.72	65.17	13.48	31.03	13.02
16	A2/45/R0/C1	100.62	17.77	92.29	15.38	81.51	19.45
17	B1/58/R+45/C3	24.36	3.15	20.67	7.85	30.74	4.58
18	B1/58/R+45/C1	83.03	20.19	61.95	19.47	81.68	9.44
19	B1/58/R-45/C3	23.72	6.86	24.74	3.62	35.39	5.80
20	B1/58/R-45/C1	72.34	8.69	46.41	6.32	64.98	11.15
21	B1/45/R+45/C3	17.71	2.03	18.47	2.46	13.38	2.14
22	B1/45/R+45/C1	60.32	3.59	23.31	5.69	54.10	3.13
23	B1/45/R-45/C3	6.58	5.02	12.70	6.06	28.79	1.83
24	B1/45/R-45/C1	49.00	5.43	33.58	5.28	61.02	4.49
25	A1/60/R90/C3	141.13	33.71	106.04	14.90	148.63	49.87
26	A1/60/R90/C1	222.57	70.55	202.40	29.55	190.84	37.44
27	A1/60/R0/C3	85.38	42.90	66.87	28.11	113.24	58.21
28	A1/60/R0/C1	177.88	64.66	248.38	32.46	170.84	72.79
29	A1/45/R90/C3	45.19	8.56	83.49	2.86	80.28	3.76
30	A1/45/R90/C1	74.60	8.04	159.19	12.24	136.97	7.90
31	A1/45/R0/C3	36.34	12.50	42.31	16.64	26.10	12.46
32	A1/45/R0/C1	45.81	13.39	61.04	14.15	81.54	19.34

Table 3-9: Responses for the second plan (Nmm).

Run	Sub-group	S1 <i>AVG</i>	S1 <i>STD</i>	S2 <i>AVG</i>	S2 <i>STD</i>	S3 <i>AVG</i>	S3 <i>STD</i>
1	B3/58/R90/C3	27.24	11.22	23.36	6.03	43.90	5.87
2	B3/58/R90/C1	47.21	11.68	75.58	5.22	47.45	8.40
3	B3/58/R0/C3	38.24	12.47	40.99	7.59	47.21	8.19
4	B3/58/R0/C1	39.87	26.44	79.78	8.80	76.27	8.62
5	B3/45/R90/C3	65.71	11.83	6.50	3.92	38.67	4.04
6	B3/45/R90/C1	39.76	5.18	25.07	1.42	26.76	6.68
7	B3/45/R0/ C3	24.06	7.31	28.38	6.01	49.10	3.36
8	B3/45/R0/C1	75.52	4.56	21.37	8.13	50.67	5.60
9	A3/60/R90/ C3	43.90	5.57	37.83	2.13	27.19	4.05
10	A3/60/R90/C1	28.88	6.40	44.68	5.31	42.56	3.60
11	A3/60/R0/C3	16.32	7.70	34.44	8.78	35.83	5.20
12	A3/60/R0/C1	55.51	7.62	40.00	4.76	22.20	13.73
13	A3/45/R90/C3	65.71	11.83	50.66	7.88	49.64	6.49
14	A3/45/R90/C1	161.32	46.62	89.76	9.05	99.30	12.46
15	A3/45/R0/C3	43.94	29.64	24.37	53.77	77.26	60.51
16	A3/45/R0/C1	112.27	42.72	52.53	60.01	140.83	89.05
17	B1/58/R+45/C3	24.36	3.15	20.67	7.85	30.74	4.58
18	B1/58/R+45/C1	83.03	20.19	61.95	19.47	81.68	9.44
19	B1/58/R-45/C3	23.72	6.86	24.74	3.62	35.39	5.80
20	B1/58/R-45/C1	72.34	8.69	46.41	6.32	64.98	11.15
21	B1/45/R+45/C3	17.71	2.03	18.47	2.46	13.38	2.14
22	B1/45/R+45/C1	60.32	3.59	23.31	5.69	54.10	3.13
23	B1/45/R-45/C3	6.58	5.02	12.70	6.06	28.79	1.83
24	B1/45/R-45/C1	49.00	5.43	33.58	5.28	61.02	4.49
25	A1/60/R90/C3	141.13	33.71	106.04	14.90	148.63	49.87
26	A1/60/R90/C1	222.57	70.55	202.40	29.55	190.84	37.44
27	A1/60/R0/C3	85.38	42.90	66.87	28.11	113.24	58.21
28	A1/60/R0/C1	177.88	64.66	248.38	32.46	170.84	72.79
29	A1/45/R90/C3	45.19	8.56	83.49	2.86	80.28	3.76
30	A1/45/R90/C1	74.60	8.04	159.19	12.24	136.97	7.90
31	A1/45/R0/C3	36.34	12.50	42.31	16.64	26.10	12.46
32	A1/45/R0/C1	45.81	13.39	61.04	14.15	81.54	19.34

Once quantitative data is available as presented in Tables 3-8 and 3-9, the first step consists in performing a one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan and for each of the responses collected in each plan, culminating in the calculation of a value of an F-ratio in each case. The value of the F-ratio is then compared with tabulated values, indicating that the value of the F-ratio obtained is significant in the case where the value derived from the data is superior to the tabulated value, or not significant in the opposite case. A significant F-ratio indicates that differences between values for given subgroups are sufficiently large to be detected despite noise present in the data; in other words, a significant F-ratio obtained from a one-way ANOVA performed on the data as a whole provides an indication that some parameters or their interactions may have a quantifiable effect of the response, above and beyond fluctuations in the data due to experimental variability. The one-way ANOVA does not, however, provide any indication as to which parameters or interactions of parameters may be significant [207].

Quantities pertaining to the four one-way ANOVAs performed as part of the analysis of the bending data appear in Tables 3-10 to 3-13. $LAVG(AVG)$, $LSTD2(AVG)$, $LAVG(STD)$ and $LSTD(STD)$ represent the line average and the line standard deviation of either AVG or STD values for each run, or the average and variance of values of AVG and STD collected for the 3 samples associated with a given run. Equations for these quantities are as follows:

$$LAVG(AVG) = \frac{S1\ AVG + S2\ AVG + S3\ AVG}{3} \quad (3.27)$$

$$LAVG(STD) = \frac{S1\ STD + S2\ STD + S3\ STD}{3} \quad (3.28)$$

$$LSTD^2(AVG) = \frac{1}{3} [(S1\ AVG - LAVG(AVG))^2 + (S2\ AVG - LAVG(AVG))^2 + (S3\ AVG - LAVG(AVG))^2] \quad (3.29)$$

$$LSTD^2(STD) = \frac{1}{3} [(S1\ STD - LAVG(STD))^2 + (S2\ STD - LAVG(STD))^2 + (S3\ STD - LAVG(STD))^2] \quad (3.30)$$

Values of the F-Ratio associated with one-way ANOVA performed for each plan for both *AVG* and *STD* are obtained in each case by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 3 *AVG* or *STD* values associated with a given run.

The overall variance between subgroups, which is the numerator of the F-ratio, is obtained as the product of the variance of line averages and sub-group size. The former quantity is calculated as the square of the standard deviation of line averages; the simpler terminology variance will be used forthwith. The latter quantity is invariably equal to 3 for the four one-way ANOVAS presented here.

The overall variance within subgroups, which is the denominator of the F-ratio, is obtained as the average of line variances, equivalent to the average of line standard deviations squared; here again the simpler variance terminology will be used forthwith.

Considering response *AVG* for the first plan evaluating the effect of the number of layers along with other parameters with data reported in Table 3-10, variances between subgroups and within subgroups were calculated as 8879.82 and 359.25 respectively for

an F-ratio equal to 24.718. Considering total, between and within numbers of degrees of freedom of 95, 31 and 64 respectively, arrived at by subtracting 1 from the product of the number of sub-groups and sub-group size, 32 and 3 respectively in the first case, by subtracting 1 from number of subgroups 31 in the second case, and by subtracting the between value from the total value in the third case, and using a stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 2.02 [207]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG* and the first plan, 24.718 and 2.02, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Considering response *STD* for the first plan with data reported in Table 3-11, variances between subgroups and within subgroups were calculated as 569.12 and 60.70 respectively for an F-ratio equal to 9.375. Unchanged values of degrees of freedom and false alarm theoretical risk lead to an unchanged tabulated value indicating significant differences between groups of 2.02. Here again, the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *STD* and the first plan, 9.375 and 2.02, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *STD*.

Considering response *AVG* for the second plan evaluating the effect of the orientation of yarns along with other parameters with data reported in Table 3-12, variances between subgroups and within subgroups were calculated as 6607.55 and 458.04 respectively for

Table 3-10: One-way ANOVA for AVG response, first plan (Nmm).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$
1	B2/63/R+45/C3	33.41	234.92
2	B2/63/R+45/C1	128.32	245.52
3	B2/63/R-45/C3	62.67	25.28
4	B2/63/R-45/C1	128.20	34.11
5	B2/45/R+45/C3	26.21	323.08
6	B2/45/R+45/C1	35.92	148.28
7	B2/45/R-45/C3	23.49	417.59
8	B2/45/R-45/C1	55.57	11.20
9	A2/66/R90/C3	147.42	973.16
10	A2/66/R90/C1	189.68	380.89
11	A2/66/R0/C3	55.89	177.21
12	A2/66/R0/C1	131.44	328.57
13	A2/45/R90/C3	65.07	323.13
14	A2/45/R90/C1	116.67	450.53
15	A2/45/R0/C3	46.18	302.44
16	A2/45/R0/C1	91.47	91.80
17	B1/58/R+45/C3	25.26	25.95
18	B1/58/R+45/C1	75.55	139.24
19	B1/58/R-45/C3	27.95	41.78
20	B1/58/R-45/C1	61.24	178.56
21	B1/45/R+45/C3	16.52	7.54
22	B1/45/R+45/C1	45.91	392.74
23	B1/45/R-45/C3	16.02	131.60
24	B1/45/R-45/C1	47.87	189.20
25	A1/60/R90/C3	131.93	516.91
26	A1/60/R90/C1	205.27	257.88
27	A1/60/R0/C3	88.50	544.83
28	A1/60/R0/C1	199.03	1838.71
29	A1/45/R90/C3	69.65	451.42
30	A1/45/R90/C1	123.59	1923.20
31	A1/45/R0/C3	34.92	67.21
32	A1/45/R0/C1	62.80	321.47
	Average		359.25
	Variance	8879.82	
	F-Ratio		24.718

Table 3-11: One-way ANOVA for *STD* response, first plan (Nmm).

Run	Sub-group	$LAVG(STD)$	$LSTD^2(STD)$
1	B2/63/R+45/C3	9.69	16.33
2	B2/63/R+45/C1	11.94	18.51
3	B2/63/R-45/C3	8.85	7.72
4	B2/63/R-45/C1	16.66	21.12
5	B2/45/R+45/C3	5.89	12.22
6	B2/45/R+45/C1	8.03	14.86
7	B2/45/R-45/C3	6.23	15.53
8	B2/45/R-45/C1	7.41	7.27
9	A2/66/R90/C3	23.70	3.84
10	A2/66/R90/C1	43.39	77.74
11	A2/66/R0/C3	15.60	52.11
12	A2/66/R0/C1	19.04	10.30
13	A2/45/R90/C3	11.60	23.09
14	A2/45/R90/C1	14.68	93.19
15	A2/45/R0/C3	15.41	14.01
16	A2/45/R0/C1	17.53	4.18
17	B1/58/R+45/C3	5.19	5.80
18	B1/58/R+45/C1	16.37	36.11
19	B1/58/R-45/C3	5.43	2.73
20	B1/58/R-45/C1	8.72	5.83
21	B1/45/R+45/C3	2.21	0.05
22	B1/45/R+45/C1	4.14	1.86
23	B1/45/R-45/C3	4.30	4.86
24	B1/45/R-45/C1	5.07	0.26
25	A1/60/R90/C3	32.83	306.31
26	A1/60/R90/C1	45.85	473.25
27	A1/60/R0/C3	43.07	226.53
28	A1/60/R0/C1	56.64	454.91
29	A1/45/R90/C3	5.06	9.39
30	A1/45/R90/C1	9.39	6.08
31	A1/45/R0/C3	13.87	5.77
32	A1/45/R0/C1	15.63	10.49
	Average		60.70
	Variance	569.12	
	F-Ratio		9.375

an F-ratio equal to 14.426. Unchanged values of degrees of freedom and false alarm theoretical risk lead to an unchanged tabulated value indicating significant differences between groups of 2.02. Yet again the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG* and the second plan, 14.426 and 2.02, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Finally, considering response *STD* for the second plan with data reported in Table 3-13, variances between subgroups and within subgroups were calculated as 871.61 and 93.67 respectively for an F-ratio equal to 9.305. The tabulated value indicating significant differences between groups remains at 2.02. The same conclusion is reached from this last one-way ANOVA: the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *STD* and the first plan, 9.305 and 2.02, indicate that there is scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *STD*.

Given the above conclusions, the next step in analysing the effects of the parameters on bending consists in calculating contrasts associated with each parameter and interaction of parameters, for each response and each plan. Contrasts, which are quantified comparisons of responses obtained under opposed effect of a given parameter or interaction of parameters, are calculated as follows. Given k subgroups, a contrast defined upon the subgroup averages $\mu_1, \mu_2, \dots, \mu_j, \dots, \mu_k$ by the coefficients $c_1, c_2, \dots, c_j, \dots, c_k$ can be estimated using equation 3.31:

Table 3-12: One-way ANOVA for *AVG* response, second plan (Nmm).

Run	Sub-group	<i>LAVG</i> (<i>AVG</i>)	<i>LSTD</i> ² (<i>AVG</i>)
1	B3/58/R90/C3	31.50	119.08
2	B3/58/R90/C1	56.75	266.04
3	B3/58/R0/C3	42.15	21.12
4	B3/58/R0/C1	65.31	488.35
5	B3/45/R90/C3	36.96	878.65
6	B3/45/R90/C1	30.53	64.61
7	B3/45/R0/ C3	33.85	179.16
8	B3/45/R0/C1	49.19	734.71
9	A3/60/R90/ C3	36.31	71.55
10	A3/60/R90/C1	38.71	73.55
11	A3/60/R0/C3	28.86	118.48
12	A3/60/R0/C1	39.24	277.83
13	A3/45/R90/C3	55.34	80.96
14	A3/45/R90/C1	116.79	1509.72
15	A3/45/R0/C3	48.52	715.09
16	A3/45/R0/C1	101.88	2030.24
17	B1/58/R+45/C3	25.26	25.95
18	B1/58/R+45/C1	75.55	139.24
19	B1/58/R-45/C3	27.95	41.78
20	B1/58/R-45/C1	61.24	178.56
21	B1/45/R+45/C3	16.52	7.54
22	B1/45/R+45/C1	45.91	392.74
23	B1/45/R-45/C3	16.02	131.60
24	B1/45/R-45/C1	47.87	189.20
25	A1/60/R90/C3	131.93	516.91
26	A1/60/R90/C1	205.27	257.88
27	A1/60/R0/C3	88.50	544.83
28	A1/60/R0/C1	199.03	1838.71
29	A1/45/R90/C3	69.65	451.42
30	A1/45/R90/C1	123.59	1923.20
31	A1/45/R0/C3	34.92	67.21
32	A1/45/R0/C1	62.80	321.47
	Average		458.04
	Variance	6607.55	
	F-Ratio		14.426

Table 3-13: One-way ANOVA for *STD* response, second plan (Nmm).

Run	Sub-group	$LAVG(STD)$	$LSTD^2(STD)$
1	B3/58/R90/C3	7.71	9.26
2	B3/58/R90/C1	8.43	10.43
3	B3/58/R0/C3	9.42	7.08
4	B3/58/R0/C1	14.62	104.79
5	B3/45/R90/C3	6.60	20.54
6	B3/45/R90/C1	4.43	7.34
7	B3/45/R0/ C3	5.56	4.05
8	B3/45/R0/C1	6.10	3.37
9	A3/60/R90/ C3	3.92	2.97
10	A3/60/R90/C1	5.10	1.99
11	A3/60/R0/C3	7.23	3.37
12	A3/60/R0/C1	8.70	21.00
13	A3/45/R90/C3	8.73	7.68
14	A3/45/R90/C1	22.71	431.67
15	A3/45/R0/C3	47.97	263.44
16	A3/45/R0/C1	63.93	548.12
17	B1/58/R+45/C3	5.19	5.80
18	B1/58/R+45/C1	16.37	36.11
19	B1/58/R-45/C3	5.43	2.73
20	B1/58/R-45/C1	8.72	5.83
21	B1/45/R+45/C3	2.21	0.05
22	B1/45/R+45/C1	4.14	1.86
23	B1/45/R-45/C3	4.30	4.86
24	B1/45/R-45/C1	5.07	0.26
25	A1/60/R90/C3	32.83	306.31
26	A1/60/R90/C1	45.85	473.25
27	A1/60/R0/C3	43.07	226.53
28	A1/60/R0/C1	56.64	454.91
29	A1/45/R90/C3	5.06	9.39
30	A1/45/R90/C1	9.39	6.08
31	A1/45/R0/C3	13.87	5.77
32	A1/45/R0/C1	15.63	10.49
	Average		93.67
	Variance	871.61	
	F-Ratio		9.305

$$\hat{C} = \sum_{j=1}^k c_j \bar{X}_j \quad (3.31)$$

where values $X_1, X_2, \dots, X_j, \dots, X_k$ are averages associated with each subgroup, which are estimates of means.

An F-ratio may be calculated for each individual contrast as the ratio of the sum of squares for the contrast $SS(C)$ and mean square within for all the data, MSW :

$$F - ratio = \frac{MS(C)}{MSW} = \frac{SS(C)}{MSW} \quad (3.32)$$

Term $SS(C)$ is calculated as:

$$SS(C) = \frac{(\hat{C})^2}{Adjustment\ Term} \quad (3.33)$$

$$Adjustment\ Term = \sum_{j=1}^k \left(\frac{c_j^2}{n_j} \right) = \frac{1}{n} \sum_{j=1}^k c_j^2 \quad (3.34)$$

The adjustment term in equation 3.34 is equal to 32/3, obtained as the number of data entries compared using the contrast to the number of entries in subgroups, which is systematically 3 for contrast F-ratios as calculated here.

Term MSW is the average of variances for all contrasts, also equal to the within sum of squares divided by the number of degrees of freedom; values, which already appeared in Tables 3-10 to 3-13, reappear for each parameter and each plan in Tables 3-14 to 3-17.

Table 3-14: Contrasts for *AVG* response, first plan (Nmm).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	105.6	1045	2.91
<i>B</i>	-949.4	84 503	235
<i>C</i>	813.9	62 103	173
<i>D</i>	303.2	8 615	24.0
<i>E</i>	-827.5	64 187	179
<i>AB</i>	249.3	5 828	16.2
<i>AC</i>	19.0	34	0.09
<i>AD</i>	-7.5	5	0.01
<i>AE</i>	-6.4	4	0.01
<i>BC</i>	-263.7	6 520	18.1
<i>BD</i>	-375.0	13 181	36.7
<i>BE</i>	133.3	1 667	4.64
<i>CD</i>	60.6	345	0.96
<i>CE</i>	-264.0	6 532	18.2
<i>DE</i>	16.6	26	0.07
<i>ABC</i>	276.5	7 165	19.9
<i>ABD</i>	-105.0	1 032	2.87
<i>ABE</i>	-108.5	1 102	3.07
<i>ACD</i>	126.2	1 494	4.16
<i>ACE</i>	-15.2	22	0.06
<i>ADE</i>	23.4	51	0.14
<i>BCD</i>	-59.0	326	0.91
<i>BCE</i>	-18.1	30	0.08
<i>BDE</i>	-59.7	334	0.93
<i>CDE</i>	31.7	94	0.26
<i>ABCD</i>	-176.8	2 931	8.16
<i>ABCE</i>	-177.4	2 952	8.22
<i>ABDE</i>	-8.3	7	0.02
<i>ACDE</i>	-56.0	293	0.82
<i>BCDE</i>	-174.1	2 840	7.91
<i>ABCDE</i>	-8.6	7	0.02
<i>MSW</i>	359.3		

Table 3-15: Contrasts for *STD* response, first plan (Nmm).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-38.1	136	2.24
<i>B</i>	-257.1	6 200	102
<i>C</i>	216.5	4 395	72.4
<i>D</i>	-9.4	8	0.14
<i>E</i>	-91.5	786	12.9
<i>AB</i>	84.6	672	11.1
<i>AC</i>	-92.3	800	13.2
<i>AD</i>	53.9	272	4.48
<i>AE</i>	8.2	6	0.10
<i>BC</i>	-137.4	1 769	29.1
<i>BD</i>	11.0	12	0.19
<i>BE</i>	30.4	87	1.43
<i>CD</i>	39.4	146	2.40
<i>CE</i>	-57.0	304	5.01
<i>DE</i>	-23.7	53	0.87
<i>ABC</i>	91.5	785	12.9
<i>ABD</i>	-69.9	458	7.54
<i>ABE</i>	-0.64	0	0.00
<i>ACD</i>	30.6	87	1.44
<i>ACE</i>	7.7	5	0.09
<i>ADE</i>	-1.6	0	0.00
<i>BCD</i>	-26.9	68	1.11
<i>BCE</i>	20.0	37	0.61
<i>BDE</i>	14.7	20	0.34
<i>CDE</i>	-12.3	14	0.24
<i>ABCD</i>	-59.7	334	5.50
<i>ABCE</i>	2.4	1	0.01
<i>ABDE</i>	28.8	78	1.28
<i>ACDE</i>	-5.1	2	0.04
<i>BCDE</i>	12.0	13	0.22
<i>ABCDE</i>	31.7	94	1.55
<i>MSW</i>	60.7		

Table 3-16: Contrasts for *AVG* response, second plan (Nmm).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-420.2	16 547	36.1
<i>B</i>	-718.7	48 435	105
<i>C</i>	263.2	6 495	14.2
<i>D</i>	149.3	2 088	4.56
<i>E</i>	-595.4	33 237	72.6
<i>AB</i>	480.0	21 596	47.2
<i>AC</i>	-531.7	26 502	57.9
<i>AD</i>	-161.4	2 444	5.34
<i>AE</i>	225.6	4 771	10.4
<i>BC</i>	-45.4	194	0.42
<i>BD</i>	-198.4	3 692	8.06
<i>BE</i>	191.2	3 425	7.48
<i>CD</i>	-51.2	246	0.54
<i>CE</i>	-61.9	359	0.78
<i>DE</i>	16.2	24	0.05
<i>ABC</i>	494.7	22 941	50.1
<i>ABD</i>	71.7	481	1.05
<i>ABE</i>	-50.6	240	0.52
<i>ACD</i>	14.2	19	0.04
<i>ACE</i>	186.9	3 276	7.15
<i>ADE</i>	23.0	50	0.11
<i>BCD</i>	70.1	460	1.01
<i>BCE</i>	61.8	358	0.78
<i>BDE</i>	-5.9	3	0.01
<i>CDE</i>	36.0	122	0.27
<i>ABCD</i>	-47.8	214	0.47
<i>ABCE</i>	-221.3	4 589	10.0
<i>ABDE</i>	45.4	194	0.42
<i>ACDE</i>	-51.5	249	0.55
<i>BCDE</i>	-122.7	1 410	3.08
<i>ABCDE</i>	42.7	172	0.38
<i>MSW</i>	458.0		

Table 3-17: Contrasts for *STD* response, second plan (Nmm).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-42.6	170	1.82
<i>B</i>	-276.3	7 159	76.4
<i>C</i>	53.6	269	2.87
<i>D</i>	-127.5	1 526	16.3
<i>E</i>	-86.7	705	7.53
<i>AB</i>	65.4	402	4.29
<i>AC</i>	-255.4	6 112	65.3
<i>AD</i>	-64.2	387	4.13
<i>AE</i>	13.0	16	0.17
<i>BC</i>	21.4	43	0.46
<i>BD</i>	119.4	1 335	14.3
<i>BE</i>	43.8	180	1.92
<i>CD</i>	70.7	469	5.01
<i>CE</i>	-12.5	15	0.16
<i>DE</i>	-1.6	0	0.00
<i>ABC</i>	250.4	5 875	62.7
<i>ABD</i>	38.4	138	1.47
<i>ABE</i>	12.8	15	0.16
<i>ACD</i>	61.8	358	3.83
<i>ACE</i>	52.0	254	2.71
<i>ADE</i>	20.5	40	0.42
<i>BCD</i>	-64.5	389	4.15
<i>BCE</i>	-26.1	64	0.68
<i>BDE</i>	-2.1	0	0.00
<i>CDE</i>	-3.5	1	0.01
<i>ABCD</i>	-97.3	886	9.46
<i>ABCE</i>	-43.5	178	1.90
<i>ABDE</i>	12.0	13	0.14
<i>ACDE</i>	3.7	1	0.01
<i>BCDE</i>	-6.4	4	0.04
<i>ABCDE</i>	13.3	17	0.18
<i>MSW</i>	93.67		

F-ratios for each contrast, response and plan appear in the same tables. It may be noted that the average of contrast F-ratios presented in Tables 3-14 to 3-17 are equal to the one-way ANOVA F-ratios presented in Tables 3-10 to 3-13, as expected.

Calculated contrast F-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with MSW remains unchanged at 64. Using the same stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 7.07 [207].

Values of contrast F-ratios superior to 7.07, deemed significant, are highlighted in Tables 3-14 to 3-17. Results from Table 3-14 reveal that 12 main effects and interactions of parameters have a significant effect on response *AVG* in the first plan; results from Table 3-15 reveal that 8 main effects and interactions of parameters have a significant effect on response *STD* in the first plan. Results from Table 3-16 reveal that 12 main effects and interactions of parameters have a significant effect on response *AVG* in the second plan, and results from Table 3-17 reveal that 7 main effects and interactions of parameters have a significant effect on response *STD* in the second plan. Significant main effects and interactions of parameters are summarised in Table 3-18, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 3-19 to 3-22.

The tables and figures show that parameter *B*, uO-APT reinforcement (-) vs. industrial

Table 3-18: Summary of significant main effects and interactions of parameters.

First plan, response <i>AVG</i>	First plan, response <i>STD</i>	Second plan, response <i>AVG</i>	Second plan response <i>STD</i>
		<i>A</i> (-)	
<i>B</i> (-)	<i>B</i> (-)	<i>B</i> (-)	<i>B</i> (-)
<i>C</i> (+)	<i>C</i> (+)	<i>C</i> (+)	
<i>D</i> (+)			<i>D</i> (-)
<i>E</i> (-)	<i>E</i> (-)	<i>E</i> (-)	<i>E</i> (-)
<i>AB</i> (+)	<i>AB</i> (+)	<i>AB</i> (+)	
	<i>AC</i> (-)	<i>AC</i> (-)	<i>AC</i> (-)
		<i>AE</i> (+)	
<i>BC</i> (-)	<i>BC</i> (-)		
<i>BD</i> (-)		<i>BD</i> (-)	<i>BD</i> (+)
		<i>BE</i> (+)	
<i>CE</i> (-)			
<i>ABC</i> (+)	<i>ABC</i> (+)	<i>ABC</i> (+)	<i>ABC</i> (+)
	<i>ABD</i> (-)		
		<i>ACE</i> (+)	
<i>ABCD</i> (-)			<i>ABCD</i> (-)
<i>ABCE</i> (-)		<i>ABCE</i> (-)	
<i>BCDE</i> (-)			

reinforcement (+), has a leading effect on the average bending stiffness *AVG* and its standard deviation *STD* for both responses and both plans, where stiffness and its variability are systematically higher for uO-APT reinforcements. Beyond its strong main effects, parameter *B* is also involved in 19 significant interactions of parameters out of 25. Parameter *E*, bending cycle 1 (-) vs. bending cycle 3 (+), has the second strongest effect on the average bending stiffness *AVG* for both plans with stiffness being higher on the first

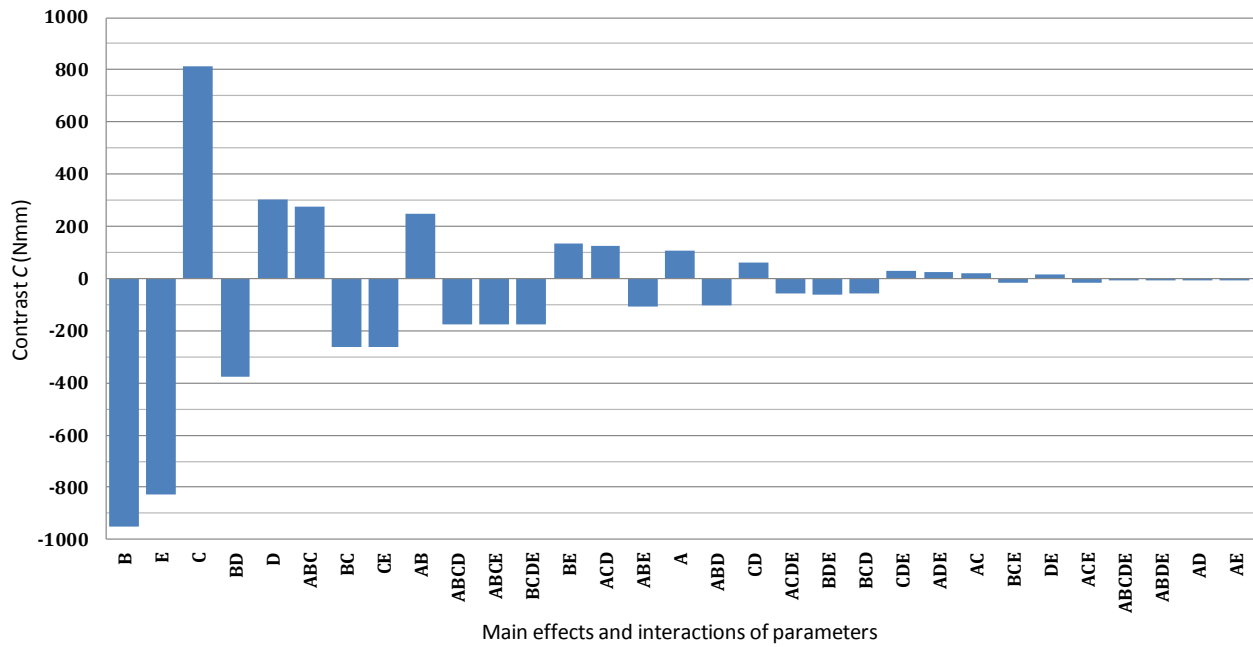


Figure 3-19: Main effects and interactions of parameters in decreasing order, response *AVG*, first plan.

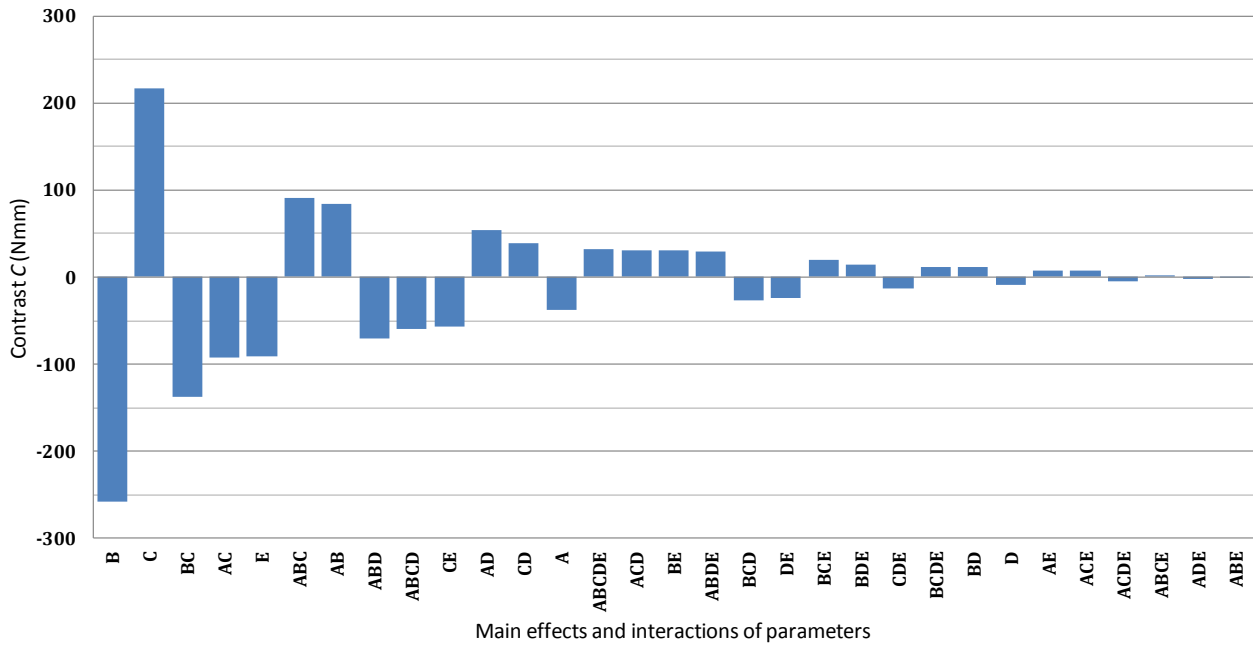


Figure 3-20: Main effects and interactions of parameters in decreasing order, response *STD*, first plan.

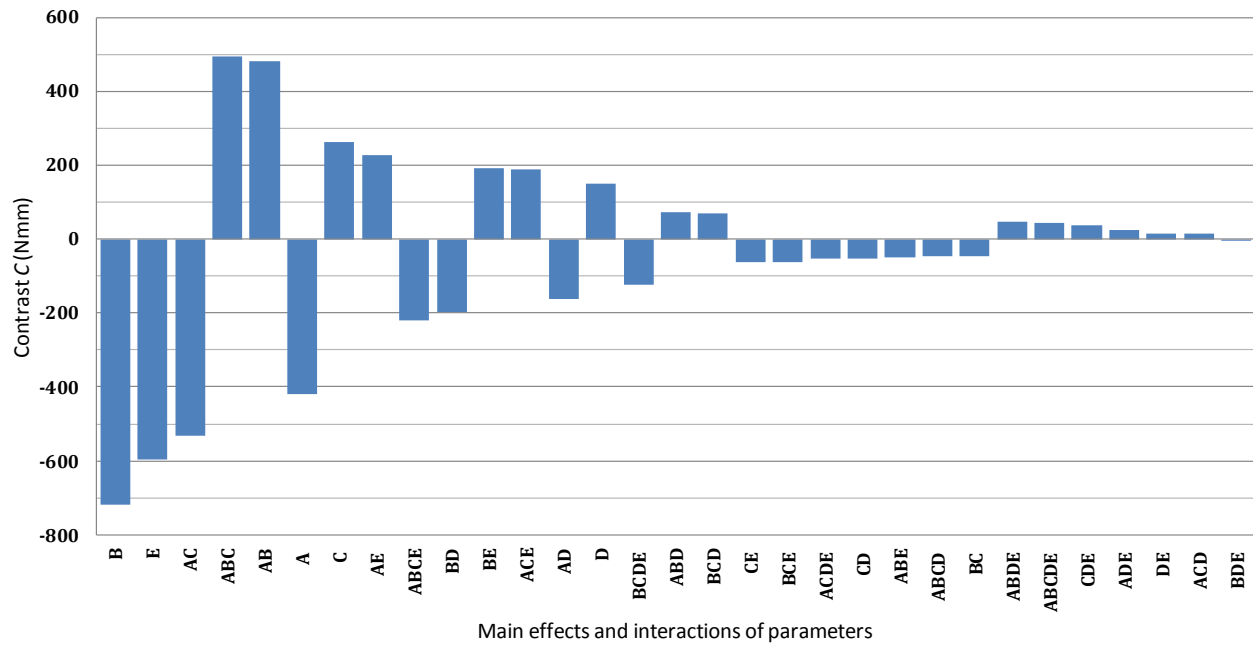


Figure 3-21: Main effects and interactions of parameters in decreasing order, response *AVG*, second plan.

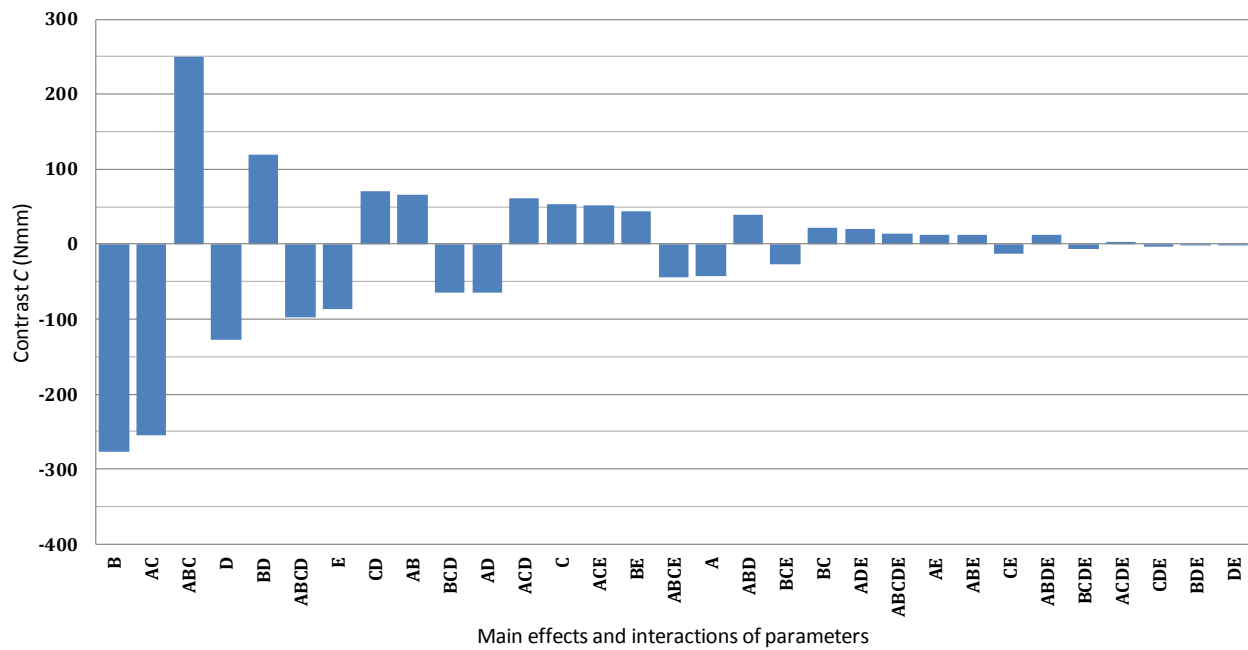


Figure 3-22: Main effects and interactions of parameters in decreasing order, response *STD*, second plan.

cycle. Parameter E also has a lesser but significant effect on the standard deviation STD with STD being lower on bending cycle 3, and is involved in 7 significant interactions of parameters out of 25. Parameter C , low v_f (-) vs. high v_f (+) also had a significant effect on the average bending stiffness AVG with stiffness higher at high v_f and standard deviation STD being significantly higher in the first plan. Parameter C is also involved in 16 significant interactions.

Changes in parameters A and D related to the numbers of layers, yarn orientation and orientation setup in the bending apparatus induced limited effects as main parameters; however, parameter A was present in numerous interactions for both plans.

3.5.3 Qualitative discussion of experimental results

The above systematic plans identify very clearly that the most important differences in bending behaviour arise when comparing uO-APT and industrial textiles. Perhaps this was to be expected given the different means of assembly used for each type of reinforcement fabrics, despite the fact that the low-stiffness stitches represent a small proportion of material present in the fabric stacks. This highlights the effect of relative displacements between layers on the bending behaviour.

The second most important main effect on the average bending moment is the cycle number. Such effect of cycling is not surprising as reorganisation of fibres upon successive loading and unloading leading to changes in mechanical behaviour was observed in other cases [208-210]. However, it is worth noting that cycling generally has a stronger effect

than other parameters related to the architecture of the reinforcement stacks, namely the fibre volume fraction, number of layers, yarn orientations and setup orientations. This confirms the observation made above to the effect that stitching through the thickness of the reinforcement stacks has a strong effect on the observed bending moment.

Bending curves appear in Appendix C. Analysing the moment data resulted in identifiable differences in bending behaviour, above experimental noise. On the other hand, no major changes in behaviour during bending tests lead to suspecting the occurrence of major instabilities such as buckling, and no evidence of such behaviour could be seen using visual observation.

3.6 Analysis

In bending tests, samples ranging between 95 mm to 115 mm were fixed at one end of the apparatus whilst the other end was free. Although this entails approximations and hypotheses that are discussed within this section, it is appropriate to model the bent sample as a cantilever beam or series of cantilever beams with a span length that evolves during the test, and cross-sectional area or compound cross-sectional area defined by the sample width and thickness under the roller, say 100 mm by 2 mm when a 2 mm spacer is used, replicating the experimental setup.

The first approximation that may or may not be made relates to whether the whole sample, which is not continuous, bends as a continuous beam with material in flat sections remaining in flat sections perpendicular to a global neutral plane; or else behaves as a

series of yarns essentially unattached which themselves behave like a continuous beam would; or else individual fibres in yarns all behave essentially as unattached beams. Whether the sample, yarns or fibres behave as a continuous beam would, will result in different force levels and so analysing the sample as a beam or combination of beams will provide further insight to the way in which bending actually happens within the fabric reinforcement. Experimental results and analytical predictions were compared through modelling the moment of inertia for the sample cross-section under the roller. The modelling procedure applies to all sample groups; a detailed example is provided for sample cross-sections from group A1.

Group A1 samples consisted of 8 layers of parallel Toray HTS40 12K carbon yarns. Nominal yarn width was 4 mm hence each 100 mm wide layer contained 25 yarns. Labelling stitch orientation as 0° for referencing orientations in the fabric, the yarn orientation sequence was $[90^\circ / 0^\circ / 90^\circ / 0^\circ / 0^\circ / 90^\circ / 0^\circ / 90^\circ]$ with half of layers oriented at 0° and the other half oriented at 90° . During bending tests, 4 out of 8 layers were parallel to the roller and the other 4 were perpendicular to the roller; some tests were performed with the stitch oriented parallel to the roller (R0), whilst in others the stitch was perpendicular to the roller (R90). In all cases, this means that yarns in only 4 layers were normal to the bending cross-section, largely controlling bending stiffness. Yarns in the other 4 layers, which were parallel to the roller, were reasonably assumed not to influence or contribute to the bending stiffness of the sample. Figure 3-23 shows how yarn alignment in a cross-section of a sample from group A was represented. It was safely assumed that the low stiffness thermoplastic stitching thread did not contribute directly to the bending stiffness.

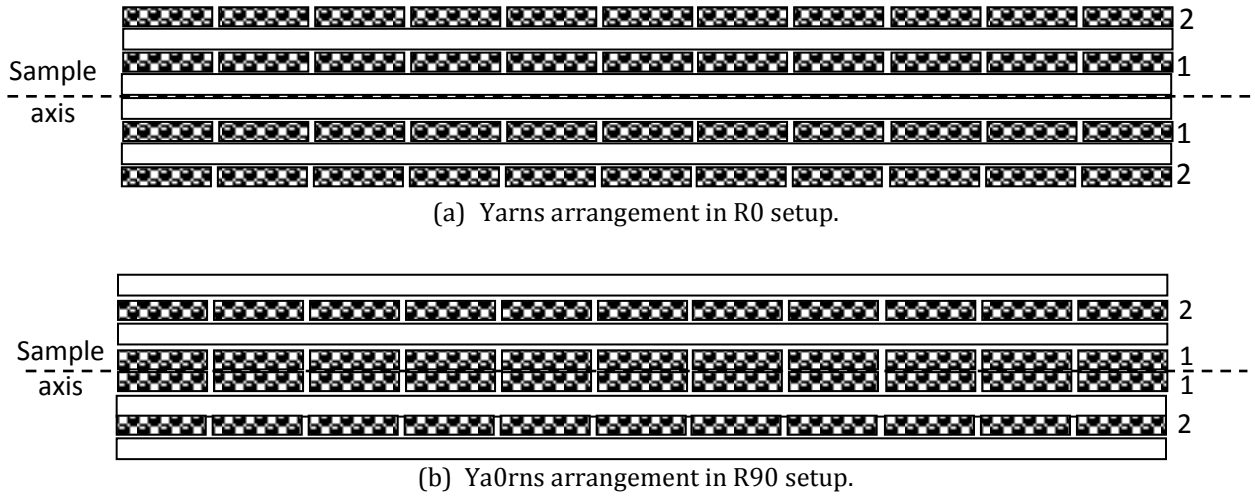


Figure 3-23: Yarn alignment in sample cross-sections from group A1.

As shown in the figure above, yarns of the 4 layers that are perpendicular to the roller have been considered whilst yarns forming the other 4 layers that are parallel to the roller were ignored in probing bending stiffness. In following sections of this chapter, different models are introduced for calculating the moment of inertia of the sample based on this geometry.

3.7 Modelling the moment of inertia of a single yarn

To compare experimental bending results with values obtained analytically, the moment of inertia of the samples has to be calculated. To calculate such a value the following models were used.

3.7.1 Fibre model

In this first approach, the fibre model assumes that all fibres bend independently as distinct elastic beams. Yarns used for manufacturing the preforms were Toho Tenax HTS 40 12K. A

single yarn measures 4 mm in nominal width by 0.25 mm in nominal height at a v_f of approximately 45%, and contains 12000 fibres with a fibre radius r_f of approximately 5 μ m. As shown in Figure 3-24, in the fibre model the cross-section of a single yarn was represented as rectangular while the fibres were modeled as circular.

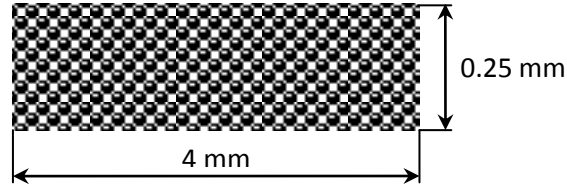


Figure 3-24: Fibre model, sample moment of inertia.

The moment of inertia of a single fibre I_{fibre} with circular cross-section and 5 μ m radius is:

$$I_{fibre} = \frac{\pi r_f^4}{4} = 4.9 \times 10^{-10} \text{ mm}^4 \quad (3.35)$$

As there are 12,000 fibres in each yarn, the moment of inertia of the yarn I_{yarn} obtained when assuming that each fibre bends around its own centroid and independently of other fibres, neglecting friction between fibres, is:

$$I_{yarn} = 12,000 I_{fibre} = 5.89 \times 10^{-6} \text{ mm}^4 \quad (3.36)$$

3.7.2 Yarn model

In this second approach, the moment of inertia of a single yarn is obtained assuming that each fibre bends around the yarn centroid, hence yarns behave as porous but continuous beams. This may arise from individual fibres being intertwined, from fibre to fibre friction, or from fibre sizing. Yarns are represented as 25 rows of fibres with 480 fibres in each row as shown in Figure 3-25, proportionally to their nominal dimensions.

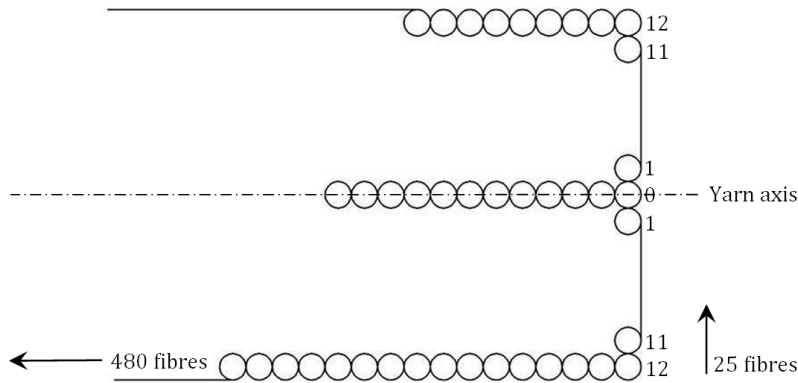


Figure 3-25: Yarn model, sample moment of inertia.

Fibre rows are numbered symmetrically around the yarn axis from 0 to 12. All row numbers are repeated twice except for row 0 which lies on the yarn axis hence the moment of inertia for row 0, I_0^{Row} is:

$$I_0^{Row} = 480 I_{fibre} = 2.35 \times 10^{-7} mm^4 \quad (3.37)$$

The moment of inertia for any pairs of rows excluding row 0 is:

$$I_n^{Row} = 2 \left(I_0^{Row} + 480 \left(\pi r_f^2 \cdot (2nr_f)^2 \right) \right) \quad (3.38)$$

Factor 2 in the above equation indicates that each row is repeated twice, and n is the row number. For example, the moment of inertia of rows 1, I_1^{Row} , is:

$$I_1^{Row} = 2 \left(I_0^{Row} + 480 \left(\pi r_f^2 \cdot (2r_f)^2 \right) \right) = 8 \times 10^{-6} \text{ mm}^4 \quad (3.39)$$

The moment of inertia for the single yarn is:

$$I_{yarn} = \sum_0^{12} I_n^{Row} = 4.9 \times 10^{-3} \text{ mm}^4 \quad (3.40)$$

3.7.3 Cantilever model

In this third approach, the moment of inertia of a single yarn was obtained from experimental measurements performed on yarns extracted individually from textiles, using a cantilever beam model with the yarn subjected to its own weight as a uniform distributed load w_o and a span length L_o . Here it is reasonably assumed that the yarn remains well within its linear elastic domain, and so that it is subjected to small strains only with the relevant equations being entirely applicable. The mass of 0.5 m yarn length was measured as 0.4×10^{-3} kg, corresponding to a distributed load of 7.848×10^{-3} N/m. Figure 3-26 shows the cantilever model of the yarn for a span length of 0.1 m.

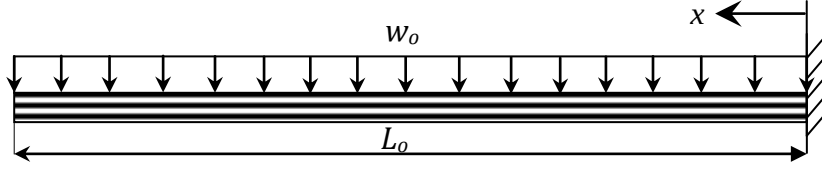


Figure 3-26: Cantilever model of a single yarn bending under its mass.

The above model was used for calculating the moment of inertia of the dry fabric yarn from measurements. The first step was to derive the deflection equation for such a beam using the integration method:

$$EI_{yarn}v'' = M(x) \quad (3.41)$$

$$EI_{yarn}v'' = \frac{1}{2}w_oL_o^2 - w_oL_o x + \frac{1}{2}w_o x^2 \quad (3.42)$$

$$EI_{yarn}v' = \frac{1}{2}w_oL_o^2 x - \frac{1}{2}w_oL_o x^2 + \frac{1}{6}w_o x^3 + c_1 \quad (3.43)$$

$$EI_{yarn}v(x) = \frac{1}{4}w_oL_o^2 x^2 - \frac{1}{6}w_oL_o x^3 + \frac{1}{24}w_o x^4 + c_1 x + c_2 \quad (3.44)$$

where Young's modulus of the fibres E is known from supplier data [211].

Applying the double boundary condition at $x = 0$ with deflection $v = 0$ and rotation $v' = 0$ leads to $c_1 = 0$ and $c_2 = 0$. Therefore,

$$EI_{yarn}v(x) = \frac{1}{4}w_oL_o^2 x^2 - \frac{1}{6}w_oL_o x^3 + \frac{1}{24}w_o x^4 \quad (3.45)$$

which is the deflection equation for a cantilever beam. The maximum deflection for the HTS 40 12K yarn that was cantilevered experimentally with a span length of 0.1 m was measured at the free end of the yarn using a caliper. The measurement repeated several times. Small differences of ± 0.05 around 4 mm were measured. Therefore, an average value of $v_{max} = 4 \text{ mm}$ was used. The deflection equation can be rewritten as:

$$EI_{yarn} v_{max} = \frac{w_o L_o^4}{8} \quad (3.46)$$

and the moment of inertia for the single yarn was evaluated as:

$$I_{yarn} = \frac{w_o L_o^4}{8E v_{max}} = \frac{7.848 \times (100)^4}{8 \times 238 \times 10^3 \times 4} = 1 \times 10^{-4} \text{ mm}^4 \quad (3.47)$$

Values of the moment of inertia obtained for the yarn from the three above approaches are summarised in Table 3-12 for comparison purposes.

Table 3-19: Values of yarn moment of inertia obtained from different approaches.

Yarn moment of inertia values	
Model	$I_{yarn} \text{ (mm}^4\text{)}$
Fibre model	5.89×10^{-6}
Cantilever model	1×10^{-4}
Yarn model	4.9×10^{-3}

3.7.4 Observations on the moment of inertia of a single yarn

Comparing the different values obtained for the moment of inertia of a single yarn, it can be concluded that the value obtained from the fibre model, $5.89 \times 10^{-6} \text{ mm}^4$, is the lowest bound for the moment inertia of a single yarn as it assumes that each fibre bends around its own centroid and there is no interaction or friction between fibres. It is readily seen that this hypothesis is not sound given results obtained from the cantilever approach. On the other hand, the value obtained from the yarn model, $4.9 \times 10^{-3} \text{ mm}^4$, is the highest bound as it assumes that all fibres inside the yarn bend as one porous but continuous unit. The value of the moment of inertia for a single yarn lies about midway between $5.89 \times 10^{-6} \text{ mm}^4$ and $4.9 \times 10^{-3} \text{ mm}^4$. As such, the level of interactions between fibres is far from being negligible, even for a yarn that is not being compressed or subjected to external loads normal to its axis. The cantilever approach enables the quantification of the value of the moment of inertia for this specific type of yarn through experimental means. The value $1 \times 10^{-4} \text{ mm}^4$ for the moment of inertia, obtained from the cantilever model lies at the approximate center of the range and therefore, it may be used in calculations of the moment of inertia of complete textile samples. As a final remark, one may notice the small deflection obtained for yarns, despite the relatively long sample used. This shows that methods relying on the measurement of deflection induced by the mass of a cantilevered sample are not suited to the reinforcements probed here, as discussed in Chapter 2.

3.8 Calculation of the moment of inertia of the sample

The moment of inertia of the sample can be calculated from the above values of I_{yarn} using two approaches. The first approach consists in assuming that each yarn bends around its

own centroid, with the moment of inertia of the whole sample being obtained by summation. Values of the moment of inertia of the whole sample obtained using this assumption can be calculated using the fibre model, the yarn model and the cantilever model as follows. The moment of inertia of the whole sample I_{sample} cross-section obtained using the yarn moment of inertia derived from the fibre model is:

$$I_{sample} = I_{yarn} \cdot NY \cdot NL = 5.89 \times 10^{-6} \cdot 25 \cdot 4 = 5.89 \times 10^{-4} \text{ mm}^4 \quad (3.48)$$

The moment of inertia of the whole sample cross-section obtained using the yarn moment of inertia derived from the yarn model is:

$$I_{sample} = I_{yarn} \cdot NY \cdot NL = 4.9 \times 10^{-3} \cdot 25 \cdot 4 = 0.49 \text{ mm}^4 \quad (3.49)$$

Finally, the moment of inertia of the whole sample cross-section obtained using the yarn moment of inertia derived from the cantilever model is:

$$I_{sample} = I_{yarn} \cdot NY \cdot NL = 1 \times 10^{-4} \cdot 25 \cdot 4 = 1 \times 10^{-2} \text{ mm}^4 \quad (3.50)$$

where NY is number of yarns normal to the cross-section along the width and NL is the number of layers containing yarns normal to the cross-section along the thickness.

Alternatively, the values may be obtained by assuming that all yarns in the sample cross-section bend around the sample centroid; this approach is demonstrated below for both setups R0 and R90.

3.8.1 Parallel setup (R0)

Stitching is parallel to the roller in setup R0, with only yarns perpendicular to the cross-section of the sample contributing to the stiffness of the sample. These yarns are arranged as shown in Figure 3-27.

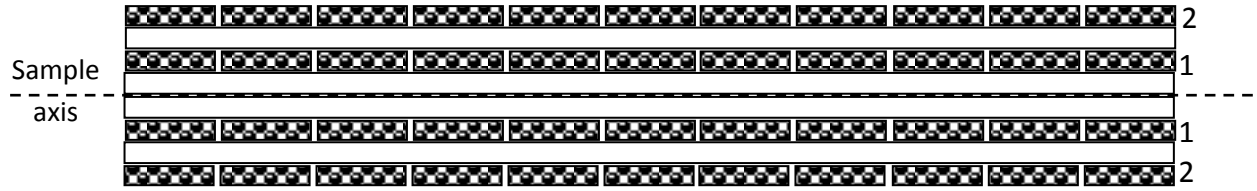


Figure 3-27: Yarns arrangement in R0 setup.

Using value $I_{yarn} = 5.89 \times 10^{-6} mm^4$ for the yarn moment of inertia obtained from the fibre model with $NY = 25$ yarns in each row, the moment of inertia of any row around its own axis I_{yarns}^{Row} is:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 5.89 \times 10^{-6} = 1.4725 \times 10^{-4} mm^4 \quad (3.51)$$

Since nominal yarn width is 4 mm, nominal yarn height is 0.25 mm and there is symmetry about the axis of the sample, using the parallel axis theorem for calculating the moment of inertia around the axis of the sample leads to the moment of inertia of rows 1 about the sample axis, I_{SAxis}^{Row1} , as shown in Figure 3-27:

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{3}{2} \cdot 0.25 \right)^2 \right) \right) = 7 \text{ mm}^4 \quad (3.52)$$

For rows 2, I_{Axis}^{Row2} is:

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{7}{2} \cdot 0.25 \right)^2 \right) \right) = 38.3 \text{ mm}^4 \quad (3.53)$$

The moment of inertia for the whole sample, I_{sample} , is:

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 45.3 \text{ mm}^4 \quad (3.54)$$

Repeating the above calculations using value $I_{yarn} = 4.9 \times 10^{-3} \text{ mm}^4$ for the yarn moment of inertia obtained from the yarn model, the value for any row around its axis, the value for rows 1 and the value for rows 2 are obtained as:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 4.9 \times 10^{-3} = 0.1225 \times 10^{-4} \text{ mm}^4 \quad (3.55)$$

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{3}{2} \cdot 0.25 \right)^2 \right) \right) = 7.3 \text{ mm}^4 \quad (3.56)$$

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{7}{2} \cdot 0.25 \right)^2 \right) \right) = 38.5 \text{ mm}^4 \quad (3.57)$$

The moment of the inertia for the whole sample becomes:

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 45.8 \text{ mm}^4 \quad (3.58)$$

Similar calculations performed using the moment of inertia value $I_{yarn} = 1 \times 10^{-4} \text{ mm}^4$ for the yarn obtained from the cantilever model, the value for any row around its axis, the value for row 1 and the value for rows 2 are respectively obtained as:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 1 \times 10^{-4} = 2.5 \times 10^{-3} \text{ mm}^4 \quad (3.59)$$

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{3}{2} \times 0.25 \right)^2 \right) \right) = 7 \text{ mm}^4 \quad (3.60)$$

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{7}{2} \times 0.25 \right)^2 \right) \right) = 38.3 \text{ mm}^4 \quad (3.61)$$

Finally, the moment of inertia for the complete sample is:

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 45.3 \text{ mm}^4 \quad (3.62)$$

3.8.2 Perpendicular setup (R90)

Stitching is perpendicular to the roller in setup R90. Yarns in the perpendicular direction of the sample cross-section that contribute towards the stiffness of the sample are arranged as shown in Figure 3-28.

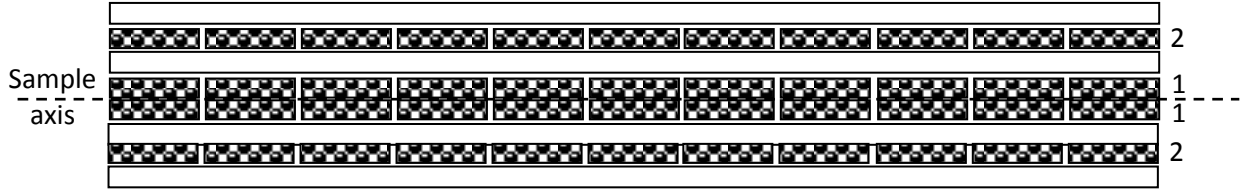


Figure 3-28: Yarns arrangement in R90 setup.

Using value $I_{yarn} = 5.89 \times 10^{-6} mm^4$ for the yarn moment of inertia obtained from the fibre model, the moment of inertia values are:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 5.89 \times 10^{-6} = 1.4725 \times 10^{-4} mm^4 \quad (3.63)$$

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{1}{2} \cdot 0.25 \right)^2 \right) \right) = 0.78 mm^4 \quad (3.64)$$

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{5}{2} \cdot 0.25 \right)^2 \right) \right) = 19.5 mm^4 \quad (3.65)$$

The moment of inertia for the complete sample is:

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 20.3 mm^4 \quad (3.66)$$

Following the same calculation procedures with $I_{yarn} = 4.9 \times 10^{-3} \text{ mm}^4$:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 4.9 \cdot 10^{-3} = 0.1225 \times 10^{-4} \text{ mm}^4 \quad (3.67)$$

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{1}{2} \cdot 0.25 \right)^2 \right) \right) = 1 \text{ mm}^4 \quad (3.68)$$

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{5}{2} \cdot 0.25 \right)^2 \right) \right) = 19.78 \text{ mm}^4 \quad (3.69)$$

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 20.8 \text{ mm}^4 \quad (3.70)$$

Following the same calculation procedures with $I_{yarn} = 1 \times 10^{-4} \text{ mm}^4$:

$$I_{yarns}^{Row} = NY \cdot I_{yarn} = 25 \cdot 1 \cdot 10^{-4} = 2.5 \times 10^{-3} \text{ mm}^4 \quad (3.71)$$

$$I_{SAxis}^{Row1} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{1}{2} \cdot 0.25 \right)^2 \right) \right) = 0.8 \text{ mm}^4 \quad (3.72)$$

$$I_{SAxis}^{Row2} = 2 \left(I_{yarns}^{Row} + 25 \left(4 \cdot 0.25 \cdot \left(\frac{5}{2} \cdot 0.25 \right)^2 \right) \right) = 19.5 \text{ mm}^4 \quad (3.73)$$

$$I_{sample} = I_{SAxis}^{Row1} + I_{SAxis}^{Row2} = 20.3 \text{ mm}^4 \quad (3.74)$$

The diverse values for the moment of inertia of the sample obtained above, using the different models, are summarized in the following table:

Table 3-20: Values of the moment of inertia of the sample obtained from different methods.

Model	$I_{sample} \text{ (mm}^4\text{)}$
Yarn - Fibre model	5.89×10^{-4}
Yarn - Cantilever model	1×10^{-2}
Yarn - Yarn model	0.49
Sample - Fibre model, R0	45.3
Sample - Cantilever model, R0	45.3
Sample - Yarn model, R0	45.8
Sample - Fibre model, R90	20.3
Sample - Cantilever model, R90	20.3
Sample - Yarn model, R90	20.8

3.8.3 Observations on the moment of inertia of the sample

The value of the sample moment of inertia obtained using the fibre model, $5.89 \times 10^{-4} \text{ mm}^4$, is the lowest bound as it assumes that each fibre bends around its own centroid in the yarn, with no interactions between fibres. This was disproved from experimental measurements performed on the single yarn. On the other hand, the value obtained from the yarn model, 0.49 mm^4 , showed that it is not realistic to assume that all fibres within the yarn behave as if the yarn was monolithic.

Similarly, values obtained for the sample from different sample models, ranging between 20.3 mm^4 and 45.8 mm^4 , are the highest that may be obtained as they assume that the yarns in the sample cross-section act as a one solid unit. The above indicates that this is likely an

overestimate. It is interesting to note that in this hypothesis where yarns behave as if they were connected cohesively within the fabric, the behaviour of individual fibres within the yarns becomes largely insignificant. On the other hand, if the hypothesis of a cohesive textile is applicable although maybe only partially, then experimental results should differ markedly for test conducted in configurations R0 versus R90. And so, comparing results obtained in configurations R0 and R90 enables the probing of whether the textile bends cohesively.

Experimental results presented above did not identify the setup as a parameter that has significant effects on the average bending moment. However, through-thickness stitching does have a strong effect on the bending behaviour.

3.9 Bending moment calculations

In this section the bending moment (M) acting on the sample, Figure 3-29, is calculated analytically from two different methods and compared with experimental bending moments (M_B) obtained from experimental tests. Once the moment of inertia of the sample cross-section is determined, the bending moment (M) can be calculated analytically. As such, whilst the numerous experimental data generated enables the direct probing of the effect of textile construction on the bending behaviour, this analysis enables further understanding of this behaviour through the analysis of the moment of inertia and of interactions between fibres.

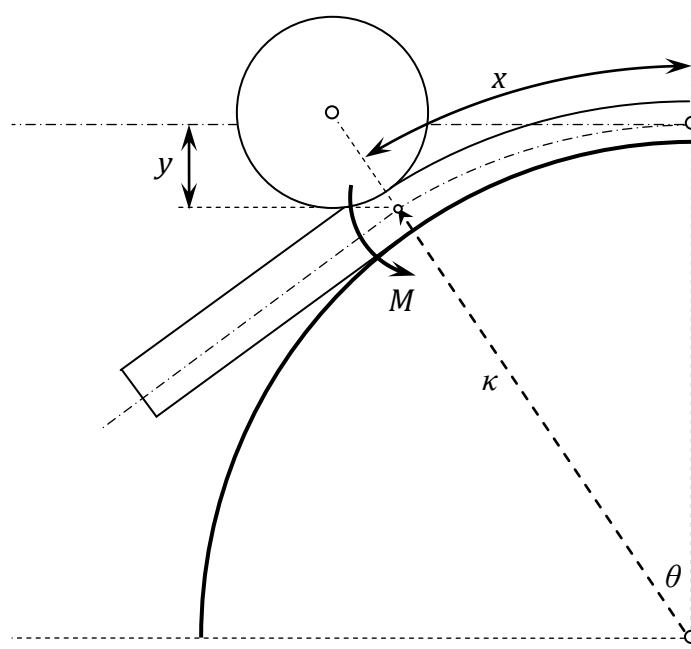


Figure 3-29: The analytical bending moment acting on the sample.

3.9.1 Bending moment calculations using the elastic curvature formula (CF)

The radius of curvature of a beam subjected to bending is written as [212]:

$$\frac{1}{\kappa} = \frac{M}{EI} \quad (3.75)$$

where E is the elastic modulus of the fibres which is equal to 215 GPa [211], I is the moment of inertia of the sample calculated using any of approaches presented above, and κ is the curvature radius of the neutral axis of the sample. In using this quantity it is assumed that a sample with a thickness of 2 mm bending over a radius of approximately 50 mm remains in the realm of small strains (<10%), which is indeed reasonable. This being said, relative motions between fibres and yarns will lead to smaller strains in the fibres in real terms. Then, the bending moment M can be calculated as:

$$M = \frac{EI}{\kappa} \quad (3.76)$$

where I can take any of the values appearing above.

For illustration, calculation of the sample bending moments from the moment of inertia based on the different models using A1/45/R0/S1 sample are presented here. For a 2 mm spacer and 50.8 mm rig radius, the curvature radius of the neutral axis of the sample κ is:

$$\kappa = RR + \frac{SPR}{2} = 50.8 + \frac{2}{2} = 51.8 \text{ mm}$$

Therefore, the sample bending moments calculated CF using I_{FM} and I_{CM} are:

$$M_{CF-IFM} = \frac{215 \times 10^3 \cdot 5.89 \times 10^{-4}}{51.8} = 2.45 \text{ N.mm}$$

$$M_{CF-ICM} = \frac{215 \times 10^3 \cdot 1.0 \times 10^{-2}}{51.8} = 41.51 \text{ N.mm}$$

The corresponding analytical bending moment values M_{CF-ICM} and M_{CF-IFM} calculated from the curvature formula using the moment of inertia derived from the cantilever model I_{CM} and the fibre model I_{FM} , respectively, are plotted in Figure 3-30 along with the experimental bending moments M_B in each cycle.

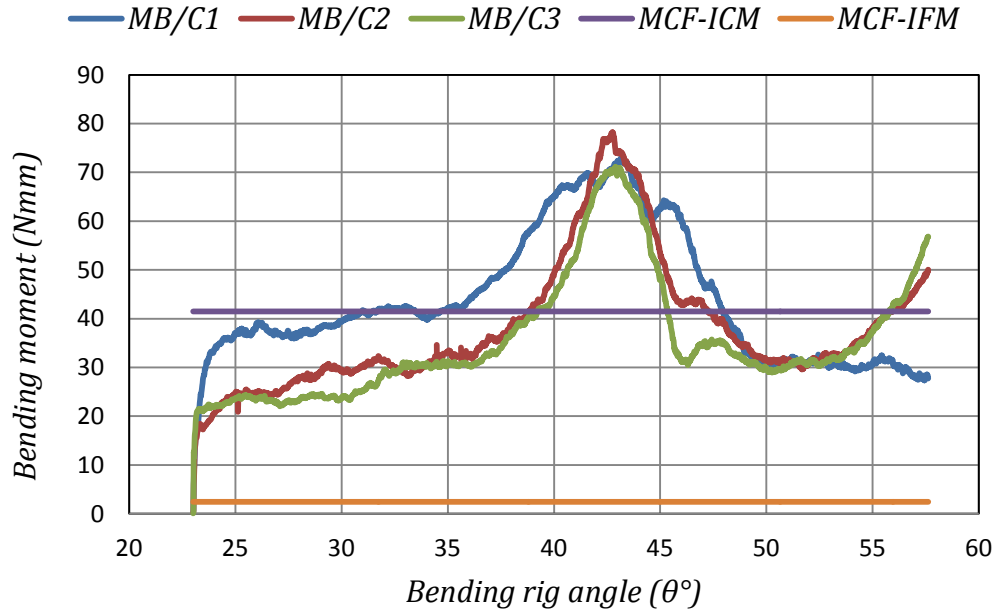


Figure 3-30: Bending moment between experimental curves for A1/45/R0/S1 sample and curvature formula.

3.9.2 Bending moment calculations using the deflection formula (DF)

The analytical bending moment (M) can be also derived from the deflection formula of a cantilever beam. The deflection formula of such a cantilever beam [212] is written as:

$$M = \frac{2EIy}{x^2} \quad (3.77)$$

where y is the deflection at the roller and x is the effective span as shown in Figure 3-28.

Rewriting distance x and the deflection y as functions of κ and θ :

$$x = \kappa\theta \quad (3.78)$$

$$y = \kappa - \kappa\cos\theta \quad (3.79)$$

$$M = 2EI \cdot \frac{(\kappa - \kappa\cos\theta)}{(\kappa\theta)^2} \quad (3.80)$$

Similarly, for A1/45/R0/S1 sample, the bending moments can be calculated from the DF using I_{FM} and I_{CM} as:

$$M_{DF-IFM} = 2 \cdot 215 \times 10^3 \cdot 5.89 \times 10^{-4} \cdot \frac{(51.8 - 51.8\cos\theta)}{(51.8 \cdot \theta)^2}$$

$$M_{DF-ICM} = 2 \cdot 215 \times 10^3 \cdot 1.0 \times 10^{-2} \cdot \frac{(51.8 - 51.8\cos\theta)}{(51.8 \cdot \theta)^2}$$

θ is the only independent variable in the above equations, with all other values being constant for each sample group and test setup. As the cross-head moves down, it moves the roller down over the curvature of the quarter tube, increasing the value of angle θ . The corresponding analytical bending moment values M_{DF-ICM} and M_{DF-IFM} calculated from the deflection formula using the cantilever model moment of inertia I_{CM} and the fibre model

moment of inertia I_{FM} , respectively, are plotted in Figure 3-31 along with the experimental bending moments M_B for C1, C2 and C3.

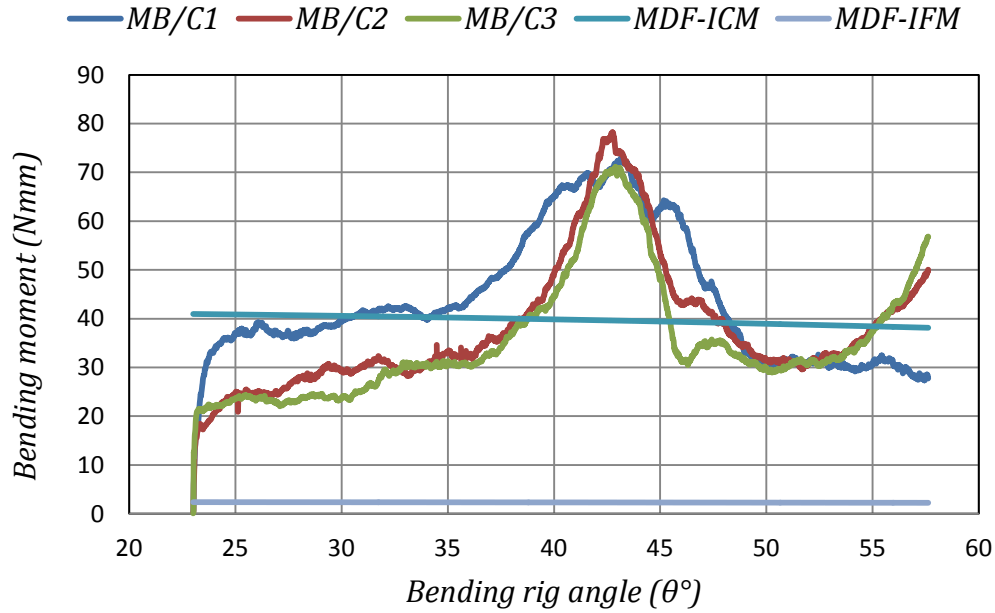


Figure 3-31: Bending moments from experimental curves for A1/45/R0/S1 sample and deflection formula.

3.9.3 Observations on analytical bending moment modelling

The analytical bending moment results from both formulas, CF and DF, gave the same results as they should since they are derived from the same hypothesis. This observation can be made when comparing the results of the analytical bending moment obtained from both equations (3.76) and (3.80) as shown in Figure 3-32.

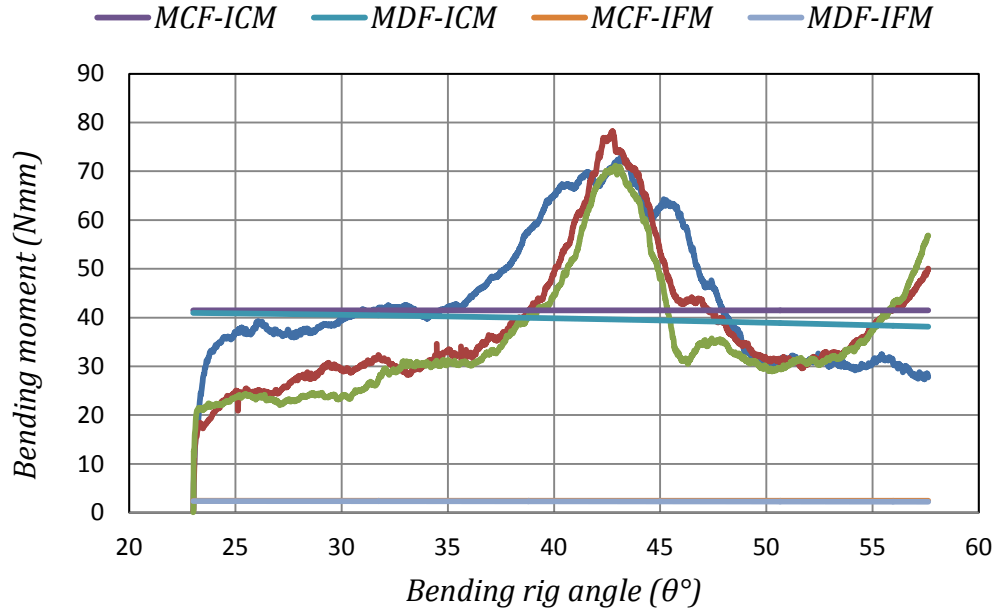


Figure 3-32: Bending moments from experimental curves and CF and DF formulas for A1/45/R0/S1 sample.

As a general conclusion, the analytical bending moments obtained from both CF and DF formulas using cantilever model moment of inertia I_{CM} , M_{CF-ICM} and M_{DF-ICM} , respectively, give results that are in good agreement with the experimental data for M_B as shown in Figure 3-31, in contrast to the values calculated using the fibre model moment of inertia I_{FM} denoted as M_{CF-IFM} and M_{DF-IFM} or any other model.

3.10 Conclusion

To define the behaviour of new preforms during forming, one of the major aspects of the response of such thick preforms that needs to be investigated is the bending behaviour. In contrast to the ASTM cantilever bending test and the KES-FB test which are not suitable for testing thick fabrics, the bending apparatus used in this work was devised to investigate the bending behaviour of thick fabrics. The newly introduced apparatus proved to be a

good method that can be used to investigate bending behaviour of reinforcement of varied thickness and v_f on a single curvature. Also, the adjustable design of the bending radius enables extending the investigation to different radii.

Since such an apparatus was newly introduced with no similar bending test results available to compare with, two approaches were used for verifying the bending results obtained from testing uO-APT fabrics. The first approach was experimental, and it was done by conducting bending tests on industrial fabrics and comparing the bending moment results obtained for the uO-APT fabrics by means of the Taguchi method. The Taguchi analysis highlights the most parameters having the stronger effects on testing. The main parameters investigated in bending were the type of reinforcements, reinforcement thickness, yarn orientations, v_f and bending cycles. Two plans were devised for investigating the *AVG* and *STD* of bending moments M_B measured between 25° and 55° bending angles. The Taguchi analysis revealed that the type of reinforcement, number of cycles and v_f have the largest effect on bending behaviour of these fabrics. The second approach was analytical; using the bending beam theory to calculate the bending moment and compare it with experimental results obtained from testing the uO-APT fabric. In this approach, the CF and the DF approaches were used for verifying the calculations, since they are derived from the same hypothesis. The moment of inertia of the sample cross-section was needed in both formulas, to be calculated first before the bending moment was evaluated. This lead to different possibilities in calculating the moment of inertia of the sample cross-section which was the key point to applying beam bending theory in calculating the bending moments analytically. Three models, the FM, the CM and the YM, were introduced for calculating the moment of inertia of a single yarn towards calculating

the moment of inertia of uO-APT sample cross-sections. The I_{FM} and I_{YM} returned bending moments that were unreasonable. Only the I_{CM} proved to give the most reasonable values of the bending moment that agreed with experimental results.

In closing, this apparatus and approach enabled the ability to investigate the bending behaviour of thick reinforcements. The measured bending moments were in the range of 0 to 500 Nmm. The apparatus design proved the possibility of measuring such a low bending moments needed to bend thick fabrics onto a single curvature. Results were verified in two ways, experimental against another type of fabric and analytical using the bending beam theory which was assumed to be applicable since samples of a few mm thickness under the roller were bent over a radius of approximately 50 mm. In terms of fabric bending this is indeed a reasonable assumption. Bending moments were in the same range, giving a confidence in the new results.

Chapter 4

In-plane shear behaviour of structural stitched textile reinforcements

4.1 Introduction

Wrinkling is one of the most common and critical defects that may occur during draping and forming operations performed on textile reinforcements [203, 213-214]. The behaviour of dry thick fabrics subjected to in-plane shear plays an important role, along with the bending behaviour, in the onset of wrinkles during draping and forming [215, 216]. Wrinkling is especially critical to single layer, thick fabrics such as uO-APT fabrics being investigated in this thesis. Since the ability of biaxial stitched non-crimp reinforcement fabrics to conform to a surface featuring double curvatures depends directly on their in-plane shear behaviour, that behaviour must be probed and quantified for uO-APT fabrics in order to identify their ability to deform upon draping, which is a required

procedure in manufacturing processes for dry preforms used towards the production of composite parts based on LCM processes. Comparisons are made with the behaviour observed with stacks of industrial reinforcements.

4.2 Literature review on fabric shear testing and behaviour

Three test methods are generally used for characterizing the in-plane shear behaviour of fabrics, namely the bias extension test, the biaxial test and the articulated frame test, the latter often being referred to as the picture frame test. Two of these methods are in more widespread use and appear in the majority of published work relevant to the topic, namely the bias extension test [217-221] and the articulated frame test [222-227] shown in Figure 4-1.

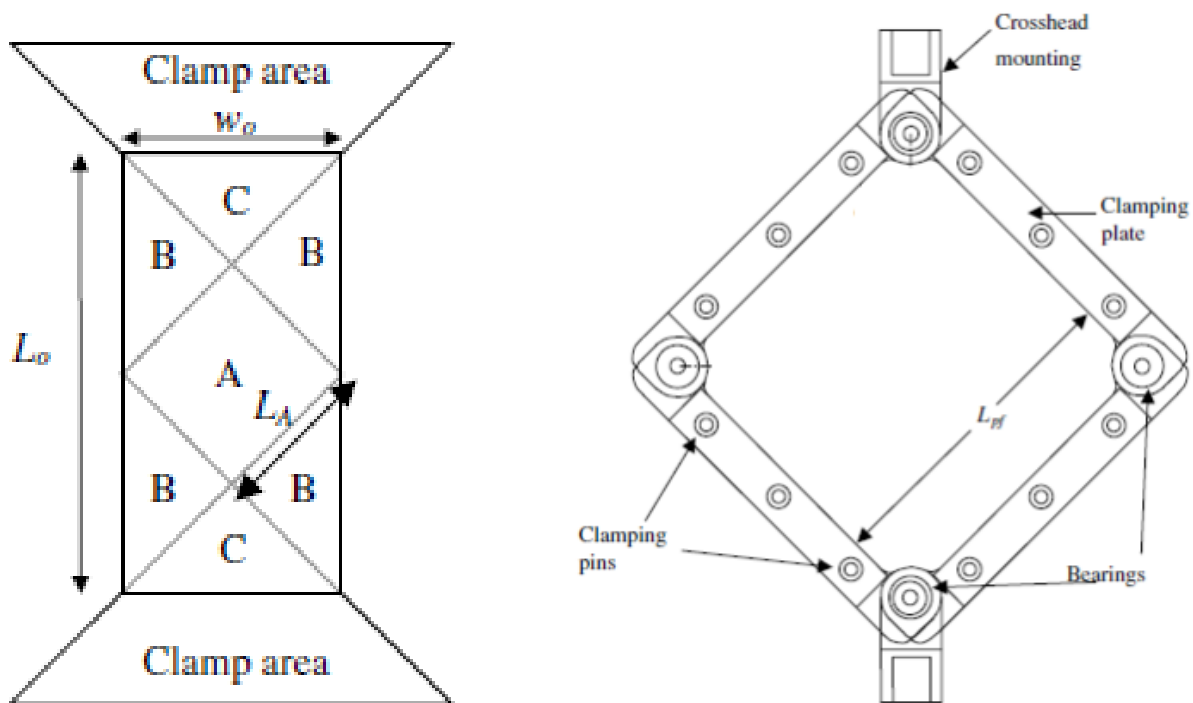


Figure 4-1: Bias extension test (left) and articulated frame test (right) [233].

The bias extension test is conducted by clamping both extremities of a vertically oriented rectangular sample in two horizontal grips, with the principal directions of the fabric typically corresponding to the warp and weft of a weave oriented at 45° from the vertical direction of applied tensile load and displacement. In analysis the specimen is divided into zones A, B and C with zone C being subjected to pure in-plane shear. Conducting a bias extension test is straightforward and provides useful data on shear angle, but reliable measurements of the shear angle within zone C of the sample are difficult to make; angles cannot be obtained directly from the displacement of the machine cross-head [228, 229].

On the other hand, the articulated frame test has been found by many authors to be an effective testing method for characterising the in-plane shear behaviour of fabrics [222, 229-231]. An articulated frame test is conducted by clamping the sample into an articulated frame which consists of four hinged bars of equal length. The sample is typically cruciform with its central square section being subjected to pure in-plane shear, and the extensions used for securing the sample in the frame. The principal directions of the fabric, typically corresponding to the warp and weft of a weave, are parallel to the frame bars. The frame is then mounted into a standard uniaxial universal testing machine at two of its opposed corners, so that the principal directions of the fabric lie at 45° from the machine axis at the onset of the test. As the machine cross-head imposes a force and displacement to the articulated frame, the shape of the frame changes from an initial square configuration into a progressively more acute rhomboid. Forces and displacements are recorded and the data is transformed into shear forces and shear angles by means of calculations highlighted in this chapter.

Lebrun *et al.* [232] compared experimental results obtained from bias extension and articulated frame in-plane shear tests conducted on woven glass fibre reinforcement fabrics. The authors evaluated primarily the difficulty of obtaining accurate values for in-plane shear angles in bias extension tests, and the unwanted fibre tension effect that can corrupt load-displacement curves obtained from articulated frame tests as a result of fibres not being mounted perfectly parallel to the frame bars. Their results showed that misalignments of fibres within the articulated frame causing tension forces in the fibres may lead to the recording of higher loads than those necessary for shearing the sample. Eliminating these fibre tension forces through careful alignment led to shear loads similar to those obtained from the bias extension test.

Harrison *et al.* [233] proposed a novel procedure for normalising shear test data aimed at making meaningful comparisons of results obtained from bias extension and articulated frame tests. A 2x2 twill glass fibre weave and a 5 harness satin carbon fibre weave were considered in this work. Results showed that deformations occurring in articulated frame tests are closer to those induced during a forming operation, when compared with bias extension tests. Also, the study showed that results of articulated frame tests should be normalised using sample length as opposed to sample area.

A benchmarking study conducted by Cao *et al.* [234] compared results obtained from bias extension and articulated frame tests conducted at seven research laboratories on identical balanced and unbalanced twill weaves. Results obtained using different test setups in each laboratory were compared using normalization. The study showed consistent behaviours

for the balanced twill weave reinforcement fabrics even as different testing methods were used. As for the unbalanced twill weave reinforcement fabrics, results were not consistent.

Peng *et al.* [235] investigated ways in which articulated frame in-plane shear test data generated at different laboratories may be correlated and normalised so that they may be compared. The analysis concluded that normalisation methods depend on sample setup within the shear frame. Samples may be setup in the shear frame with or without corner cut-offs, although corner cut-offs are generally needed for preventing immediate wrinkling of the fabric upon shearing and for allowing some rotation movement at yarns crossovers. The authors recommended minimizing cut-offs or pulling out all yarns that are not clamped to the shear frame. They also highlighted the importance of ensuring good clamping of yarns in the bars to avoid slippage.

Lomov *et al.* [236] investigated major aspects of articulated frame testing using plain and twill woven fabric reinforcements made of glass fibres. The authors investigated how sample pretension influences yarns gripping and shear cycling. The study recommended that pretension should be characterized, as different levels of pretension lead to different shear resistances. It also recommended taking out yarns near the grips. The work also showed higher resistance to fabric in-plane shear in the first cycle compared with the second cycle, and no further differences in fabric shear resistance beyond the second cycle. The authors also found that differences between local shear angles within fabric samples and the imposed frame shear angle were negligible.

Launay et al. [237] investigated the effect of yarn tension on the shear behaviour of a plain weave made of glass/PP fibres and an interlock weave of carbon fibres subjected to articulated frame in-plane shear testing. The authors proposed an experimental device enabling the measurement of tensions in the warp and weft directions during the test. The study showed that initial tension in the yarns affects the fabric shear behaviour, especially in the first part of the shear curve.

Some experimental studies of in-plane shear of textile reinforcements for composites related the onset of wrinkling to the shear locking angle [238-243]. The shear locking angle of a fabric is a major characteristic that defines the ability of the fabric to deform. When the imposed shear angle exceeds the shear locking angle, wrinkles start to appear in the sample. The shear angle at wrinkle onset may be obtained from the shear diagrams, or shear curves, see Figure 4-2.

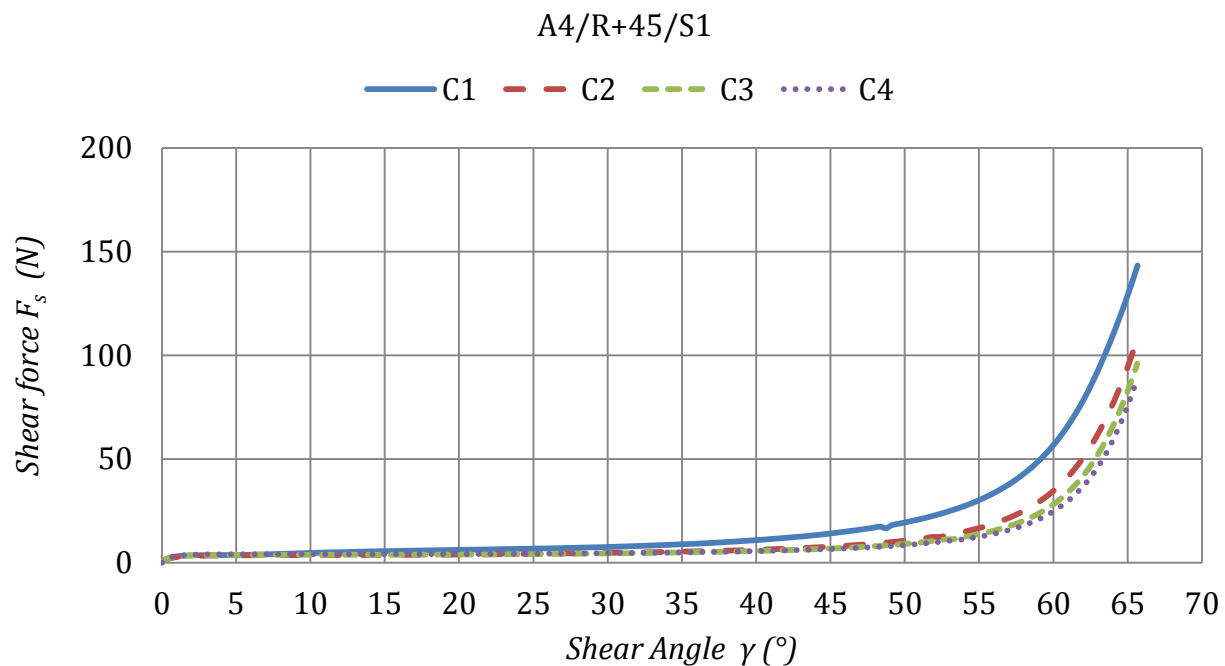


Figure 4-2: Shear curves resulting from testing a sample made from uO-APT fabrics.

Shear curves present the relation between the shear force and shear angle; typically they feature two mostly distinct parts. A first part represents the initial, low stiffness behaviour of the fabric whilst a second part features a rapid increase in shear stiffness eventually leading to the start of wrinkling. The angle defined by extending a line defined along the maximum slope of the second part of the curve is generally used in representing the shear locking angle of the fabric. Low stiffness values in the first portion of the shear diagram result from limited resistance to the relative movements of yarns, essentially in the form of friction. When no further lateral movement is possible between yarns, an angle known as the interlocking angle is reached and yarns start to compress laterally against each other causing rapid increases in stiffness in the second part of the curve. Deformation modes and mechanisms associated with the different parts of the curve are presented in great detail in the literature [216, 244-247].

4.3 Experimental

Carbon reinforcements of the same types as those tested for the bending work reported in Chapter 3 were used in characterizing their in-plane shear behaviour in the present chapter as presented in Section 4.3.1. The articulated frame in-plane shear apparatus used for testing both types of reinforcements is described in Section 4.3.2. The effects of reinforcement thickness, yarn and stitch orientations on shear behaviour were investigated. Figure 4-3 shows flow chart of the tests conducted to investigate in-plane shear behaviour.

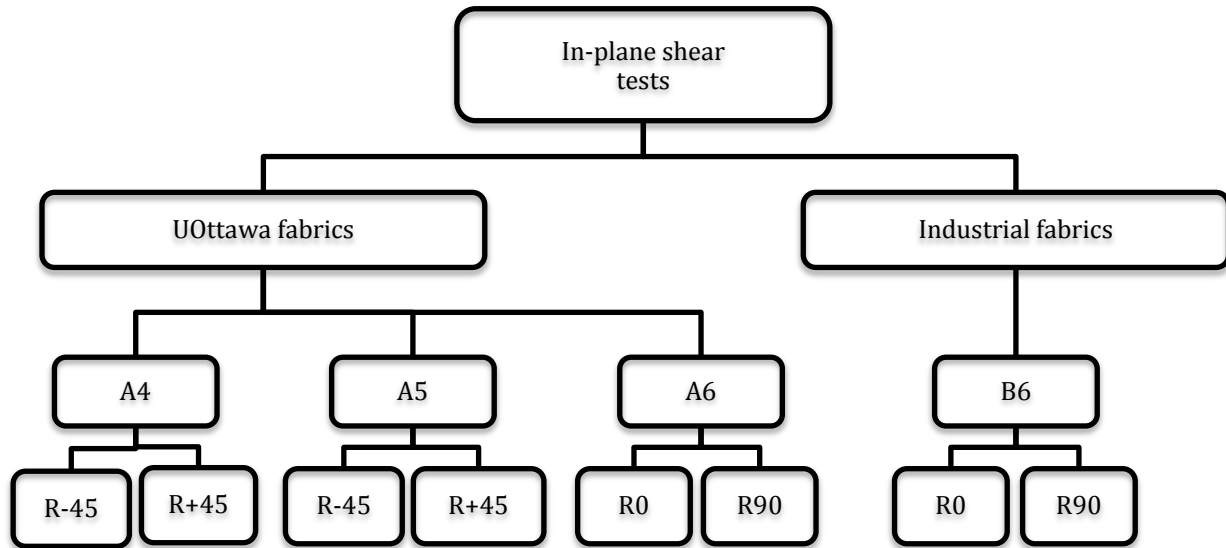


Figure 4-3: In-plane shear tests flow chart.

4.3.1 Reinforcement fabrics

The same two types of carbon fibre reinforcements described in Chapter 3 were characterized in the present chapter, labeled as types A and B similarly to Chapter 3. Type A reinforcements were made at the University of Ottawa using dedicated manufacturing equipment, from Tenax-J grade HTS40 E13 12K, 800 tex carbon fibre yarns. Type A reinforcements consisted of single, thick bidirectional fabric layers made of parallel carbon fibre yarns assembled by stitching. Stitch lines ran along the 0° direction with 20 mm centre-to-centre in-plane spacing as described in Section 3.3.1. Type B reinforcements consisted of stacked layers of Saertex 534 g/m² bidirectional non-crimp stitched carbon fabrics made from Tenax HTS40 12K yarns. Stitch lines ran along the 0° direction with 5.0 mm centre-to-centre in-plane spacing. Reinforcements of both types are illustrated in Figure 3-5, and in the following pages in the context of tests done towards evaluating their in-plane shear behaviour.

4.3.2 Apparatus

The in-plane shear testing apparatus was designed to be attached to a screw-driven Instron 4482 universal testing frame as shown in Figure 4-4. The frame was equipped with an Instron 1 kN load cell for in-plane shear tests. Dimensions of the apparatus were set so as to allow in-plane shear angles up to 65° , starting from 0° . In Figure 4-4 it should be noted that the visible carbon yarns run parallel to two of the four bars; the other carbon yarns that extend beyond those readily visible in the image run parallel to the other two bars of the articulated frame. Joints of the frame were equipped with low resistance ball bearings.



Figure 4-4: In-plane shear testing apparatus attached to 4482 Instron universal testing frame.

4.3.3 Experimental plan

Samples featuring different numbers of layers of carbon yarns as well as different stitch line orientations were tested for both type A and type B reinforcements. All sample and testing configurations are summarized in Tables 4-1 through 4-4.

Tests conducted using type A reinforcements were classified into test groups A4, A5 and A6 where samples used in groups A4, A5 and A6 featured 8, 12 and 8 superimposed arrays of parallel yarns respectively. The tests were further classified into sub-groups based on orientations of stitch lines in the shear apparatus, Figure 4-5. All samples were symmetrical balanced bidirectional with yarns running at 0° and 90° from stitch lines in groups A4 and A5, and at -45° and $+45^\circ$ from stitch lines in group A6. Tests were conducted with stitch lines running at -45° and $+45^\circ$ from apparatus reference direction R0 for groups A4, A5 and running at 0° and 90° for group A6 leading to six type A reinforcement sub-groups A4/R-45, A4/R+45, A5/R-45, A5/R+45, A6/R0 and A6/R90; apparatus reference orientation R0 corresponds to the horizontal axis of the Instron universal testing frame.

Lastly for type A reinforcements, 2 different physical samples were used for every testing configuration, with each sample sheared for 4 consecutive cycles leading to 48 shear tests performed for these reinforcements. Samples and cycles are identified by appending to the above testing configuration labels, such as S1-C2 for sample 1 and cycle 2 for example. Sample data including the number of layers, yarn stacking sequence defined relatively to apparatus reference orientation R0, and stitch line orientation defined using the same reference appear in Tables 4-1, 4-2 and 4-3.

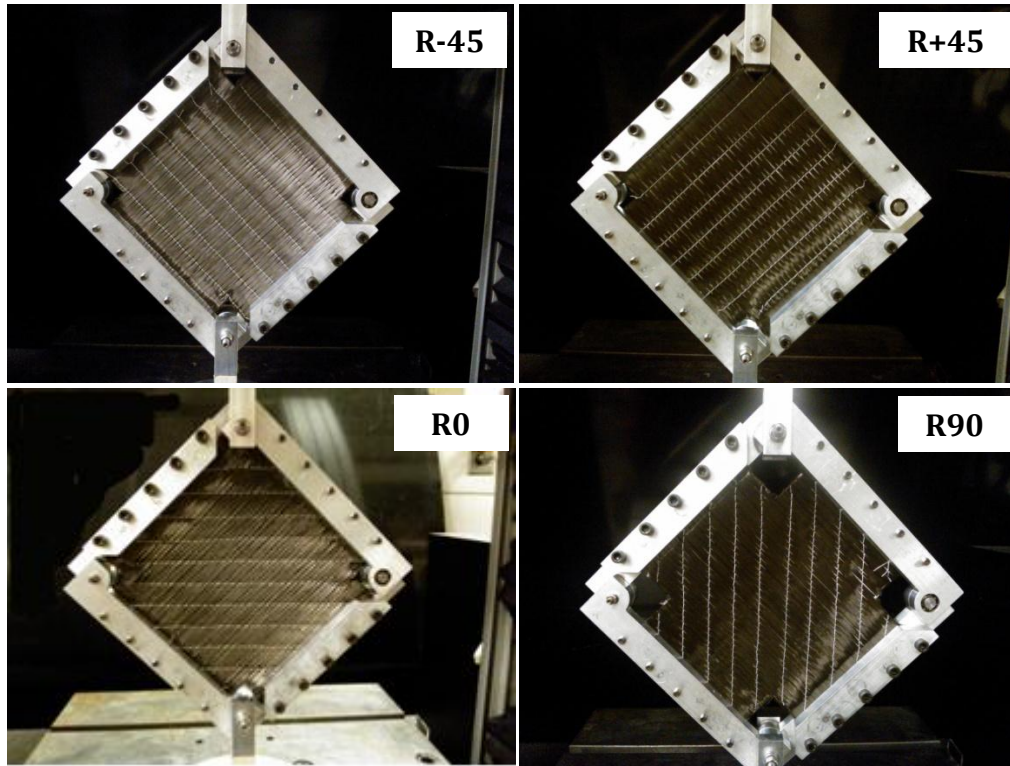


Figure 4-5: Stitching setup directions for in-plane shear tests, shown for type A reinforcements

Tests conducted using type B reinforcements were labelled as group B6 in reference to relative orientations of yarns and stitch lines, and to sample surface density, which compare to those in group A6. Tests were further classified into sub-groups based on the orientation of stitch lines relative to the testing apparatus and universal testing frame. All samples were balanced bidirectional with yarns running at -45° and $+45^\circ$ from stitch lines in both sub-groups, as per construction defined by Saertex for this specific reinforcement. In-plane shear tests were conducted with stitch lines running at 0° and 90° from apparatus reference orientation as shown in Figure 4-6, hence leading to two sub-groups B6/R0 and B6/R90. It is to be noted that type B6 reinforcement stacks were balanced but not symmetrical, as a result of numbers of layers and reinforcement construction.

Table 4-1: Characteristics of group A4 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sample set-up in apparatus	Sample	Mass (g)
uO- ATP	A4	8 parallel yarn arrays [90/0/90/0] _s	Along 0° in reinforcement	R-45	S1	56
					S2	56
				R+45	S1	55
					S2	56

Table 4-2: Characteristics of group A5 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sample set-up in apparatus	Sample	Mass (g)
uO-ATP	A5	12 parallel yarn arrays [90/0/90/0/90/0] _s	Along 0° in reinforcement	R-45	S1	86
					S2	85
				R+45	S1	85
					S2	85

Table 4-3: Characteristics of group A6 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sample set-up in apparatus	Sample	Mass (g)
uO-ATP	A6	8 parallel yarn arrays [90/0/90/0] _s	Along 45° in reinforcement	R0	S1	56
					S2	56
				R90	S1	56
					S2	57

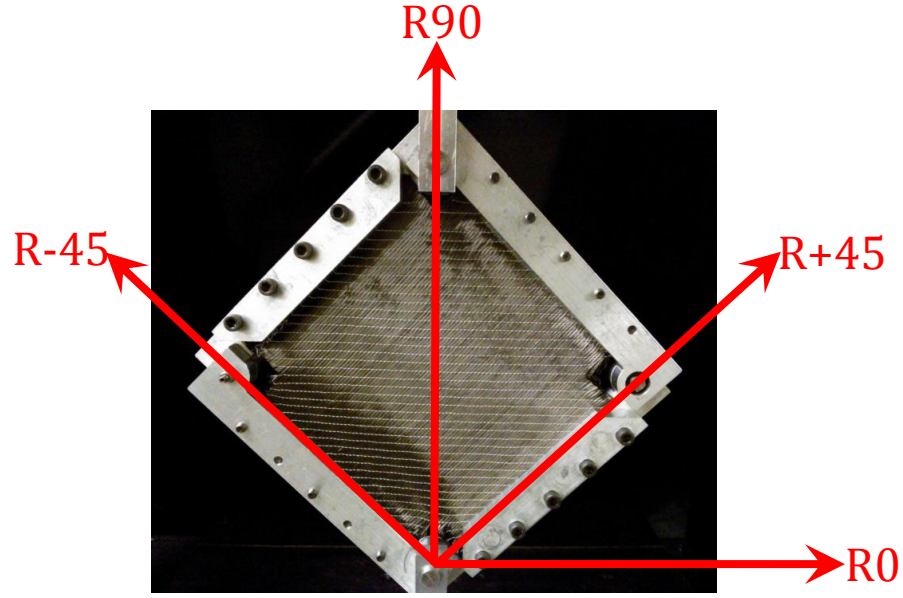


Figure 4-6: Stitching setup directions for in-plane shear tests, shown for type B reinforcement.

Lastly for B6 type reinforcements, 2 distinct physical samples were used for every testing configuration, with each sample sheared for 4 consecutive cycles leading to an additional 16 in-plane shear tests, bringing the total to 64 tests for reinforcement types A and B. Sample data for reinforcement type B appears in Table 4-4. It should be noted that test groups equivalent to groups A4 and A5 were not conducted as such tests could be defined, simply as a result of the construction of the industrial reinforcement fabric used in performing this work.

Table 4-4: Characteristics of group B6 samples made from industrial reinforcements.

Type	Arrays	Arrays	Stitching	Sample set-up in apparatus	Sample	Mass (g)
Saertex industrial . reinf.	B6	3 layers $[(0/90)]_3$	Along 45° in reinforcement	R0	S1	57
					S2	58
				R90	S1	58
					S2	57

4.3.4 In-plane shear test procedure

The procedure used for conducting in-plane shear tests is described in the following pages using sample A4/R-45/S1/C4 as an example. From the sample and test name, the following information is readily obtained:

- The sample is from group A4 hence made from a uO-APT fabric featuring 8 superimposed arrays of parallel yarns;
- The test was conducted with the sample mounted in a R-45 configuration in the apparatus, hence stitch lines run at -45° from universal testing frame reference orientation;
- S1 means that the first sample tested in this sub-group is discussed;
- C4 indicates that the fourth in-plane shear testing cycle performed on the sample is discussed.

The first step in preparing a given test was to cut samples from a larger, finished uO-APT preform with specific dimensions that may fit the in-plane shear apparatus. Figure 4-7 shows such a sample from group A4 after being cut and prepared towards testing. All samples were defined with constant lengths L_{fabric} of 140 mm that circumscribed the central area actually subjected to in-plane shear, labeled as fabric length and shown in Figure 4-7. The four squared 30 mm offcut corners were cut off using sharp disposable blades to prevent any interaction between the fabric and the frame during the shear test.

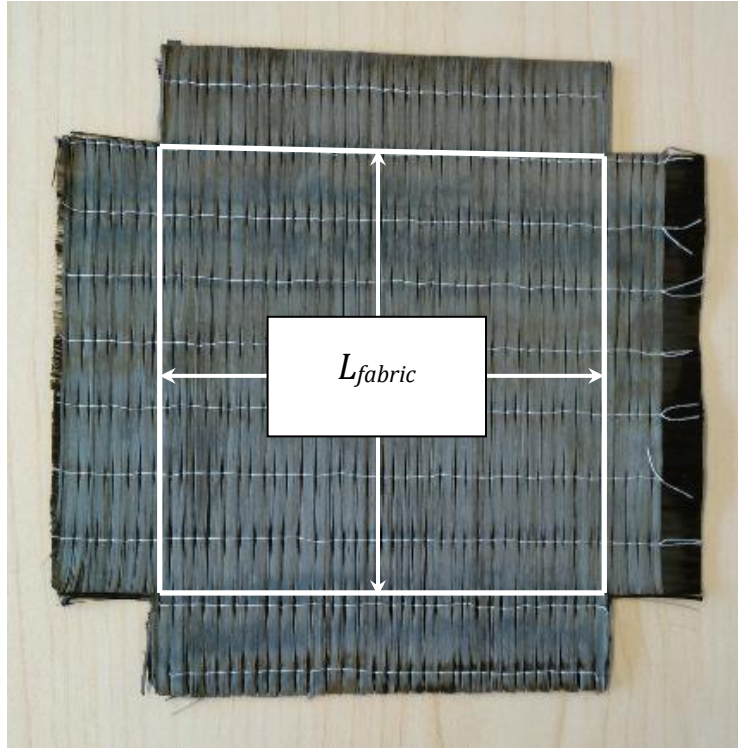


Figure 4-7: In-plane shear sample length labeled as L_{fabric} .

The second step consisted in mounting and securing the sample into the articulated frame and attaching the sample and frame into the 4482 Instron universal testing frame as shown in Figure 4-4, whilst ensuring an initial angle of 90° between adjacent bars of the frame corresponding to the initial, respective orientations of carbon fibre yarns in the samples prior to shear. As yarns should be parallel with either set of bars in the articulated frame, four different shear test setups can be defined in relation to the orientation of stitching lines namely R-45, R+45, R0 and R90 as shown in Figures 4-4 and 4-6.

The third step in preparing an in-plane shear test consisted in moving the machine cross-head to its starting position and calibrating the load cell, Figure 4-8. Appropriate

positioning was ensured by securing the articulated frame at a 90° angle between bars using a removable brace mounted vertically.

The fourth step consisted in launching the universal testing frame with the cross-head moving vertically at a constant displacement rate, whilst recording both the force measured by the load cell and displacement of the cross-head through data acquisition software Bluehill 2.0 from Instron which controlled the testing frame. When displacement reached 95 mm the test ended as shown in the lower part of Figure 4-6.

The fifth and last step was to return the cross-head to its starting position and repeat the test for the same sample. Data acquisition was not used during the return phase of the four consecutive shear cycles applied to each sample.

It should be noted that the contributions of the shear frame to the total recorded shear load were not removed from the data. In order to eliminate any contributions of the frame to the measured load, shear test should be conducted with an empty frame and the recorded loads should be deducted from the measured loads obtained upon regular shear test procedure. Such tests were conducted upon commissioning of the apparatus and at the onset of tests performed towards this thesis work. Loads measured during these trials were negligible, which was expected from the low friction bearings used in building the apparatus. Therefore, whilst the procedure was not repeated systematically, any parasitic loads arising from friction in the apparatus can be safely neglected.

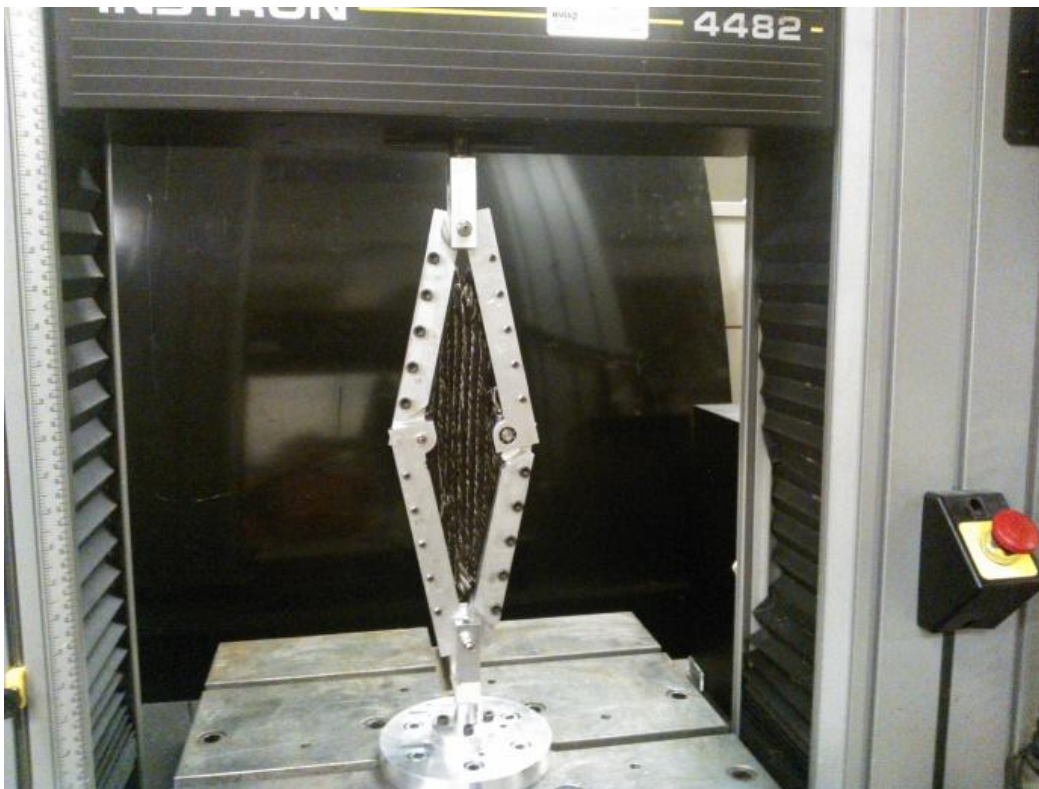
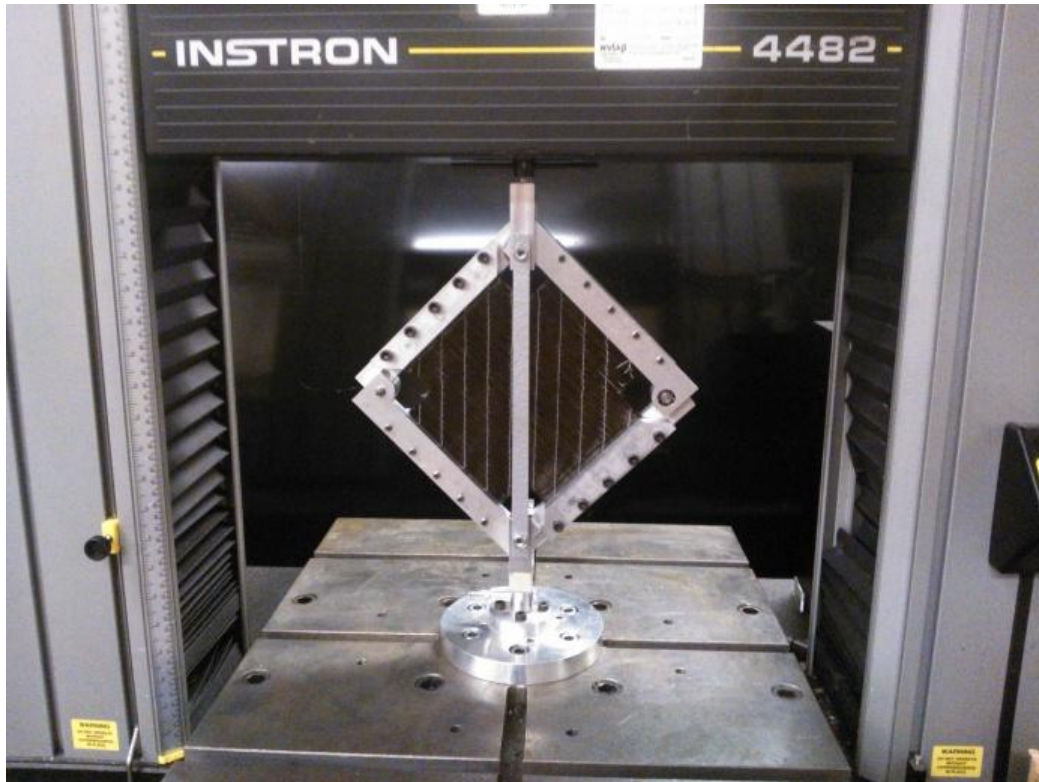


Figure 4-8: Top: initial configuration position of sample in shear test, with brace still in place;
bottom: final configuration of sample.

4.4 Results

In this section the shear apparatus and sample geometry are quantified, and the system of forces is reviewed leading to curves of shear force F_s as a function of shear angle γ . Typical in-plane shear curves are introduced, along with quantities used in summarizing them for data analysis. The effects of the type of reinforcements, number of layers and stitch orientation are quantified along with variability arising from different samples and cycles.

4.4.1 Geometry and forces

Vertical force F_M illustrated in Figure 4-9 is the vertical force applied by the machine cross-head on the shear apparatus. The analysis of the shear force F_s requires that all geometrical quantities and angles pertaining to the shear apparatus be defined and determined. The schematic diagram of the articulated frame shear apparatus in Figure 4-9 shows the lengths, angles the forces applied on the apparatus during shear tests. The shear apparatus frame length L_{frame} is 175 mm and fabric length L_{fabric} is 140 mm.

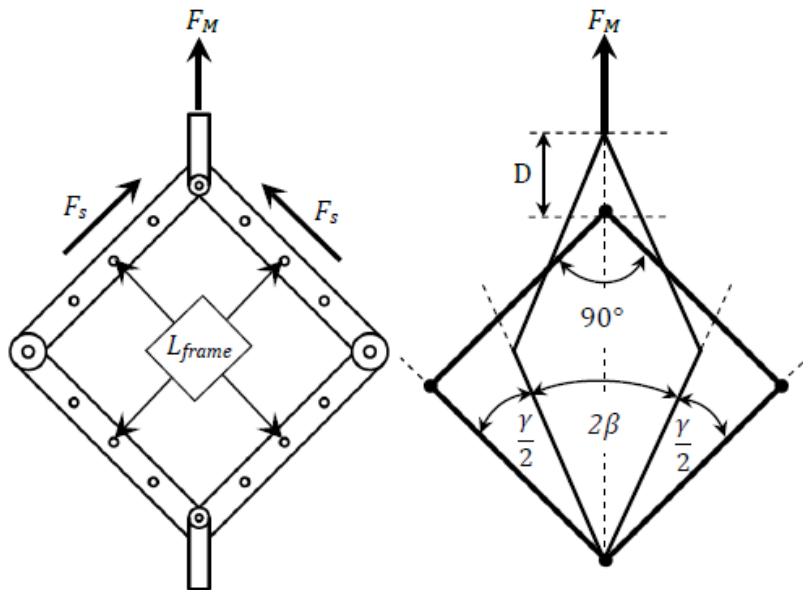


Figure 4-9: Shear apparatus (left) and altered configuration with lengths, angles and forces (right).

Upon starting the test and machine cross-head travel, the machine force F_M and vertical displacement D are recorded. D has a value of zero at the starting position. The curve showed in Figure 4-10 describes the relation between the raw data F_M and D for the four consecutive shearing cycles applied to sample A4/R-45/S1, for illustration.

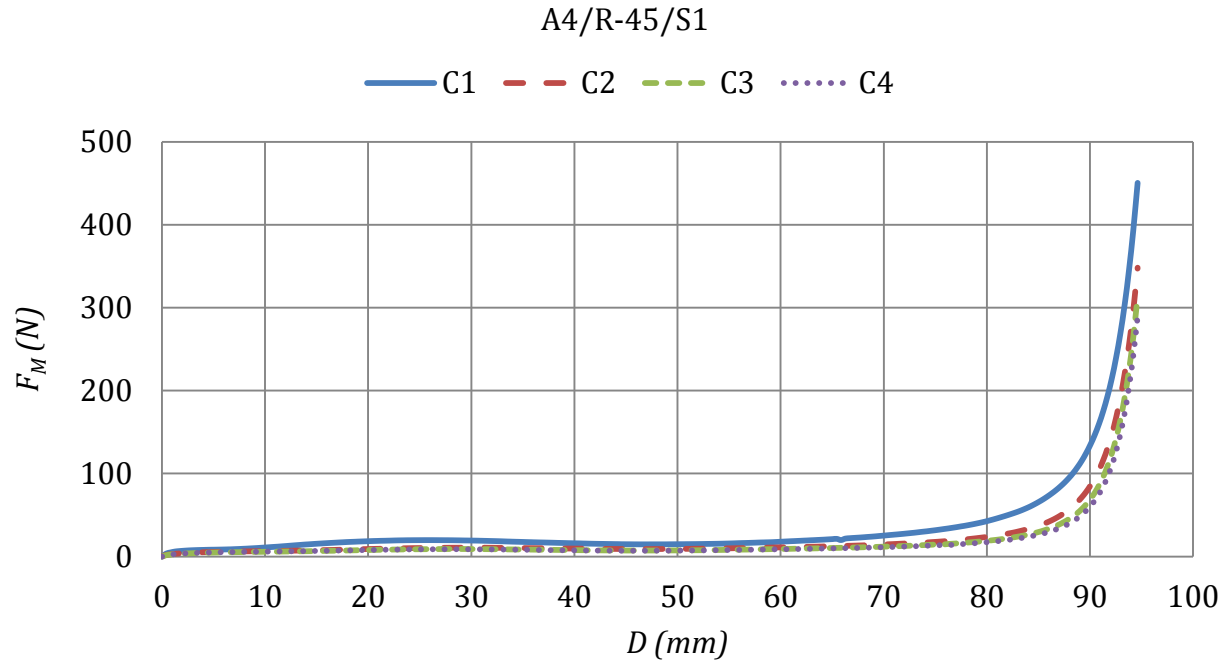


Figure 4-10: Raw in-plane shear curves obtained for sample A4/R-45/S1.

4.4.2 Curves and analysis of experimental results

Raw data was converted to relationships between the shear force F_s and shear angle γ . Conversion was done through analysis of the geometry of the in-plane shear apparatus shown in Figure 4-9 as follows:

$$\cos\beta = \frac{\sqrt{2}L_{frame}+D}{2L_{frame}} \quad (4.1)$$

where 2β represents the inner angle defined by the deformed in-plane shear apparatus, taking an initial value of 90° at the starting position and progressively decreasing as the cross-head travels upwards. Further inspection of the geometry leads to:

$$\gamma = 90^\circ - 2\beta \quad (4.2)$$

where γ represents the shear angle which takes an initial value of 0° at the starting position and progressively increases as the cross-head travels upwards. The shear force F_s as defined in Figure 4-9 is calculated as follows:

$$F_s = \frac{F_M}{2\cos\beta} \quad (4.6)$$

By conducting the above conversion the shear angle γ can be determined for all recorded displacements D during a shear test and the corresponding values of the shear force F_s are obtained. Curves representing the relationship between shear force F_s and shear angle γ obtained for 4 consecutive shear cycles imposed on sample A4/R-45/S1 appear in Figure 4-11 for illustration purposes. Curves for all samples and cycles are included in Appendix E.

Similarities and differences in behaviour were observed for the 16 series of 4 consecutive compaction cycles applied to reinforcements as part of this work; those similarities and

differences are presented and discussed. As a general observation for all samples, the maximum shear forces recorded ranged from 50 N to 300 N at shear angles nearing 65°. Values of the shear force reached in the first cycle C1 are always greater than in following cycles C2, C3, and C4. Although some elements of behaviour are common to all samples and tests, differences also emerge between samples.

For groups A4 and A5, shear curves tend to show the same general behaviour in terms of featuring three main parts. The first part of the shear curve is linear with forces increasing along a low slope due to the lateral deformation of yarns that progressively fill the spaces that are initially between them. The second part is parabolic where the space between yarns has become smaller to the point where there are no open gaps between them and they are pushed laterally against each other, leading to the third part of the curves where forces increase rapidly with a slope several orders of magnitude higher than that seen in the first part, as illustrated in Figure 4-11 for sample A4/R-45/S1. Shear curves are linear with limited forces until a shear angle of approximately 50° is reached, after which the force starts to increase following an exponential profile until a shear angle of approximately 63° is reached. Beyond this angle the shear force tends to increase rapidly following an essentially linear trend.

Samples from group A4 made from 8 arrays of yarns, and from group A5 made from 12 arrays of yarns, overall behaved essentially in the same way upon shearing. Both thicknesses and stitch configurations (R-45 and R+45) did not seem to have a strong influence on the shear behaviour, with similar shear locking angles generally around 60°.

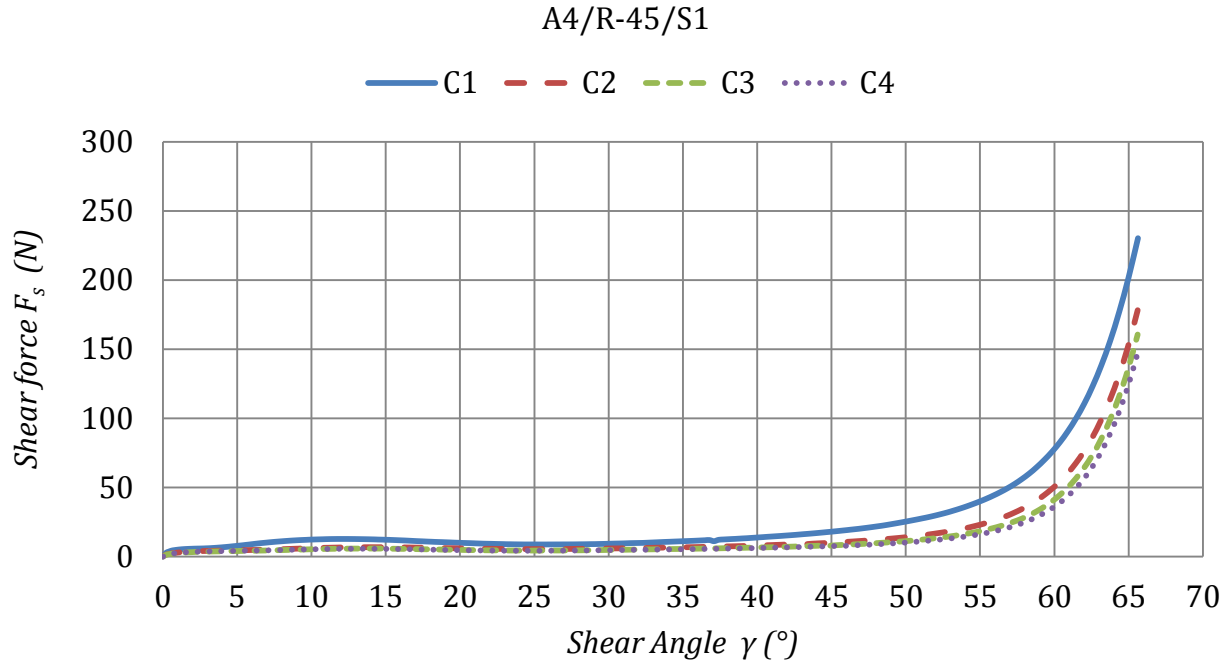


Figure 4-11: Relation between shear force and shear angle for sample A4/R-45/S1.

Curves obtained from testing some samples in these groups featured small bumps in the first part of shear curves, as shown in Figure 4-12 for sample A4/R-45/S2. Such bumps can be related to small misalignments of stitch lines inside the shear apparatus. These misalignments seem to affect the first part of the shear curve, and also the slope at the end of the curve; as a result they are thought to affect values of the shear locking angle. It is also noted that these small bumps were seen in the first test cycles C1 and largely disappeared in subsequent test cycles C2, C3 and C4.

Larger peaks were seen for sub-groups A6/R0 and B6/R0, caused by stitch lines not being parallel with either set of yarns and limiting their relative rotation, Figures 4-13 and 4-14.

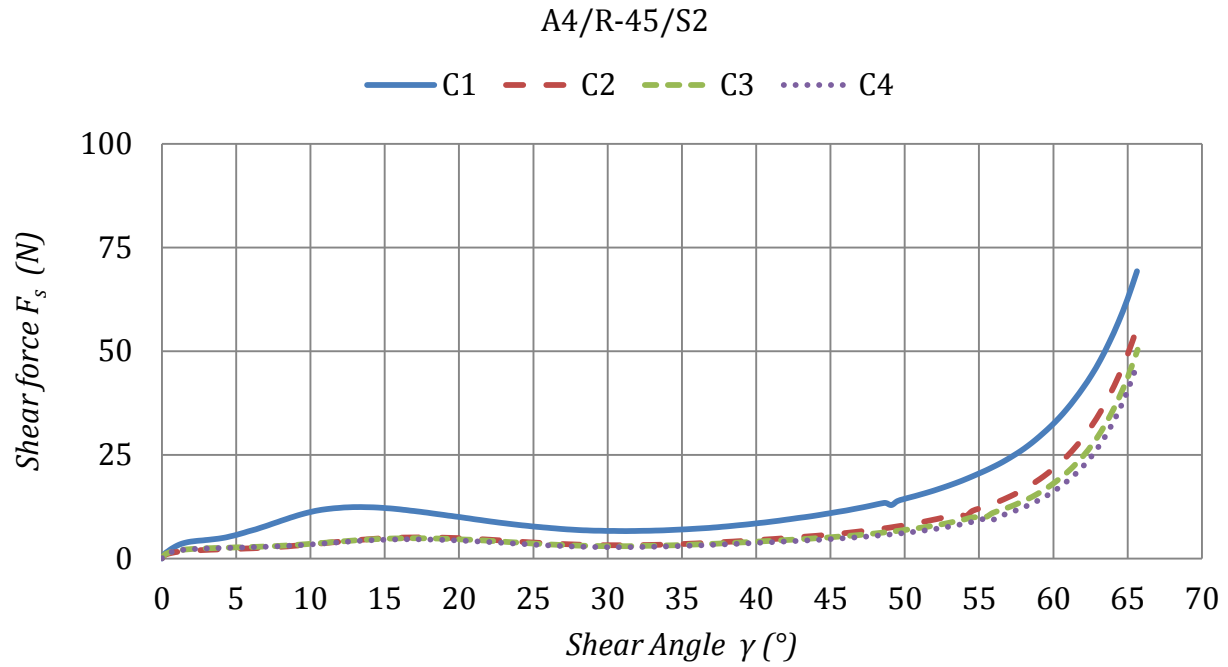


Figure 4-12: Relation between shear force and shear angle for sample A6/R-45/S2.

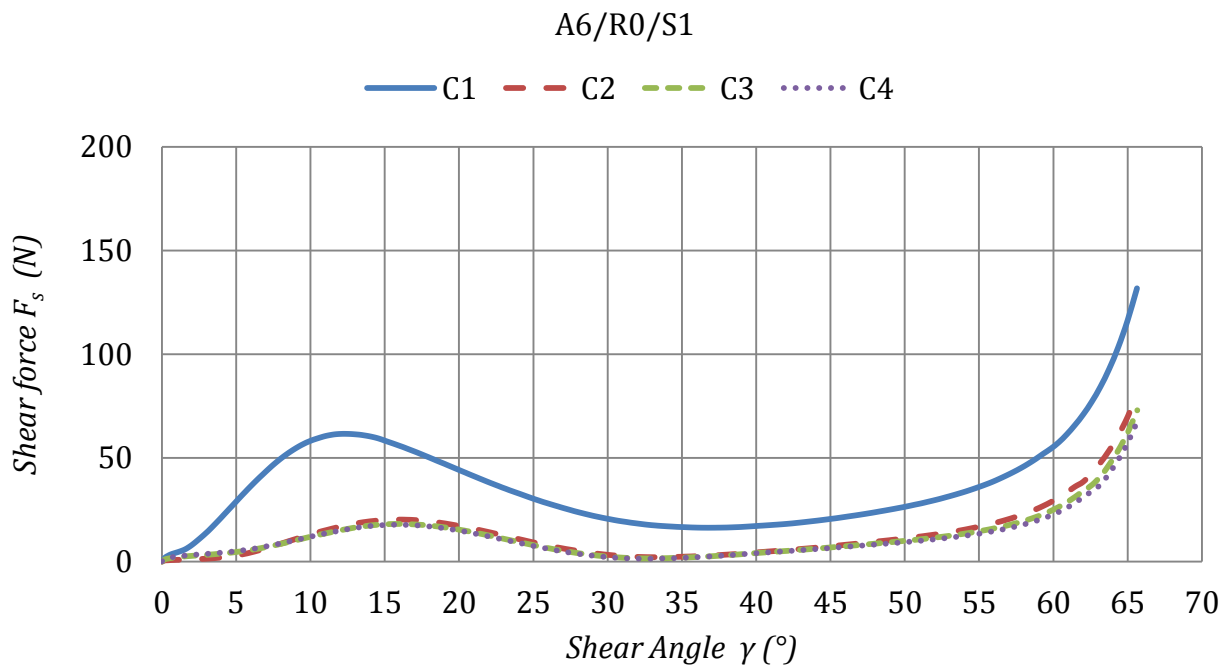


Figure 4-13: Shear force curves resulting from testing sample A6/R0/S1.

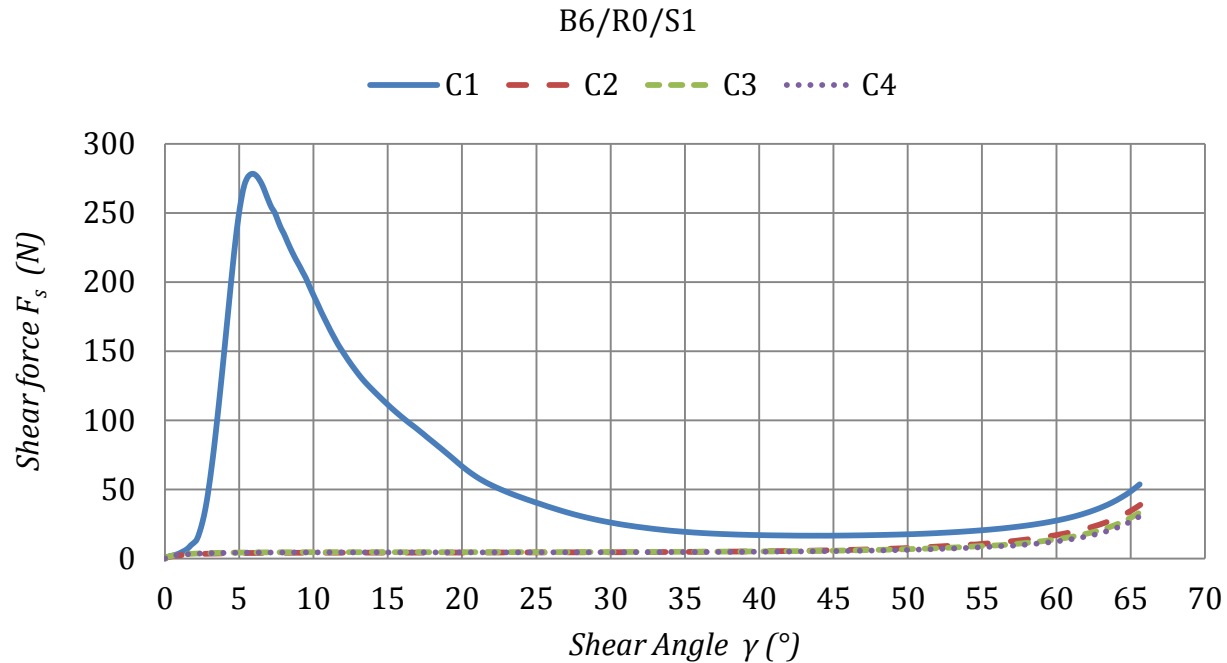


Figure 4-14: Shear force curves resulting from testing sample B6/R0/S1.

The peaks in sub-group B6/R0 samples made from Type B fabric shown in Figure 4-14 were much larger than for sub-group A6/R0 upon the first cycle, and they essentially disappeared in subsequent cycles – contrary to sub-group A6/R0 where smaller peaks could be seen in subsequent cycles. The difference in amplitude reflects the presence of more numerous and more closely spaced stitch lines in samples sub-group B6/R0 made from the Saertex industrial reinforcement as illustrated in Figure 4-15. Peaks disappeared in subsequent cycles for sub-group B6/R0 samples due to damage to stitches upon the first shear cycle. Stitches in the R0 configuration were subjected to compression but withstood tension in the transverse direction from loss of alignment. This may be observed from increasing distances between stitching lines as the sample is sheared further; Figure 4-15 shows spacing between stitch lines, which are no longer straight as the test progresses, that becomes larger than at the beginning of the shear test; this causes stitch lines to fail.

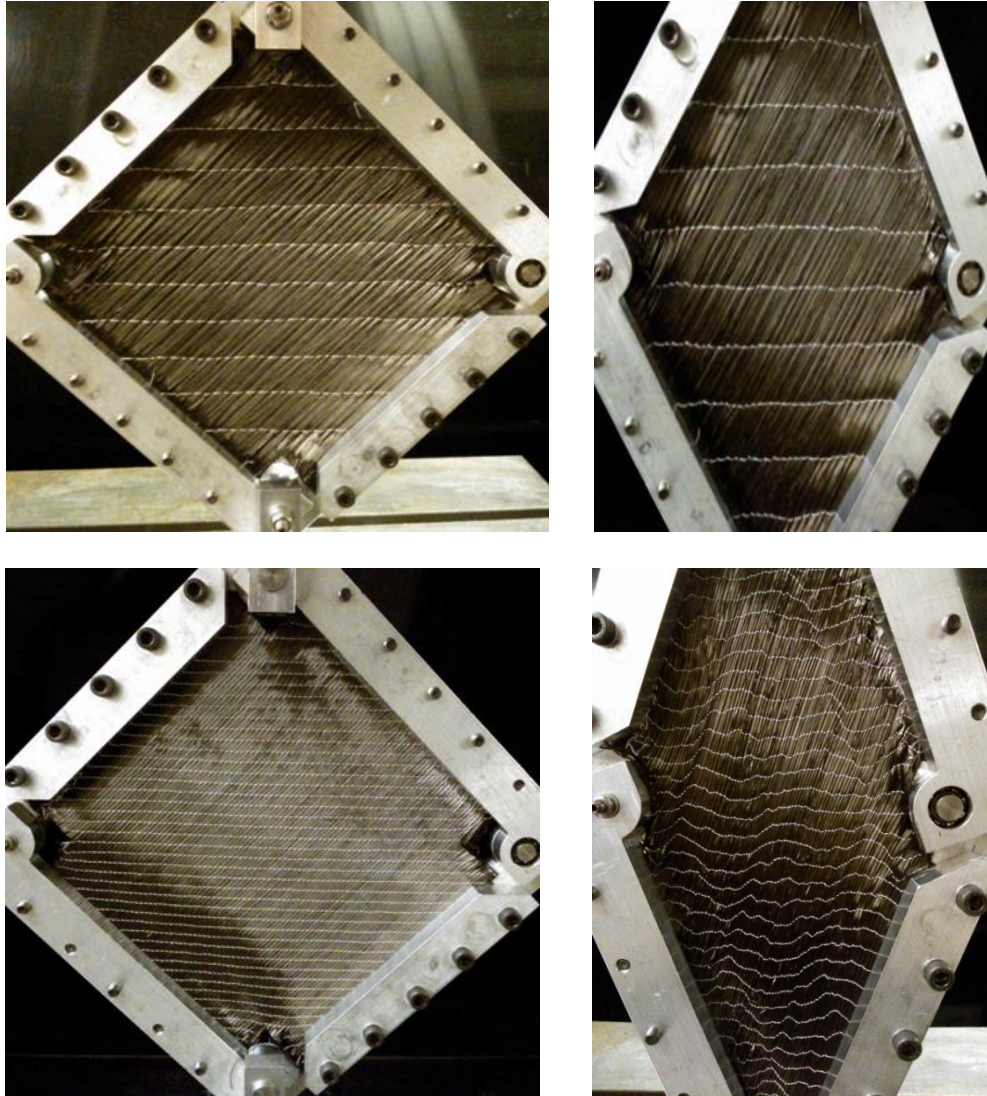


Figure 4-15: Spacing between stitch lines in type A (above) and in type B (bottom).

Peaks also appeared in curves obtained from testing A6 samples in the R90 stitch configuration, but they were smaller and rougher as shown in Figure 4-16. This resulted from stitch lines failing one after another from an earlier stage of the shear tests, with samples of uO-APT shearing to larger angles with limited resistance as the fabric is not interlaced. This explains the lower amounts of shear force recorded in the R90 configuration compared with those recorded in the R0 configuration, with A6 samples.

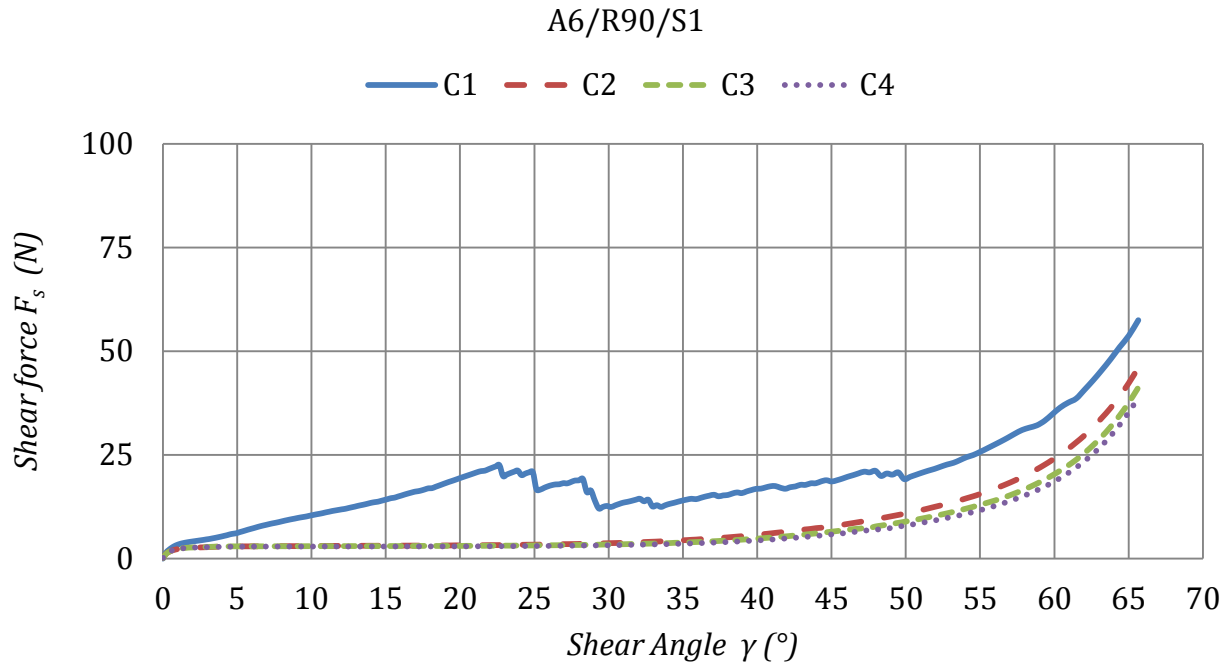


Figure 4-16: Shear force curves resulting from testing sample A6/R90/S1.

B6 samples tested in the R90 stitch configuration behave in a way similar to that seen with A6/R90 samples but failures of more numerous stitch lines lead to more linear curves as shown in Figure 4-17. This results from differences in stitching used in Saertex samples.

In conclusion, when comparing results of shear tests A6/R0 with stitch lines under compression with those of shear tests A6/R90 with stitch lines under tension, guessing would dictate that shear forces would be larger in the second case. This was not so, with A6/R0 samples showing early failure of stitch lines that allowed layers of the reinforcements to shear easily. Comparing results of shear tests in B6/R0 and B6/R90 sample configurations, despite larger peaks recorded with the former in the first cycle caused by the stitch lines, shear forces recorded in following cycles were much lower as shown in Figures E-13 to E-16, Appendix E.

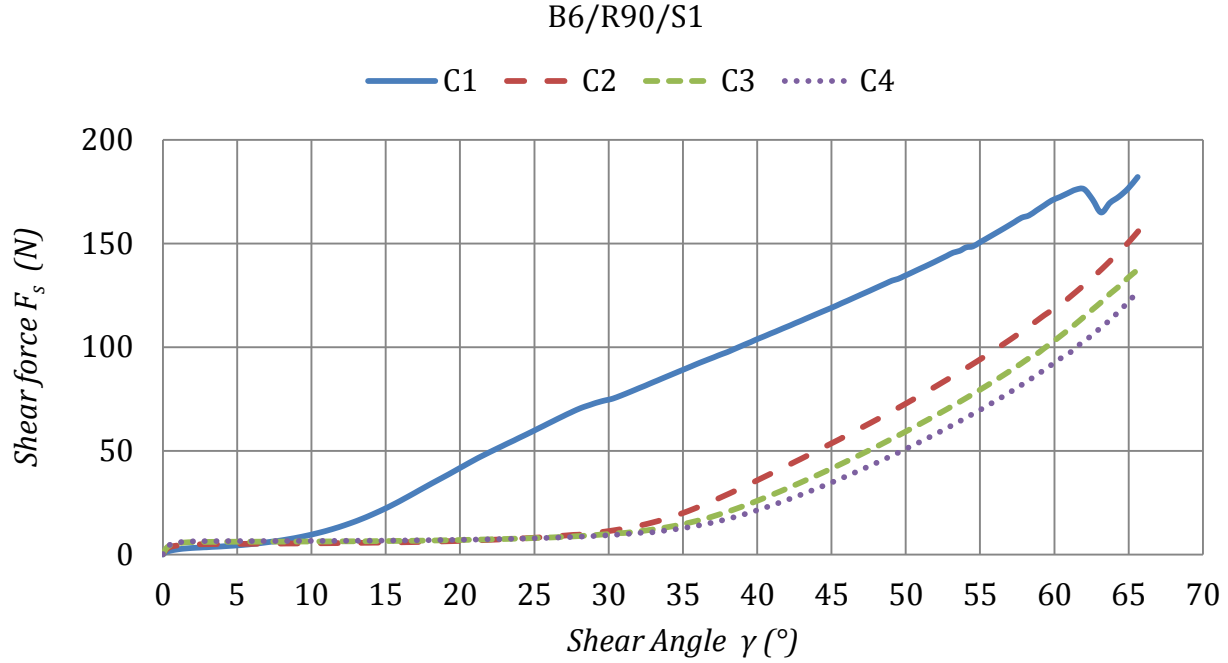


Figure 4-17: Shear force curves resulting from testing of sample B6/R90/S1.

The quantitative analysis of in-plane shear test results was performed as follows. Data generated in the shear tests is investigated, namely the effect of the type of reinforcement (A and B), the effect of the number of layers, and the effect of stitching setup (R-45, R+45, R0 and R90) on the behaviour of the reinforcements, primarily analysed as the extent to which the reinforcement may shear and the force required to do so. The limit to in-plane shear may be evaluated using established practice reported in the literature [238-243], through quantification of the in-plane shear locking angle γ_L . The locking angle is determined as the intercept of a tangent to the shear force to shear angle curve with the horizontal, abscissa axis taken where the slope approaches maximum value, at which the onset of wrinkling can be observed visually. Figure 4-18 and Table 4-5 show shear locking angle γ_L values determined for A4 samples, for illustration purposes.

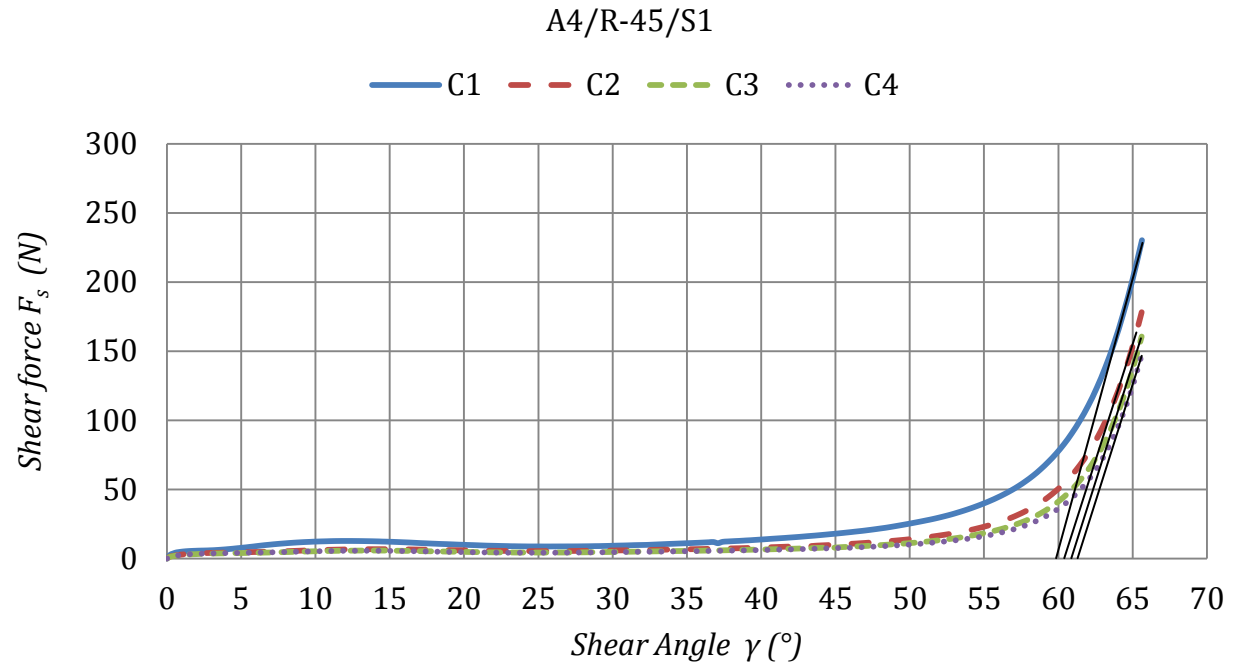


Figure 4-18: Locking angles determined for sample A4/R-45/S1.

Table 4-5: Values of the shear locking angle γ_L obtained for group A4 samples.

Type	Group	Arrays	Stitching	Stitching setup	Sample	<i>Shear locking angle γ_L (°)</i>			
						C1	C2	C3	C4
uO-APT	A4	8 parallel yarn arrays - [90/0/90/0] _s	Along 0° in reinforcement	R-45	S1	60.0	60.5	61.0	61.5
					S2	58.5	59.5	60.0	60.5
				R+45	S1	58.5	60.0	60.5	61.0
					S2	58.5	60.0	60.5	61.0

At cycle C1 the average value of the shear locking angle γ_L is approximately 60.0° and it increases to 60.5° , 61.0° and 61.5° as the sample is cycled (C2, C3 and C4). Shear test results from R+45 stitching configuration gave approximately the same average shear locking angle values as the R-45 stitching configuration, although the standard deviation was marginally larger. Table 4-5 shows the shear locking angle γ_L at each cycle for both sub-groups samples. Values of the shear locking angle for all samples and test groups are listed in Appendix F.

Each quantitative response was analysed using three 2-level Taguchi [207] plans labelled as the first, second and third plans. The first, second and third plans featured 3, 2 and 3 parameters respectively. In-plane shear data was analysed as a longer series of smaller plans for lack of symmetry in the data: whilst there is an equivalent group B6 (Table 4-4) featuring tests performed on industrial reinforcements to group A6 (Table 4-3) featuring tests performed on uO-APT reinforcements, there are no such equivalents to groups A4 (Table 4-1) and A5 (Table 4-2). This results from the fact that whilst stitch orientation could be modified in uO-APT reinforcements, the same could not be done with the Saertex industrial reinforcements used in the context of this work. As such more comparisons may be made, with each one pertaining to a smaller set of data as explained below.

The first plan compared the effect of the 3 following parameters and their interactions using data from groups A4 and A5, for two modalities represented as (-) and (+) in the plan on each quantitative response: the in-plane shear locking angle γ_L , the average *AVG* of the shear force F_S , and the standard deviation *STD* of the shear force F_S :

- Parameter *A*: smaller number of layers (-) vs. larger number of layers (+);
- Parameter *B*: setup in rig at R-45 (-) vs. setup in rig at R+45 (+);
- Parameter *C*: shear cycle 1 (-) vs. shear cycle 4 (+).

The second plan compared the effect of the 2 following parameters and their interactions using data from groups A4 and A6, for two modalities represented as (-) and (+) in the plan on each of the same three quantitative responses:

- Parameter *A*: setup in rig at R+45 (-) vs. setup in rig at R90 (+);
- Parameter *B*: shear cycle 1 (-) vs. shear cycle 4 (+).

It can be noticed that whilst the first plan compares setup in apparatus at R-45 with setup in apparatus at R+45 through parameter *B*, the second plan compares setup in apparatus at R+45 with setup in apparatus at R90 through parameter *A*. The comparison defined by parameter *B* in the first plan is not expected to identify a significant effect; however, it is useful in quantifying its amplitude with those of comparisons made through parameters *A* and *C* in the same plan. On the other hand, and again because of data structure resulting from the physical reality of the reinforcements tested, comparing the effect of having stitch that is either parallel with yarns with stitch at 45° from them through parameter *A* in the second plan is expected to be of much greater significance.

Finally, the third plan compared the effect of the 3 following parameters and their interactions using data from groups A6 and B6, for two modalities represented as (-) and (+) in the plan on the same three quantitative responses:

- Parameter *A*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *B*: setup in rig at R0 (-) vs. setup in rig at R90 (+);
- Parameter *C*: shear cycle 1 (-) vs. shear cycle 4 (+).

Parameter *B* which pertains to setup and orientation of stitch lines in the apparatus, differs from both parameter *A* in the second plan and parameter *B* in the first plan. Whilst its effect is not expected to be as strong as that of parameter *A* in the second plan, it is expected to be stronger than that of parameter *B* in the first as the difference in physical configurations is more significant with stitch lines being either subject to tension, or collapsed.

The first plan focuses on the effect of the number of layers along with other parameters on the response in shear. Data analysed in this plan was generated from tests listed in Tables 4-1 and 4-2. The second plan focuses on the effect of the orientation of stitch lines, either parallel to yarn orientations or along a bisector between these orientations, along with the cycle number on the response in shear. Data analysed in this plan was generated from tests listed in Tables 4-1 and 4-3. The third plan focuses on differences in behaviour observed with uO-APT and industrial reinforcements, along with other parameters on the response in shear. Data analysed in this plan was generated from tests listed in Tables 4-3 and 4-4.

The plans are fully factorial. The first and third plans quantify independently the main effects of parameters A , B , and C as well as all the effects of all 3 interactions of two parameters AB , AC and BC and the interaction of 3 parameters ABC . The second plan quantifies independently the main effects of parameters A and B as well as the effect of the single interaction AB . All tests were replicated on 2 samples which enables the quantitative evaluation of inner-group variability and comparison with between-group variability; the statistical significance of the effects of parameters could, here again, be assessed through multi-factorial analyses of variances and calculation of F-ratios [207] as it was in Chapter 3.

The modalities taken by each parameter for each test in all plans are listed in Table 4-6 for the first and third plan, and in Table 4-7 for the second plan. Actual parameters corresponding to labels A to C along with the modalities corresponding to labels $+$ and $-$ in each case appear in the previous pages for all plans; one should note that parameters corresponding to the various labels change from plan to plan.

Table 4-6: Modalities taken by all parameters and interactions for first and third plans.

Run	A	B	C	AB	BC	ABC
1	+	+	+	+	+	+
2	+	+	-	+	-	-
3	+	-	+	-	-	-
4	+	-	-	-	+	+
5	-	+	+	-	+	-
6	-	+	-	-	-	+
7	-	-	+	+	-	+
8	-	-	-	+	+	-

Table 4-7: Modalities taken by all parameters and interactions for second plan..

Run	A	B	AB
1	+	+	+
2	+	-	-
3	-	+	-
4	-	-	+

4.4.3 Analysis of shear locking angle results

Values of the locking angle γ_L appear in Tables 4-8 for the first plan evaluating the effect of the number of layers along with other parameters, in Table 4-9 for the second plan evaluating the effect of the orientation of stitch lines along with other parameters, and in Table 4-10 for the third plan evaluating the effect of reinforcement type along with other parameters. In these tables, labels S1 and S2 identify the sample number as mentioned previously. Therefore, one value of the locking angle γ_L is reported for each specific shear test, cycle number and sample number. Tables 4-8, 4-9 and 4-10 also state explicitly the correspondence between the run numbers as introduced in Tables 4-6 and 4-7 along with the systematic variation of parameters *A* to *C* and their interactions. Here again as for the plan discussed in Chapter 3. It should be noted that modalities taken by each interaction at each run, as presented by + and – labels in Tables 4-6 and 4-7, are the product of modalities taken by the corresponding individual parameter on the same line and therefore, all evaluations of the effects of main parameters and interactions are independent [207].

Table 4-8: Responses for the first plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	A5/R+45/C4	61.5	60.5	61.00	0.500
2	A5/R+45/C1	58.0	58.0	58.00	0.000
3	A5/R-45/C4	60.0	61.0	60.50	0.500
4	A5/R-45/C1	56.0	58.5	57.25	3.125
5	A4/R+45/C4	61.0	61.0	61.00	0.000
6	A4/R+45/C1	58.5	58.5	58.50	0.000
7	A4/R-45/C4	61.5	60.5	61.00	0.500
8	A4/R-45/C1	60.0	58.5	59.25	1.125
	Average				0.719
	Variance			4.598	
	F-Ratio				6.395

Table 4-9: Responses for the second plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	A6/R90/C4	59.5	60.5	60.00	0.500
2	A6/R90/C1	55.0	56.5	55.75	1.125
3	A4/R+45/C4	61.0	61.0	61.00	0.000
4	A4/R+45/C1	58.5	58.5	58.50	0.000
	Average				0.406
	Variance			10.448	
	F-Ratio				25.734

Table 4-10: Responses for the third plan (°).

Run	Sub-group	S1	S2	$LAVG(\gamma_L)$	$LSTD^2(\gamma_L)$
1	B6/R90/C4	46.0	45.5	45.75	0.125
2	B6/R90/C2	36	34	35.00	2.000
3	B6/R0/C4	61.5	61.5	61.50	0.000
4	B6/R0/C2	58.5	58.5	58.50	0.000
5	A6/R90/C4	59.5	60.5	60.00	0.500
6	A6/R90/C2	55	56.5	55.75	1.125
7	A6/R0/C4	62.5	61.5	62.00	0.500
8	A6/R0/C2	59	58	58.75	1.125
	Average				0.672
	Variance			179.355	
	F-Ratio				266.95

The first step in the quantitative analysis of the data presented in Tables 4-8, 4-9 and 4-10 is the one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan, culminating in the calculation of an F-ratio in each case. The F-ratios are compared with tabulated values, indicating an F-ratio that is significant or not. A significant F-ratio obtained from a one-way ANOVA performed on the data as a whole provides an indication that some parameters or their interactions may have a quantifiable effect of the response, above and beyond fluctuations in the data due to experimental variability [207].

Quantities pertaining to the three one-way ANOVAs performed as part of the analysis of the shear data appear in Tables 4-8 to 4-10. $LAVG(\gamma_L)$ and $LSTD^2(\gamma_L)$ represent the line average

and the line standard deviation of γ_L for each run, for the 2 samples associated to the given run. Equations for these quantities are similar to Eq. 3.27 to 3.30.

Values of the F-Ratio associated with one-way ANOVAs performed for each plan are obtained by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 2 values of locking angle γ_L associated with a given run, in a procedure similar to that described in Section 3.5.2. Values of the overall variances between and within subgroups appear in Tables 4-8, 4-9 and 4-10. It is interesting to note that the three plans return values of the F-ratio that differ very significantly. The values indicate that the effect of the thickness of reinforcements that are otherwise constructed in the same way, including similar orientations of stitch lines extending parallel to the yarns, is less pronounced along with the effect of cycling.

Considering the first plan, the F-ratio was calculated at 6.395 from experimental data. Considering total, between and within numbers of degrees of freedom of 15, 7 and 8 respectively, arrived at by subtracting 1 from the product of the number of sub-groups and sub-group size, 8 and 2 respectively in the first case, by subtracting 1 from number of subgroups 8 in the second case, and by subtracting the between value from the total value in the third case, and using a stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 6.18 [207]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 6.395 and 6.18, indicate that there is marginal scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the shear locking angle.

Considering the second plan, the F-ratio was calculated at 25.734 from experimental data. Considering total, between and within numbers of degrees of freedom of 7, 3 and 4 respectively, and using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 16.7 [207]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted from the second plan, 25.734 and 16.7, indicate that there is stronger scope in calculating contrast F-ratios for this plan.

Finally, considering the third and F-ratio was calculated at 266.95 from experimental data, using the same false alarm theoretical risk α of 0.01 will lead to the same value critical value of 6.18 [207]. The calculated and tabulated values of the F-ratio indicate very strong scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the shear locking angle in this case.

Given the above conclusions, the next step in analysing the effects of the parameters on shear consists in calculating contrasts associated with each parameter and interaction of parameters, for each plan. Contrasts are defined in Section 3.5.2. Adjustment terms were equal to 8/2 for the first and third plans, and to 4/2 for the second plan. Values of the mean square within for all the data *MSW*, for each plan, appear in Tables 4-8 to 4-10. They also appear in Tables 4-11 to 4-13 as they are used towards calculating the F-ratios for individual contrasts, which appear in these tables. Here again it is verified that the average of contrast F-ratios presented in Tables 4-11 to 4-13 are equal to the one-way ANOVA F-ratios presented in Tables 4-8 to 4-10, as expected.

Table 4-11: Contrasts for first plan (°).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-3	2.25	3.13
<i>B</i>	0.5	0.06	0.09
<i>C</i>	10.5	27.56	38.35
<i>AB</i>	2.0	1.0	1.39
<i>AC</i>	2.0	1.0	1.39
<i>BC</i>	0.5	0.06	0.09
<i>ABC</i>	-1.0	0.25	0.35
<i>MSW</i>	0.719		

Table 4-12: Contrasts for second plan (°).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-3.75	7.03	17.31
<i>B</i>	6.75	22.78	56.08
<i>AB</i>	1.75	1.53	3.77
<i>MSW</i>	0.406		

Table 4-13: Contrasts for third plan (°).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-35.75	319.52	475.56
<i>B</i>	-44.25	489.52	728.58
<i>C</i>	21.25	112.89	168.02
<i>AB</i>	-34.25	293.27	436.49
<i>AC</i>	6.25	9.77	14.53
<i>BC</i>	8.75	19.14	28.49
<i>ABC</i>	6.75	11.39	16.95
<i>MSW</i>	0.672		

Calculated contrast F-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with MSW remains unchanged at 8 for the first and third plans and 4 for the second plan. Using the same stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 11.3 for first and third plans and 21.2 for the second plan [207]. Values of contrast F-ratios superior to 11.3 and 21.2, deemed significant, are highlighted in Tables 4-11, 4-12 and 4-13. Results from Table 4-11 reveal that one main parameter has a significant effect on response γ_L for the first plan. Results from Table 4-12 reveal that two main parameters have significant effect on response γ_L for the second plan. Finally, results from Table 4-13 reveal that all 3 main parameters and 4 interactions have significant effect on response γ_L for the third plan. Significant main effects and interactions of parameters are summarised in Table 4-14, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 4-19 and 4-21.

Table 4-14: Summary of significant main effects and interactions of parameters.

First plan, response γ_L	Second plan, response γ_L	Third plan, response γ_L
$C(+)$	$B(+)$	$A(-)$
		$B(-)$
		$C(+)$
		$AB(-)$
		$AC(+)$
		$BC(+)$
		$ABC(+)$

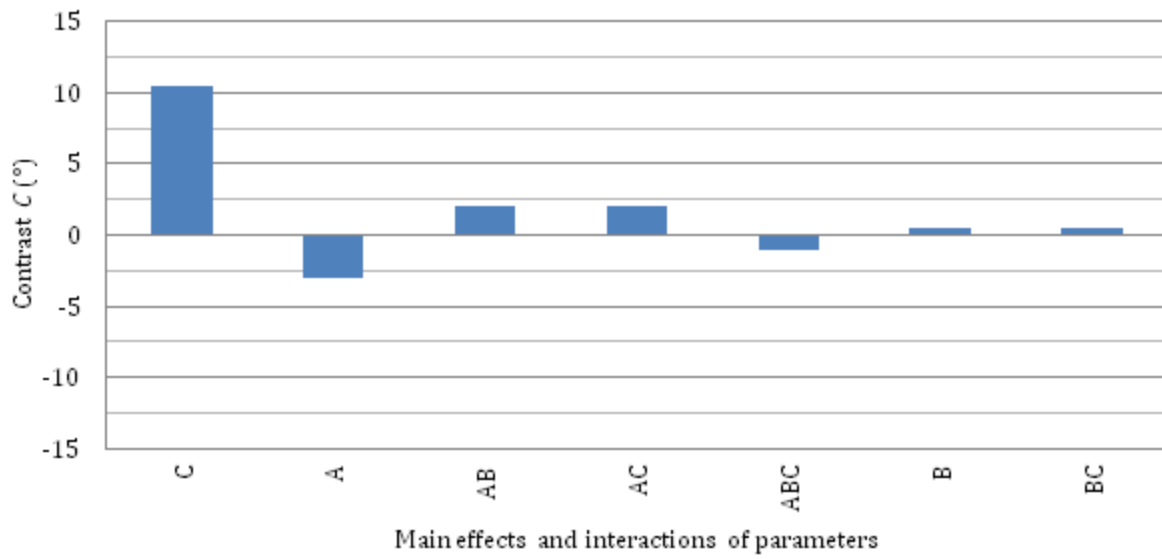


Figure 4-19: Main effects and interactions of parameters in decreasing order, response γ_L , first plan.

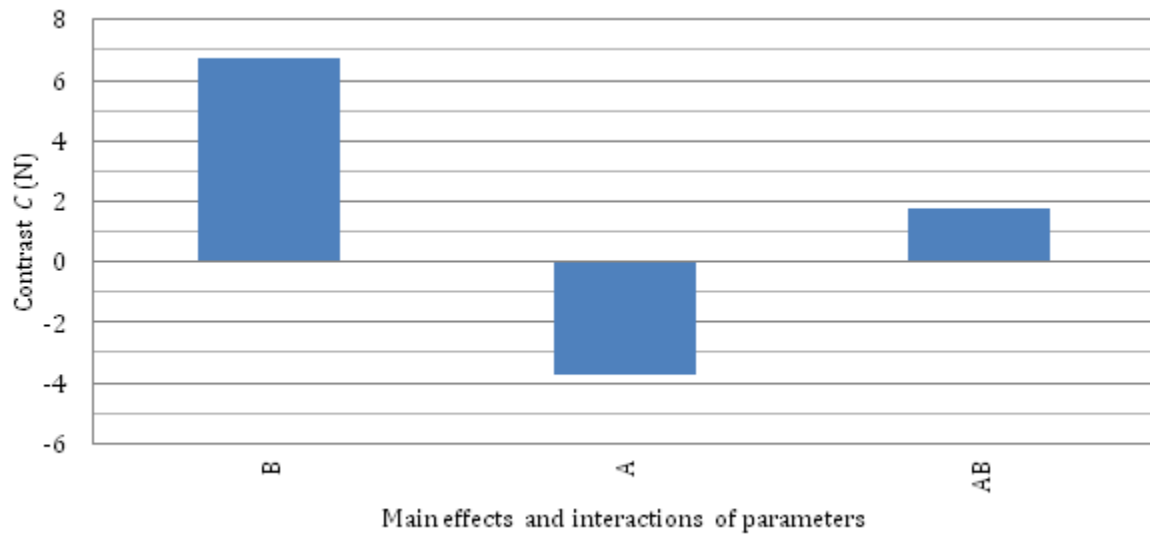


Figure 4-20: Main effects and interactions of parameters in decreasing order, response γ_L , second plan.

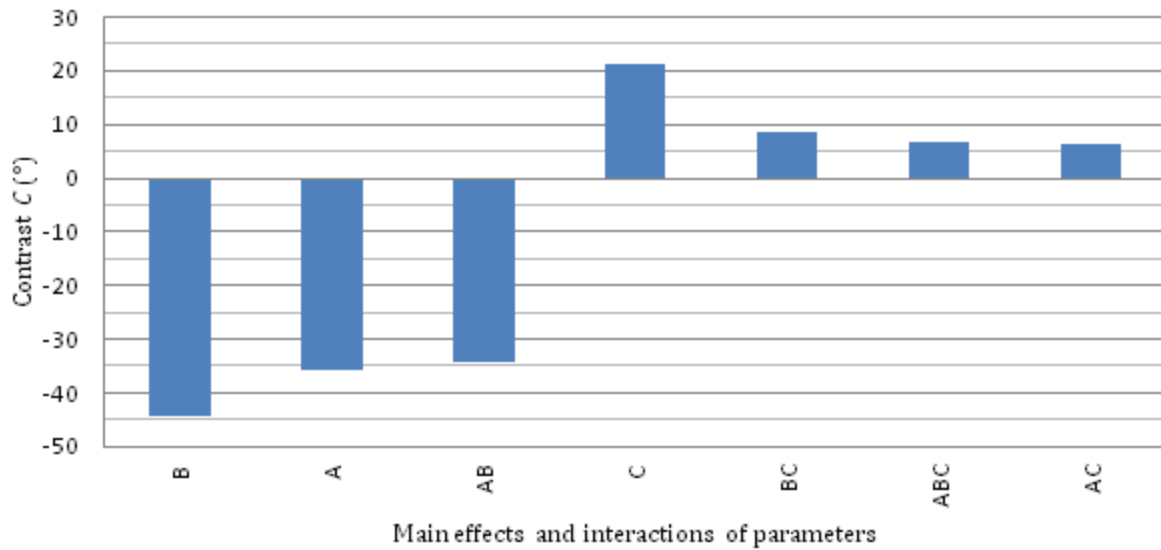


Figure 4-21: Main effects and interactions of parameters in decreasing order, response γ_L , third plan.

4.4.4 Qualitative discussion of locking angle results

The tables and figures show that in the first plan parameter C , $C1$ (-) vs. $C4$ (+), which compared shear locking angle values in cycle 1 with cycle 4, has a leading effect on the shearing locking angle response. In contrast to parameter C , parameter A , smaller number of layers (-) vs. larger number of layers (+), and parameter B , setup in rig at R-45 (-) vs. setup in rig at R+45 (+), have no significant effect on the shearing locking angle response.

In the second plan, parameter B representing cycle $C1$ (-) vs. $C4$ (+) has again a leading effect on the shearing locking angle response. Unexpectedly, parameter A , setup in rig at R+45 (-) vs. setup in rig at R90 (+) has a minor effect on the locking angle response.

In the third plan parameter B , setup in rig at R0 (-) vs. setup in rig at R90 (+), has the leading effect. Parameter A , uO-APT reinforcement (-) vs. industrial reinforcement (+), has the second leading effect, followed by the interaction between them AB , comes has the third leading effect on the shearing locking angle response. Cycle C1 (-) vs. C4 (+) has again a significant effect but it is a distant fourth, followed by other interactions.

4.4.5 Analysis of shear force results

The above three 2-level experimental plans were also used for analysing two quantitative responses derived from the shear force, which were the value of the average force AVG and standard deviation STD . Each plan was used in analysing each response for a total of six analyses. Table 4-15 shows values of the average AVG and standard deviation STD of the shear force F_s determined for A4 samples, for illustration purposes. AVG and STD values for all samples and test groups are listed in Appendix G.

Values derived from the shear force appear in Tables 4-16 for the first plan evaluating the effect of the number of layers along with other parameters, in Table 4-17 for the second plan evaluating the effect of the orientation of stitch lines along with other parameters, and in Table 4-18 for the third plan evaluating the effect of reinforcement type along with other parameters. In these tables, the labels AVG and STD represent the average and the standard deviation of the values of shear force F_s respectively, whilst the labels S1 and S2 identify the sample number as mentioned previously. Therefore, one value of the average AVG of F_s and one value of the standard deviation STD of F_s are reported for each specific shear test, cycle number and sample number.

Table 4-15: Values of the average and standard deviation of shear force obtained for group A4 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear force F_s (N)</i>			
							<i>AVG</i>		<i>STD</i>	
							C1	C4	C1	C4
uO-APT	A4	8 parallel yarn arrays - [90/0/90/0] _s	Along 0° in reinforcement	R-45	2.0	S1	19.88	9.73	29.93	17.50
						S2	11.59	5.22	9.51	5.80
				R+45	2.0	S1	13.47	7.46	20.46	10.55
						S2	15.52	8.25	20.36	11.51

Tables 4-16, 4-17 and 4-18 also state explicitly the correspondence between the run numbers as introduced in Tables 4-6 and 4-7 along with the systematic variation of parameters *A* to *C* and their interactions. Here again as for the plan discussed in Chapter 3, it should be noted that modalities taken by each interaction at each run, as presented by + and - labels in Tables 4-6 and 4-7, are the product of modalities taken by the corresponding individual parameter on the same line and therefore, all evaluations of the effects of main parameters and interactions are independent [207].

Table 4-16: Responses for the first plan (N).

Run	Sub-group	S1 <i>AVG</i>	S1 <i>STD</i>	S2 <i>AVG</i>	S2 <i>STD</i>
1	A5/R+45/C4	12.54	22.80	12.09	17.15
2	A5/R+45/C1	27.31	34.77	22.39	30.38
3	A5/R-45/C4	15.30	28.06	12.54	21.70
4	A5/R-45/C1	26.77	34.68	23.31	35.97
5	A4/R+45/C4	7.46	10.55	8.25	11.51
6	A4/R+45/C1	13.47	20.46	15.52	20.36
7	A4/R-45/C4	9.73	17.50	5.22	5.80
8	A4/R-45/C1	19.88	29.93	11.59	9.51

Table 4-17: Responses for the second plan (N).

Run	Sub-group	S1 <i>AVG</i>	S1 <i>STD</i>	S2 <i>AVG</i>	S2 <i>STD</i>
1	A6/R90/C4	5.25	5.68	4.55	5.63
2	A6/R90/C1	16.35	8.94	19.22	9.17
3	A4/R+45/C4	7.46	10.55	8.25	11.51
4	A4/R+45/C1	13.47	20.46	15.52	20.36

Table 4-18: Responses for the third plan (N).

Run	Sub-group	S1 <i>AVG</i>	S1 <i>STD</i>	S2 <i>AVG</i>	S2 <i>STD</i>
1	B6/R90/C4	21.79	27.36	19.01	26.52
2	B6/R90/C1	65.89	53.83	55.24	48.06
3	B6/R0/C4	5.55	4.04	6.60	4.80
4	B6/R0/C1	72.36	76.03	80.50	78.11
5	A6/R90/C4	5.25	5.68	4.55	5.63
6	A6/R90/C1	16.35	8.94	19.22	9.17
7	A6/R0/C4	9.96	8.91	12.41	11.53
8	A6/R0/C1	35.11	20.24	65.77	30.86

Again, the first step in quantitative analysis of the data presented in Tables 4-16, 4-17 and 4-18 is the one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan, culminating in the calculation of an F-ratio in each case. The F-ratios are compared with tabulated values, indicating an F-ratio that is significant or not. A significant F-ratio obtained from a one-way ANOVA performed on the data as a whole provides an indication that some parameters or their interactions may have a quantifiable effect of the response, beyond fluctuations in the data due to experimental variability [207].

Quantities pertaining to the six one-way ANOVAs performed as part of the analysis of the shear force appear in Tables 4-18 to 4-23. $LAVG(AVG)$ and $LSTD^2(AVG)$ represent the line average and the line variance of the average shear force F_s for each run, for the 2 samples associated to the given run. Similarly, $LAVG(STD)$ and $LSTD^2(STD)$ represent the line average and the line variance of the standard deviation of the shear force F_s for each run, for the 2 samples associated to the given run. Equations defining these quantities are similar to Eq. 3.27 to 3.30. Values of the F-Ratio associated with one-way ANOVAs performed for each plan are obtained by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 2 values derived from the shear force F_s associated with a given run, in a procedure similar to that described in Section 4.4.2. Values of the overall variances between and within subgroups appear in Tables 4-19 to 4-24. As seen for the analysis of the shear angle γ_L it is interesting, though expected at this stage, that the three plans return values of the F-ratio that show significant differences.

Considering the first plan applied to response *AVG*, the F-ratio was calculated at 12.21 from experimental data. Considering total, between and within numbers of degrees of freedom of 15, 7 and 8 respectively and using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 6.18 [207]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 12.21 and 6.18, indicate scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on *AVG* . Considering the first plan applied to response *STD*, the F-ratio was calculated at 3.787 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 3.787 and 6.18, indicate that there may be no scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the *STD* shear force values; all contrasts should be of no significance.

Table 4-19: One-way ANOVA for *AVG* responses, first plan (N).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$
1	A5/R+45/C4	12.32	0.10
2	A5/R+45/C1	24.85	12.10
3	A5/R-45/C4	13.92	3.81
4	A5/R-45/C1	25.04	5.99
5	A4/R+45/C4	7.86	0.31
6	A4/R+45/C1	14.50	2.10
7	A4/R-45/C4	6.48	3.15
8	A4/R-45/C1	15.74	34.36
Average			7.741
Variance		94.475	
F-Ratio			12.21

Table 4-20: One-way ANOVA for *STD* responses, first plan (N).

Run	Sub-group	$LAVG(STD)$	$LSTD^2(STD)$
1	A5/R+45/C4	19.98	15.96
2	A5/R+45/C1	32.58	9.64
3	A5/R-45/C4	24.88	20.22
4	A5/R-45/C1	35.33	0.83
5	A4/R+45/C4	11.03	0.46
6	A4/R+45/C1	20.41	0.01
7	A4/R-45/C4	11.65	68.45
8	A4/R-45/C1	19.72	208.49
Average Variance F-Ratio		153.414	40.507 3.787

Considering the second plan applied to response *AVG*, the F-ratio was calculated at 41.35 from experimental data. Considering total, between and within numbers of degrees of freedom of 7, 3 and 4 respectively, and using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 16.7 [207]. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted from the second plan, 41.35 and 16.7, indicate scope in calculating contrast F-ratios for this plan. Considering the second plan applied to response *STD*, the F-ratio was calculated at 647.05 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 647.05 and 6.18, indicate very strong scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the *STD* shear force values.

Table 4-21: One-way ANOVA for *AVG* responses, second plan (N).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$
1	A6/R90/C4	4.90	0.24
2	A6/R0/C1	17.79	4.12
3	A4/R+45/C4	7.86	0.31
4	A4/R+45/C1	14.50	2.10
Average Variance F-Ratio		70.056	1.694 41.35

Table 4-22: One-way ANOVA for *STD* responses, second plan (N).

Run	Sub-group	$LAVG(STD)$	$LSTD^2(STD)$
1	A6/R90/C4	5.66	0.00
2	A6/R0/C1	9.06	0.03
3	A4/R+45/C4	11.03	0.46
4	A4/R+45/C1	20.41	0.01
Average Variance F-Ratio		79.830	0.123 647.05

Finally, an F-ratio was calculated at 21.18 from the third plan applied to response *AVG*. False alarm risk α of 0.01 returns the same value critical value of 6.18 [207], indicating scope in calculating contrast F-ratios identifying parameters that affect the response. A similar analysis for the third plan and *STD* response lead to an F-ratio of 133.93 which, compared to a tabulated value of 6.18, indicates strong scope in calculating contrast F-ratios.

Table 4-23: One-way ANOVA for *AVG* responses, third plan (N).

Run	Sub-group	<i>LAVG</i> (<i>AVG</i>)	<i>LSTD</i> ² (<i>AVG</i>)	
1	B6/R90/C4	20.40	3.86	
2	B6/R90/C1	60.57	56.71	
3	B6/R0/C4	6.08	0.55	
4	B6/R0/C1	76.43	33.13	
5	A6/R90/C4	4.90	0.24	
6	A6/R90/C1	17.79	4.12	
7	A6/R0/C4	11.19	3.00	
8	A6/R0/C1	50.44	470.02	
Average Variance F-Ratio		1513.708	71.455	21.18

Table 4-24: One-way ANOVA for *STD* responses, third plan (N).

Run	Sub-group	<i>LAVG</i> (<i>STD</i>)	<i>LSTD</i> ² (<i>STD</i>)	
1	B6/R90/C4	26.94	0.35	
2	B6/R90/C1	50.95	16.65	
3	B6/R0/C4	4.42	0.29	
4	B6/R0/C1	77.07	2.16	
5	A6/R90/C4	5.66	0.00	
6	A6/R90/C1	9.06	0.03	
7	A6/R0/C4	10.22	3.43	
8	A6/R0/C1	25.55	56.39	
Average Variance F-Ratio		1327.660	9.913	133.93

The next step is analysing the effects of the parameters on shear consisted in calculating contrasts associated with each parameter and interaction of parameters, for each plan and each response. Contrasts are defined in Section 3.5.2. Adjustment terms were equal to 8/2 for the first and third plans, and to 4/2 for the second plan. Values of the mean square within for all the data *MSW*, for each plan, appear in Tables 4-19 to 4-24. They also appear in Tables 4-25 to 4-30 as they are used towards calculating the F-ratios for individual contrasts, which appear in these tables. Here again it is verified that the average of contrast F-ratios presented in Tables 4-25 to 4-30 are equal to the one-way ANOVA F-ratios presented in Tables 4-18 to 4-23, as expected.

Table 4-25: Contrasts for *AVG* response, first plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast F-ratio
<i>A</i>	31.57	249.09	32.18
<i>B</i>	-1.66	0.68	0.09
<i>C</i>	-39.56	391.15	50.53
<i>AB</i>	-1.94	0.94	0.12
<i>AC</i>	-7.76	15.04	1.94
<i>BC</i>	1.21	0.36	0.05
<i>ABC</i>	-4.04	4.07	0.53
<i>MSW</i>	7.741		

Table 4-26: Contrasts for *STD* response, first plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	49.95	623.63	15.40
<i>B</i>	-7.59	14.38	0.36
<i>C</i>	-40.50	409.96	10.12
<i>AB</i>	-7.73	14.92	0.37
<i>AC</i>	-5.60	7.83	0.19
<i>BC</i>	-3.47	3.0	0.07
<i>ABC</i>	-0.84	0.18	0.00
<i>MSW</i>	40.507		

Table 4-27: Contrasts for *AVG* response, second plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	0.34	0.06	0.03
<i>B</i>	-19.53	190.61	112.51
<i>AB</i>	-6.25	19.50	11.51
<i>MSW</i>	1.694		

Table 4-28: Contrasts for *STD* response, second plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-16.73	139.95	1134.32
<i>B</i>	-12.78	81.66	661.92
<i>AB</i>	5.98	17.88	144.93
<i>MSW</i>	0.123		

Table 4-29: Contrasts for *AVG* response, third plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	79.16	1566.58	21.92
<i>B</i>	-40.48	409.66	5.73
<i>C</i>	-162.66	6614.57	92.57
<i>AB</i>	37.4	349.69	4.89
<i>AC</i>	-58.38	852.06	11.92
<i>BC</i>	56.56	799.76	11.19
<i>ABC</i>	3.82	3.65	0.05
<i>MSW</i>	71.455		

Table 4-30: Contrasts for *STD* response, third plan (N).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	108.90	2964.53	299.06
<i>B</i>	-24.67	152.09	15.34
<i>C</i>	-115.39	3328.42	335.77
<i>AB</i>	17.46	76.17	7.68
<i>AC</i>	-77.93	1518.08	153.14
<i>BC</i>	60.58	917.33	92.54
<i>ABC</i>	36.72	337.00	34.00
<i>MSW</i>	9.913		

Calculated contrast *F*-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with *MSW* remains unchanged at 8 for first and third plans and at 4 for second plan. Using the same stringent false alarm theoretical risk α of 0.01, the

tabulated value indicating significant differences between groups is 11.3 for the first and third plans and 21.2 for the second plan [207]. Values of contrast F-ratios superior to 11.3 and 21.2, deemed significant, are highlighted in Tables 4-25 to 4-30.

For the first plan, results from Table 4-25 reveal that two main parameters, A and C , have significant effects on response $F_S AVG$ while results from Table 4-26 reveal that no parameter or interaction of parameters has a significant effect on response $F_S STD$. The average force is affected by the number of layers, but this was not so for the shear angle; the variance of the force is not affected significantly.

For the second plan, results from Table 4-27 reveal that one main parameter has a significant effect on response $F_S AVG$ while results from Table 4-28 reveal that both main parameters and their interaction have significant effect on response $F_S STD$. Both main parameters were significant for the shear angle but their interaction was not.

Finally for the third plan, results from Table 4-29 reveal that two main parameters and their interaction have significant effects on response $F_S AVG$ while results from Table 4-30 reveal that three main parameters and three of their interactions have significant effect on response $F_S STD$.

Significant main effects and interactions of parameters are summarised in Table 4-31, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 4-22 to 4-27.

Table 4-31: Summary of significant main effects and interactions of parameters.

First plan, response <i>AVG</i>	First plan, response <i>STD</i>	Second plan, response <i>AVG</i>	Second plan response <i>STD</i>	Third plan response <i>AVG</i>	Third plan response <i>STD</i>
<i>A</i> (+)	<i>A</i> (+)		<i>A</i> (-)	<i>A</i> (+)	<i>A</i> (+)
		<i>B</i> (-)	<i>B</i> (-)		<i>B</i> (-)
<i>C</i> (-)				<i>C</i> (-)	<i>C</i> (-)
			<i>AB</i> (+)		
				<i>AC</i> (-)	<i>AC</i> (-)
					<i>BC</i> (+)
					<i>ABC</i> (+)

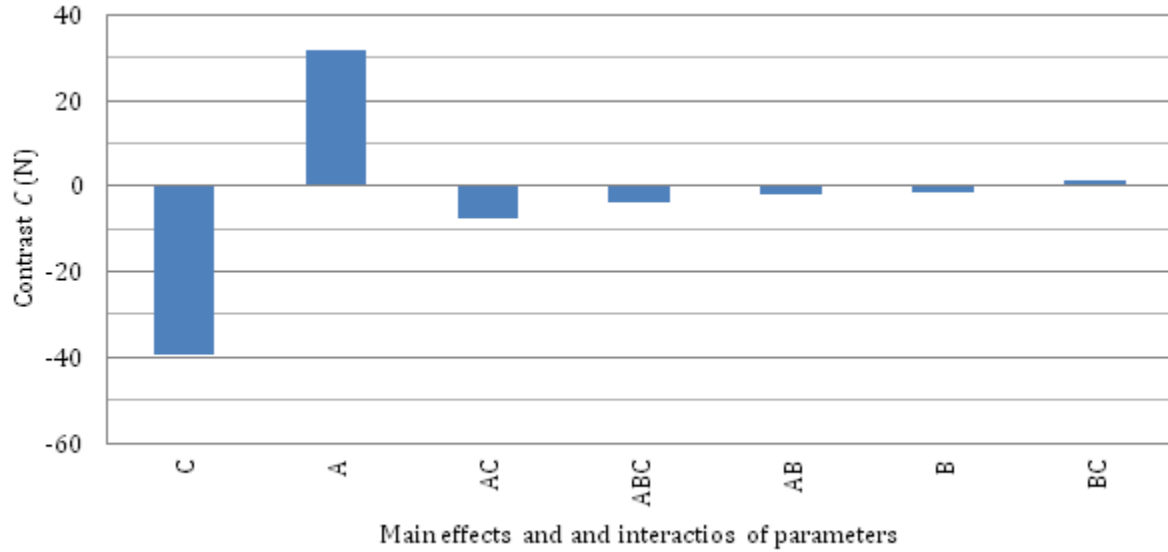


Figure 4-22: Main effects and interactions of parameters in decreasing order, response *AVG*, first plan.

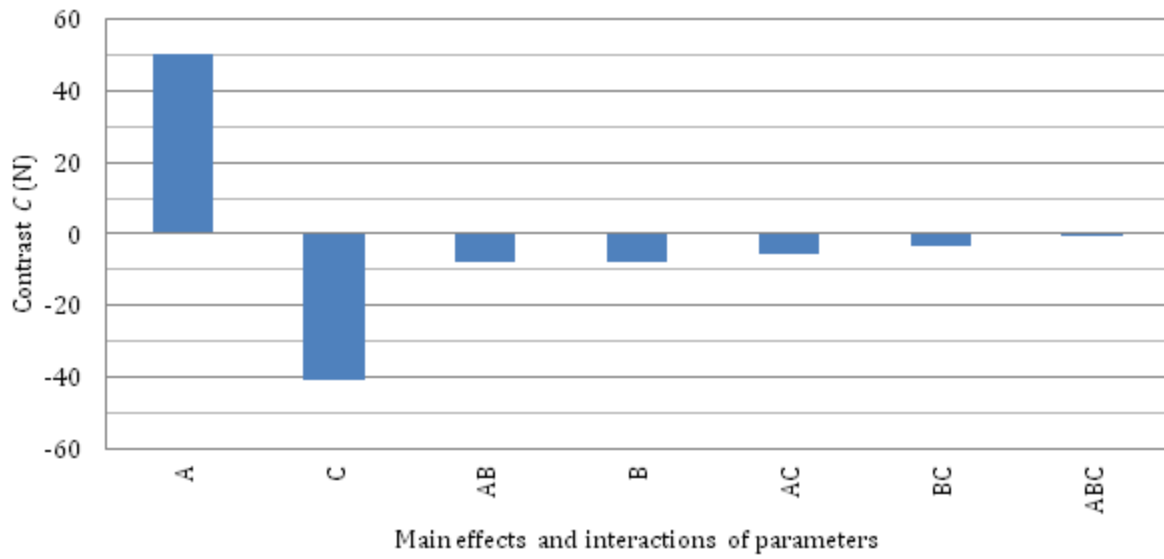


Figure 4-23: Main effects and interactions of parameters in decreasing order, response *STD*, first plan.

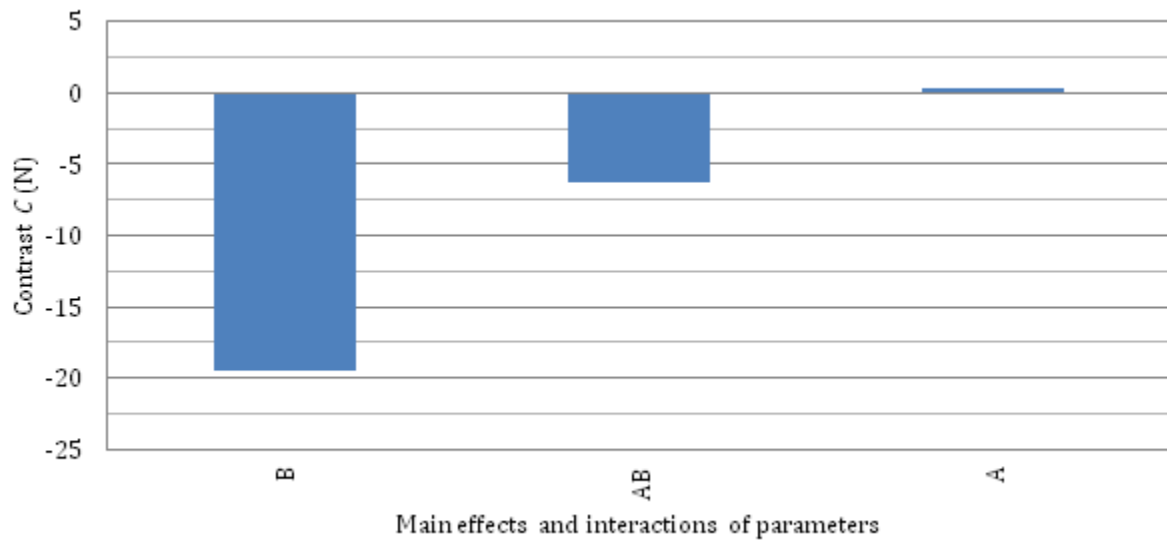


Figure 4-24: Main effects and interactions of parameters in decreasing order, response *AVG*, second plan.

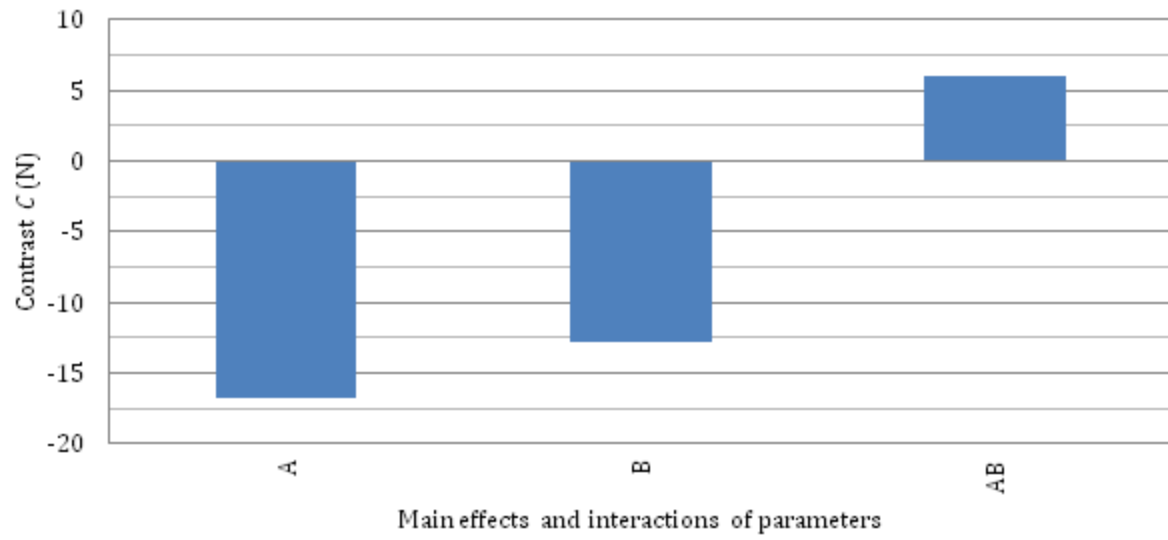


Figure 4-25: Main effects and interactions of parameters in decreasing order, response *STD*, second plan.

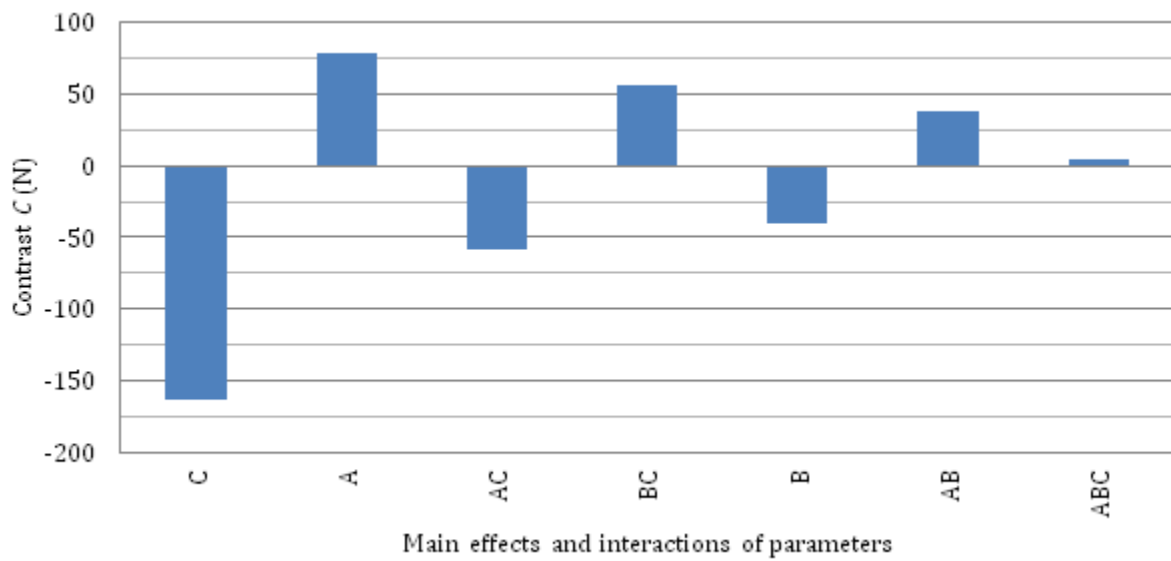


Figure 4-26: Main effects and interactions of parameters in decreasing order, response *AVG*, third plan.

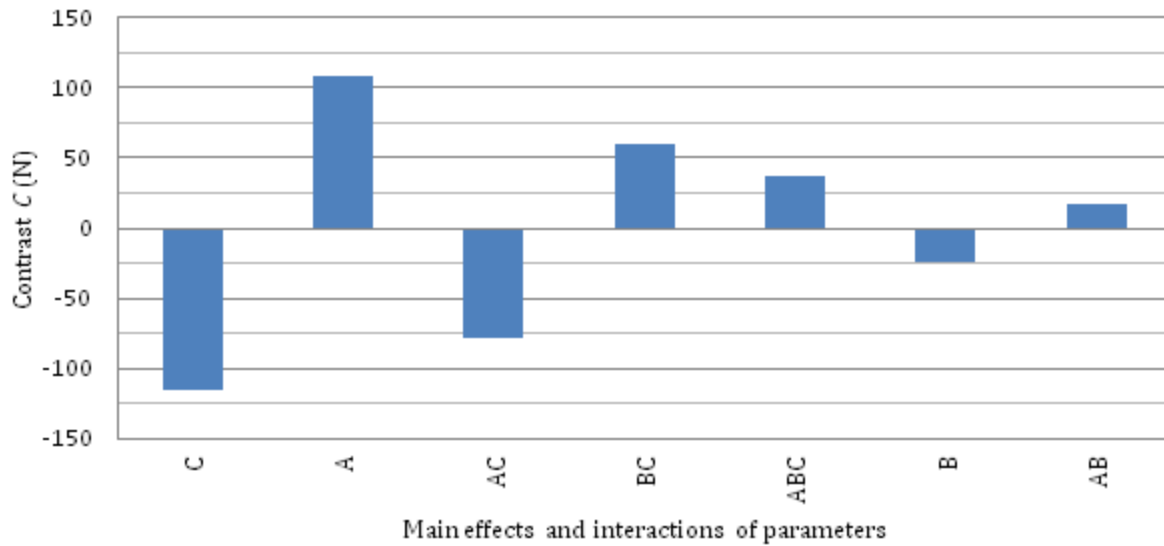


Figure 4-27: Main effects and interactions of parameters in decreasing order, response *STD*, third plan.

4.4.6 Qualitative discussion of shear force results

The tables and figures of the first plan show that parameter *C*, *C*1 (+) vs. *C*4 (-), and parameter *A*, smaller number of layers (-) vs. larger number of layers (+), have significant effect on the average shear force *AVG* but not on its standard deviation *STD* response. The tables and figures for the second plan show that parameter *B*, which represents *C*1 (+) vs. *C*4 (-), has a strong effect on the *AVG* response and a second but significant effect on *STD* response. The plan shows also a significant effect of parameter *A*, setup in rig at R+45 (-) vs. setup in rig at R90 (+), and its interaction with parameter *B* on the *STD* response.

Considering the third plan, it also shows that parameter *C*, *C*1 (+) vs. *C*4 (-), has the most significant effect on the average shear force *AVG* and its standard deviation *STD* response.

The plan also shows that parameter *A*, uO-APT reinforcement (+) vs. industrial reinforcement (-), and *B*, setup in rig at R0 (-) vs. setup in rig at R90 (+), have lesser but significant effects on both responses along with all other interactions.

4.5 Conclusion

The behaviour of dry thick reinforcements such as uO-APT subjected to in-plane shear plays an important role in the onset of wrinkles during shearing. The in-plane shear behaviour of uO-APT thick reinforcements and Saertex industrial reinforcements were investigated in this chapter. The above systematic plans identify very clearly that the most important differences in shear behaviour arise when comparing shear test results obtained at the first shearing cycle C1 with those obtained at fourth cycle C4. This is related mainly to failure of stitches that most likely to happen at the first shearing cycle.

Both systematic plans show that fabric type, stitching orientations and thickness have also some important effects on the shear behaviour of a fabric. UO-APT and industrial reinforcements have different constructions and different stitching assembly methods which explain the different behaviour in shear as observed from curves recorded and presented in Appendix E. It should be mentioned that setup in apparatus at R-45 (-) vs. setup in apparatus at R+45 (+) induced little significant differences to be reported on the response to shear; both setups led to the same behaviour.

As a general conclusion, a numbers of shear tests were conducted to define the behaviour of the new uO-APT reinforcements upon shearing. The limit to in-plane shear for any fabric

may be evaluated using the in-plane shear locking angle γ_L . The locking angle is defined as the angle at which the onset of wrinkling may be observed. This value along with the shear force determines the ability of a fabric to undergo in-plane shear. Shear test results for stitching orientation R-45 and R+45, Figures E-1 to E-8 in Appendix E, show the ability of the new fabric to shear under lower shear forces, which ranged between 0 N and 25 N needed to shear uO-APT reinforcements to shear angles ranging from 50° to 55° before wrinkling was observed, leading to differences when compared with shear results obtained for stitching orientation R0 and R90.

Chapter 5

Inspection of dry reinforcement textiles using infrared imaging

5.1 Introduction

When certain characteristics of a material or structure must be evaluated, a test for doing so must be devised. Testing may be classified as destructive or non-destructive. Destructive testing (DT) includes methods that have been used for many decades for examining and characterising materials and structures towards precise quantitative characteristics. As the name entails, specimens under examination are altered or destroyed during testing. While information obtained from such destructive tests is accurate and comprehensive, such methods cannot apply readily to textile performs in terms of verifying their integrity and consistency prior to PMC manufacturing on an ongoing basis.

Non-destructive testing (NDT) refers to methods used for examining objects without changing or altering them. NDT can be used for examining a material prior to processing it, during processing, on finishing products, or even on structures during service. Major NDT methods may be listed as follows [248, 249]:

- Visual testing (VT): uses human eye or light sensing devices for evaluating surface conditions of a sample [250];
- Penetrant testing (PT): a liquid fluorescent or visible dye is applied to the surface of a sample and enters any discontinuities present on that surface by capillary action [251];
- Magnetic testing (MT): fine ferromagnetic particles are applied to the surface of a sample that has been magnetized. The ferromagnetic particles align with any discontinuity present on the surface [252, 253];
- Radiographic testing (RT): done by exposing radiographic film or sensor to radiation that has passed through the sample tested [254, 255];
- Ultrasonic testing (UT): conducted by applying high frequency sound pulses that propagate from a transducer through the sample tested, reflecting at any interface [256, 257];
- Acoustic emission testing (AE): energy waves are detected by sensors as they travel through the tested sample [258];
- Eddy current testing (ET): electric fields generated by electromagnetic induction are induced into a conductive test sample. Defects will change the magnitude and

distribution of the eddy currents recorded or expected from a defect-free sample [251];

- Thermal infrared testing (TIR): uses thermal sensors to detect patterns in temperature variations at the surface of the sample tested [259], resulting from the presence of defects at or underneath the surface.

When manufacturing composites for load-bearing structures toward critical applications such as aerospace components, it is imperative to ensure the integrity and safety of said composites. In order to do so, each composite structure must be evaluated based on non-destructive testing methods. Inspection of composites aims at detecting flaws and defects in composites that may emerge during manufacturing or in service, to fibres, matrix and/or their interface. A wide range of NDT methods were and are used successfully for inspecting composites including ultrasonic, radiographic, acoustic emission, thermal imaging and others [260].

R. A. Smith [261] proposed a comprehensive review of possible defects and flaws in monolithic composites and sandwich structures occurring during manufacturing and in service. Regarding manufacturing defects the study showed that porosity, seen as the presence of small voids, is a common defect that can arise in the matrix during manufacturing as a result of an incorrect cure process. Fibre misalignments or waviness, which also are common, are defects that can arise during composites manufacturing, especially when using dry fibre preforms and LCM processes. Sandwich structures may suffer from poor bonding between skins and core. Regarding in service defects, the author

states that matrix cracking and delamination of ply layers are common types of damage caused primarily by impacts. Delaminations may form externally visible damage, or internal only damage, which is often referred to as barely visible impact damage (BVID).

All the methods listed above are primarily aimed at detecting voids or discontinuities within a continuous solid, and they are well established for such purposes. On the other hand, they are generally not well suited or developed toward the inspection of textiles.

The scope of this work was devoted to extend the use of the non-destructive testing method using thermal infrared imaging to detecting defects in textiles such as uO-APT fabrics. The work started with series of infrared tests numbered as IR-Test-1 to IR-Test-6 used for different purposes. IR-Test-1, IR-Test-2 and IR-Test-6 were used for calibrating the exposure time pulse and emissivity that should be selected with the infrared camera used. IR-Test-3, IR-Test-4 and IR-Test-5 were used as initial trials to assess the effectiveness of such a method in detecting defects in uO-APT fabrics.

5.2 Literature review on textile inspection

Generally, the inspection of textiles for defects is performed manually by expert technicians. Textile quality usually involves the integrity of assembly, the finish of the textile surface, and assessment of general dimensions [262]. Such detection methods are time consuming and result in low levels of quality control. Therefore, the need for inspection systems aimed at replacing manual techniques has increased. Techniques available for inspection of fabrics and identification of defects, and for fibre characterisation, are reported in the literature [263-268].

Textile quality control using computer vision was described by C. Anagnostopoulos et al. [269]. The study proposed a software algorithm aiming at ensuring high quality standards in products for the clothing industry. The proposed algorithm uses established image processing routines to detect common defects in textiles. The algorithm was tested on images of textiles containing different types of defects; such common defects in textiles are shown in Figure 5-1. Results showed high performance in the identification of surface defects in textiles.

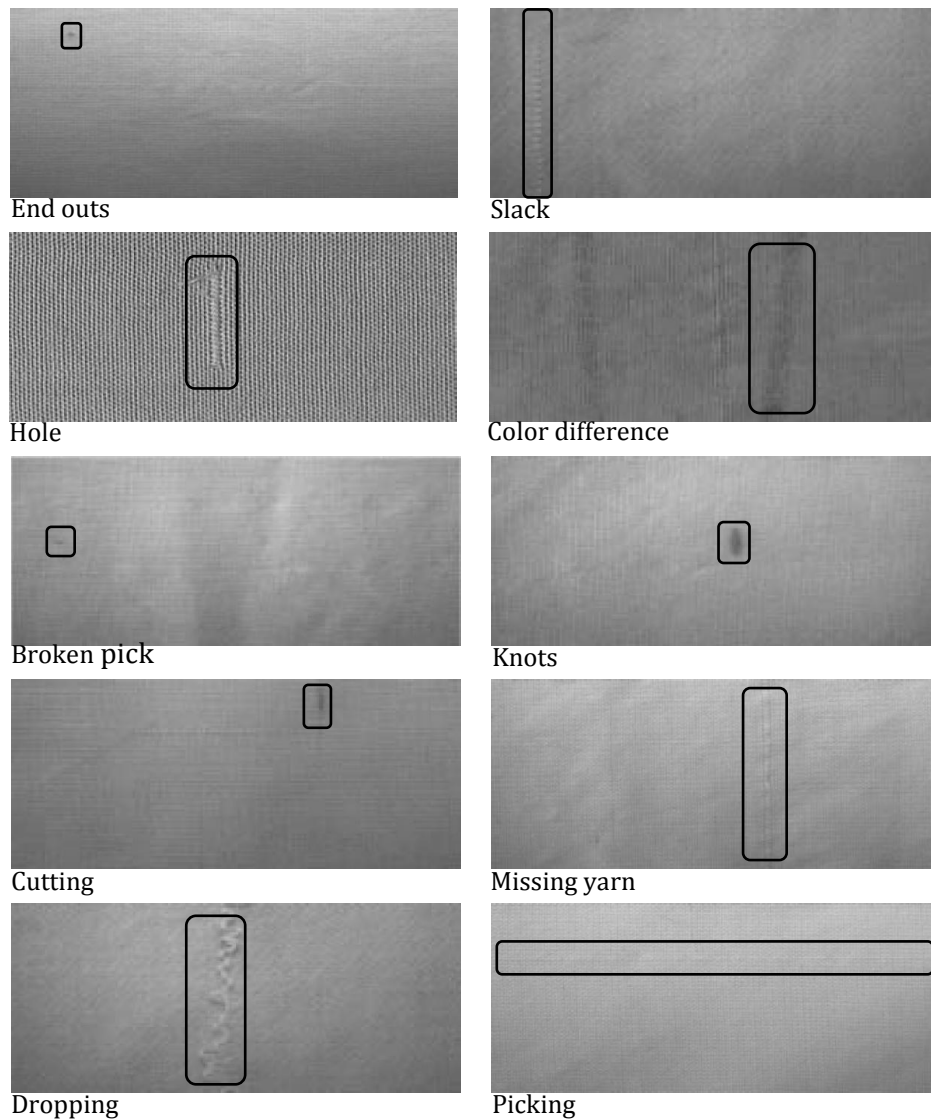


Figure 5-1: Images of textiles containing defects for system training [269].

X. Yang et al. [270] studied the possibility of classifying defects in textiles with minimum error through wavelet frames training method. Wavelet frames are mathematical functions featuring wave shapes, used in image processing for different purposes [271, 272]. The method classified defects in textiles based on a set of training images such as those shown in Figure 5-1. Results showed that the proposed method is effective in classifying defects in fabrics. L. Jianli et al. [273] similarly used wavelet transforms for detecting fabric defects. The authors found that the proposed approach showed an average recognition accuracy of defects of 99.2%.

C. F. J. Kuo et al. [274, 275] used computer-based filtering and thresholding of gray levels to process images of plain white fabric samples. Sample images with visible defects such as holes and oil stains as well as lacking warp and weft yarns were used. Results showed the feasibility of using such technique in recognizing visible surface fabric defects.

Much open literature alludes to the effectiveness of Gabor filters in detecting fabric defects [276-281]. In 1946 D. Gabor introduced his theory to describe human sensations, especially auditory sensations, as signals defined in time and frequency [282]. In the field of inspection of textiles, Gabor theory was developed to be used for image processing with the so-called Gabor filters in order to visualize the surface texture of textiles in a way similar to the human eye through using different types of mathematical functions such as exponential and Gaussian functions to capture these surfaces details.

K. L. Mak et al. [283] proposed a new filter selection method to detect fabric defects through an algorithm that updated the Gabor filters to match fabric texture. The authors showed that the proposed method is accurate in detecting defects, but requires supervision

in order to lead to an optimal Gabor filter; a defect-free image of the fabric to be inspected is also needed. R. Han et al. [284] classified defect detection approaches as supervised and unsupervised. The authors designed an unsupervised method through optimizing only one Gabor filter, based on a defect-free image of the fabric under study. The method enabled satisfactory detection of fabric defects, but the authors suggested further research aiming at finding the most suitable Gabor filter.

G. M. Nasira et al. [285] proposed a computer-based inspection system for identifying defects in woven fabrics. The system used image processing and an artificial neural network (ANN). ANN are computer network programs that work as a brain, trained to recognise fabric defects through processing and responding to input information [275, 286]. Images were processed and converted to gray scale images, and the resulting gray scale histogram was used for obtaining a threshold value. This threshold value was then used for converting images into binary images, Figure 5-2. The resulting binary images were then imported into the ANN, which was previously trained using 115 images defect-free textiles and textiles featuring defects to identify the type of defect. The authors found that the system was accurate and could be used in textile industries.

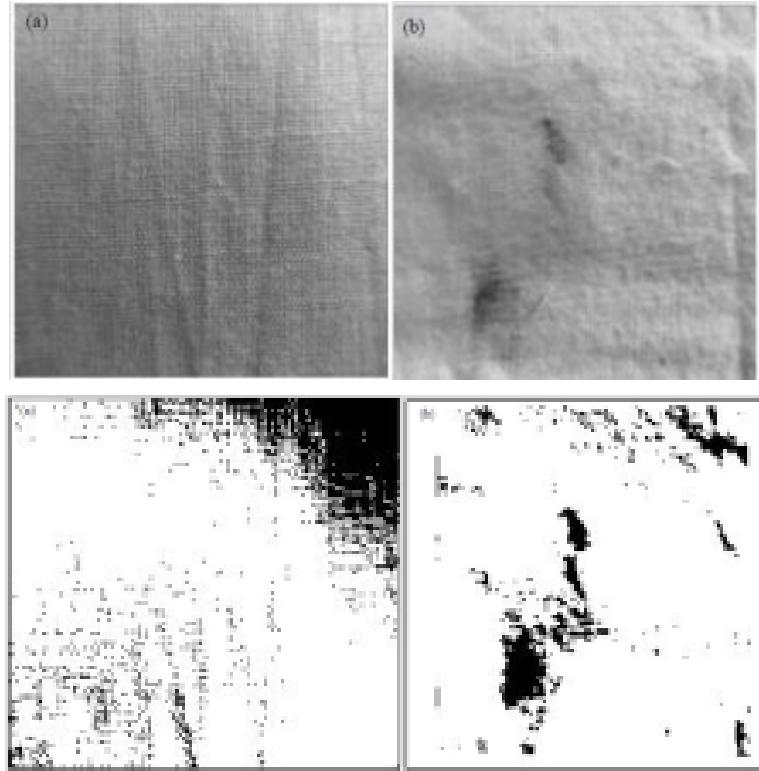


Figure 5-2: Gray scale images of textiles (top) and binary images (bottom), obtained for defect-free image (left) and image featuring defect (right) [287].

Kumar [287] conducted a comprehensive review of techniques and algorithms used for detecting defects in fabrics. The review divided methodologies into three categories based on features of textile surfaces: the statistical approach, the spectral approach and the model-based approach. The first approach detects defects in fabrics by comparing them with stored statistical data using for example gray levels, threshold value or ANNs. The second approach uses algorithms with mathematical functions such as Fourier Transform and Gabor filters to identify defects in fabrics. The third approach uses models that are developed to detect new types of fabric defects. The study concluded that defect detection in fabrics still remains challenging and needs more development.

5.3 Literature review on infrared thermography

Infrared thermography (IRT) is based on the basic physical principle whereby bodies emit infrared radiation when their temperature is above 0 K. Infrared radiation emitted from an object can be measured using devices such as infrared cameras. This in turn, can be used for detecting internal defects in continuous bodies which are identified from the analysis of said infrared images, as described below. IRT is generally divided into two groups of methods known as passive and active, Figure 5-3. In passive methods, infrared thermography is used for observing natural heat in the form of radiation emanating from a structure, while in active methods external or internal excitation is used as applied heat transferred by conduction, convection or radiation towards the structure, or using other means. In mechanical internal excitation methods, ultrasonic waves typically are used for exciting internal features of the structure while in optical external excitation methods, an external exciter such as a halogen lamp is used.

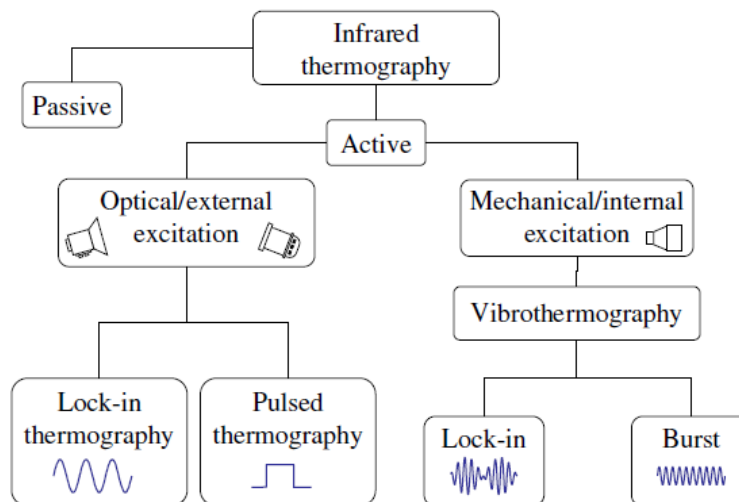


Figure 5-3: Types of infra-red thermography methods [288].

Active optical methods can be further classified into two groups according to the type of external excitation used, as pulse thermography methods or lock-in thermography methods [289-292]. Furthermore, two configurations may be used. The first is based on heat reflection, whereby the thermal excitation source and infrared camera are on the same side of the sample. The second is based on heat transmission, whereby the infrared camera and thermal excitation source are on opposite sides of the sample [293].

In a 2013 review paper, Banerjee et al. [294] discussed the use of infrared thermography in applications pertaining to textile manufacturing. The authors found this to be in early trial stages, with most current applications reported being for the qualitative observation of surface temperatures. However, the authors expect increased use of the technology in textile research and characterization for the relatively near future.

The second configuration based on heat transfer through the sample and measurement on the opposite side was used in this work; Figure 5-4 shows elements of the active pulsed thermography apparatus. Contrary to typical laboratory setups, the apparatus consists of portable handheld devices as the aim was to investigate a method that may be replicated in an actual industrial production environment and for large preforms and composite parts. The innovation brought by this work is the ability to identify manufacturing defects that may be present in thick dry carbon fabrics, beyond visual range, using infrared imaging so that such defects in preforms may be detected before preforms are used for manufacturing composites parts. Such an ability would constitute a tremendous advantage in manufacturing practice.

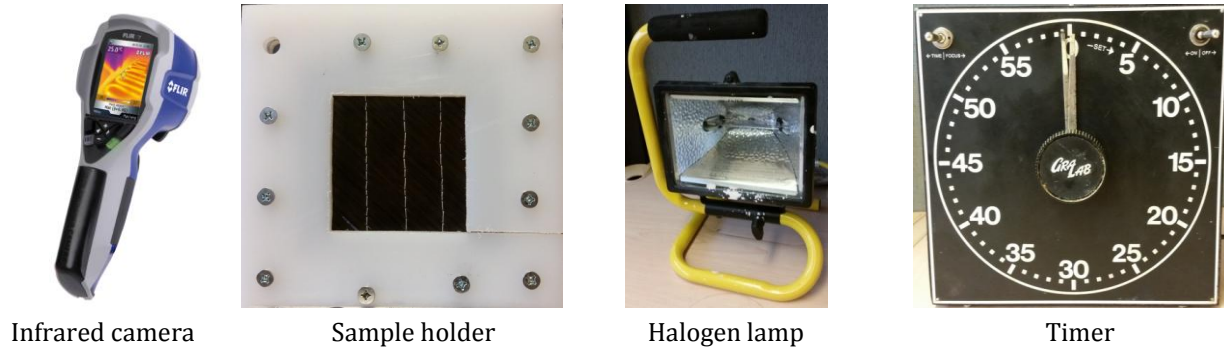


Figure 5-4: Elements of the active pulsed IRT test setup.

5.4 Experimental

Type A and B samples used in bending and shear tests reported in Chapters 3 and 4 were investigated for defect detection, using active pulse thermography tests. Pulse excitation was used for exciting one surface of the sample using a light source, and the distribution of temperatures on the opposite face of the sample was measured using a FLIR i7 infrared camera as described below. All details pertaining to the samples tested appear in Tables 3-1 through 3-6, Section 3.3 and Tables 4-1 through 4-4, Section 4.3.

5.4.1 Reinforcement fabrics

Type A reinforcements were made at the University of Ottawa from Tenax-J grade HTS40 E13 12K, 800 tex carbon fibre yarns. Type A preforms consisted of single, thick bidirectional fabric constituted from layers made of parallel carbon fibre yarns, and assembled by stitching. Type B preforms consisted of stacked layers of Saertex 534 g/m² bidirectional non-crimp stitched carbon fabrics made from Tenax HTS40 12K yarns. Samples from both types of fabrics measured 10 cm by 10 cm (bending) or 20 cm by 20 cm (shear).

5.4.2 Apparatus

A FLIR i7 infrared camera from FLIR systems, shown in Figure 5-4 was used for recording temperature distributions on the surface of samples made from dry reinforcement fabrics. The camera has a resolution of 140 x 140 pixels, with 29° x 29° field of view and 0.6 m minimum focal distance. The camera can measure temperatures ranging between -20°C and +250°C with a spectral range of 7.5 µm to 13 µm. The camera displays center spot temperature; images are presented in colour with a corresponding scale spanning the variable minimum to maximum temperatures recorded [295- 297]. Pulse excitation was used for exciting one surface of the sample using a portable light source. Samples were positioned between the heat source and the infrared camera using polyethylene holders with a 7 cm by 7 cm opening for bending samples and 14 cm by 14 cm opening for shear samples. Holders were made from two 6.5 mm thick plates. A 500 watt halogen lamp was used as a heat source, connected into a laboratory timer that was used for controlling the pulse time during which a sample was exposed to heat. At the end of each pulse the light was masked, before an IR image was taken. Figure 5-5 shows the active pulsed thermography test setup.

Several factors affect infrared imaging such as sample exposure time to heat (pulse), the distance between the heat source and sample and the time delay after which the IR image is made. Samples from the bending tests measured 10 cm by 10 cm; a distance of 19 cm between the sample and camera enabled capturing images of whole sample.

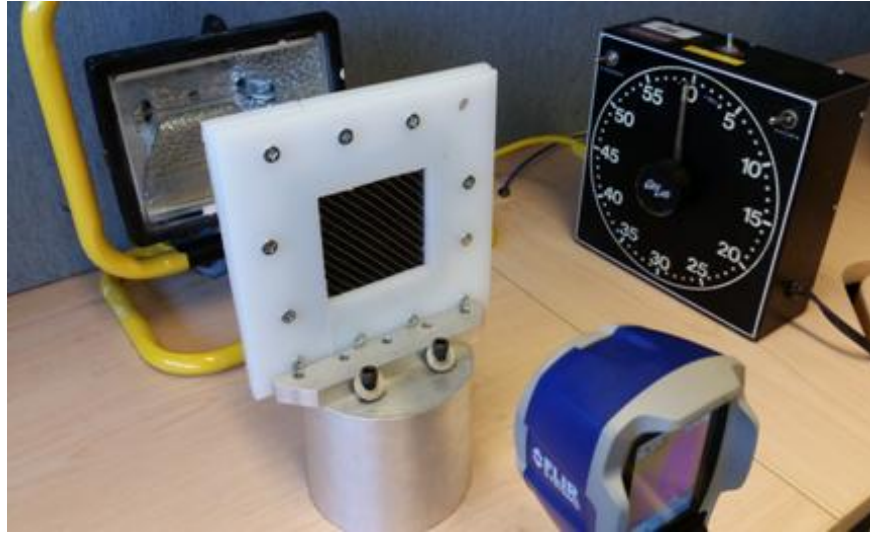


Figure 5-5: Active pulsed thermography test setup based on heat transmission.

Regarding the heat source, it should not be in too close proximity to the sample so as to enable even heat radiation across its whole surface. A distance of 19 cm between the sample and halogen lamp used in the work fulfilled this requirement, leading to a symmetric setup. Samples from shear tests measured 140 cm by 140 cm, which put the infrared camera at a distance of 35 cm from the sample to enable capturing images of the whole area of the sample. The distance between the heat source and the sample remained unchanged at 19 cm, which also enabled an even heat radiation across the whole surface of shear samples.

Using a constant distance between the halogen lamp and sample in all experiments, pulse time and time delay between pulse and imaging were the other factors that required defining.

5.4.3 IR calibration tests

Assuming no radiation losses and neglecting heat transfer through convection, radiation from the heat source is absorbed by the sample and propagates through it as per thermal diffusion which can be quantified using Fourier's law and the following partial differential equation [298-300]:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + Q = \rho \cdot C_p \frac{\partial T}{\partial t} \quad (5.1)$$

where ρ is the mass density, C_p is the specific heat capacity of the material, T is temperature, t is the time, k_x , k_y and k_z are the thermal conductivities in the x, y and z directions respectively, and Q is the heat flux generated in the sample.

In a simplified case where the thermal conductivity is isotropic and all properties are constant, after the end of thermal excitation the above equation can be written as:

$$\lambda \cdot \nabla^2 T = \frac{\partial T}{\partial t} \quad (5.2)$$

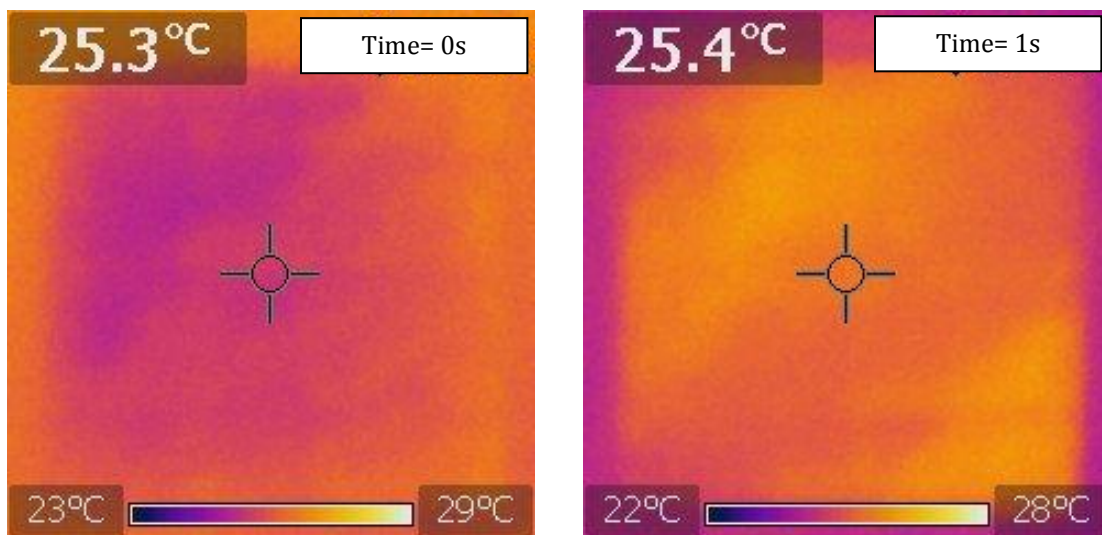
Fourier's equation can be used for quantifying thermal diffusion within the sample; term λ in the above equation is the thermal diffusivity, written as:

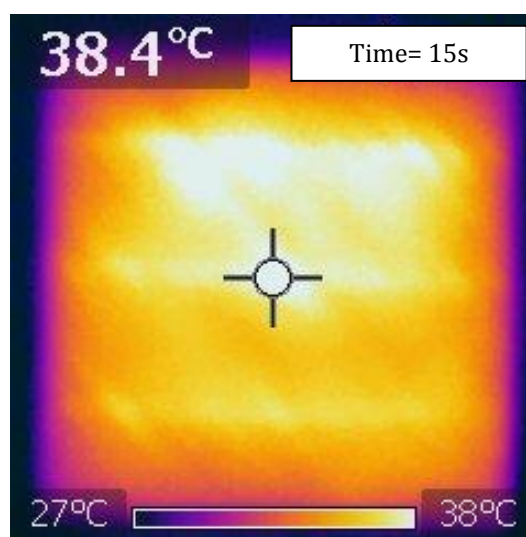
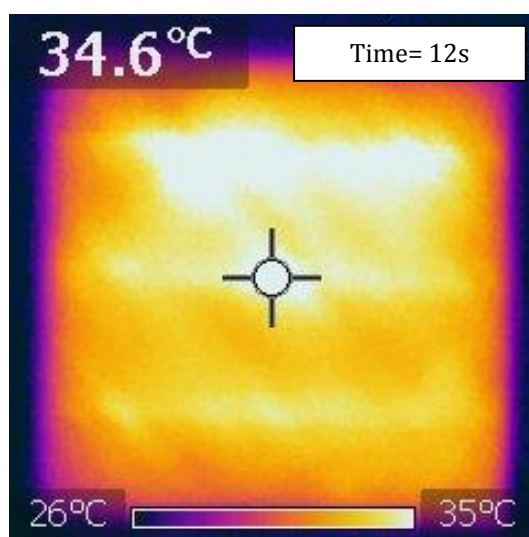
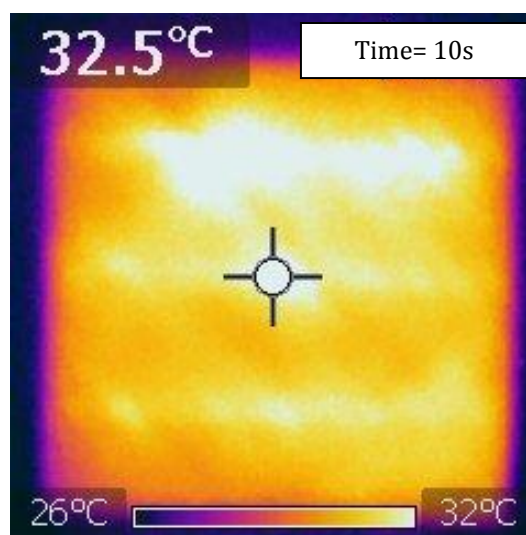
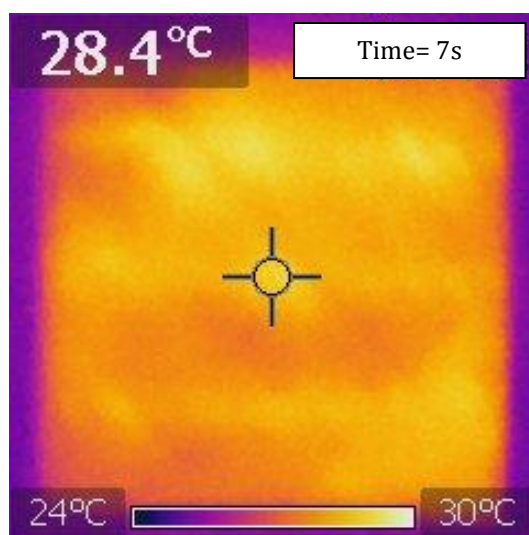
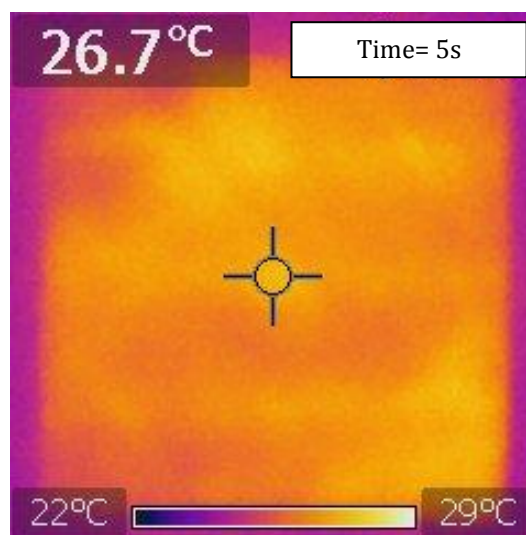
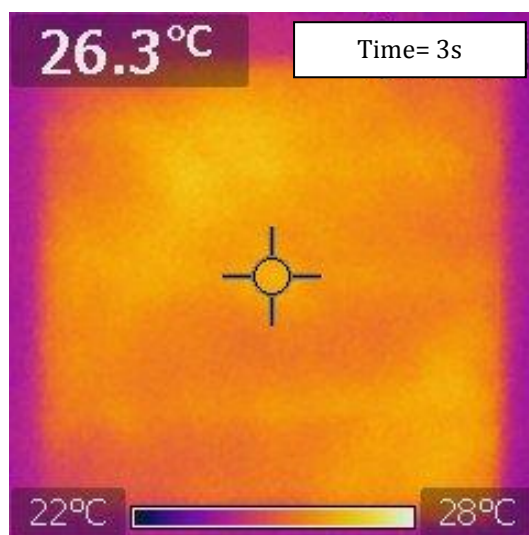
$$\lambda = \frac{k}{\rho \cdot C_p} \quad (5.3)$$

To determine the pulse time that should be used in obtaining infrared images, numerous preliminary experimental trials were conducted as series IR-Test-1, Figure 5-6, for samples made from a uO-APT preform featuring 8 layers of symmetrical balanced bidirectional yarns running at -45° and $+45^\circ$ from stitch lines. Pulse times were chosen based on details

captured in infrared images, and the extent of changes that occurred with these exposure times. If the pulse time was either too short or too long, details of the sample structure were not visualised.

The following figures show that pulse times shorter than 5 seconds led to samples not being heated sufficiently, with no details appearing on the image. On the contrary, pulse times longer than 20 seconds in the first series of preliminary tests led to samples being overheated, again with no details of the sample structure being visible in the image. Therefore, exposure times of 5 seconds, 10 seconds and 15 seconds were selected, where the most information on sample structure details and differences could be captured from the infrared thermal images.





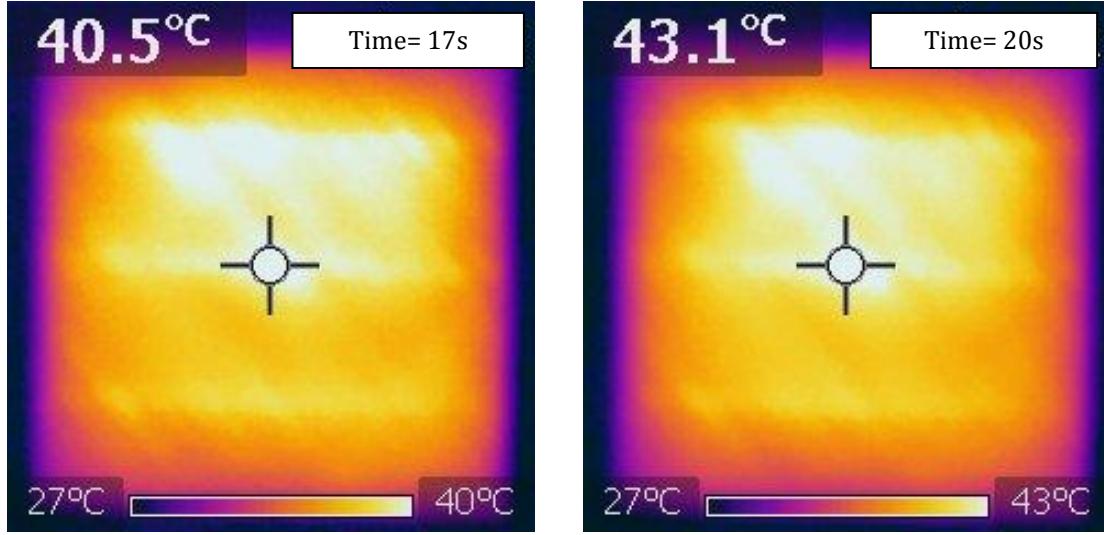


Figure 5-6: IR-Test-1 images captured using different exposure times.

Any defect in a sample will appear as an area of different temperature. Since thermal diffusion occurs in time, there is a maximum time limit τ after the end of thermal excitation beyond which surface temperature differences within the sample will not be observable. τ represents the time limit needed for the thermal pulse to propagate from the surface to a subsurface defect, before temperature differences disappear due to fast thermal diffusion and the infrared image of the sample becomes blurry. This time limit can be estimated from the following equation [301-304]:

$$\tau \approx \frac{z^2}{\lambda} \quad (5.4)$$

where z is the depth of the defect. Table 5-1 shows estimated time limits τ for different sample depths along with physical constants for uO-APT and Saertex fabrics. The density of the fabric is 45% of the fibre density which is 1760 kg.m^3 based on estimated fibre volume fraction. The specific heat capacity of the fabric is calculated from the rule of mixture. Both fabrics feature about 45% HTS40 fibres with specific heat capacity of $710 \text{ J.kg}^{-1}.\text{K}^{-1}$, and

55% air with specific heat capacity of $1000 \text{ J.kg}^{-1}.\text{K}^{-1}$. The in-plane thermal conductivity for both types of fabrics has a representative value of $2.0 \text{ W.m}^{-1}.\text{K}^{-1}$ [305].

Table 5-1: Estimated time τ for uO-APT and Saertex fabrics at two different depths z .

Fabric type	Thermal conductivity $k \text{ (W.m}^{-1}.\text{K}^{-1})$	Mass density $\rho \text{ (kg.m}^3)$	Specific heat capacity $C_p \text{ (J.kg}^{-1}.\text{K}^{-1})$	Thermal diffusivity $\lambda \text{ (m}^2.\text{s}^{-1})$	$\tau \text{ (s)}$ for $z=2\text{mm}$	$\tau \text{ (s)}$ for $z=3\text{mm}$
uO-APT	2.0	792	869.5	2.9×10^{-6}	1.4	3.1
Saertex	2.0	792	869.5	2.9×10^{-6}	1.4	3.1

According to the above table, time τ within which infrared images should be captured for a uO-APT type A sample and Saertex type B sample, is less than 1.4s for a thickness of 2 mm, and 3.1s for a thickness of 3 mm. These times imply that in practice infrared images should be captured immediately after the end of the excitation or pulse period.

Heat absorbed by the sample propagates through it by thermal diffusion. On the opposite side of the sample, temperatures will be captured using the IR camera. In the experiments reported here, the IR camera measures temperatures as heat radiates from the surface of the sample opposite to the heat source. Temperatures reported by the IR camera depend on the emissivity stated for the sample material. IR measurements are based on the Stefan-Boltzmann law [294, 306 and 307]:

$$E_b = \sigma T^4 \quad (5.5)$$

where E_b is the total energy radiated by an ideal black body, σ is the Stefan-Boltzmann constant and T is the absolute temperature.

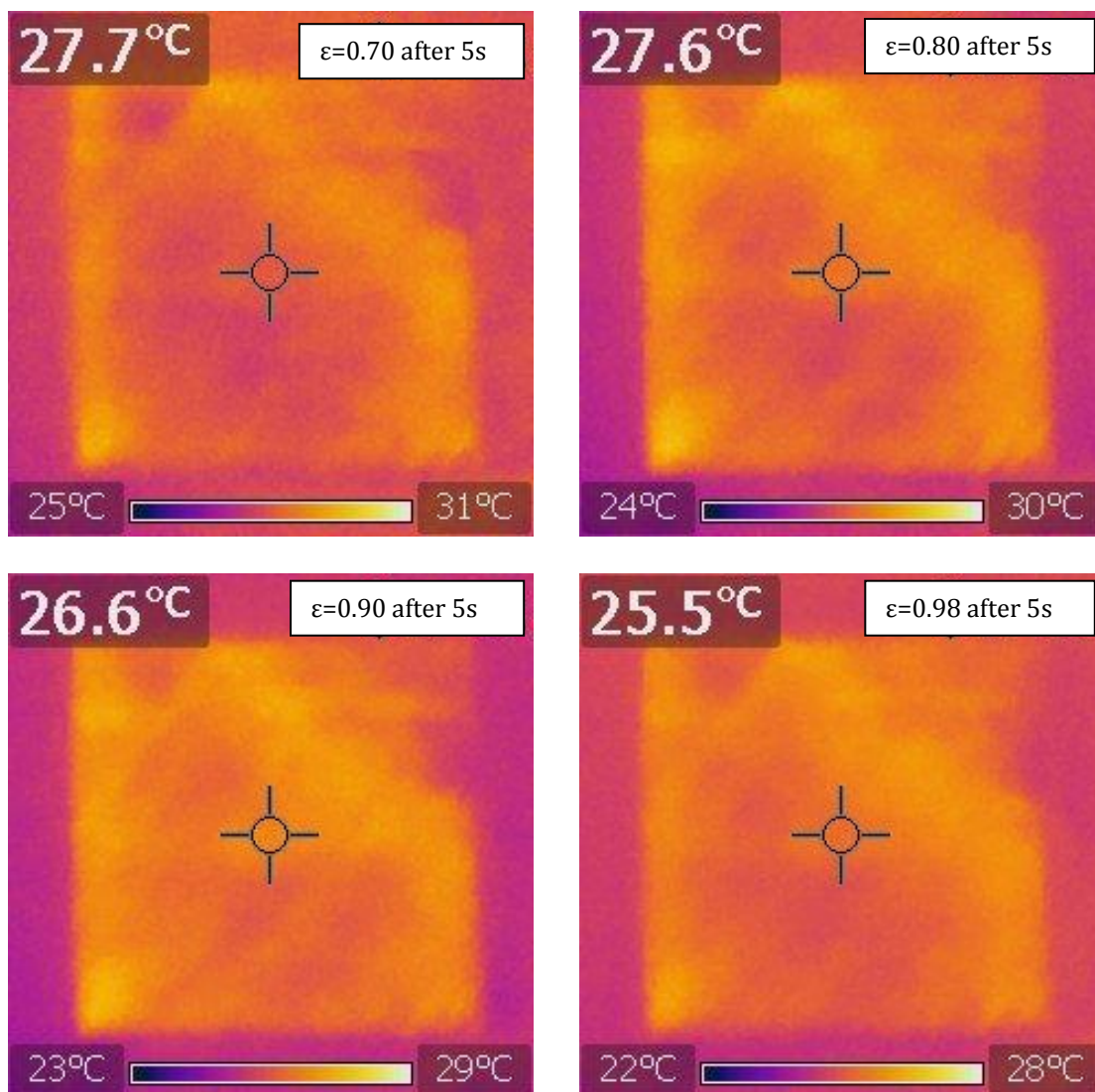
A real body radiates only E_f , a fraction of the radiation emitted by an ideal black body at the same temperature; this fraction is introduced in the Stefan-Boltzmann law through the emissivity ε :

$$E_f = \varepsilon \sigma T^4 \quad (5.6)$$

The emissivity ε of a sample surface depends on the material from which the sample is made; its value varies from 0.0 to 1.0. The review conducted by Banerjee et al. [294] found that accuracy of IR thermography in actual temperature measurements requires a precise knowledge of the emissivity of the textile, which is generally not well documented. Emissivity values for carbon filaments range between 0.70 and 0.98 as stated in different data sheets [296, 308-310]. As a result of this wide range, the emissivity value was determined experimentally through a number of tests where different emissivity values ranging between 0.70 and 0.98 were used for calibrating the FLIR i7 camera. Different samples made from uO-APT fabric featuring 8 layers of symmetrical balanced bidirectional yarns were used. Different emissivity values were set in the FLIR i7 infrared camera in order to evaluate a most appropriate value of emissivity in a relatively dark surrounding environment, to avoid reflections in the images. This being said, whilst emissivity will affect absolute temperature values it will not affect relative values, imaging accuracy or measurement times. Therefore, a highly accurate value of emissivity was not deemed an absolute necessity.

Images generated as part of the IR-Test-2 series of preliminary tests aimed at calibrating emissivity for the FLIR i7 camera. Images captured after pulse times of 5 and 10 seconds

and using emissivity values above 0.70 are shown in Figure 5-7. No differences in term of information gathered from the images arose from using emissivity values above 0.70. Actual differences in temperatures were limited. Therefore, and considering reported values, emissivity was calibrated at 0.90 in the FLIR i7 infrared camera used for capturing infrared images for all samples, throughout the chapter.



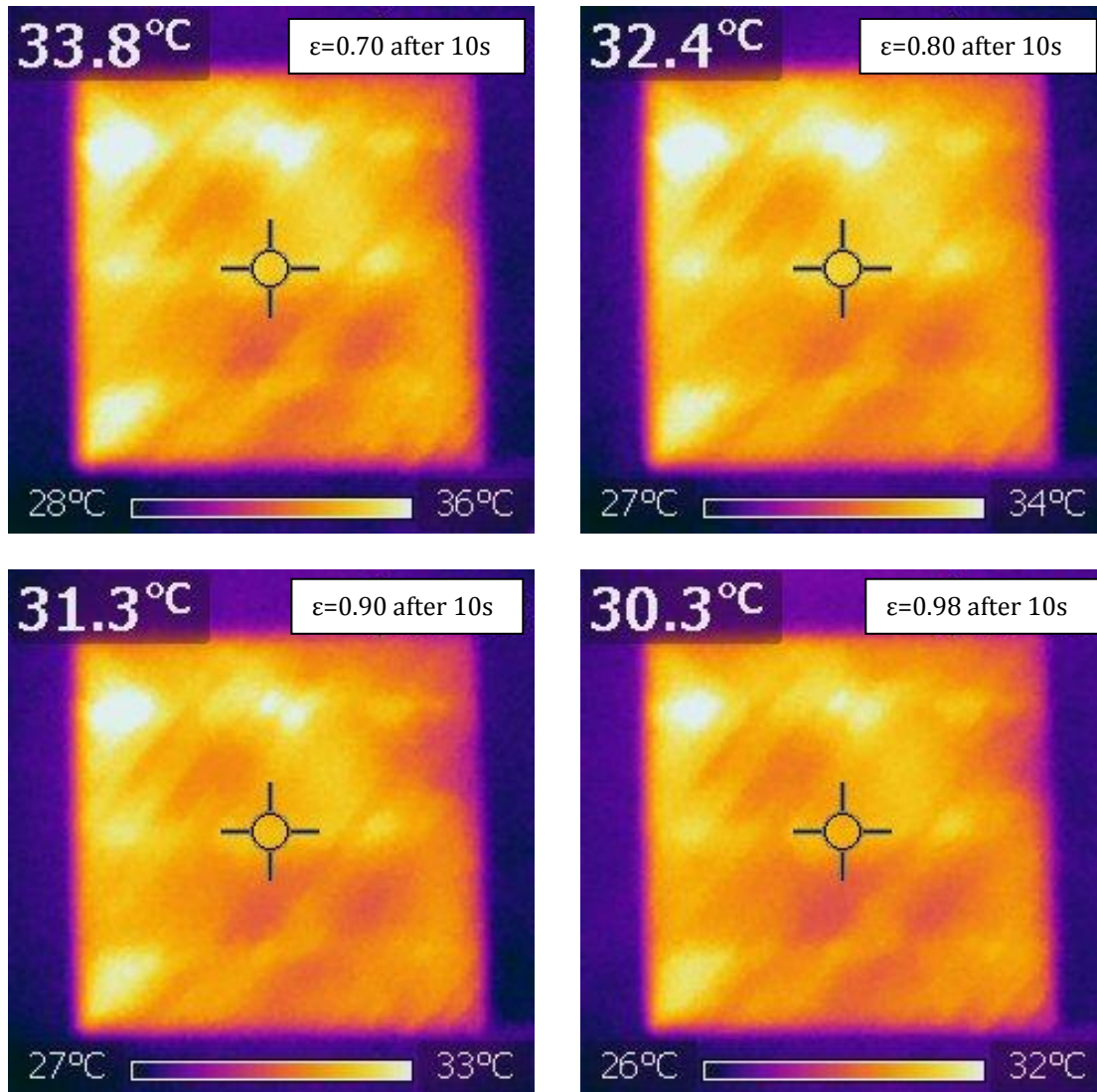


Figure 5-7: IR-Test-2 for FLIR i7 images captured with different emissivity values for sample from A3 group.

5.4.4 Initial IRT tests

Non-destructive infrared thermography characterisation work reported in the literature is mostly focused on the inspection of composite parts, after they have been manufactured [311-314]. The motivation of the present work arose from the absence of any papers related to using IRT to detect defects in dry reinforcement fabrics and preforms at the beginning of the manufacturing process of composite parts, before resin is injected.

The technique was investigated first on samples that featured unrealistically large, purposely induced defects so as to assess its viability. Series of initial tests IR-Test-3 were conducted, where samples featured a clearly visible defect in the form of a central hole and missing yarns. These tests were conducted on a Type A reinforcement made from Tenax-J grade HTS40 E13 12K, 800 tex. The sample featured 8 layers of symmetrical balanced bidirectional yarns running at 0° and 90°, stitched at 45°. Figure 5-8 shows an image from an IR-Test-3 infrared test, captured after 5 seconds pulse time. Figure 5-8 (left) shows the intentionally imparted defect in the sample in the form of missing yarns in both vertical and horizontal directions through the whole sample thickness, resulting in a large hole at the center of the sample.

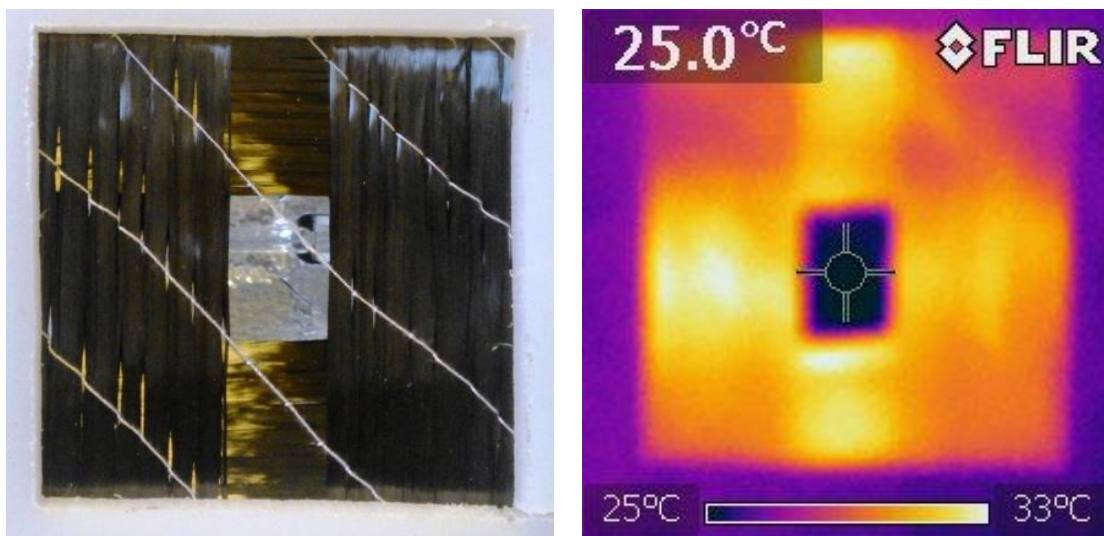


Figure 5-8: Shows IR-Test-3 conducted on sample with visible defects made intentionally.

This defect appeared as areas of different temperatures in the infrared image as shown in Figure 5-8 (right). The central hole was visible as a cold zone, while zones where vertical yarns were removed were visible as warmer zones. More remarkably, adjacent zones where yarns were missing in the horizontal direction could also be observed clearly,

indicating an ability to identify defects present in the thickness but not fully visible from the surface.

Images generated from test IR-Test-4 shown in Figure 5-9 investigated a defect that was not fully visible from the surface of the sample, also made intentionally in a uO-APT sample featuring 8 layers of symmetrical balanced bidirectional yarns running at 0° and 90° from stitch lines. The invisible defect was induced by removing all yarns extending horizontally from the top half of the sample, while the bottom half remained unchanged. The infrared image in Figure 5-9 (right) shows a clear difference between the upper defected area and the lower area, highlighting missing yarns within the sample.

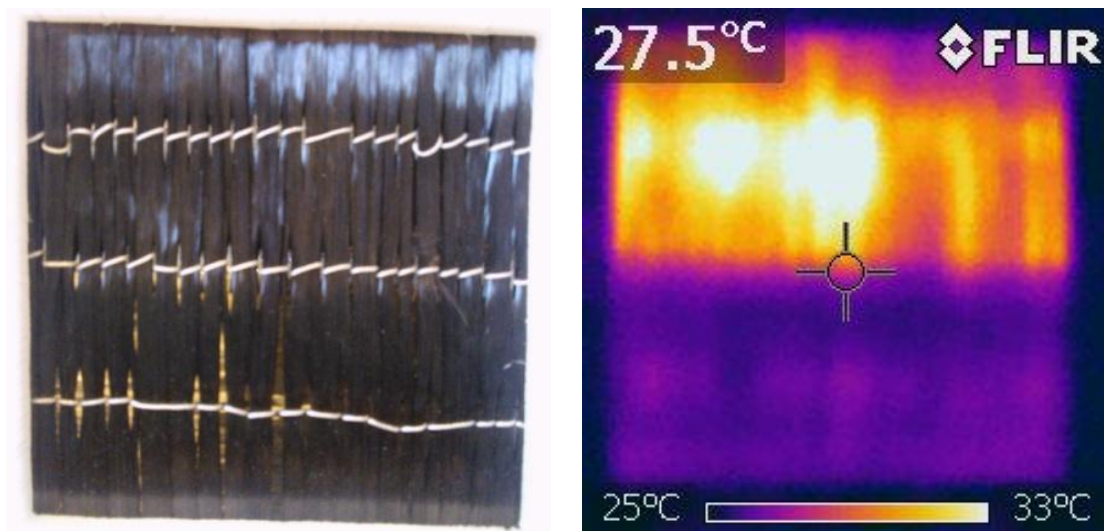


Figure 5-9: IR-Test-4 shows defect invisible from the surface of uO-APT sample.

As a final preliminary test, IR-Test-5 shown in Figure 5-10 was performed on a uO-APT sample made from 8 layers of symmetrical balanced bidirectional yarns running at 0° and 90° from stitch lines. The sample featured an even fibre distribution with no induced defects. The infrared image in Figure 5-10 (right) shows no major differences in

temperatures, compared with those resulting from the extremely poor fibre distributions reported in the previous tests leading to irregular temperatures as appeared in the infrared image in Figure 5-9 (right). On the other hand, it is encouraging to note that perturbations resulting from the presence of stitch lines, which are defined at a much smaller scale, are clearly visible.

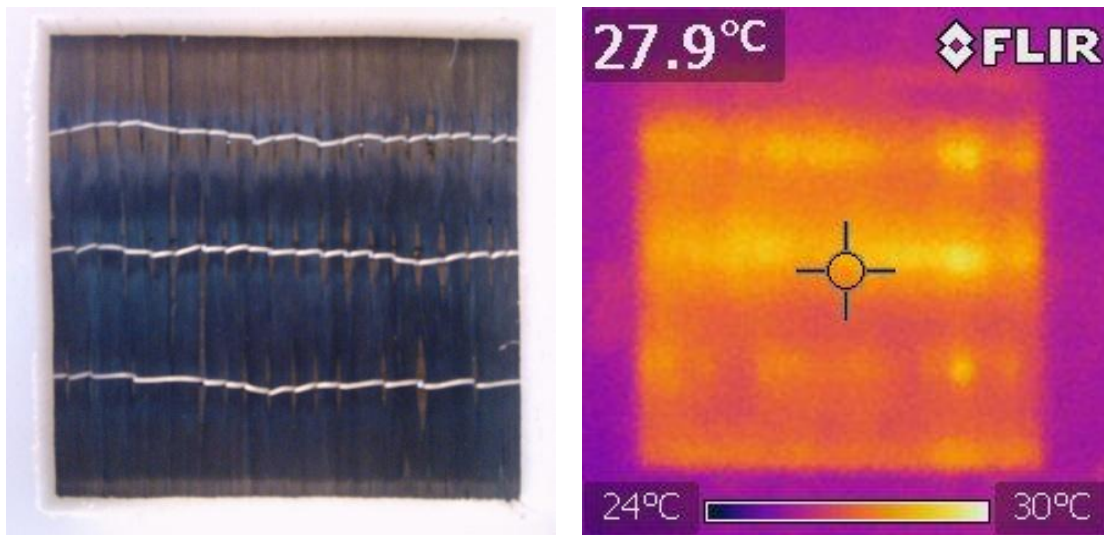


Figure 5-10: IR-Test-5 performed on uO-APT sample with even fibre distributions across sample area.

Figure 5-11 shows images of a preform made from uO-APT fabric for industrial applications; the preform is designed for manufacturing an automotive body component out of carbon fibre composites. The preforms featured 8 layers of symmetrical balanced bidirectional yarns running at 0° and 90° from stitch lines. Preform thickness stood at approximately 2.0 mm. The preform was inspected visually through its thickness using a 500 Watt halogen lamp on its back surface. Stitching lines were identified by light visible through stitching, Figure 5-11. It should be noted that in this imaging, which aims at visualising some realistic defects in uO-APT preforms and can only show zones where no

fibres are present through the entire preform thickness, the light is powered upon imaging. This is not so when IR images are generated for inspection; in such cases the halogen light is switched off and masked prior to acquiring the image.

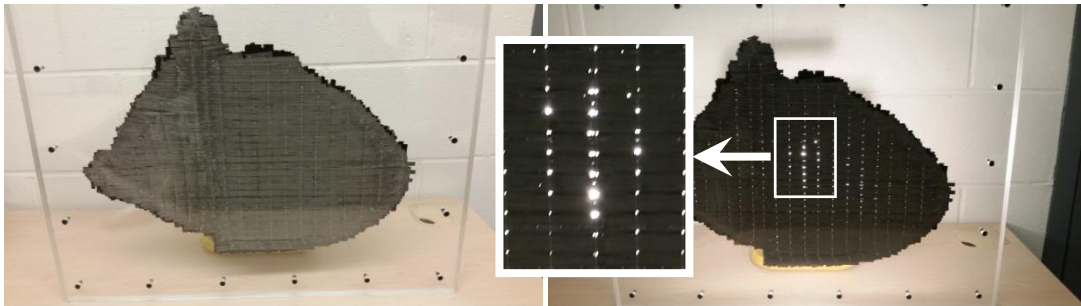


Figure 5-11: Automotive preform inspected using 500 Watt halogen lamp.

Figure 5-12 shows another preform made from uO-APT fabric backlit with halogen lighting for visualisation purposes. This preform was designed towards manufacturing of a jet engine coil component. The thickness also stood at approximately 2.0 mm and construction was similar. Similar observations to the previous preform were made here as shown in Figure 5-12.

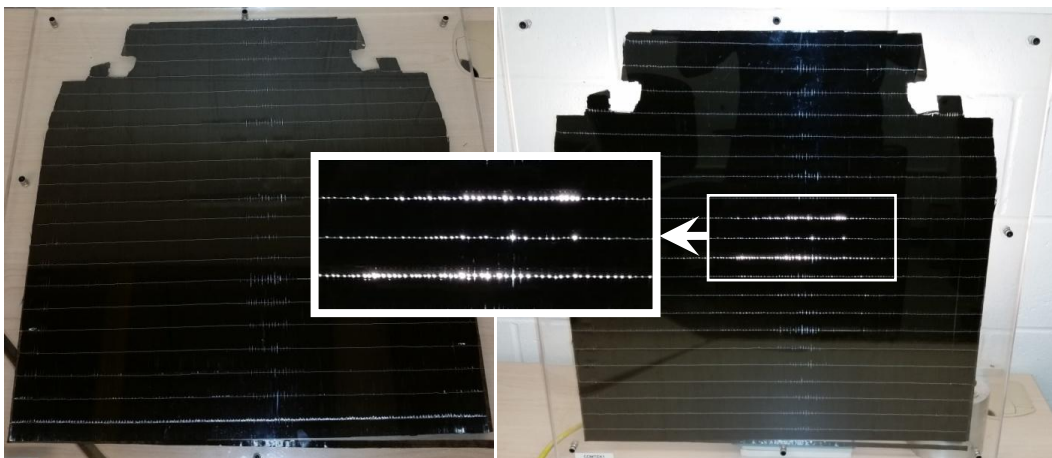


Figure 5-12: Aerospace preform inspected using 500 Watt halogen lamp.

Such images highlight the necessity to inspect thick dry fabrics for less visible flaws or defects before using them in any composite manufacturing process, to ensure the quality of final composite parts. From the above initial trials, the potential offered by infrared thermography towards inspecting carbon fibre preforms can be seen as the technique identifies defects that may result from manufacturing process, especially for uO-APT fabrics. The technique may also assist in overcoming such manufacturing defects to improve the quality of the final composites parts that are made from dry thick preforms as these are being developed.

The following sections report on systemic series of IRT tests conducted on all samples made from uO-APT and Saertex industrial preforms that were characterised in Chapters 3 and 4. Comparisons of the results from both types of preforms are made. Figure 5-13 shows a flow chart of the IRT tests that conducted on bending and shear samples.

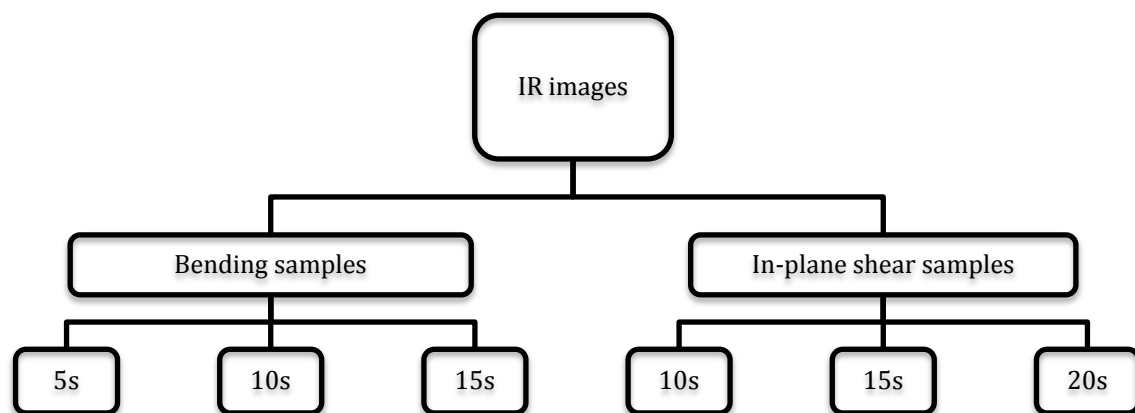


Figure 5-13: IRT tests flow chart.

5.5 Tests performed on samples subjected to bending

An active pulsed symmetric IRT test setup was used for capturing thermal images of all samples used in bending tests, which are listed in Tables 3-1 through 3-6 in Chapter 3. Samples featured two thicknesses and were made from two types of preforms. In distinct tests, each sample was exposed to pulses of 5 seconds, 10 seconds and 15 seconds generated using the apparatus described previously.

5.5.1 Experimental IRT test procedures for bending samples

The procedure used for conducting IR imaging is described in this section using case A1/45/R0/S1/5s sample as an example. Similarly to remarks made in Section 3.4:

- Sample is from group A1 hence made from uO-APT reinforcement featuring 8 superimposed arrays of parallel yarns;
- Sample had a fibre volume fraction of 45% under the roller in bending tests;
- Sample was tested in bending in the R0 setup;
- S1 indicates that it is the first sample tested in its sub-group;
- 5s indicates an exposure time of 5 seconds.

The first step was to mount the sample inside the holder frame between the infrared camera and halogen lamp, both at symmetric distances of 19 cm as shown in Figure 5-5.

The second step was to expose one surface of the sample to the heat source for 5 seconds and capture an image of the other surface of the sample using the FLIR i7 infrared camera immediately upon the end of exposure period and masking of the heat source.

The third step was to wait for the exposed sample surface to cool down to its initial temperature. This interval ranged between 3 to 5 minutes depending on exposure time; cooling was verified using the infrared camera.

Then, the above three steps were repeated for the same sample, using 10 seconds and then 15 seconds pulse excitation times. These test procedures brought the total number of images to 216 IR images generated for samples used previously in bending tests as listed in Chapter 3.

5.5.2 Results

All samples used in bending tests, made from both types of reinforcements, were investigated in this work. One side of each sample was exposed to heat for 5 seconds, then 10 seconds and then 15 seconds in three separate intervals and the temperature distribution on the other side of the sample was captured using FLIR i7 infrared camera, immediately after the end of each pulse exposure and masking of the heat source.

5.5.3 IR images and temperatures: bending samples

Images representing the distribution of temperatures, captured for sample A1/45/R0/S1 using the FLIR i7 infrared camera, are shown in Figure 5-14 for illustration. The image in Figure 5-14 (left) shows the temperature distribution on the unexposed surface of the

sample after 5 seconds of heat pulse exposure using the halogen lamp. Similarly, the image in Figure 5-14 (center) shows the temperature distribution after 10 seconds of exposure and image in Figure 5-14 (right) shows the temperature distribution after 15 seconds of exposure. After exposure of sample A1/45/R0/S1 to heat for 5 seconds, infrared camera measured a minimum temperature (T_{min}) of 26°C over the surface of the sample, a temperature (T_{cen}) of 28.1°C at the center of the image and a maximum temperature (T_{max}) of 32°C over the surface of the sample.

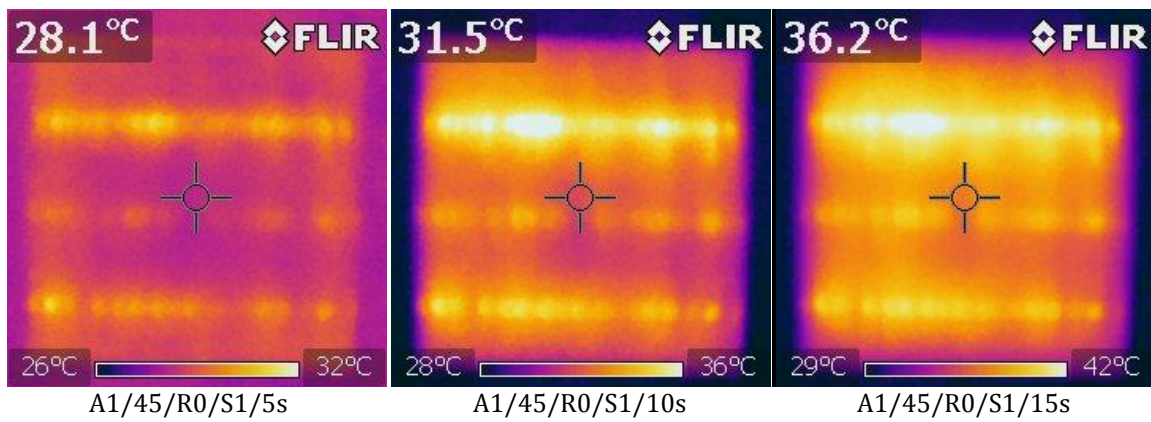


Figure 5-14: Infrared images captured for A1/45/R0/S1 sample after pulse expose for 5s (left), 10s (center) and 15s (right).

As the exposure time increased, higher temperatures were recorded over the same sample as expected. After exposure of sample A1/45/R0/S1 for 10 seconds, infrared camera measured T_{min} at 28°C, T_{cen} at 31.5°C and T_{max} at 36°C. After 15 seconds of exposure, infrared camera measured a T_{min} at 29°C, T_{cen} at 36.2°C and T_{max} at 42°C. All images captured with the infrared camera for all bending samples are included in Appendix H.

Samples made from uO-APT fabrics and tested in bending featured two different numbers of layers; samples were also tested to two different fibre volume fractions under the roller. All samples were tested here, in order to assess whether bending in different conditions may have induced defects that can be captured using IR imaging.

As a general observation, regions with low temperatures on infrared images indicate the presence of more fibres at that area, while regions with higher temperatures indicate either a stitching line, or a lower volume of fibres and so the possible presence of a defect in that area.

5.5.4 IR images processed to binary images for defect detections

High temperature areas on infrared images were highlighted using the MATLAB 7.0 software. Infrared images were processed towards obtaining MATLAB binary images rendered in the form of black and white (BW) image. This is demonstrated for sample A1/45/R0/S1, IR images, Figure 5-15 (top). MATLAB processed IR images by converting them to gray scale images, and then MATLAB used a default setting to replace all pixels with luminance greater than 0.5 to the value 1 (white) and pixels with luminance less than 0.5 to the value 0 (black) [315]. The resulting binary images for sample A1/45/R0/S1 at three different pulse exposure times are shown in Figure 5-15 (bottom).

A binary image with 5 seconds exposure time appears on the left side of Figure 5-15, where white areas clearly correspond to areas of higher temperatures. High temperature areas in the binary image represent possible defects in the sample; these areas coincide with stitching lines. White areas in binary images generated for 10 and 15 seconds pulse

exposure times increased, and with it details of sample structure were lost. Binary images produced for all bending samples using pulse exposure times of 5, 10 and 15 seconds are included in Appendix H.

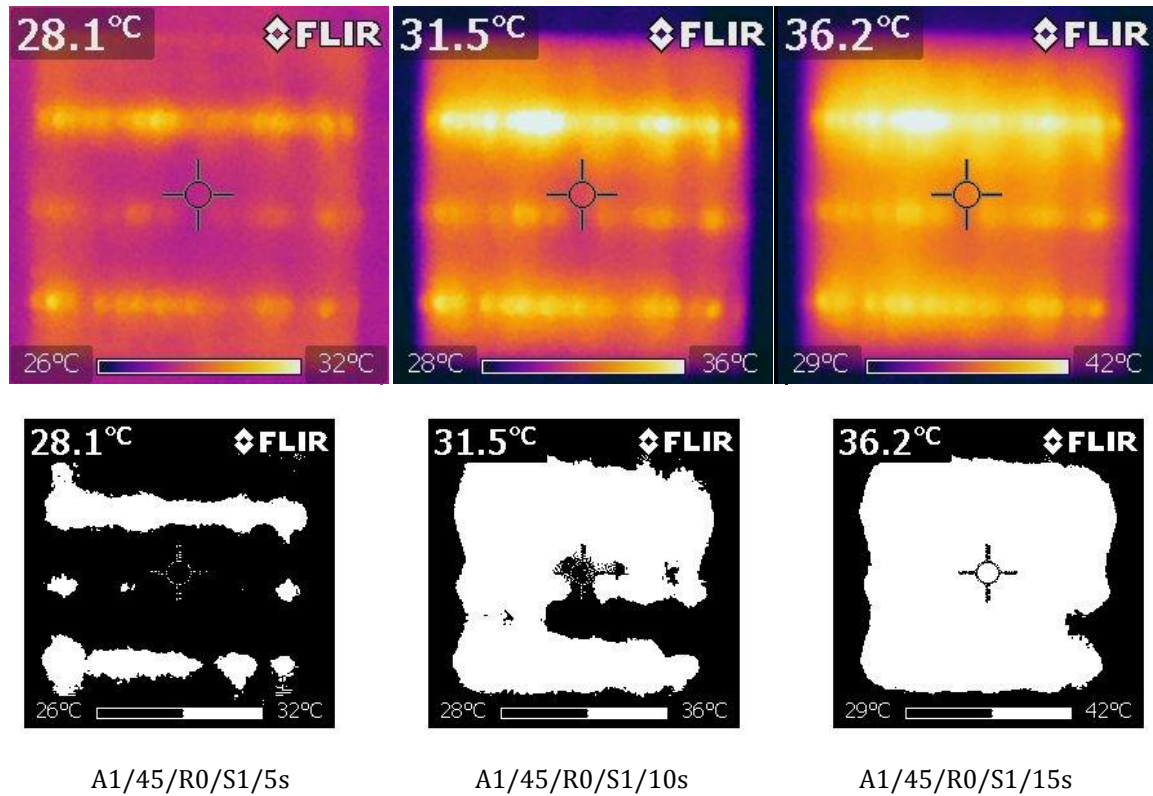


Figure 5-15: Infrared images (top) and binary images (bottom) for sample A1/45/R0/S1 processed with MATLAB 7.0 software at three pulse exposure times.

It should be noted that with all A1 and A3 samples that featured 8 layers of yarns, good identification of structure heterogeneities could be achieved using a 5 seconds pulse exposure. However, details started to disappear from binary images when using 10 seconds and 15 seconds exposure times, Figure 5-15. This was also true for all A2 samples, but using a 10 seconds pulse exposure time. Obviously, samples in group A2 needed longer exposure than those in groups A1 and A3 since they featured 12 layers. Figure 5-16 shows

infrared images and corresponding binary images for sample A2/45/R0/S1 after 5, 10 and 15 seconds exposure time. In this case the intermediate time gives superior results. From infrared and binary images in Figure 5-15 obtained for sample A1/45/R0/S1 after 5 seconds pulse exposure time, and similar images in Figure 5-16 obtained for sample A2/45/R0/S1 after 10 seconds pulse exposure time, it can be seen that images generated from these times provide generally comparable information. The temperature distributions in both cases are broadly similar.

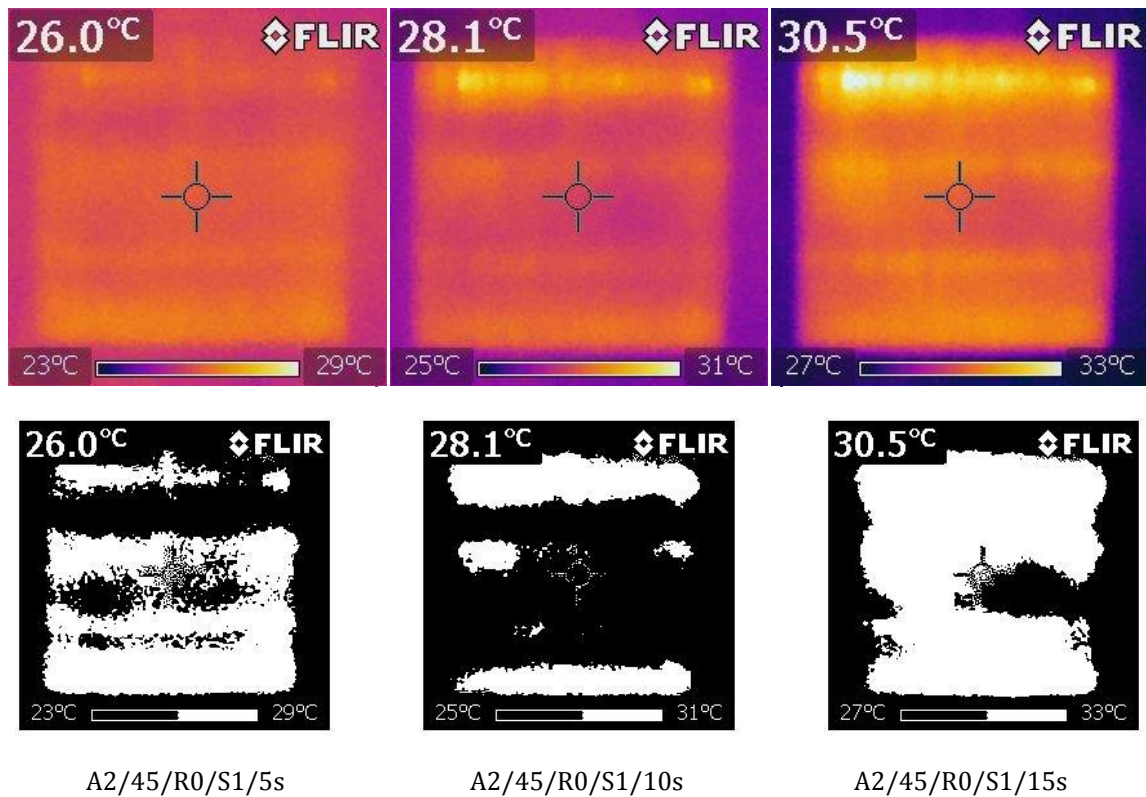


Figure 5-16: Infrared images and corresponding binary images for sample A2/45/R0/S1 after 5, 10 and 15 seconds exposure time.

Such similarity is also seen when comparing images from A2 and A3 samples, leading to comparisons of A1/5s or A3/5s images with A2/10s images, and of A1/10s or A3/10s

images with A2/15s images. Therefore, comparison of inspection results is done for sample defects identified using binary images obtained as A1/5s, A3/5s and A2/10s.

Figure 5-17 shows infrared and corresponding binary images for sample B1/45/R-45/S1 made from Saertex industrial fabrics. When comparing binary images obtained for type A samples with those obtained for type B samples, one can see that less identifiable details appear in images from the latter samples. The above observation applies to all images generated using type B samples as see in Figures H-37 to H-72, Appendix H. The above observation is related to the differences in assembly methods used for the Saertex industrial reinforcement and samples of type B, and the general quality and reproducibility of this fabric.

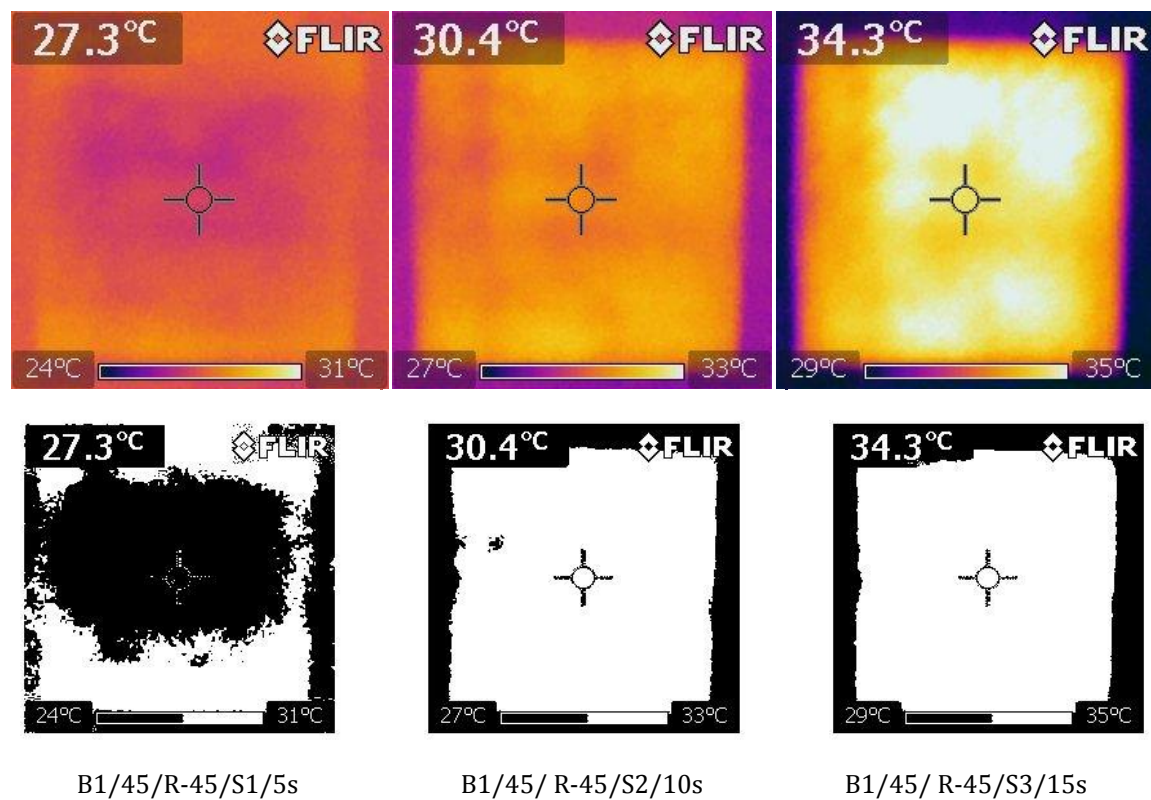


Figure 5-17: Infrared images captured for B1/45/ R-45/S1 sample, and corresponding binary images.

It should be noted here that the active thermography test was used for identifying defects in bending samples and shear samples that are made from uO-APT and Saertex industrial fabrics. The resulted data was in the form of temperatures and percentage of white area. Temperatures were obtained from IR images while the percentage of white area was calculated from binary images that were obtained by converting IR images to black and white images using MATLAB 7.0 software. Next in this chapter, the resultant from IR images and binary images for bending and shear samples were analysed and compared.

5.6 Analysis of IR images of bending samples

Temperature distributions measured on images captured with the FLIR i7 infrared camera after three different exposure times showed some similarities and some differences. Temperature distributions were converted to the average *AVG* temperature calculated from T_{min} and T_{max} and the temperature difference between T_{max} and T_{min} calculated as ΔT . All temperature distributions obtained from infrared images were organised in tables similar to Table 5-2 which are included in Appendix I.

For reasons stated in the previous section, results obtained for A1, B1, A3 and B3 samples at 5 and 10 seconds exposure times should be analysed with comparable results obtained for A2 and B2 samples at 10 and 15 seconds exposure times, as the latter two groups featured more layers than the first groups.

Plans used in Chapter 3 are valid for use here, to investigate the IR response. Data generated in Appendix I was analysed using similar two 2-level Taguchi [207] plans used in Chapter 3 labelled here as the IR-Bending-plan-1 and IR-Bending-plan-2. IR-Bending-plan-

1 compared the effect of the 5 following parameters and their interactions, for two modalities represented as (-) and (+) in the plans, on 2 quantitative responses, the averages of temperatures AVG and the temperature differences ΔT :

- Parameter *A*: smaller number of layers (-) vs. larger number of layers (+);
- Parameter *B*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *C*: samples tested in bending at low v_f (-) vs. samples tested in bending at high v_f (+);
- Parameter *D*: samples tested in bending at R0/R90 setups (-) vs. samples tested in bending at R-45/R+45 setups (+).
- Parameter *E*: 5s/10s exposure time (-) vs. 10s/15s exposure time (+).

IR-Bending-plan-2 compared the effect of the 5 following parameters and their interactions on the same 2 quantitative responses AVG and ΔT :

- Parameter *A*: rovings bent at $0^\circ/90^\circ$ (-) vs. rovings bent at $-45^\circ/+45^\circ$ (+);
- Parameter *B*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *C*: samples tested in bending at low v_f (-) vs. samples tested in bending at high v_f (+);
- Parameter *D*: samples tested in bending at setup R0/R90 (-) vs. samples tested in bending at setup R-45/R+45 (+);
- Parameter *E*: 5s exposure time (-) vs. 10s exposure time (+).

In the IR-Bending-plan-1, parameter A identifies the effect of the number of layers along with other parameters.

Table 5-2: Averages and differences of temperatures obtained for sub-group A1/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A1	A1/45	R0	5	S1	26.0	28.1	32.0	29.0	6.0
					S2	27.0	28.5	33.0	30.0	6.0
					S3	26.0	28.7	32.0	29.0	6.0
				10	S1	28.0	31.5	36.0	32.0	8.0
					S2	28.0	32.7	38.0	33.0	10.0
					S3	28.0	32.1	34.0	31.0	6.0
				15	S1	29.0	36.2	42.0	35.5	13.0
					S2	29.0	38.0	44.0	36.5	15.0
					S3	29.0	37.1	39.0	34.0	10.0
			R90	5	S1	26.0	28.3	32.0	29.0	6.0
					S2	26.0	28.1	32.0	29.0	6.0
					S3	26.0	28.1	32.0	29.0	6.0
				10	S1	29.0	32.2	35.0	32.0	6.0
					S2	28.0	31.8	35.0	31.5	7.0
					S3	28.0	31.0	34.0	31.0	6.0
				15	S1	29.0	37.4	41.0	35.0	12.0
					S2	29.0	36.6	40.0	34.5	11.0
					S3	29.0	35.4	39.0	34.0	10.0

In order to validate the comparison between the 8/3 layers samples at 5 and 10 seconds with the 12/4 layers samples at 10 and 15 seconds, parameter *A* in the first plan was expected not to have a significant effect. Parameter *B* identifies the effect of the type of fabric. Parameter *C* compares the response of samples tested in bending at two different v_f . If the comparison defined by parameter *C* has a significant effect on the temperature response, this may be interpreted as possible defects that were imparted in samples tested

in bending at high v_f . Parameter D will identify if the setup orientation in bending has any significant effect. The IR-Bending-plan-2 focuses on the effect of the orientation of the yarns along with other parameters on the response as AVG and ΔT values.

The responses analysed with both plans are the average temperature AVG and temperature difference ΔT calculated from T_{min} and T_{max} measured for each sample by the infrared camera after three exposure times which are 5, 10 and 15 seconds. The AVG value characterises a general average in temperature distributions on the surface of a sample during a given exposure time, whilst the ΔT value characterises the extent of these temperatures differences. Values of the average and temperature difference for both plans appear in Table 5-4 and 5-5. In these tables, the labels AVG and ΔT represent the average and the difference of the temperature distributions, whilst the labels S1, S2 and S3 identify the sample number as mentioned previously. Therefore, one value of the average AVG of temperatures and one value of the temperature difference ΔT is reported for each specific IRT test exposure time.

Tables 5-3 and 5-4 also state clearly the correspondence between the run numbers as introduced in Table 5-2 along with the systematic variation of parameters A to E and their interactions. It should be noted here again that modalities taken by each interaction at each run, as presented by + and – labels in Chapter 3 Table 3-7, are the product of modalities taken by the corresponding individual parameter on the same line.

The first step in quantitative analysis of the data presented in Table 5-3 and 5-4 is the one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan,

culminating in the calculation of an F-ratio in each case. The F-ratios are compared with tabulated values, indicating an F-ratio that is significant or not.

Table 5-3: Responses for IR-Bending-plan-1 (°C).

Run	Sub-group	S1 <i>AVG</i>	S1 ΔT	S2 <i>AVG</i>	S2 ΔT	S3 <i>AVG</i>	S3 ΔT
1	B2/63/R+45/15S	31.0	6.0	29.5	7.0	30.0	6.0
2	B2/63/R+45/10S	29.5	7.0	29.0	6.0	29.0	6.0
3	B2/63/R-45/15S	29.0	6.0	29.5	7.0	29.5	7.0
4	B2/63/R-45/10S	29.0	6.0	29.0	6.0	28.0	6.0
5	B2/45/R+45/15S	30.0	6.0	30.0	6.0	29.0	6.0
6	B2/45/R+45/10S	29.0	6.0	29.0	6.0	28.0	6.0
7	B2/45/R-45/15S	30.0	6.0	29.0	6.0	29.0	6.0
8	B2/45/R-45/10S	28.5	7.0	28.0	6.0	27.0	6.0
9	A2/66/R90/15S	31.0	6.0	31.0	6.0	30.5	7.0
10	A2/66/R90/10S	29.5	7.0	29.5	7.0	29.5	7.0
11	A2/66/R0/15S	31.0	6.0	31.0	6.0	31.0	6.0
12	A2/66/R0/10S	28.0	6.0	29.0	6.0	30.0	6.0
13	A2/45/R90/15S	30.0	6.0	30.0	6.0	30.5	7.0
14	A2/45/R90/10S	29.0	6.0	29.0	6.0	29.0	6.0
15	A2/45/R0/15S	30.0	6.0	30.0	6.0	30.0	6.0
16	A2/45/R0/10S	28.0	6.0	29.0	6.0	29.0	6.0
17	B1/58/R+45/10S	29.0	6.0	30.0	6.0	29.0	6.0
18	B1/58/R+45/5S	28.0	6.0	28.0	6.0	27.0	6.0
19	B1/58/R-45/10S	28.0	6.0	29.5	7.0	29.5	7.0
20	B1/58/R-45/5S	27.0	6.0	28.0	6.0	28.0	6.0
21	B1/45/R+45/10S	30.0	6.0	29.5	7.0	30.0	6.0
22	B1/45/R+45/5S	28.0	6.0	28.5	7.0	28.0	6.0
23	B1/45/R-45/10S	30.0	6.0	30.0	6.0	29.5	7.0
24	B1/45/R-45/5S	27.5	7.0	28.0	6.0	28.0	6.0
25	A1/60/R90/10S	31.0	6.0	32.0	6.0	31.0	6.0
26	A1/60/R90/5S	29.0	6.0	29.0	6.0	29.0	6.0
27	A1/60/R0/10S	30.5	7.0	31.0	6.0	31.0	6.0
28	A1/60/R0/5S	28.0	6.0	28.5	7.0	29.0	6.0
29	A1/45/R90/10S	32.0	6.0	31.5	7.0	31.0	6.0
30	A1/45/R90/5S	29.0	6.0	29.0	6.0	29.0	6.0
31	A1/45/R0/10S	32.0	8.0	33.0	10.0	31.0	6.0
32	A1/45/R0/5S	29.0	6.0	30.0	6.0	29.0	6.0

Table 5-4: Responses for IR-Bending-plan-2 (°C).

Run	Sub-group	S1 AVG	S1 ΔT	S2 AVG	S2 ΔT	S3 AVG	S3 ΔT
1	B3/58/R90/10S	30.0	6.0	29.0	6.0	30.0	6.0
2	B3/58/R90/5S	28.0	6.0	28.5	7.0	28.0	6.0
3	B3/58/R0/10S	30.0	6.0	30.0	6.0	29.0	6.0
4	B3/58/R0/5S	28.0	6.0	29.0	6.0	28.0	6.0
5	B3/45/R90/10S	29.5	7.0	30.0	6.0	30.0	6.0
6	B3/45/R90/5S	28.0	6.0	29.0	6.0	29.0	6.0
7	B3/45/R0/10S	29.0	6.0	30.0	6.0	30.0	6.0
8	B3/45/R0/5S	28.0	6.0	28.0	6.0	29.0	6.0
9	A3/60/R90/10S	32.0	6.0	32.5	7.0	32.0	6.0
10	A3/60/R90/5S	30.0	6.0	29.5	7.0	30.0	6.0
11	A3/60/R0/10S	32.0	6.0	32.0	6.0	32.0	6.0
12	A3/60/R0/5S	29.5	7.0	30.0	6.0	30.0	6.0
13	A3/45/R90/10S	30.0	6.0	31.5	7.0	32.0	6.0
14	A3/45/R90/5S	28.5	7.0	29.0	6.0	29.0	6.0
15	A3/45/R0/10S	31.0	6.0	31.0	6.0	31.0	6.0
16	A3/45/R0/5S	29.0	6.0	29.0	6.0	29.0	6.0
17	B1/58/R+45/10S	29.0	6.0	30.0	6.0	29.0	6.0
18	B1/58/R+45/5S	28.0	6.0	28.0	6.0	27.0	6.0
19	B1/58/R-45/10S	28.0	6.0	29.5	7.0	29.5	7.0
20	B1/58/R-45/5S	27.0	6.0	28.0	6.0	28.0	6.0
21	B1/45/R+45/10S	30.0	6.0	29.5	7.0	30.0	6.0
22	B1/45/R+45/5S	28.0	6.0	28.5	7.0	28.0	6.0
23	B1/45/R-45/10S	30.0	6.0	30.0	6.0	29.5	7.0
24	B1/45/R-45/5S	27.5	7.0	28.0	6.0	28.0	6.0
25	A1/60/R90/10S	31.0	6.0	32.0	6.0	31.0	6.0
26	A1/60/R90/5S	29.0	6.0	29.0	6.0	29.0	6.0
27	A1/60/R0/10S	30.5	7.0	31.0	6.0	31.0	6.0
28	A1/60/R0/5S	28.0	6.0	28.5	7.0	29.0	6.0
29	A1/45/R90/10S	32.0	6.0	31.5	7.0	31.0	6.0
30	A1/45/R90/5S	29.0	6.0	29.0	6.0	29.0	6.0
31	A1/45/R0/10S	32.0	8.0	33.0	10.0	31.0	6.0
32	A1/45/R0/5S	29.0	6.0	30.0	6.0	29.0	6.0

Quantities pertaining to the three one-way ANOVAs performed as part of the analysis of the infrared data appear in Tables 5-5 to 5-8. $LAVG$ and $LSTD^2$ represent the line average and the line standard deviation of temperatures for each run, for the 3 samples associated with the given run. Equations for these quantities are as follows:

$$LAVG(AVG) = \frac{S1\ AVG + S2\ AVG + S3\ AVG}{3} \quad (5.7)$$

$$LAVG(\Delta T) = \frac{S1\ \Delta T + S2\ \Delta T + S3\ \Delta T}{3} \quad (5.8)$$

$$LSTD^2(AVG) = \frac{1}{3} [(S1\ AVG - LAVG(AVG))^2 + (S2\ AVG - LAVG(AVG))^2 + (S3\ AVG - LAVG(AVG))^2] \quad (5.9)$$

$$LSTD^2(\Delta T) = \frac{1}{3} [(S1\ \Delta T - LAVG(\Delta T))^2 + (S2\ \Delta T - LAVG(\Delta T))^2 + (S3\ \Delta T - LAVG(\Delta T))^2] \quad (5.10)$$

Values of the F-Ratio associated with one-way ANOVA performed for each plan for both AVG and ΔT responses are obtained in each case by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 3 AVG or ΔT values associated with a given run, in a procedure similar to that described in Section 3.5.2. Values of the overall variances between and within subgroups appear in Tables 5-5 through Table 5-8.

Table 5-5: One-way ANOVA for *AVG* response, IR-Bending-plan-1 (°C).

Run	Sub-group	<i>LAVG</i> (<i>AVG</i>)	<i>LSTD</i> ² (<i>AVG</i>)
1	B2/63/R+45/15S	30.17	0.58
2	B2/63/R+45/10S	29.17	0.08
3	B2/63/R-45/15S	29.33	0.08
4	B2/63/R-45/10S	28.67	0.33
5	B2/45/R+45/15S	29.67	0.33
6	B2/45/R+45/10S	28.67	0.33
7	B2/45/R-45/15S	29.33	0.33
8	B2/45/R-45/10S	27.83	0.58
9	A2/66/R90/15S	30.83	0.08
10	A2/66/R90/10S	29.50	0.00
11	A2/66/R0/15S	31.00	0.00
12	A2/66/R0/10S	29.00	1.00
13	A2/45/R90/15S	30.17	0.08
14	A2/45/R90/10S	29.00	0.00
15	A2/45/R0/15S	30.00	0.00
16	A2/45/R0/10S	28.67	0.33
17	B1/58/R+45/10S	29.33	0.33
18	B1/58/R+45/5S	27.67	0.33
19	B1/58/R-45/10S	29.00	0.75
20	B1/58/R-45/5S	27.67	0.33
21	B1/45/R+45/10S	29.83	0.08
22	B1/45/R+45/5S	28.17	0.08
23	B1/45/R-45/10S	29.83	0.08
24	B1/45/R-45/5S	27.83	0.08
25	A1/60/R90/10S	31.33	0.33
26	A1/60/R90/5S	29.00	0.00
27	A1/60/R0/10S	30.83	0.08
28	A1/60/R0/5S	28.50	0.25
29	A1/45/R90/10S	31.50	0.25
30	A1/45/R90/5S	29.00	0.00
31	A1/45/R0/10S	32.00	1.00
32	A1/45/R0/5S	29.33	0.33
	Average		0.266
	Variance	3.80	
	F-Ratio		14.307

Table 5-6: One-way ANOVA for ΔT response, IR-Bending-plan-1 (°C).

Run	Sub-group	$LAVG(\Delta T)$	$LSTD^2(\Delta T)$	
1	B2/63/R+45/15S	6.33	0.33	
2	B2/63/R+45/10S	6.33	0.33	
3	B2/63/R-45/15S	6.67	0.33	
4	B2/63/R-45/10S	6.00	0.00	
5	B2/45/R+45/15S	6.00	0.00	
6	B2/45/R+45/10S	6.00	0.00	
7	B2/45/R-45/15S	6.00	0.00	
8	B2/45/R-45/10S	6.33	0.33	
9	A2/66/R90/15S	6.33	0.33	
10	A2/66/R90/10S	7.00	0.00	
11	A2/66/R0/15S	6.00	0.00	
12	A2/66/R0/10S	6.00	0.00	
13	A2/45/R90/15S	6.33	0.33	
14	A2/45/R90/10S	6.00	0.00	
15	A2/45/R0/15S	6.00	0.00	
16	A2/45/R0/10S	6.00	0.00	
17	B1/58/R+45/10S	6.00	0.00	
18	B1/58/R+45/5S	6.00	0.00	
19	B1/58/R-45/10S	6.67	0.33	
20	B1/58/R-45/5S	6.00	0.00	
21	B1/45/R+45/10S	6.33	0.33	
22	B1/45/R+45/5S	6.33	0.33	
23	B1/45/R-45/10S	6.33	0.33	
24	B1/45/R-45/5S	6.33	0.33	
25	A1/60/R90/10S	6.00	0.00	
26	A1/60/R90/5S	6.00	0.00	
27	A1/60/R0/10S	6.33	0.33	
28	A1/60/R0/5S	6.33	0.33	
29	A1/45/R90/10S	6.33	0.33	
30	A1/45/R90/5S	6.00	0.00	
31	A1/45/R0/10S	8.00	4.00	
32	A1/45/R0/5S	6.00	0.00	
	Average		0.271	
	Variance	0.489		
	F-Ratio			1.805

Table 5-7: One-way ANOVA for *AVG* response, IR-Bending-plan-2 (°C).

Run	Sub-group	<i>LAVG(AVG)</i>	<i>LSTD²(AVG)</i>
1	B3/58/R90/10S	29.67	0.33
2	B3/58/R90/5S	28.17	0.08
3	B3/58/R0/10S	29.67	0.33
4	B3/58/R0/5S	28.33	0.33
5	B3/45/R90/10S	29.83	0.08
6	B3/45/R90/5S	28.67	0.33
7	B3/45/R0/10S	29.67	0.33
8	B3/45/R0/5S	28.33	0.33
9	A3/60/R90/10S	32.17	0.08
10	A3/60/R90/5S	29.83	0.08
11	A3/60/R0/10S	32.00	0.00
12	A3/60/R0/5S	29.83	0.08
13	A3/45/R90/10S	31.17	1.08
14	A3/45/R90/5S	28.83	0.08
15	A3/45/R0/10S	31.00	0.00
16	A3/45/R0/5S	29.00	0.00
17	B1/58/R+45/10S	29.33	0.33
18	B1/58/R+45/5S	27.67	0.33
19	B1/58/R-45/10S	29.00	0.75
20	B1/58/R-45/5S	27.67	0.33
21	B1/45/R+45/10S	29.83	0.08
22	B1/45/R+45/5S	28.17	0.08
23	B1/45/R-45/10S	29.83	0.08
24	B1/45/R-45/5S	27.83	0.08
25	A1/60/R90/10S	31.33	0.33
26	A1/60/R90/5S	29.00	0.00
27	A1/60/R0/10S	30.83	0.08
28	A1/60/R0/5S	28.50	0.25
29	A1/45/R90/10S	31.50	0.25
30	A1/45/R90/5S	29.00	0.00
31	A1/45/R0/10S	32.00	1.00
32	A1/45/R0/5S	29.33	0.33
	Average		0.247
	Variance	5.139	
	F-Ratio		20.774

Table 5-8: One-way ANOVA for ΔT response, IR-Bending-plan-2 (°C).

Run	Sub-group	$LAVG(\Delta T)$	$LSTD^2(\Delta T)$
1	B3/58/R90/10S	6.00	0.00
2	B3/58/R90/5S	6.33	0.33
3	B3/58/R0/10S	6.00	0.00
4	B3/58/R0/5S	6.00	0.00
5	B3/45/R90/10S	6.33	0.33
6	B3/45/R90/5S	6.00	0.00
7	B3/45/R0/10S	6.00	0.00
8	B3/45/R0/5S	6.00	0.00
9	A3/60/R90/10S	6.33	0.33
10	A3/60/R90/5S	6.33	0.33
11	A3/60/R0/10S	6.00	0.00
12	A3/60/R0/5S	6.33	0.33
13	A3/45/R90/10S	6.33	0.33
14	A3/45/R90/5S	6.33	0.33
15	A3/45/R0/10S	6.00	0.00
16	A3/45/R0/5S	6.00	0.00
17	B1/58/R+45/10S	6.00	0.00
18	B1/58/R+45/5S	6.00	0.00
19	B1/58/R-45/10S	6.67	0.33
20	B1/58/R-45/5S	6.00	0.00
21	B1/45/R+45/10S	6.33	0.33
22	B1/45/R+45/5S	6.33	0.33
23	B1/45/R-45/10S	6.33	0.33
24	B1/45/R-45/5S	6.33	0.33
25	A1/60/R90/10S	6.00	0.00
26	A1/60/R90/5S	6.00	0.00
27	A1/60/R0/10S	6.33	0.33
28	A1/60/R0/5S	6.33	0.33
29	A1/45/R90/10S	6.33	0.33
30	A1/45/R90/5S	6.00	0.00
31	A1/45/R0/10S	8.00	4.00
32	A1/45/R0/5S	6.00	0.00
	Average		0.281
	Variance	0.418	
	F-Ratio		1.486

Considering response *AVG* for IR-Bending-plan-1 with data reported in Table 5-5, variances between subgroups and within subgroups were calculated as 3.80 and 0.266 respectively for an F-ratio equal to 14.307. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG*, 14.307 and 2.02, indicate that there is a scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Considering response ΔT for IR-Bending-plan-1 with data reported in Table 5-6, variances between subgroups and within subgroups were calculated as 0.489 and 0.271 respectively for an F-ratio equal to 1.805. Here, the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response ΔT , 1.805 and 2.02, indicate that no likely scope in calculating contrasts F-ratios meaning that parameters have no strong effect on ΔT .

Considering response *AVG* for IR-Bending-plan-2 with data reported in Table 5-7, variances between subgroups and within subgroups were calculated as 5.139 and 0.247 respectively for an F-ratio equal to 20.774. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG*, 20.774 and 2.02, indicate that there is strong scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Considering response ΔT for IR-Bending-plan-2 with data reported in Table 5-8, variances between subgroups and within subgroups were calculated as 0.418 and 0.281 respectively

for an F-ratio equal to 1.486. Also here, the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response ΔT , 1.486 and 2.02, indicate that there may be no scope in calculating contrasts F-ratios meaning that parameters likely have no strong effect on ΔT .

Given the above conclusions, the next step in analysing the effects of the parameters consists in calculating contrasts associated with each parameter and interaction of parameters for those plans which indicate a scope in calculating contrasts F-ratios. Contrasts are defined in Section 3.5.2. Adjustment terms were equal to 32/3. Contrast F-ratios are presented in Table 5-9 and 5-10.

Calculated contrast F-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with MSW remains unchanged at 64. Using the same stringent false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 7.07 [207].

Table 5-9: Contrasts for AVG response, IR-Bending-plan-1 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	0.17	0.00	0.01
<i>B</i>	-17.50	28.71	108.09
<i>C</i>	0.17	0.00	0.01
<i>D</i>	4.17	1.63	6.13
<i>E</i>	26.50	65.84	247.85
<i>AB</i>	6.83	4.38	16.48
<i>AC</i>	8.50	6.77	25.50
<i>AD</i>	2.50	0.59	2.21
<i>AE</i>	-6.50	3.96	14.91
<i>BC</i>	-0.50	0.02	0.09
<i>BD</i>	2.17	0.44	1.66
<i>BE</i>	-4.83	2.19	8.25
<i>CD</i>	1.83	0.32	1.19
<i>CE</i>	-1.17	0.13	0.48
<i>DE</i>	-1.17	0.13	0.48
<i>ABC</i>	-0.83	0.07	0.25
<i>ABD</i>	1.17	0.13	0.48
<i>ABE</i>	1.50	0.21	0.79
<i>ACD</i>	-1.83	0.32	1.19
<i>ACE</i>	1.17	0.13	0.48
<i>ADE</i>	-0.83	0.07	0.25
<i>BCD</i>	-1.50	0.21	0.79
<i>BCE</i>	-1.83	0.32	1.19
<i>BDE</i>	0.83	0.07	0.07
<i>CDE</i>	1.17	0.13	0.48
<i>ABCD</i>	2.17	0.44	1.66
<i>ABCE</i>	-1.50	0.21	0.79
<i>ABDE</i>	0.50	0.02	0.09
<i>ACDE</i>	-0.50	0.02	0.09
<i>BCDE</i>	1.83	0.32	1.19
<i>ABCDE</i>	0.83	0.07	0.25
<i>MSW</i>	0.266		

Table 5-10: Contrasts for *AVG* response, IR-Bending-plan-2 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	5.33	2.67	10.78
<i>B</i>	-23.67	52.51	212.25
<i>C</i>	-1.00	0.09	0.38
<i>D</i>	1.33	0.17	0.67
<i>E</i>	30.67	88.17	356.38
<i>AB</i>	0.67	0.04	0.17
<i>AC</i>	7.33	5.04	20.38
<i>AD</i>	-0.33	0.01	0.04
<i>AE</i>	-2.33	0.51	2.06
<i>BC</i>	-4.33	1.76	7.12
<i>BD</i>	0.67	0.04	0.17
<i>BE</i>	-6.67	4.17	16.84
<i>CD</i>	1.33	0.17	0.67
<i>CE</i>	-0.67	0.04	0.17
<i>DE</i>	0.33	0.01	0.04
<i>ABC</i>	-4.67	2.04	8.25
<i>ABD</i>	-0.33	0.01	0.04
<i>ABE</i>	-0.33	0.01	0.04
<i>ACD</i>	-2.33	0.51	2.06
<i>ACE</i>	1.67	0.26	1.05
<i>ADE</i>	0.67	0.04	0.17
<i>BCD</i>	-2.67	0.67	2.69
<i>BCE</i>	0.00	0.00	0.00
<i>BDE</i>	-0.33	0.01	0.04
<i>CDE</i>	1.00	0.09	0.38
<i>ABCD</i>	1.00	0.09	0.38
<i>ABCE</i>	0.33	0.01	0.04
<i>ABDE</i>	-0.67	0.04	0.17
<i>ACDE</i>	-0.67	0.04	0.17
<i>BCDE</i>	1.00	0.09	0.38
<i>ABCDE</i>	0.00	0.00	0.00
<i>MSW</i>	0.247		

Values of contrast F-ratios superior 7.07, deemed significant, are highlighted in Tables 5-9 and 5-10. Results from Table 5-9 reveal that 6 main effects and interactions of parameters have a significant effect on *AVG* response in the IR-Bending-plan-1. Results from Table 5-10 reveal that 7 main effects and interactions of parameters have a significant effect on *AVG* response in the IR-Bending-plan-2.

Significant main effects and interactions of parameters are summarised in Table 5-11, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 5-18 and 5-19.

Table 5-11: Summary of significant main effects and interactions of parameters for IR bending plans.

IR-Bending-plan-1, response <i>AVG</i>	IR-Bending-plan-2, response <i>AVG</i>
	<i>A</i> (+)
<i>B</i> (+)	<i>B</i> (+)
<i>E</i> (+)	<i>E</i> (+)
<i>AB</i> (+)	
<i>AC</i> (+)	<i>AC</i> (+)
<i>AE</i> (+)	
<i>BE</i> (+)	<i>BC</i> (-)
	<i>BE</i> (-)
	<i>ABC</i> (-)

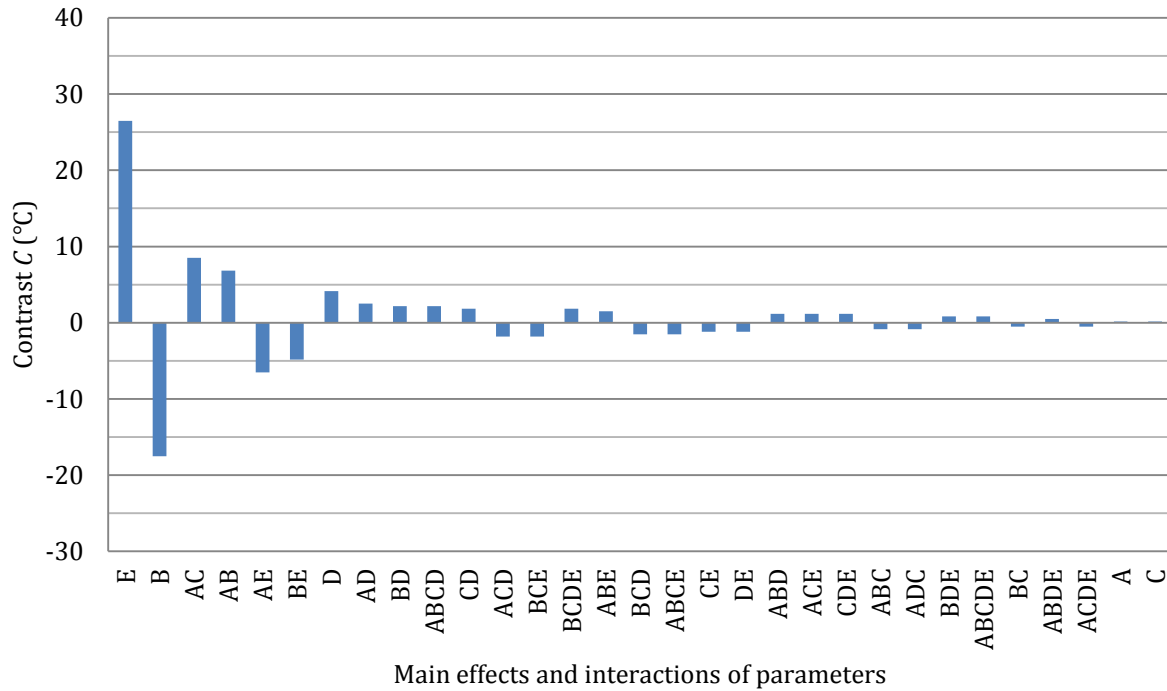


Figure 5-18: Main effects and interactions of parameters in decreasing order, response *AVG*,
IR-Bending-plan-1.

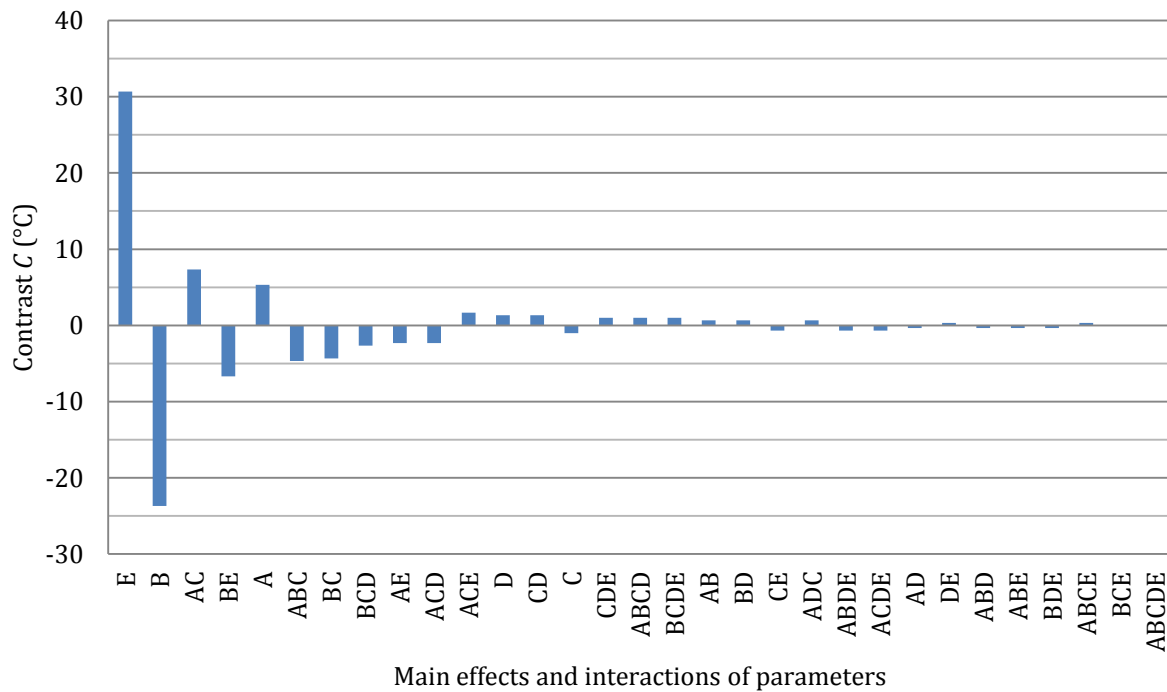


Figure 5-19: Main effects and interactions of parameters in decreasing order, response *AVG*,
IR-Bending-plan-2.

5.6.1 Qualitative discussion of IR bending plans

The tables and figures of both plans for the *AVG* response show that parameter *E* which compared infrared temperature values at 5s/10s exposure time (-) with 10s/15s exposure time(+), has a leading effect on the temperature response. Parameter *B*, uO-APT reinforcement (-) vs. industrial reinforcement (+), has the second leading effect and then the interaction between them *BE*, comes as the third leading effect on the *AVG* response. Finally, the interactions *AE* and *AB* have lesser but significant effects on the *AVG* response.

On the other hand, parameter *A*: smaller number of layers (-) vs. larger number of layers (+), parameter *C*: samples tested in bending at low v_f (-) vs. samples tested in bending at high v_f (+), and parameter *D*: samples tested in bending at R0/R90 setups (-) vs. samples tested in bending at R-45/R+45 setups (+), have no significant effect on the *AVG* response along with the remaining interactions.

5.6.2 Conclusions for IR bending plans

The *AVG* response in both plans show that exposure time has a leading effect on the temperature response. This was expected as when increasing the exposure time, the temperatures measured on the surface of the sample with the infrared camera will increase. The IR bending plans show also that the type of fabric, uO-APT or industrial, has the second leading effect on the temperature response and then the interaction between them comes as the third leading effect on the *AVG* response. UO-APT and industrial textiles have different stacks and different stitching assembly methods which explain the

differences in temperatures. The systemic two plans also show that the interaction between type of textile and the exposure time come as the fourth leading effects on the *AVG* response.

On the other hand, the number of layers has no significant effect on the *AVG* response as expected which validate the comparison between the 8/3 layers samples at 5 and 10 seconds with the 12/4 layers samples at 10 and 15 seconds. No significant effect is also observed when comparing samples tested in bending at low v_f with samples tested in bending at high v_f . This may validate the assumption made in Chapter 3 claiming that a sample with a thickness of 2 mm bent over a radius of approximately 50 mm remains in the realm of small strains (<10%), otherwise differences between *AVG* temperatures response may be raised.

5.7 Analysis of binary images of bending samples

The percentage of white area in binary images of bending samples represents differences that may related to possible defects in these samples such as uneven fibre distributions within the samples or flaws in stitching lines. In this section the percentage of white area is analysed using Taguchi method. The percentage of white area in binary images obtained for all samples tested in bending was calculated using MATLAB 7.0 software. All values obtained for both types of fabrics were organised in tables similar to Table 5-12 and are included in Appendix J.

Data presented in Appendix J was analysed using two 2-level Taguchi [207] plans similar to those presented in Section 5.6, labelled here as A-Bending-plan-1 and A-Bending-plan-2. A-Bending-plan-1 compared the effect of the same 5 parameters and their interactions of the IR-Bending-plan-1, on one quantitative response, the average *AVG* of percentage of white area. A-Bending-plan-2 compared the effect of the same 5 parameters and interactions of the IR-Bending-plan-2 on the average *AVG* of percentage of white area.

Table 5-12: Percentage of white area in the binary images for sub-group A1/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A1	A1/45	R0	5	S1	19.86
					S2	12.99
					S3	45.77
				10	S1	52.05
					S2	41.23
					S3	60.47
				15	S1	58.66
					S2	60.10
					S3	65.23
			R90	5	S1	27.88
					S2	17.40
					S3	25.04
				10	S1	67.81
					S2	67.67
					S3	54.36
				15	S1	62.55
					S2	63.61
					S3	63.69

The responses analysed with both plans are the average *AVG* of the percentage white area calculated from binary images after three define exposure times of 5, 10 and 15 seconds. Values of averages for both plans appear in Tables 5-13 and 5-14.

Table 5-13: Responses for A-Bending-plan-1 (%).

Run	Sub-group	S1	S2	S3
1	B2/63/R+45/15S	39.55	51.41	60.29
2	B2/63/R+45/10S	29.41	35.33	31.65
3	B2/63/R-45/15S	61.44	40.13	47.96
4	B2/63/R-45/10S	34.52	33.52	29.98
5	B2/45/R+45/15S	70.69	57.46	47.25
6	B2/45/R+45/10S	55.47	40.50	32.08
7	B2/45/R-45/15S	49.97	41.55	52.85
8	B2/45/R-45/10S	37.34	35.06	33.51
9	A2/66/R90/15S	68.01	62.33	70.75
10	A2/66/R90/10S	31.96	31.46	32.49
11	A2/66/R0/15S	64.61	66.44	65.08
12	A2/66/R0/10S	65.16	50.62	38.83
13	A2/45/R90/15S	65.69	67.73	64.45
14	A2/45/R90/10S	52.70	54.60	35.87
15	A2/45/R0/15S	52.78	64.41	65.50
16	A2/45/R0/10S	22.42	55.57	54.62
17	B1/58/R+45/10S	46.10	63.15	49.12
18	B1/58/R+45/5S	45.17	39.01	65.01
19	B1/58/R-45/10S	65.20	54.41	46.41
20	B1/58/R-45/5S	70.12	41.56	36.30
21	B1/45/R+45/10S	59.14	62.76	47.59
22	B1/45/R+45/5S	47.00	41.02	47.19
23	B1/45/R-45/10S	70.05	37.80	55.75
24	B1/45/R-45/5S	36.96	39.38	47.86
25	A1/60/R90/10S	61.76	58.80	66.21
26	A1/60/R90/5S	43.39	33.55	51.19
27	A1/60/R0/10S	65.09	63.35	61.29
28	A1/60/R0/5S	51.26	44.59	46.57
29	A1/45/R90/10S	67.81	67.67	54.36
30	A1/45/R90/5S	27.88	17.40	25.04
31	A1/45/R0/10S	52.05	41.23	60.47
32	A1/45/R0/5S	19.86	12.99	45.77

Table 5-14: Responses for A-Bending-plan-2 (%).

Run	Sub-group	S1	S2	S3
1	B3/58/R90/10S	62.68	54.68	62.49
2	B3/58/R90/5S	37.36	49.13	53.95
3	B3/58/R0/10S	49.70	63.22	66.91
4	B3/58/R0/5S	49.04	42.11	35.29
5	B3/45/R90/10S	63.85	44.93	58.77
6	B3/45/R90/5S	36.67	24.76	50.80
7	B3/45/R0/10S	60.25	52.04	62.42
8	B3/45/R0/5S	39.08	49.39	43.13
9	A3/60/R90/10S	64.16	65.35	66.02
10	A3/60/R90/5S	60.60	66.46	64.98
11	A3/60/R0/10S	63.59	64.45	66.00
12	A3/60/R0/5S	52.16	55.52	60.81
13	A3/45/R90/10S	43.18	55.61	61.16
14	A3/45/R90/5S	60.17	50.33	53.33
15	A3/45/R0/10S	65.44	67.48	63.11
16	A3/45/R0/5S	31.36	59.24	49.35
17	B1/58/R+45/10S	46.10	63.15	49.12
18	B1/58/R+45/5S	45.17	39.01	65.01
19	B1/58/R-45/10S	65.20	54.41	46.41
20	B1/58/R-45/5S	70.12	41.56	36.30
21	B1/45/R+45/10S	59.14	62.76	47.59
22	B1/45/R+45/5S	47.00	41.02	47.19
23	B1/45/R-45/10S	70.05	37.80	55.75
24	B1/45/R-45/5S	36.96	39.38	47.86
25	A1/60/R90/10S	61.76	58.80	66.21
26	A1/60/R90/5S	43.39	33.55	51.19
27	A1/60/R0/10S	65.09	63.35	61.29
28	A1/60/R0/5S	51.26	44.59	46.57
29	A1/45/R90/10S	67.81	67.67	54.36
30	A1/45/R90/5S	27.88	17.40	25.04
31	A1/45/R0/10S	52.05	41.23	60.47
32	A1/45/R0/5S	19.86	12.99	45.77

The first step in quantitative analysis of the data presented in Table 5-14 and 5-15 is the one-way analysis of variance (ANOVA) over the data collected as a whole, for each plan, culminating in the calculation of an F-ratio in each case.

Quantities pertaining to the three one-way ANOVAs performed as part of the analysis of the infrared data appear in Tables 5-16 and 5-17. $LAVG(\%)$ and $LSTD^2(\%)$ represent the line average and the line standard deviation of white area percentage for each run, for the 3 samples associated to the given run. Equations for these quantities are similar to Eq. 3.27 to 3.30.

Values of the F-Ratio associated with one-way ANOVA performed for each plan are obtained in each case by dividing the overall variance between subgroups by the overall variance within subgroups, where a subgroup refers to a set of 3 values associated with a given run, in a procedure similar to that described in Section 3.5.2. Values of the overall variances between and within subgroups appear in Tables 5-15 and Table 5-16.

Table 5-15: Responses for A-Bending-plan-1 (%).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$	
1	B2/63/R+45/15S	50.42	108.28	
2	B2/63/R+45/10S	32.13	8.93	
3	B2/63/R-45/15S	49.84	116.19	
4	B2/63/R-45/10S	32.67	5.69	
5	B2/45/R+45/15S	58.47	138.12	
6	B2/45/R+45/10S	42.68	140.35	
7	B2/45/R-45/15S	48.12	34.48	
8	B2/45/R-45/10S	35.30	3.71	
9	A2/66/R90/15S	67.03	18.44	
10	A2/66/R90/10S	31.97	0.27	
11	A2/66/R0/15S	65.38	0.90	
12	A2/66/R0/10S	51.54	173.95	
13	A2/45/R90/15S	65.96	2.74	
14	A2/45/R90/10S	47.72	106.28	
15	A2/45/R0/15S	60.90	49.71	
16	A2/45/R0/10S	44.20	356.11	
17	B1/58/R+45/10S	52.79	82.78	
18	B1/58/R+45/5S	49.73	184.60	
19	B1/58/R-45/10S	55.34	88.91	
20	B1/58/R-45/5S	49.33	331.19	
21	B1/45/R+45/10S	56.50	62.77	
22	B1/45/R+45/5S	45.07	12.31	
23	B1/45/R-45/10S	54.53	261.13	
24	B1/45/R-45/5S	41.40	32.76	
25	A1/60/R90/10S	62.26	13.91	
26	A1/60/R90/5S	42.71	78.14	
27	A1/60/R0/10S	63.24	3.62	
28	A1/60/R0/5S	47.47	11.73	
29	A1/45/R90/10S	63.28	59.68	
30	A1/45/R90/5S	23.44	29.38	
31	A1/45/R0/10S	51.25	93.02	
32	A1/45/R0/5S	26.21	298.84	
Average			409.618	
Variance		90.904		
F-Ratio				4.506

Table 5-16: Responses for A-Bending-plan-2 (%).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$	
1	B3/58/R90/10S	59.95	20.84	
2	B3/58/R90/5S	46.81	72.83	
3	B3/58/R0/10S	59.94	82.10	
4	B3/58/R0/5S	42.15	47.27	
5	B3/45/R90/10S	55.85	95.89	
6	B3/45/R90/5S	37.41	169.93	
7	B3/45/R0/10S	58.24	29.98	
8	B3/45/R0/5S	43.87	26.98	
9	A3/60/R90/10S	65.18	0.89	
10	A3/60/R90/5S	64.01	9.29	
11	A3/60/R0/10S	64.68	1.49	
12	A3/60/R0/5S	56.16	19.02	
13	A3/45/R90/10S	53.32	84.76	
14	A3/45/R90/5S	54.61	25.44	
15	A3/45/R0/10S	65.34	4.78	
16	A3/45/R0/5S	46.65	199.79	
17	B1/58/R+45/10S	52.79	82.78	
18	B1/58/R+45/5S	49.73	184.60	
19	B1/58/R-45/10S	55.34	88.91	
20	B1/58/R-45/5S	49.33	331.19	
21	B1/45/R+45/10S	56.50	62.77	
22	B1/45/R+45/5S	45.07	12.31	
23	B1/45/R-45/10S	54.53	261.13	
24	B1/45/R-45/5S	41.40	32.76	
25	A1/60/R90/10S	62.26	13.91	
26	A1/60/R90/5S	42.71	78.14	
27	A1/60/R0/10S	63.24	3.62	
28	A1/60/R0/5S	47.47	11.73	
29	A1/45/R90/10S	63.28	59.68	
30	A1/45/R90/5S	23.44	29.38	
31	A1/45/R0/10S	51.25	93.02	
32	A1/45/R0/5S	26.21	298.84	
	Average		334.036	
	Variance	79.251		
	F-Ratio			4.215

Considering response *AVG* for A-Bending-plan-1 with data reported in Table 5-16, the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG*, 4.506 and 2.02, indicate that there is a scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Considering response *AVG* for A-Bending-plan-2 with data reported in Table 5-17, the calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for response *AVG*, 4.215 and 2.02, indicate that there is a scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Contrasts associated with each parameter and interaction of parameters for the *AVG* response are presented in Tables 5-17 and 5-18.

Calculated contrast F-ratios must be compared with tabulated values. In this case, a single degree of freedom is associated with each contrast and $SS(C)$ whilst the number of within degrees of freedom associated with *MSW* remains unchanged at 64. Using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is again 7.07 [207].

Table 5-17: Contrasts for the A-Bending-plan-1 (%).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-0.21	0.00	0.00
<i>B</i>	-60.23	340.05	3.74
<i>C</i>	38.81	141.23	1.55
<i>D</i>	15.42	22.29	0.25
<i>E</i>	281.72	7440.58	81.85
<i>AB</i>	-109.88	1131.90	12.45
<i>AC</i>	-83.57	654.80	7.20
<i>AD</i>	1.42	0.19	0.00
<i>AE</i>	14.05	18.52	0.20
<i>BC</i>	-58.47	320.47	3.53
<i>BD</i>	27.06	68.65	0.76
<i>BE</i>	-86.33	698.76	7.69
<i>CD</i>	-66.98	420.59	4.63
<i>CE</i>	-24.23	55.02	0.61
<i>DE</i>	40.75	155.70	1.71
<i>ABC</i>	25.17	59.41	0.65
<i>ABD</i>	27.11	68.92	0.76
<i>ABE</i>	46.80	205.34	2.26
<i>ACD</i>	-21.39	42.91	0.47
<i>ACE</i>	65.88	406.89	4.48
<i>ADE</i>	12.93	15.67	0.17
<i>BCD</i>	16.03	24.10	0.27
<i>BCE</i>	6.96	4.54	0.05
<i>BDE</i>	-41.91	164.69	1.81
<i>CDE</i>	5.57	2.91	0.03
<i>ABCD</i>	1.57	0.23	0.00
<i>ABCE</i>	-21.20	42.14	0.46
<i>ABDE</i>	4.55	1.94	0.02
<i>ACDE</i>	30.10	84.94	0.93
<i>BCDE</i>	-11.75	12.95	0.14
<i>ABCDE</i>	-31.30	91.85	1.01
<i>MSW</i>	90.904		

Table 5-18: Contrasts A-Bending-plan-2 (%).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	89.62	753.03	9.50
<i>B</i>	-40.91	156.90	1.98
<i>C</i>	104.80	1029.59	12.99
<i>D</i>	7.11	4.74	0.06
<i>E</i>	224.66	4731.62	59.70
<i>AB</i>	-90.56	768.91	9.70
<i>AC</i>	-17.59	29.01	0.37
<i>AD</i>	-6.89	4.45	0.06
<i>AE</i>	-43.01	173.42	2.19
<i>BC</i>	-58.44	320.21	4.04
<i>BD</i>	-8.48	6.74	0.08
<i>BE</i>	-29.90	83.83	1.06
<i>CD</i>	3.14	0.92	0.01
<i>CE</i>	-54.65	280.0	3.53
<i>DE</i>	-14.02	18.42	0.23
<i>ABC</i>	25.20	59.52	0.75
<i>ABD</i>	-8.42	6.65	0.08
<i>ABE</i>	103.23	999.04	12.61
<i>ACD</i>	48.72	222.56	2.81
<i>ACE</i>	35.46	117.86	1.49
<i>ADE</i>	-41.84	164.14	2.07
<i>BCD</i>	8.34	6.52	0.08
<i>BCE</i>	19.92	37.21	0.47
<i>BDE</i>	3.52	1.16	0.01
<i>CDE</i>	-8.36	6.56	0.08
<i>ABCD</i>	-6.13	3.52	0.04
<i>ABCE</i>	-8.24	6.36	0.08
<i>ABDE</i>	49.98	234.22	2.96
<i>ACDE</i>	16.17	24.51	0.31
<i>BCDE</i>	-11.59	12.59	0.16
<i>ABCDE</i>	-31.14	90.89	1.15
<i>MSW</i>	79.251		

Values of contrast F-ratios superior 7.07, deemed significant, are highlighted in Tables 5-18 and 5-19. Results from Table 5-18 reveal that 3 main effects and interactions of parameters have a significant effect on the percentage white area of binary images on the first plan. Results from Table 5-19 for the second plan reveal that 5 main effects and interactions of parameters have a significant effect on *AVG* response of the percentage of white area.

Significant main effects and interactions of parameters are summarised in Table 5-19, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figures 5-20 and 5-21.

Table 5-19: Summary of significant main effects and interactions of parameters for A-bending-plans.

A-Bending-plan-1, response <i>AVG</i>	A-Bending-plan-2, response <i>AVG</i>
	<i>A</i> (+)
	<i>C</i> (+)
<i>E</i> (+)	<i>E</i> (+)
<i>AB</i> (-)	
<i>AC</i> (-)	<i>AB</i> (-)
<i>BE</i> (-)	
	<i>ABE</i> (-)

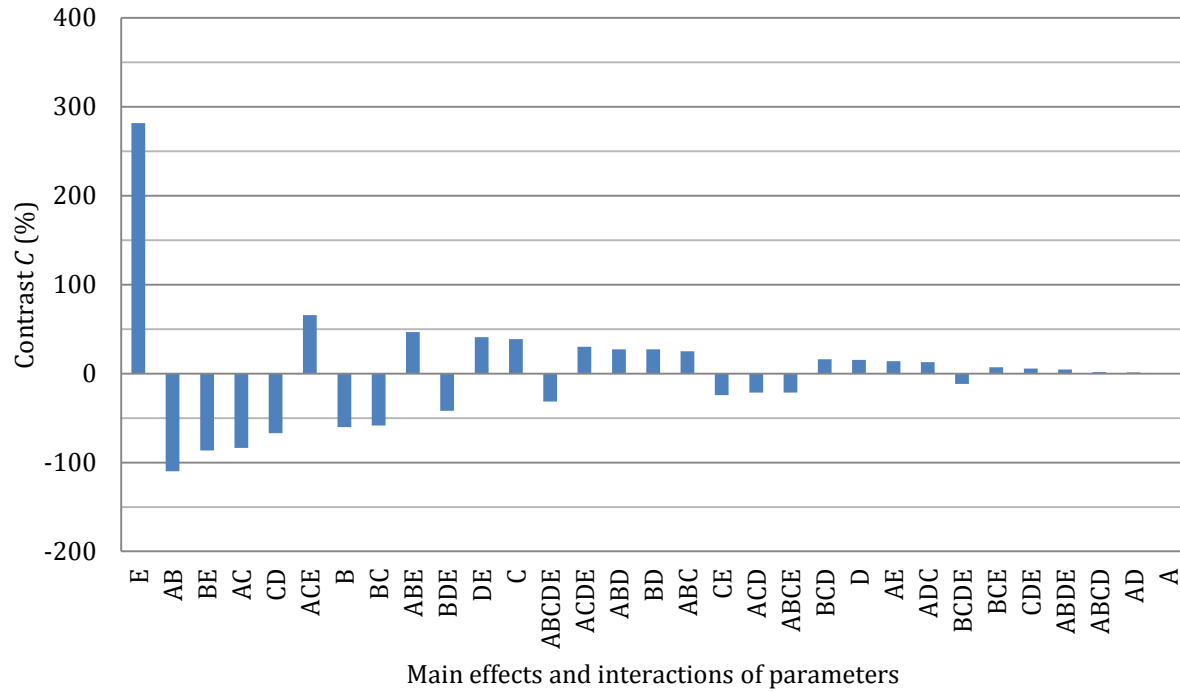


Figure 5-20: Main effects and interactions of parameters in decreasing order, response *AVG*,
A-Bending-plan-1.

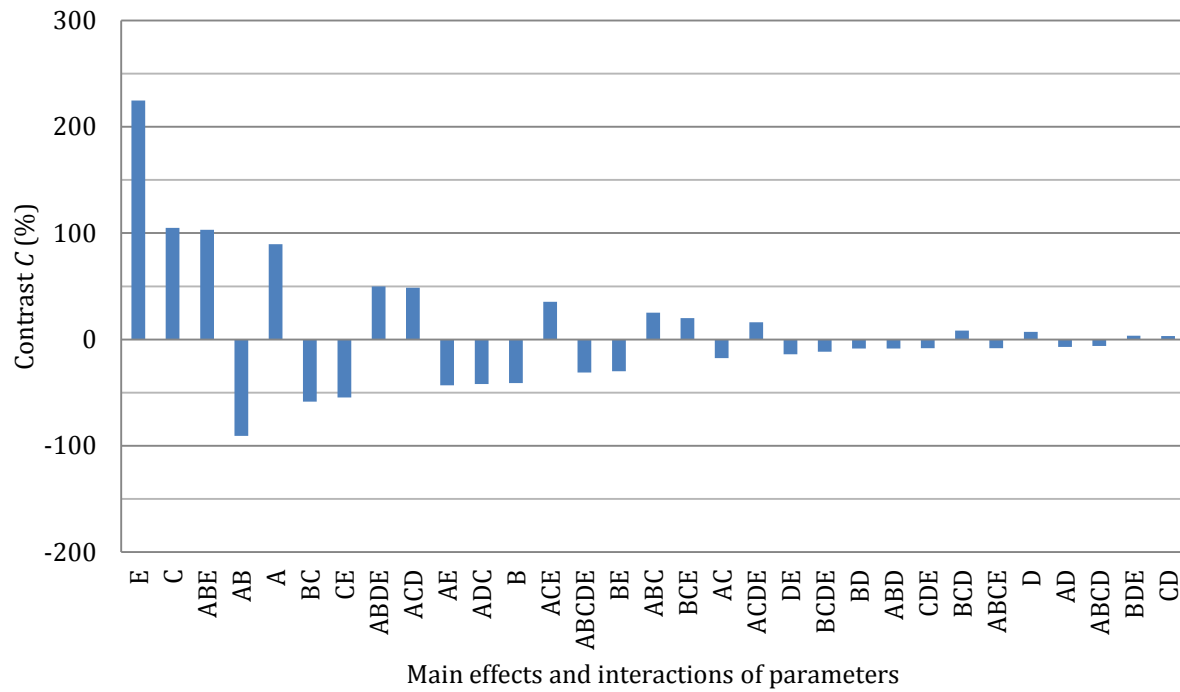


Figure 5-21: Main effects and interactions of parameters in decreasing order, response *AVG*,
A-Bending-plan-2.

5.7.1 Qualitative discussion on binary bending plans

The tables and figures for both plans show that parameter E , 5s/10s exposure time (-) vs. 10s/15s exposure time (+), which compared infrared temperature values at 5s/10s exposure time with 10s/15s exposure time, has a leading effect on the AVG response.

In A-Bending-plan-1, the interaction AB has the second leading effect, then the interaction BE comes as the third leading effect and then the interaction AC comes as the fourth leading effect on the AVG response. Parameter A in A-Bending-plan-1 represents smaller number of layers (-) vs. larger number of layers, parameter B represents uO-APT reinforcement (-) vs. industrial reinforcement (+) and parameter C represents samples tested in bending at low v_f (-) vs. samples tested in bending at high v_f (+). In A-Bending-plan-2, parameter C , samples tested in bending at low v_f (-) vs. samples tested in bending at high v_f (+), has the second leading effect and then the interaction ABE comes as the third leading effect on the AVG response. Finally, interactions AB and AB have lesser but significant effects on the AVG response. Parameter A in A-Bending-plan-2 represents rovings bent at $0^\circ/90^\circ$ (-) vs. rovings bent at $-45^\circ/+45^\circ$ (+), while the remaining parameters are the same as in A-Bending-plan-1.

5.7.2 Conclusions for binary bending plans

The AVG response in both plans shows that exposure time has a leading effect on the white area percentage. Both plans show also that the type of fabric, uO-APT or industrial, has no

effect as a main parameter. The analysis uses the percentage of white area within the binary image and this may explain why the type of fabric should have no effect.

On the other hand, fibre volume fraction in A-Bending-plan-1 has no significant effect on the *AVG* response while in A-Bending-plan-2 comes as the second leading effect on the *AVG* response. This contradiction comes from the fact that the percentage of white areas in the binary images in the first plan differ from the second plan. Finally, the number of layers also has no significant effect as a main parameter on the *AVG* response.

5.8 Tests performed on samples subjected to shear

The same active IRT technique used for capturing thermal images of all samples used in bending was used with shear samples, which are listed in Table 4-1 through Table 4-4 in Chapter 4. Each sample was exposed to pulses of 10 seconds, 15 seconds and 20 seconds of heat generated using the 500 watt halogen lamp at a distance of 19 cm. The polyethylene holder opening is 14 cm by 14 cm which put the infrared camera at a distance of 35 cm.

5.8.1 Experimental IRT test procedures for shear samples

Since distance between sample and the heat source was unchanged, pulse time would be the only variable that needed to be determined.

Shear samples had bigger areas than bending samples, and needed more time to reach the same temperatures as bending samples. Exposure times were determined through

numerous experimental trials conducted on shear samples made from uO-APT fabrics, aiming at temperature distributions as obtained with bending samples.

IR-Test-6, Figure 5-22, shows infrared images results for two uO-APT samples; Figure 5-22 (top) shows infrared images for A3/45/R0/S1 bending sample captured at 5, 10 and 15 seconds, while Figure 5-22 (bottom) shows infrared images for A6/R0/S2 shear sample captured at 10, 15 and 20 seconds. Both samples featured the same number of layers which is 8, therefore, exposure times of 10 seconds, 15 seconds and 20 seconds were used, where comparable temperature distributions can be captured in both series of infrared images.

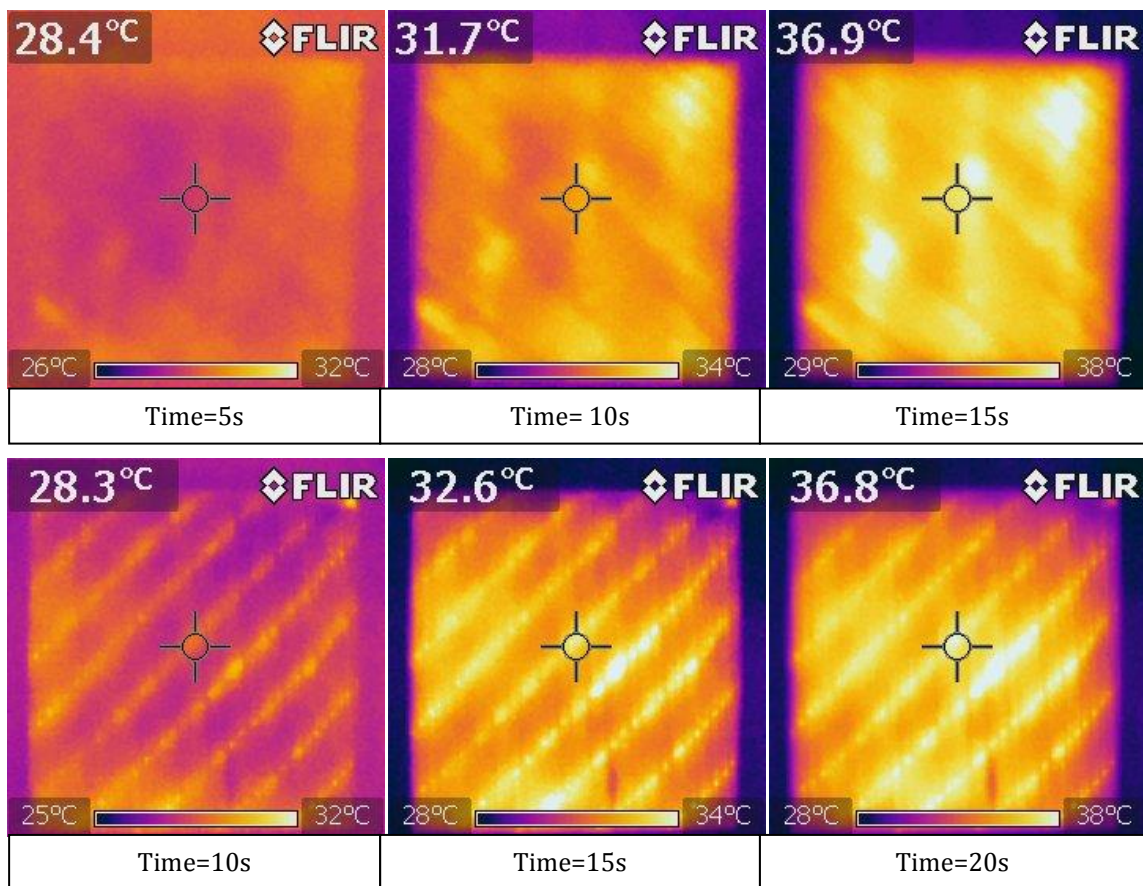


Figure 5-22: IR-Test-6 infrared images captured for bending and shear samples at different exposure times.

The same procedures followed for producing IRT images of bending samples in Section 5.5.1 were followed here with shear samples, except for exposure times of 10, 15 and 20 seconds. These tests brought the total number of infrared images to 48 for samples used in shear tests, as listed in Chapter 4. Images captured with the FLIR i7 infrared camera are included in Appendix K.

5.8.2 IR images and temperatures: shear samples

Infrared images of shear samples were also processed with MATLAB 7.0 software to obtain binary images where areas of higher temperatures appeared as white areas representing a possible defect in the sample.

From infrared images appearing in Figure 5-23 (top) obtained for sample A4/R-45/S1, which featured 8 layers, with 10 and 15 seconds exposure times, and images in Figure 5-23 (bottom) obtained for sample A5/R-45/S1, which featured 12 layers, with 15 and 20 seconds exposure times, it can be seen that results are comparable. The temperature distributions in both cases are generally the same. This similarity also exists when comparing images from A5 and A6 samples. Such similarities lead to comparing A4/10s or A6/10s images with A5/15s images and A4/15s or A6/15s images with A5/20s images.

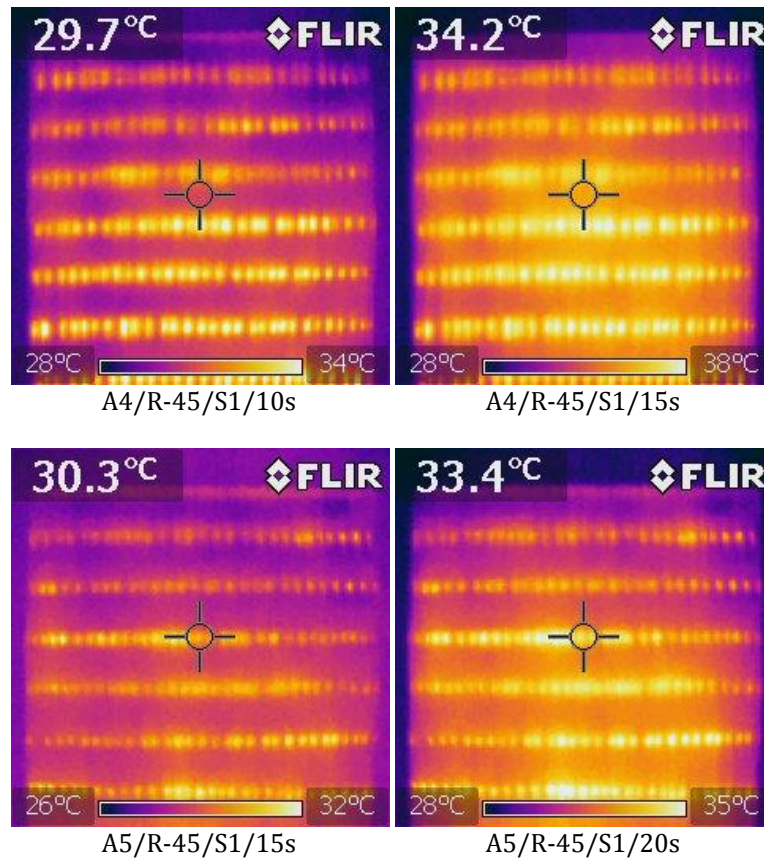


Figure 5-23: Infrared images for sample A4/R-45/S1 and A5/R-45/S1 at two different exposure times.

It should be noted that for all A4 and A6 samples made from uO-APT reinforcements that featured 8 layers of yarns, good results can be achieved using a 10 seconds exposure time as shown in Figure 5-24 (left). Details of the structure started to disappear from binary image made using 15 seconds exposure time, Figure 5-24 (middle), and further at 20 seconds, Figure 5-24 (right). It should be mentioned here again that B6 samples made from Saertex industrial fabric featured much less visible and identifiable structural details.

Infrared images for samples A4, A5 and A6 along with corresponding binary images are included in Appendix J. Defects within these samples are discussed below.

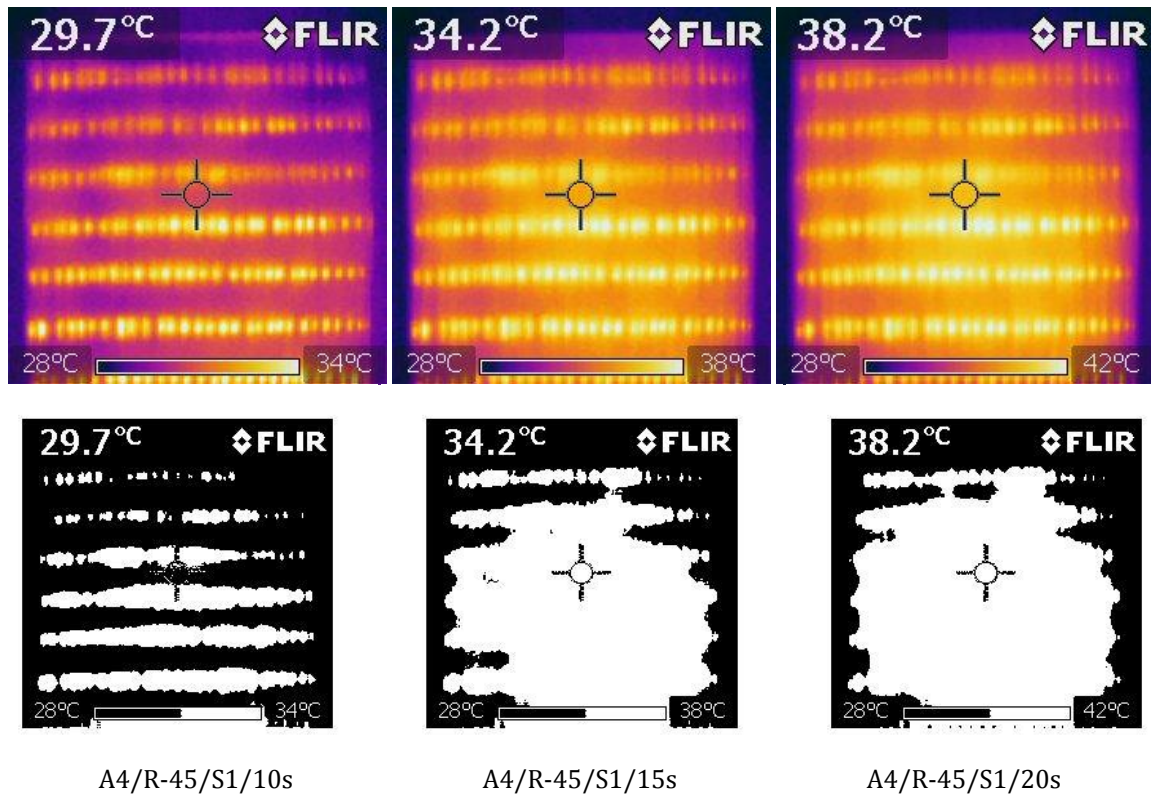


Figure 5-24: Infrared images and the corresponding binary images for sample A4/R-45/S1 at three different exposure times.

As concluded in Chapter 4, shear samples tested in R-45 setup and R+45 setup lead to no differences in shear response; both showed best ability to shear under low force. Samples A5/R-45/S1 and A5/R+45/S2, Figure 5-25, show similarity in infrared images and corresponding binary images for both setups. Such similarity can be also be seen for samples A4/R-45/S1 and A4/R+45/S2 in Appendix K. The other observation is related to the R0 and R90 configurations setup. Samples tested in shear in R0 setup show no significant damage to stitching lines, contrary to samples tested in R90 setup.

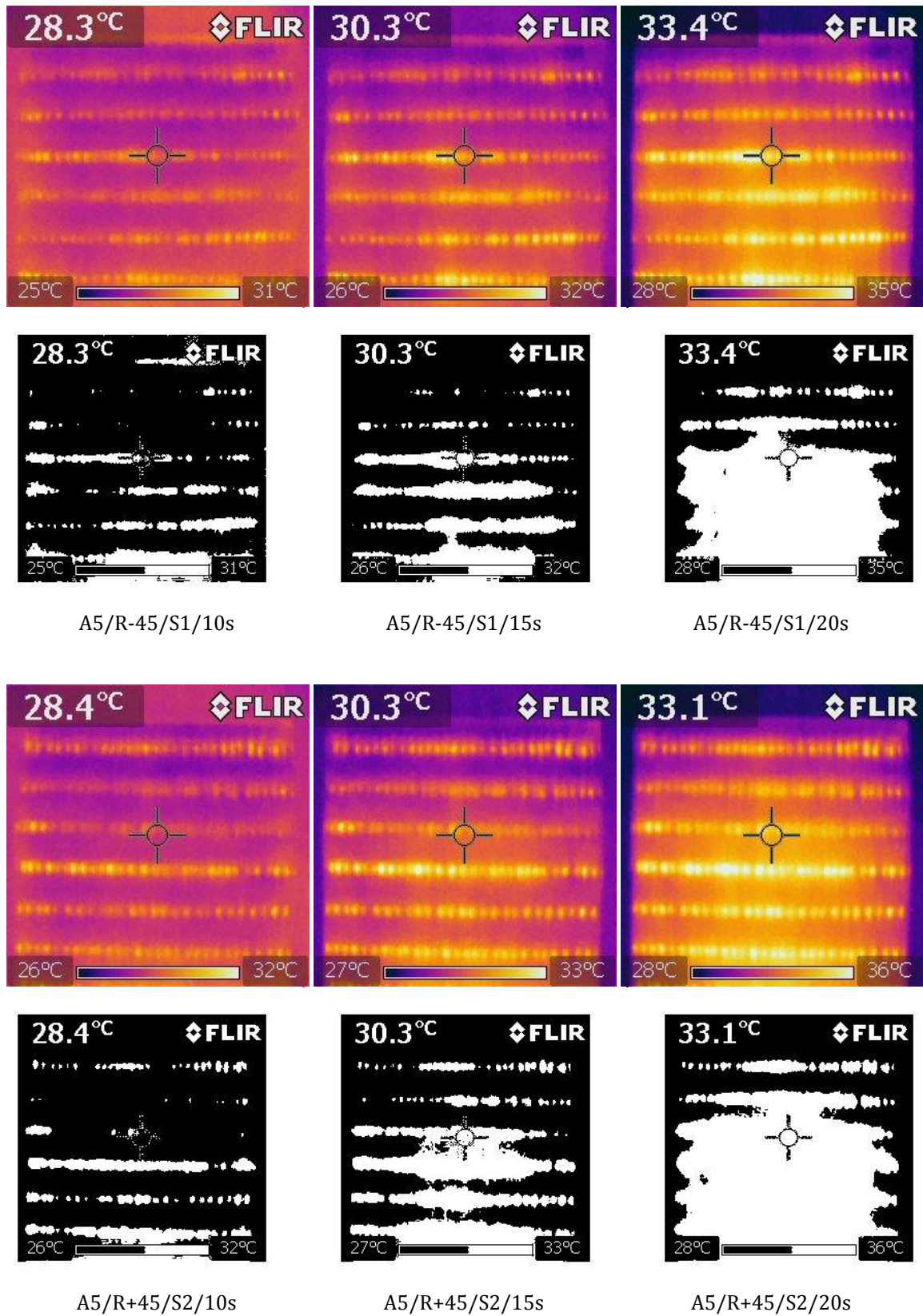


Figure 5-25: Similar temperature distributions and binary images obtained for R-45 and R+45 setups.

The binary image for sample A6/R0/S2 tested in shear at R0 setup shown in Figure 5-26 (left), shows no significant damage to stitching lines, while the binary image for sample A6/R90/S2 tested in shear in R90 setup shown in Figure 5-26 (right) shows significant damage to stitching lines.

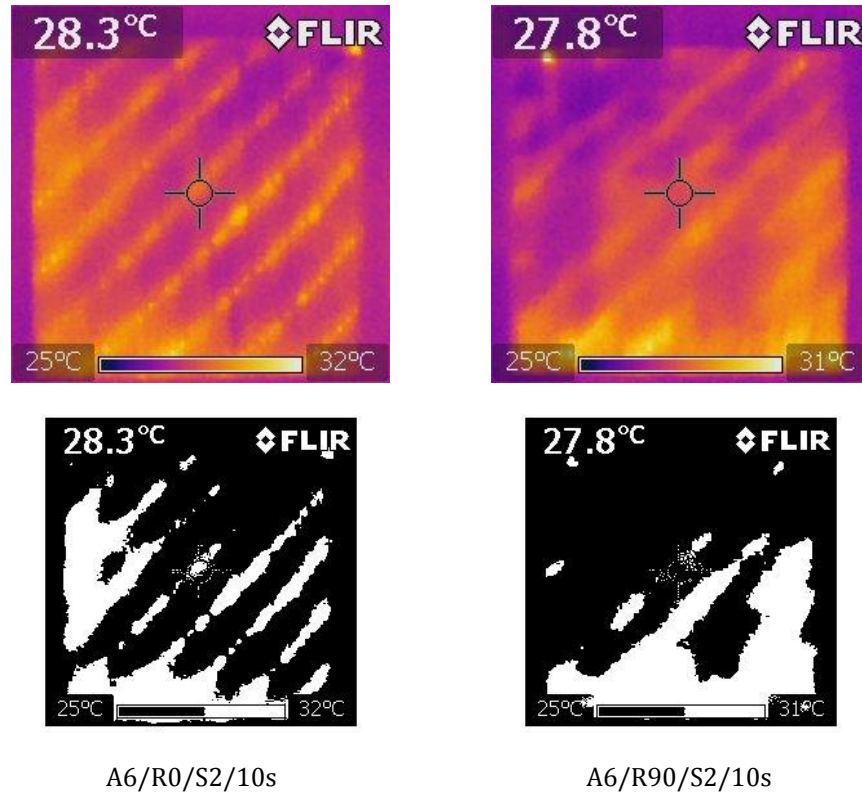


Figure 5-26: Infrared and binary images for sample A6/R0/S2 tested in shear in R0 setup (left) and A6/R90/S2 tested in shear in R90 setup (right).

5.9 Analysis of IR images of shear samples

Temperature distributions were converted to values representative of the average *AVG* and difference ΔT in a procedure similar to that used with bending samples. All temperature distributions obtained from infrared images were organised in tables similar to Table 5-20, and are included in Appendix L.

Table 5-20: Averages and differences of temperatures obtained for group A4 samples made from uO-APT reinforcements.

Type	Group	Setup			Temperature (°C)				
		Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A4	R-45	10	S1	24.0	28.6	32.0	28.0	8.0
				S2	27.0	28.5	33.0	30.0	6.0
			15	S1	25.0	32.0	36.0	30.5	11.0
				S2	27.0	32.3	37.0	32.0	10.0
			20	S1	28.0	38.2	42.0	35.0	14.0
				S2	29.0	40.7	42.0	35.5	13.0
		R+45	10	S1	28.0	29.7	34.0	31.0	6.0
				S2	28.0	31.1	34.0	31.0	6.0
			15	S1	28.0	34.2	38.0	33.0	10.0
				S2	29.0	36.1	38.0	33.5	9.0
			20	S1	25.0	36.7	41.0	33.0	16.0
				S2	28.0	37.1	41.0	34.5	13.0

For reasons stated in previous sections, results obtained for R-45 and R+45 shear setup configurations as well as for R0 and R90 shear setup configurations, were analysed using data presented in Appendix L. This can be done using similar three 2-level Taguchi [207] plans similar to those used in Chapter 4, labelled here as first IR-Shear-plan-1, second IR-Shear-plan-2 and third IR-Shear-plan-3. These plans are used here for investigating the effect of different shear test configurations on IR images.

IR-Shear-plan-1 compared the effect of the 3 following parameters and their interactions using data from groups A4 and A5, for two modalities represented as (-) and (+) in the plan, on each quantitative response:

- Parameter *A*: smaller number of layers (-) vs. larger number of layers (+);
- Parameter *B*: Samples tested in shear at R-45 (-) vs. : Samples tested in shear at R+45 (+);
- Parameter *C*: 10s/15s exposure time (-) vs. 15s/20s exposure time (+).

IR-Shear-plan-2 compared the effect of the 2 following parameters and their interactions using data from groups A4 and A6, for two modalities represented as (-) and (+) in the plan, on the same two quantitative responses:

- Parameter *A*: setup in rig at R+45 (-) vs. setup in rig at R90 (+);
- Parameter *C*: 10s exposure time (-) vs. 15s exposure time (+).

Finally, IR-Shear-plan-3 compared the effect of the 3 following parameters and their interactions using data from groups A6 and B6, for two modalities represented as (-) and (+) in the plan, on the same two quantitative responses:

- Parameter *A*: uO-APT reinforcement (-) vs. industrial reinforcement (+);
- Parameter *B*: setup in rig at R0 (-) vs. setup in rig at R90 (+);
- Parameter *C*: 10s exposure time (-) vs. 15s exposure time (+).

The modalities taken by each parameter for each test in all plans are listed in Chapter 4, Table 4-6 for the first and third plan, in Table 4-7 for the second plan.

The responses analysed with the plans are the average *AVG* temperature calculated from T_{min} and T_{max} and temperature difference ΔT calculated by subtracting T_{max} from T_{min} measured for each samples by the infrared camera after exposure times which are 10, 15 and 20 seconds. Values of the average and temperature difference for each plan appear in Tables 5-21, 5-22 and 5-23.

Table 5-21: Responses for IR-Shear-plan-1 (°C).

Run	Sub-group	S1 <i>AVG</i>	S1 ΔT	S2 <i>AVG</i>	S2 ΔT
1	A5/R+45/20s	29	6	32	8
2	A5/R+45/15s	28	6	30	6
3	A5/R-45/20s	31.5	7	30.5	7
4	A5/R-45/15s	29	6	28.5	7
5	A4/R+45/15s	33	10	33.5	9
6	A4/R+45/10s	31	6	31	6
7	A4/R-45/15s	30.5	11	32	10
8	A4/R-45/10s	28	8	30	6

Table 5-22: Responses for IR-Shear-plan-2 (°C).

Run	Sub-group	S1 <i>AVG</i>	S1 ΔT	S2 <i>AVG</i>	S2 ΔT
1	A6/R90/15s	28.5	7	30.5	7
2	A6/R90/10s	27	6	28	6
3	A4/R+45/15s	33	10	33.5	9
4	A4/R+45/10s	31	6	31	6

Table 5-23: Responses for IR-Shear-plan-3 (°C).

Run	Sub-group	S1 <i>AVG</i>	S1 ΔT	S2 <i>AVG</i>	S2 ΔT
1	B6/R90/15s	29	6	30	6
2	B6/R90/10s	28	6	28	6
3	B6/R0/15s	30	6	30	6
4	B6/R0/10s	28	6	28.5	7
5	A6/R90/15s	28.5	7	30.5	7
6	A6/R90/10s	27	6	28	6
7	A6/R0/15s	30.5	7	31	6
8	A6/R0/10s	28.5	7	28.5	7

Quantities pertaining to the six one-way ANOVAs performed as part of the analysis of the temperature distributions appear in Tables 5-24 to 5-29. Values of the F-Ratio associated with one-way ANOVAs performed for each plan are obtained by dividing the overall variance between subgroups by the overall variance within subgroups.

Considering IR-Shear-plan-1 applied to response *AVG*, the F-ratio was calculated at 3.565 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for IR-Shear-plan-1, 3.565 and 6.18, indicate there is probably no scope in calculating contrasts F-ratios aiming at identifying parameters that have a quantifiable effect on *AVG*. Considering IR-Shear-plan-1 applied to response ΔT , the F-ratio was calculated at 7.987 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for IR-Shear-plan-1, 7.987 and 6.18, indicate that there is marginal scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the ΔT shear force values.

Table 5-24: One-way ANOVA for *AVG* responses, IR-Shear-plan-1 (°C).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$
1	A5/R+45/20s	30.50	4.50
2	A5/R+45/15s	29.00	2.00
3	A5/R-45/20s	31.00	0.50
4	A5/R-45/15s	28.75	0.13
5	A4/R+45/15s	33.25	0.13
6	A4/R+45/10s	31.00	0.00
7	A4/R-45/15s	31.25	1.13
8	A4/R-45/10s	29.00	2.00
Average Variance F-Ratio		4.623	1.297 3.565

Table 4-25: One-way ANOVA for ΔT responses, IR-Shear-plan-1 (°C).

Run	Sub-group	$LAVG(\Delta T)$	$LSTD^2(\Delta T)$
1	A5/R+45/20s	7.00	2.00
2	A5/R+45/15s	6.00	0.00
3	A5/R-45/20s	7.00	0.00
4	A5/R-45/15s	6.50	0.50
5	A4/R+45/15s	9.50	0.50
6	A4/R+45/10s	6.00	0.00
7	A4/R-45/15s	10.50	0.50
8	A4/R-45/10s	7.00	2.00
Average Variance F-Ratio		5.491	0.688 7.987

Considering IR-Shear-plan-2 applied to response *AVG*, the F-ratio was calculated at 17.952 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted from the second plan, 17.952 and 16.7, indicate that there

is marginal scope in calculating contrast F-ratios for this plan. Considering the second plan applied to response ΔT , the F-ratio was calculated at 43.667 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for the first plan, 43.667 and 16.70, indicate good scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the ΔT shear force values.

Table 5-26: One-way ANOVA for *AVG* responses, IR-Shear-plan-2 (°C).

Run	Sub-group	<i>LAVG</i> (<i>AVG</i>)	<i>LSTD</i> ² (<i>AVG</i>)
1	A6/R90/15s	29.50	2.00
2	A6/R90/10s	27.50	0.50
3	A4/R+45/15s	33.25	0.13
4	A4/R+45/10s	31.00	0.00
	Average		0656
	Variance	11.781	
	F-Ratio		17.952

Table 5-27: One-way ANOVA for ΔT responses, IR-Shear-plan-2 (°C).

Run	Sub-group	<i>LAVG</i> (ΔT)	<i>LSTD</i> ² (ΔT)
1	A6/R90/15s	7.00	0.00
2	A6/R90/10s	6.00	0.00
3	A4/R+45/15s	9.50	0.50
4	A4/R+45/10s	6.00	0.00
	Average		0.125
	Variance	5.458	
	F-Ratio		43.667

Finally, considering IR-Shear-plan-3 applied to response *AVG*, the F-ratio was calculated at 6.066 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted from the second plan, 6.066 and 6.18, almost indicate scope in calculating contrast F-ratios for this plan. Considering the second plan applied to response ΔT , the F-ratio was calculated at 3.143 from experimental data. The calculated and tabulated values of the F-ratio obtained from the one-way ANOVA conducted for IR-Shear-plan-3, 3.143 and 6.18, indicate likely no scope in calculating contrast F-ratios aiming at identifying parameters that have a quantifiable effect on the ΔT shear force values.

Table 5-28: One-way ANOVA for *AVG* responses, IR-Shear-plan-3 (°C).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$
1	B6/R90/15s	29.50	0.50
2	B6/R90/10s	28.00	0.00
3	B6/R0/15s	30.00	0.00
4	B6/R0/10s	28.25	0.13
5	A6/R90/15s	29.50	2.00
6	A6/R90/10s	27.50	0.50
7	A6/R0/15s	30.75	0.13
8	A6/R0/10s	28.50	0.00
	Average		0.406
	Variance	2.464	
	F-Ratio		6.066

Table 5-29: One-way ANOVA for ΔT responses, IR-Shear-plan-3 (°C).

Run	Sub-group	$LAVG(\Delta T)$	$LSTD^2(\Delta T)$
1	B6/R90/15s	6.00	0.00
2	B6/R90/10s	6.00	0.00
3	B6/R0/15s	6.00	0.00
4	B6/R0/10s	6.50	0.50
5	A6/R90/15s	7.00	0.00
6	A6/R90/10s	6.00	0.00
7	A6/R0/15s	6.50	0.50
8	A6/R0/10s	7.00	0.00
	Average		0.125
	Variance	0.393	
	F-Ratio		3.143

The next step in analysing the effects of the parameters on IR results consisted in calculating contrasts associated with each parameter and interaction of parameters, for all plans and responses that are significant. Contrast F-ratios are listed in Tables 5-30 to 5-34. Although, the calculated and tabulated values of the F-ratio obtained for IR-Shear-plan-1 indicate there is probably no scope in calculating contrast F-ratios, calculations conducted show that parameter *C* is significant as per Table 5-30.

Table 5-30: Contrasts for *AVG* response, IR-Shear-plan-1 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast F-ratio
<i>A</i>	-5.25	6.89	5.31
<i>B</i>	3.75	3.52	2.71
<i>C</i>	8.25	17.02	13.12
<i>AB</i>	-4.25	4.52	3.48
<i>AC</i>	-0.75	0.14	0.11
<i>BC</i>	-0.75	0.14	0.11
<i>ABC</i>	-0.75	0.14	0.11
<i>MSW</i>	1.297		

Table 5-31: Contrasts for ΔT response, IR-Shear-plan-1 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast F -ratio
A	-6.5	10.56	15.36
B	-2.5	1.56	2.27
C	8.5	18.06	26.27
AB	1.5	0.56	0.82
AC	-5.5	7.56	11.00
BC	0.5	0.06	0.09
ABC	0.5	0.06	0.09
MSW	0.688		

Table 5-32: Contrasts for AVG response, IR-Shear-plan-2 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast F -ratio
A	-7.25	26.28	40.05
B	4.25	9.03	13.76
AB	-0.25	-27.50	0.05
MSW	0.656		

Table 5-33: Contrasts for ΔT response, IR-Shear-plan-2 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast F -ratio
A	-2.50	3.13	25.00
B	4.50	10.13	81.00
AB	-2.50	3.13	25.00
MSW	0.125		

Table 5-34: Contrasts for *AVG* response, IR-Shear-plan-3 (°C).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-0.5	0.06	0.15
<i>B</i>	-3.0	2.25	5.54
<i>C</i>	7.5	14.06	34.62
<i>AB</i>	1.5	0.56	1.38
<i>AC</i>	-1.0	0.25	0.62
<i>BC</i>	-0.5	0.06	0.15
<i>ABC</i>	0.0	0.00	0.00
<i>MSW</i>	0.406		

Using the same false alarm theoretical risk α of 0.01, the tabulated value indicating significant differences between groups is 11.3 for the first and third plans and 21.2 for the second plan [207]. Values of contrast *F*-ratios superior to 11.3 and 21.2, deemed significant, are highlighted in Tables 5-30 to 5-34.

Significant main effects and interactions of parameters are summarised in Table 5-35. Contrast values are presented in decreasing order in Figures 5-27 to 5-31.

Table 5-35: Summary of significant main effects and interactions of parameters for IR-shear-plans.

IR-Shear-plan-1 response <i>AVG</i>	IR-Shear-plan-1 response ΔT	IR-Shear-plan-2 response <i>AVG</i>	IR-Shear-plan-2 response ΔT	IR-Shear-plan-3 response <i>AVG</i>	IR-Shear-plan-3 response ΔT
	<i>A</i> (-)	<i>A</i> (-)	<i>A</i> (-) <i>B</i> (+)		None
<i>C</i> (+)	<i>C</i> (+)		<i>AB</i> (-)	<i>C</i> (+)	

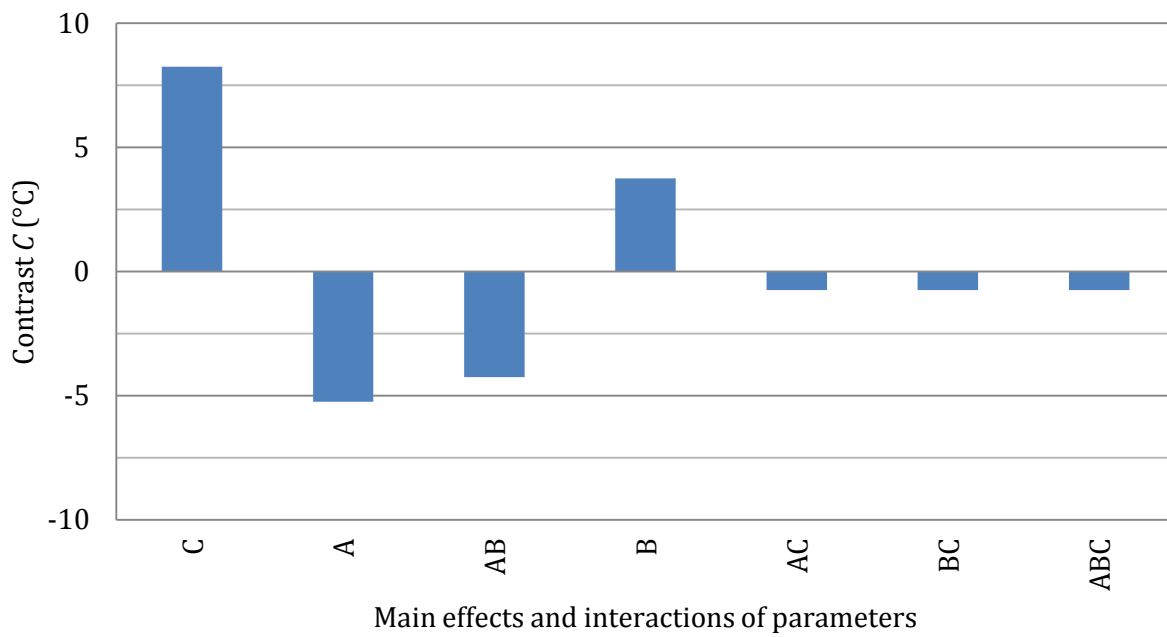


Figure 5-27: Main effects and interactions of parameters in decreasing order, response *AVG*, IR-Shear-plan-1.

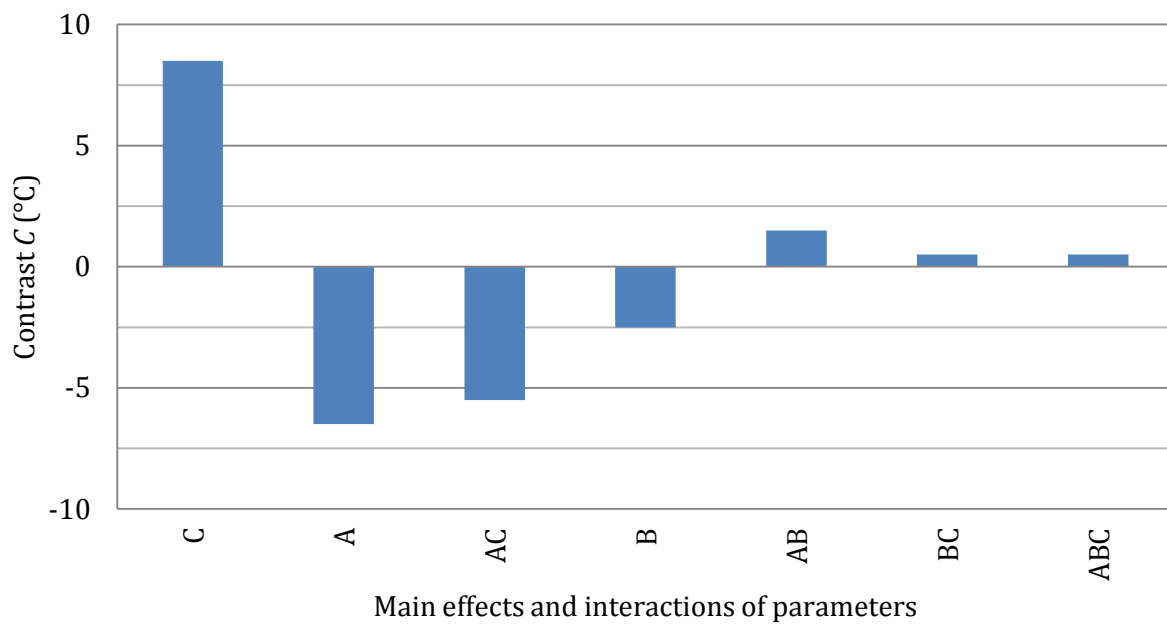


Figure 5-28: Main effects and interactions of parameters in decreasing order, response ΔT ,

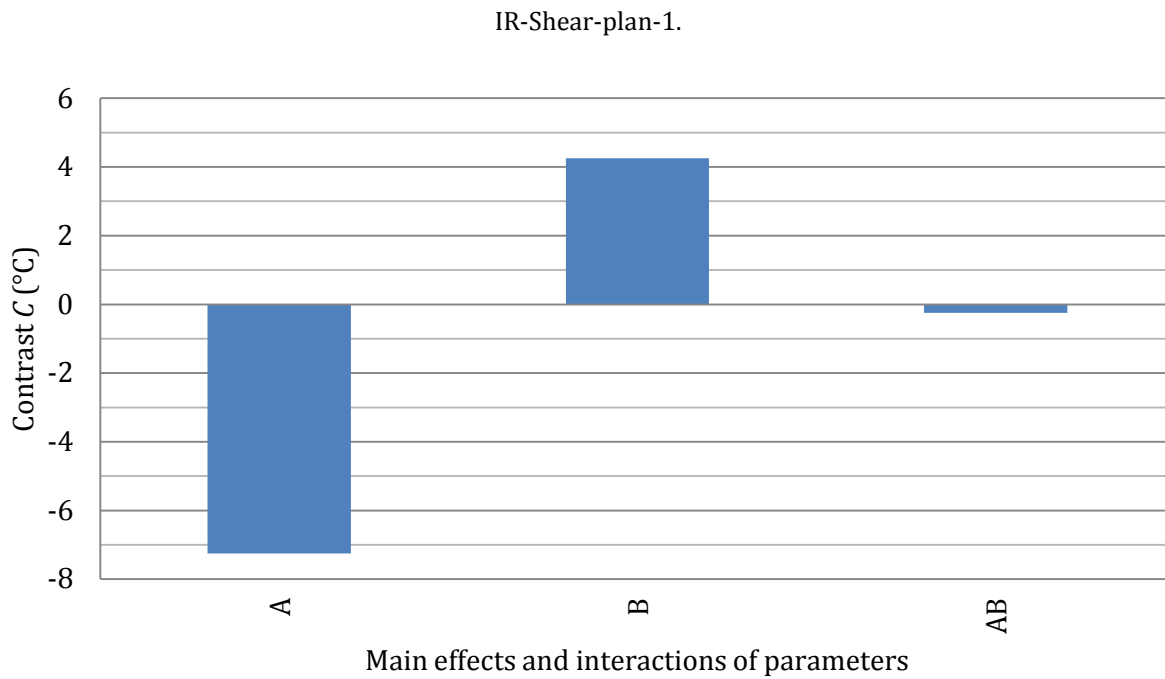


Figure 5-29: Main effects and interactions of parameters in decreasing order, response *AVG*,

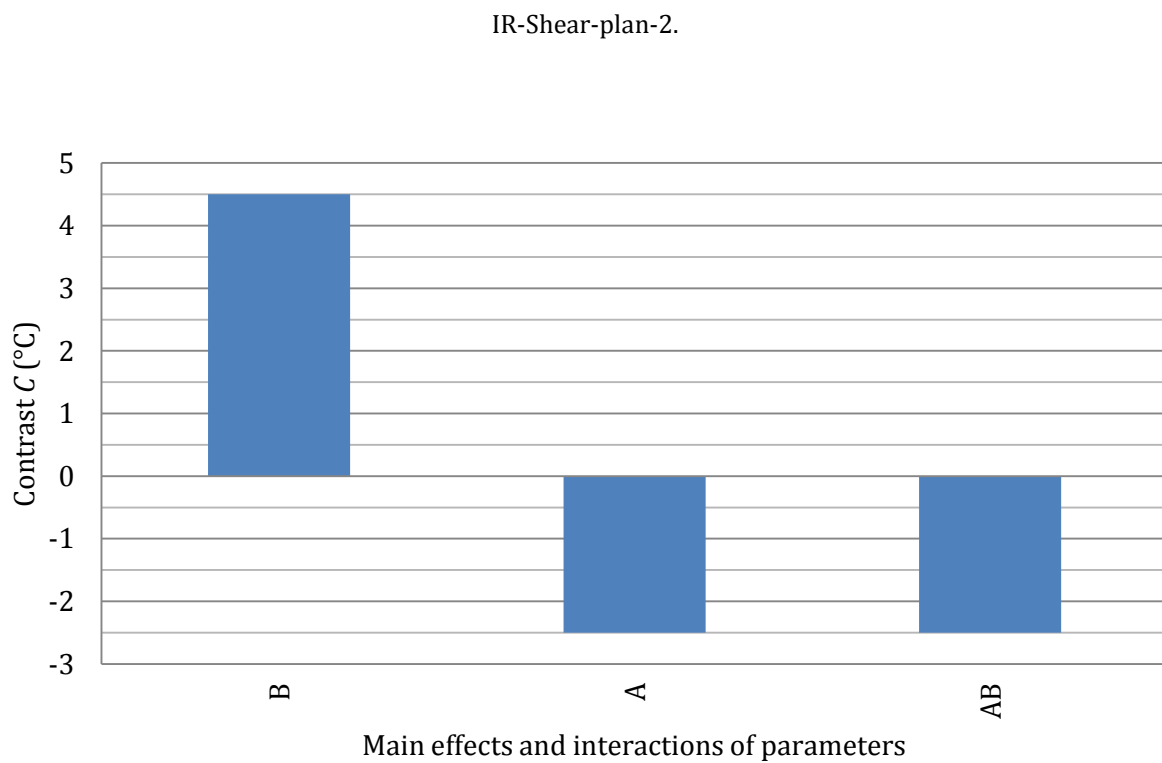


Figure 5-30: Main effects and interactions of parameters in decreasing order, response ΔT ,

IR-Shear-plan-2.

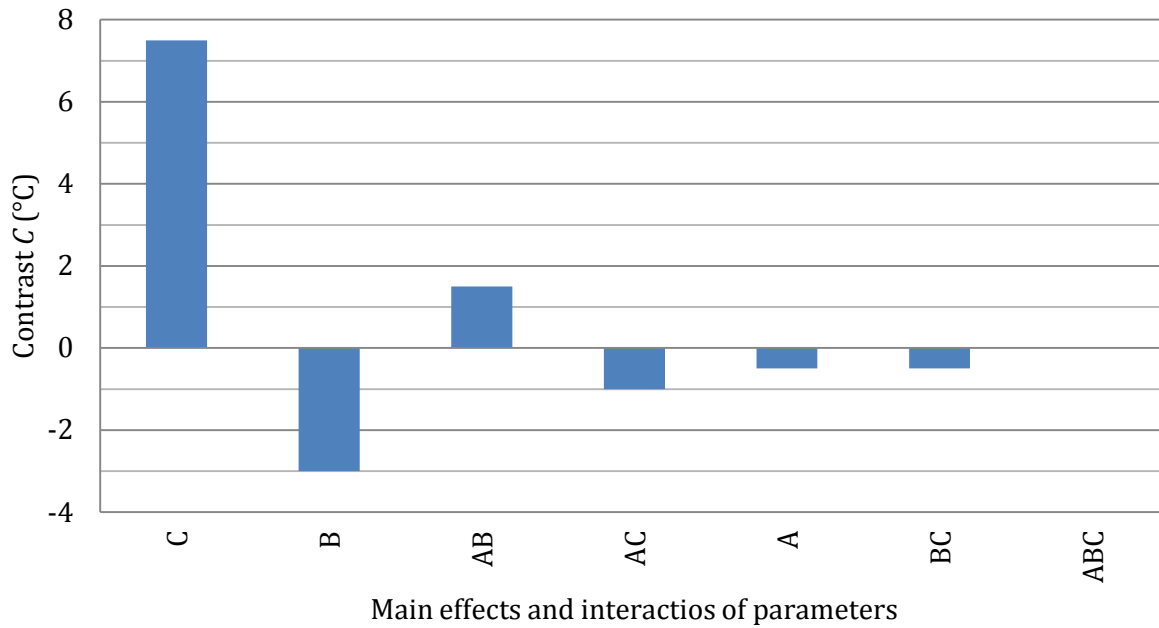


Figure 5-31: Main effects and interactions of parameters in decreasing order, response *AVG*, IR-Shear-plan-3.

5.9.1 Qualitative discussion of IR shear plans

Parameter *C*, 10s/15s exposure time (-) vs. 15s/20s exposure time (+), which compared infrared temperature values at 10s/15s exposure time with 15s/20s exposure time, has a leading effect on *AVG* temperature response in IR-Shear-plan-1 and IR-Shear-plan-2, while it has a leading effect on ΔT temperature response only on the first IR-plan-shear-1. Parameter *A*, which represents smaller number of layers (-) vs. larger number of layers in IR-Shear-plan-1 has the second leading effect on both *AVG* and ΔT responses, while in IR-Shear-plan-3 parameter *A* represents uO-APT reinforcement (-) vs. industrial reinforcement (+) and has no significant effect on both responses.

Parameter *B*, which represents samples tested in shear at R-45 setup (-) vs. samples tested in shear at R+45 setup (+) in IR-plan-shear-1, and samples tested in shear at R0 setup (-) vs. samples tested in shear at R90 setup (+) in IR-plan-shear-3, has no significant effect on both responses. On the other hand, parameter *A* in IR-Shear-plan-2 which represents samples tested in shear at R+45 setup (-) vs. samples tested in shear at R90 setup (+), has significant leading effect along with parameter *B*, 10s/15s exposure time (-) vs. 15s/20s exposure time (+), on both responses.

5.9.2 Conclusions for IR shear plans

The *AVG* and ΔT responses, in IR-Shear-plan-1 and IR-Shear-plan-3, show that exposure time has a leading effect on the temperature response. The exposure time also has a strong effect on the ΔT response in IR-Shear-plan-2 and on the *AVG* response in IR-Shear-plan-3. This was the expected in all plans as temperatures increase with increasing exposure time.

IR-Shear-plan-1 shows that there were no differences on the *AVG* and ΔT temperature responses recorded by the infrared camera when comparing R-45 setup configuration with R+45 setup configuration. This was expected as both configurations should have the same effect on shear tests.

IR-Shear-plan-2 compared the R+45 setup configuration with R90 setup configuration. The plan shows significant differences on the *AVG* and ΔT temperature responses reflecting the fact that with the R90 configuration, some damage occurred to stitching lines as can be seen in binary images, Figure K-11 and K-12 in Appendix K.

IR-Shear-plan-3 focused on two parameters, the type of fabric and the difference between R0 and R90 setup shear configurations; the plan shows that both parameters have no significant effects on the *AVG* and *STD* temperature responses.

5.10 Analysis of binary images of shear samples

The percentage of white area in binary images obtained for all samples tested in shear was calculated using MATLAB 7.0 software. All values obtained for both types of fabrics were organised in tables similar to Table 5-36 and are included in Appendix M.

Data presented in Appendix M was analysed using similar three 2-level Taguchi [207] plans similar to those presented in Section 5.9 labelled here as A-Shear-plan-1, A-Bending-plan-2 and A-Shear-plan-3.

A-Shear-plan-1 compared the effect of the same 3 parameters of IR-Shear-plan-1, which are the number of layers, the stitching configurations R-45 vs. R+45 and the exposure time, and their interactions, for two modalities represented as (-) and (+) in the plans, on one quantitative response, the average *AVG* of percentage of white area.

A-Shear-plan-2 compared the effect of the same 2 parameters of IR-Shear-plan-2, which are the stitching configurations R+45 vs. R90 and the exposure time 10s/15s vs. 15s/20s and interactions on the average *AVG* of percentage of white area in the binary images.

A-Shear-plan-3 compared the effect of the same 3 parameters of IR-Shear-plan-3, which are the type of fabric uO-APT vs. Saertex, the stitching configurations R+45 vs. R90 and the

exposure time 10s vs. 15s and their interactions, for two modalities represented as (-) and (+) in the plans, on the same responses.

Table 5-36: Percentage of white area in binary images for group A4 samples made from uO-APT reinforcements.

Type	Group	Setup			White area (%)
		Stitch	Pulse (sec)	Sample	
uO-APT	A4	R-45	10	S1	25.89
				S2	36.58
			15	S1	55.30
				S2	62.45
			20	S1	59.24
				S2	62.38
		R+45	10	S1	57.87
				S2	22.13
			15	S1	57.73
				S2	54.78
			20	S1	57.42
				S2	60.19

The response analysed with all plans is the average *AVG* of percentage of white area calculated from binary images after exposure times 10, 15 and 20 seconds. Values of the average for all plans appear in Tables 5-37 and 5-39.

Table 5-37: Responses for A-Shear-plan-1 (%).

Run	Sub-group	S1	S2
1	A5/R+45/20s	59.37	52.92
2	A5/R+45/15s	49.39	30.1
3	A5/R-45/20s	46.72	50.1
4	A5/R-45/15s	20.27	43.25
5	A4/R+45/15s	57.73	54.78
6	A4/R+45/10s	57.87	22.13
7	A4/R-45/15s	55.3	62.45
8	A4/R-45/10s	25.89	36.58

Table 5-38: Responses for A-Shear-plan-2 (%).

Run	Sub-group	S1	S2
1	A6/R90/15s	50.64	48.83
2	A6/R90/10s	36.3	25.39
3	A4/R+45/15s	57.73	54.78
4	A4/R+45/10s	57.87	22.13

Table 5-39: Responses for A-Shear-plan-3 (%).

Run	Sub-group	S1	S2
1	B6/R90/15s	26.82	19.32
2	B6/R90/10s	10.43	19.59
3	B6/R0/15s	27.47	25.99
4	B6/R0/10s	26.18	30.19
5	A6/R90/15s	50.64	48.83
6	A6/R90/10s	36.3	25.39
7	A6/R0/15s	56.87	62.31
8	A6/R0/10s	42.5	25.31

Quantities pertaining to the three one-way ANOVAs appear in Tables 5-40 to 5-42. $LAVG(\%)$ and $LSTD^2(\%)$ represent the line average and the line standard deviation of white area percentage for each run, for the 3 samples associated to the given run. Equations defining these quantities are similar to Eq. 5.7 to 5.10.

Table 5-40: Responses for A-plan-shear-1 (%).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$	
1	A5/R+45/20s	56.15	20.80	
2	A5/R+45/15s	39.75	186.05	
3	A5/R-45/20s	48.41	5.71	
4	A5/R-45/15s	31.76	264.04	
5	A4/R+45/15s	56.26	4.35	
6	A4/R+45/10s	40.00	638.67	
7	A4/R-45/15s	58.88	25.56	
8	A4/R-45/10s	31.24	57.14	
	Average		150.291	
	Variance	249.052		
	F-Ratio			1.657

Table 5-41: Responses for A-plan-shear-2 (%).

Run	Sub-group	$LAVG(AVG)$	$LSTD^2(AVG)$	
1	A6/R90/15s	49.74	1.64	
2	A6/R90/10s	30.85	59.51	
3	A4/R+45/15s	56.26	4.35	
4	A4/R+45/10s	40.00	638.67	
	Average		176.044	
	Variance	247.970		
	F-Ratio			1.409

Table 5-42: Responses for A-plan-shear-3 (%).

Run	Sub-group	<i>LAVG</i> (<i>AVG</i>)	<i>LSTD</i> ² (<i>AVG</i>)
1	B6/R90/15s	23.07	28.13
2	B6/R90/10s	15.01	41.95
3	B6/R0/15s	26.73	1.10
4	B6/R0/10s	28.19	8.04
5	A6/R90/15s	49.74	1.64
6	A6/R90/10s	30.85	59.51
7	A6/R0/15s	59.59	14.80
8	A6/R0/10s	33.91	147.75
Average			37.864
Variance		421.747	
F-Ratio			11.139

The calculated values of the F-ratio obtained from the one-way ANOVA in Table 5-42 and the tabulated F-ratio conducted for response *AVG*, for A-Shear-plan-1, 1.657 and 6.18, indicate that there is likely no scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

The calculated and tabulated values of the F-ratio for A-Shear-plan-2 conducted for response *AVG*, 1.409 and 16.70, indicate that there is little scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Finally, the calculated and tabulated values of the F-ratio for A-Shear-plan-3 conducted for response *AVG*, 11.139 and 6.18, indicate that there is some scope in calculating contrast F-ratios aiming at identifying parameters that have a strong effect on *AVG*.

Given the above conclusions, the next step in analysing the effects of the parameters on consists in calculating contrasts associated with each parameter and interaction of parameters for the third A-Shear-plan-3. Contrasts are defined in Section 3.5.2 and they appear in Table 5-43. The analysis was preformed for A-Shear-plan-1 and A-Shear-plan-2, but returned no significant contrasts; therefore, quantitative results are not presented.

Table 5-43: Contrasts for A-Shear-plan-3 (%).

Parameter	$\hat{C}$	$SS(\hat{C})$	Contrast <i>F</i> -ratio
<i>A</i>	-81.08	1643.49	43.41
<i>B</i>	-29.75	221.27	5.84
<i>C</i>	51.18	654.85	17.29
<i>AB</i>	-3.92	3.84	0.10
<i>AC</i>	-37.97	360.43	9.52
<i>BC</i>	2.72	1.85	0.05
<i>ABC</i>	16.31	66.50	1.76
<i>MSW</i>	37.864		

Calculated contrast *F*-ratios must be compared with tabulated values. In this case, the tabulated value indicating significant differences between groups is 11.3 for third plan [207]. Values of contrast *F*-ratios superior to 11.3, deemed significant, are highlighted in Table 5-43.

Significant main effects and interactions of parameters are summarised in Table 5-44, along with the sign of the associated contrast in each case. Contrast values are presented in decreasing order in Figure 5-32 for A-Shear-plan-3.

Table 5-44: Summary of significant main effects and interactions of parameters for A-shear-plans.

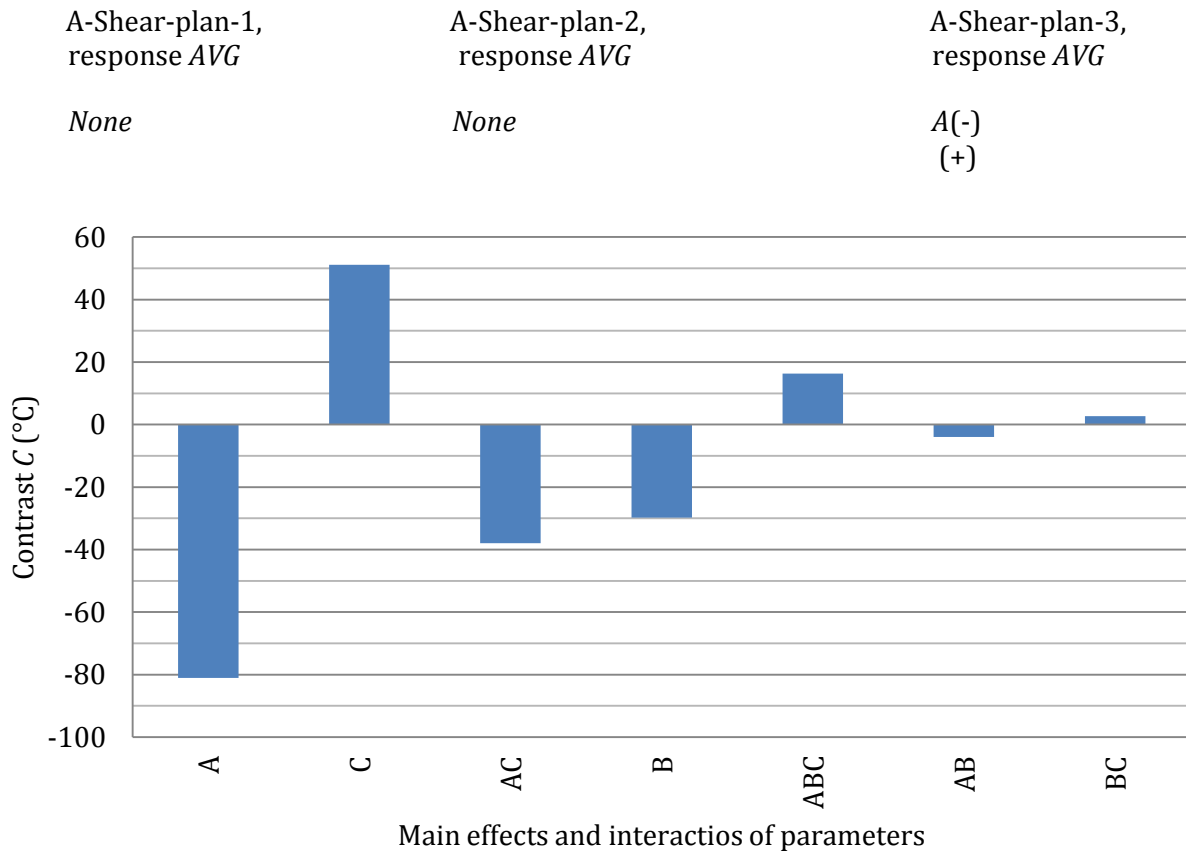


Figure 5-32: Main effects and interactions of parameters in decreasing order, response *AVG*, A-Shear-plan-3.

5.10.1 Qualitative discussion on binary shear plans

The table and figure for A-Shear-plan-3 data show that parameter *B*, uO-APT reinforcement (-) vs. industrial reinforcement (+), has a leading effect on the *AVG* response. Parameter *E*, 10s exposure time (-) vs. 15s exposure time (+), comes as the second leading effect on the *AVG* response. Results for the first and second plans showed that no parameter in both plans had a significant effect on the *AVG* response.

5.10.2 Conclusions for binary shear plans

The *AVG* response in the third A-plans-shear-E shows that the type of fabric has a leading effect on the white area percentage. The third plan also shows that the exposure time has a significant effect on *AVG* response.

On the other hand, A-Shear-plan-1 showed that number of layers and stitching configuration, R-45 vs. R+45, had no significant effect on the *AVG* response while the exposure time was deemed to have some effect at 9.85, but that was less than the tabulated value of 11.3 for statistical significance. A-Shear-plan-2 showed that none of the two parameters had a significant effect on the *AVG* response.

5.11 Conclusions on IRT tests

In this chapter, Taguchi plans similar to those used in Chapter 3, for bending samples, and Chapter 4 for shear samples, were used for analysing temperatures and white area percentage data. Temperatures were obtained from IR images while the percentage of white area was calculated from binary images that were obtained by converting IR images to black and white images using MATLAB 7.0 software.

In most plans conducted on both bending and shear samples using temperature and percentage of white area, the exposure time was the most influential parameter among all, on both results. This was expected as by increasing the exposure time, the infrared camera measured higher temperatures. and so the proportion of white area in binary images will increase.

A conflictual outcome was obtained relating to the type of fabric as a parameter for bending samples versus shear samples, and for plans using temperature as a value for analysis versus those using percentage of white area as a value for analysis. This may stem from the fact that the infrared camera recorded similar temperature values for both types of fabrics in plans conducted on shear samples, but different temperature values with bending samples from different types of fabrics. The conflict also arose between plans using temperature as a value for analysis and those using percentage of white area as a value for analysis. This may be attributed to automated processing in MATLAB upon converting IR images to binary images. Also, by increasing exposure time for a specific sample the amount of white area should generally increase. This was not always the case for some samples as can be seen in Figure 5-33.

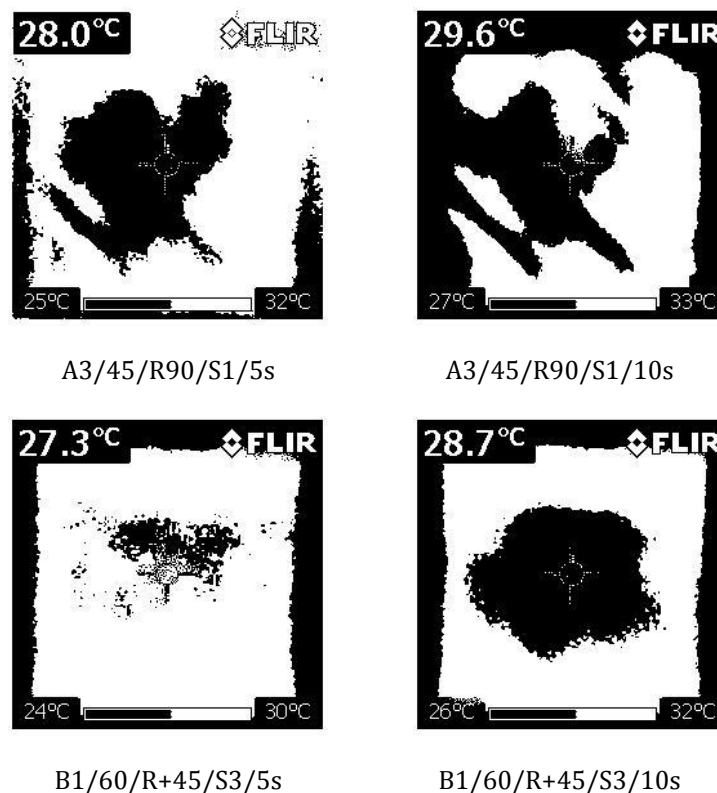


Figure 5-33: Binary images obtained at 5s and 10s for samples from Type A and B.

Regarding stitch setups in bending samples, all plans, including IR-Bending-plan-1 and IR-Bending-plan-2 which use IR data and also A-Bending-plan-1 and A-Bending-plan-2 which use white area data, showed that no significant effect on both responses resulted from differences in stitching setups, R0, R90, R-45 and R+45. This validated that no damage was captured by either infrared images nor in binary images for samples tested in bending, in the above mentioned stitching configurations.

Regarding shear samples, the R-45 and R+45 stitching setups were investigated. All plans show that these stitching configurations had no strong effects in shear tests. This was expected as both stitching setups should have the same influence on shearing as shown in Figure 5-34.

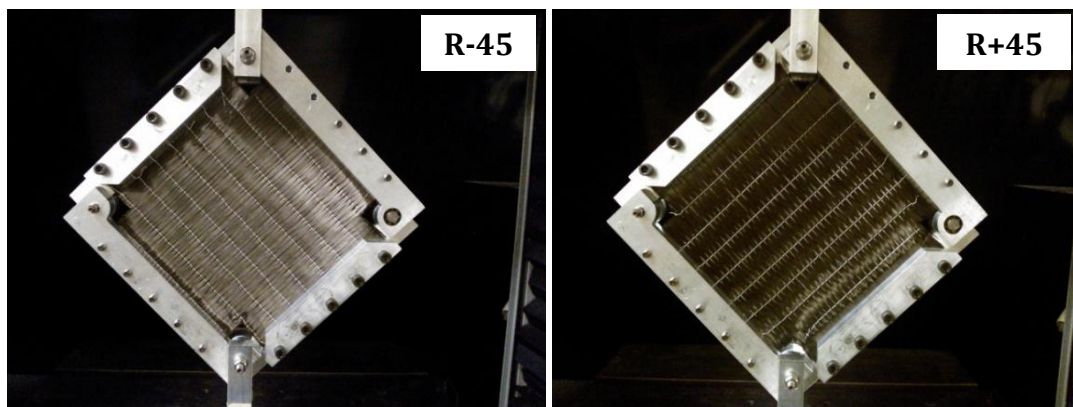


Figure 5-34: Stitching setup directions for in-plane shear tests

IR-Shear-plan-2 and A-Shear-plan-2 also compared R90 setup with R+45 setup, both plans recorded differences between setups. This was expected as shear samples tested at R90 setup suffered from clear failures in stitching lines, contrary to shear samples tested at R+45 and R0 which showed no evidence of stitching damage as shown in Figure 5-35.

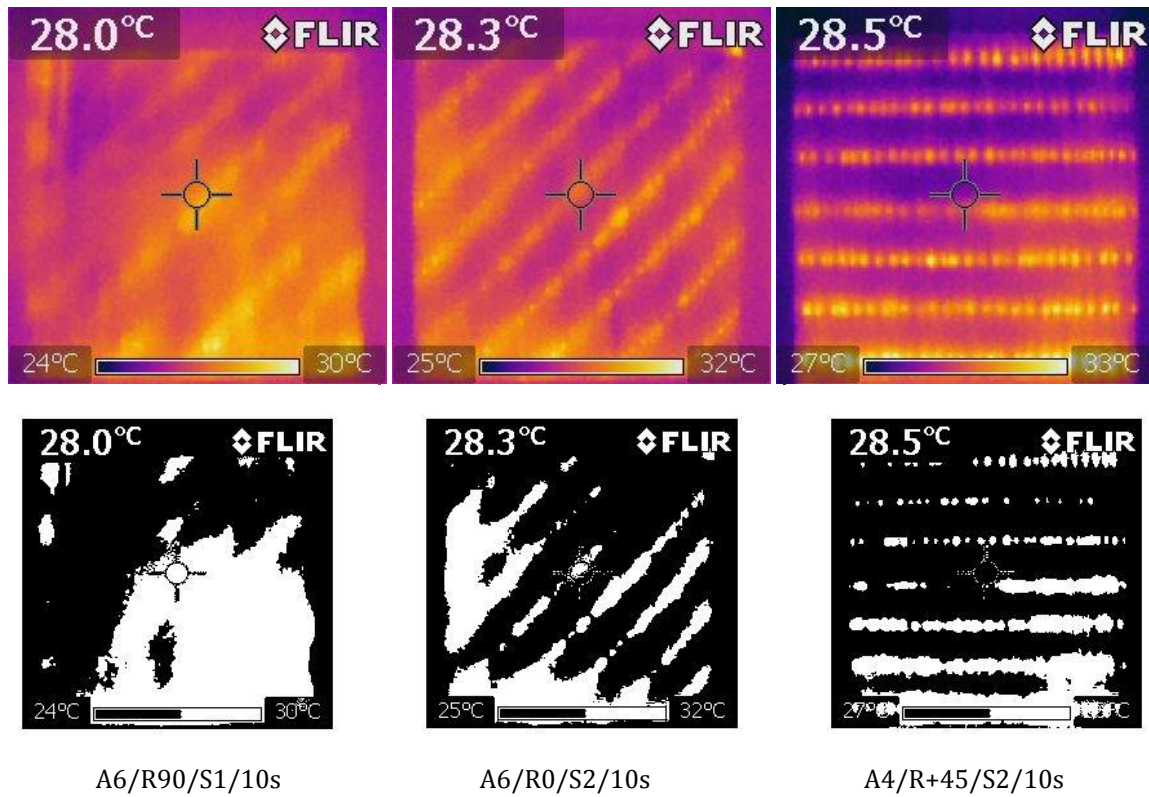


Figure 5-35: IR images and corresponding binary images showing the ability to identify failures within stitching threads for R90 setup.

Examining samples subjected to shear, Figure 5-35 shows IR images and corresponding binary images for three samples made from uO-APT fabrics and tested in shear at R90 setup, R0 setup and R+45 setup. Again it should be noted that R+45 setup is generally equivalent to R-45 setup. Stitching thread failures in IR images and binary images for R90 setup, Figure 5-35 (left), were visible contrary to the two other setups.

Regarding the fibre volume fractions as a parameter, this had no effect neither on the temperatures nor on the percentage of white area recorded for bending samples. This indicates that samples bent at high v_f did not suffer from major damage, otherwise, differences with values recorded for bending samples bent at low v_f would be seen. It is

reminded here that v_f represents the value under the roller when bent, and not values of v_f in the reinforcements during IR tests.

Shear samples were tested at two different number of layers. Both shear plans that used temperatures and percentage of white area as values for analysis gave a similar outcomes as in bending samples. There was no significant effect of the number of layers on both temperatures and percentage of white area recorded data as long as exposure times are accomodated. This outcome was expected as it validates the comparison made between the 8/3 layers samples at 5 and 10 seconds with the 12/4 layers samples at 10 and 15 seconds.

Chapter 6

Conclusions

6.1 Introduction

Novel non-crimp dry thick fabrics were manufactured using the uO-APT process to cover the growing need for thick preforms in the aerospace applications. The material behaviour of such thick preforms had to be probed towards introducing the reinforcements to the composite industry. The bending and in-plane shear behaviours were investigated using significant numbers of tests performed with a new bending apparatus designed and manufactured at UOttawa in the context of this thesis, and the well-known articulated frame shear test.

Analysis of the results obtained for samples made from the new uO-APT reinforcement fabric in bending and in-plane shear tests, was conducted from experimental and analytical

bases. This was conducted experimentally through comparing the results obtained for uO-APT samples with results obtained for samples made from an industrial fabric manufactured by GmbH Saertex. The analytical validation was conducted through systematic Taguchi [207] plans.

Finally, non-destructive infrared thermography was used for inspecting the same samples tested in bending and shear. The innovative method aimed at detect defects in samples made from uO-APT and Saertex industrial preforms, induced by manufacturing and by testing.

In this Chapter, results obtained from bending, shear and IRT tests are discussed and conclusions are reached through analysing and combining all different results that were obtained in previous chapters.

6.2 Bending behaviour of stitched textile reinforcements

The bending behaviour of the new uO-APT preforms was investigated based on six main experimental parameters using an innovative bending rig design. The first experimental parameter investigated the effect of the type of preforms on the bending behaviour. The second experimental parameter investigated the effect of number of layers on the bending behaviour. The third experimental parameter investigated the effect of different fibre volume fractions on the bending behaviour. The fourth experimental parameter investigated the effect of stitching directions bending behaviour. The fifth experimental parameter investigated the effect of rovings orientations on the bending behaviour. The

last experimental parameter investigated the effect of number of cycles on the bending behaviour.

6.2.1 Bending moment and moment of inertia

The first step in this work was the introduction of a new bending rig for measuring the bending moment generated as a thick dry reinforcements sample was bent at constant curvature. Validation of the bending moments, was conducted through two mathematical formulas, the curvature formula and the deflection formula. Both formulas needed sample cross-section moments of inertia. These values were calculated using three different models, the fibre model, the cantilever model and the yarn model. The experiment-based cantilever model proved to give the most reasonable values among three of them, indicating some level of cohesion in yarns. Bending moments for samples were in good general agreement with experimental results.

6.2.2 Effect of type of fabric on bending behaviour

The effect of the type of fabric was seen by comparing bending moment values of group A3 samples which made from uO-APT fabrics, with group B3 samples which made from Saertex industrial fabrics. Both groups featured similar v_f values and shared stitching directions. Bending moment curves and data for both groups of samples are listed in Appendix C and D respectively. Figures and curves show bending moments of different amplitudes. The average bending moment values obtained from bending tests conducted on both types of fabrics were also analysed in Chapter 3 using two 2-level, 5 parameters

Taguchi [207] plans. The analysis shows that uO-APT fabrics behave differently from Saertex industrial fabrics in bending. Samples made from uO-APT recorded bending moment values higher than those samples made from Saertex industrial fabrics. Results show clearly that the type of fabric has the strongest effects on bending moment values. This was related mainly to the different type of assemblies and yarn size. UO-APT fabrics are assembled by stitches that extend through the whole thickness, while in Saertex industrial fabrics stitching are made through each reinforcement layer only. Assembly stitching types was seen to have a strong influence on bending behaviour especially in thick fabrics. The stitching type is therefore a crucial factor that affects the mobility of yarns and the ability of fabrics to bend and drape. Bending analysis shows that Saertex fabrics are more flexible than uO-APT fabrics, because of the nature of stitching in Saertex fabrics. It has been found that Saertex fabric gained their compliant nature from the type of stitching threads.

6.2.3 Effect of number of yarn layers on bending behaviour

The effect of the number of yarn layers was investigated by testing two different numbers of layers, 8 and 12 for uO-APT fabrics, and 3 and 4 for Saertex fabrics. Samples made from uO-APT fabrics with 8 stacked layers of yarns featured a thickness of 2 mm at 45% v_f , while Samples with 12 stacked layers featured a thickness of 3 mm at the same v_f . On the other hand, Samples made from Saertex industrial fabrics with 3 stacked layers featured a thickness of 2 mm at 45% v_f , while samples with 4 stacked layers featured a thickness of 3 mm at the same v_f . Analysis shows that thicknesses ranging between 2 and 3 mm had no significant influence on the bending behaviour for both types of fabrics. This finding

confirms the possibility of bending of uO-APT fabrics with thicknesses of 3 mm and more on a single curvature of 50 mm radius.

6.2.4 Effect of fibre volume fraction on bending behaviour

The effect of the fibre volume fraction (v_f) was investigated using samples from both type of fabrics with two different fibre volume fractions, nominally 45% and 60%. These two fibre volume fractions were enforced through using different spacer sizes on the bending apparatus. The effect of different fibre volume fractions appeared clearly on the values of the bending moment recorded in bending tests. Figures included in Appendix C and bending moment data listed in Appendix D show that the bending moments recorded for all samples made from both types of fabrics at 60% v_f were higher than those recorded at 45% v_f . The same conclusion was reached from the Taguchi analysis conducted in Chapter 3. Although differences in average bending moments were in the range between 50 and 150 Nmm for uO-APT samples, and between 20 and 120 Nmm for Saertex samples, the effect of v_f on the relative change in moment could be recorded using the bending test procedure.

6.2.5 Effect of stitching directions on bending behaviour

UO-APT fabrics were made from symmetrical stacks of yarns running at 0° and 90°, assembled by stitching through the whole thickness. From this, arose the necessity to investigate the effect of stitching direction on the bending behaviour of the fabrics. Two stitching directions were investigated for uO-APT reinforcement fabrics, R0 and R90.

Saertex industrial fabrics were made from two layers of yarns with stitch lines running at -45° and $+45^\circ$ assembling each two layers of yarns. Four stitching directions were investigated for Saertex reinforcement fabrics, R0, R90, R-45 and R+45.

The analyses conducted on the bending moment in Chapter 3 confirm that stitching directions have an influence on the bending behaviour for both types of reinforcement fabrics. This influence is seen in all curves presented in Appendix C for uO-APT samples tested in the R0 setup, where higher bending moments were recorded as the roller moved over the stitch lines. In uO-APT samples tested in the R90 setup the effect in the form of shifting the bending moment curves up as the roller moved over stitch lines during the whole bending test. The same effect was captured for samples made from Saertex fabrics tested at R0 and R90. Saertex samples tested at R-45 and R+45 showed a similar effect on values of the bending moment as for R90 setup.

It should be noted that the effect of stitching directions in bending test was limited primarily to the interaction between the roller and stitching lines. So, all the aforementioned stitching directions may be used without major influence on the bending behaviour of both types of reinforcement fabrics.

6.2.6 Effect of roving orientations on bending behaviour

Two roving orientations, $0^\circ/90^\circ$ rovings and $-45^\circ/+45^\circ$ rovings, were investigated in bending tests for samples made from both types of fabrics. Taguchi analyses conducted on both types of fabrics in Chapter 3 showed conflicting results. Two plans were used for investigating the effect of roving orientations; one used the average value of the bending

moment and the other used the standard deviation. Plan using the average value of the bending moment showed that roving orientations had an effect, although this was not significant, on the bending behaviour of samples. Conversely, the plan using the standard deviation as the response value for analysis showed that the roving orientations had no effect on bending.

By comparing bending moment curves and average bending moment data presented in Appendix C and D respectively for group A1 samples which made from uO-APT fabrics and featured roving orientations $0^{\circ}/90^{\circ}$, and group A3 samples which also made from uO-APT fabrics, but featured roving orientations $-45^{\circ}/+45^{\circ}$, the effect of roving orientations could not be seen clearly. Similar findings obtained when comparing groups B1 and B3 samples made from Saertex industrial fabrics.

The effect of rovings was also investigated in Chapter 3 using Taguchi analysis. The analysis also reveals that roving orientations had little effect on the bending behaviour for both types of fabrics.

6.2.7 Effect of number of cycles on bending behaviour

The effect of the number of cycles on values of the bending moment was very clear for all samples and both types of fabrics. Taguchi analyses presented in Chapter 3 prove this effect. Curves presented in Appendix C and bending moment data presented in Appendix D show that samples bent on a first cycle return higher bending moments when compared with following cycles. This effect is related to the compaction and rearrangement of yarns that occurred during each cycles. It should be noted that each test was repeated for the

same sample for 3 to 4 cycles without removing the samples from the apparatus. Samples showed no signs of damage upon examination after removal from the bending apparatus.

6.3 In-plane shear behaviour of stitched textile reinforcements

The in-plane shear behaviour for both uO-APT and Saertex samples was investigated through four main parameters using an articulated frame shear rig. The first parameter investigated the effect of the type of reinforcements on in-plane shear behaviour. The second parameter investigated the effect of the number of layers on in-plane shear behaviour. The third parameter investigated the effect of stitch directions on in-plane shear behaviour. The last parameter investigated the effect of the number of cycles on in-plane shear behaviour.

6.3.1 Shear locking angle and shear force

Shear locking angle is a common criteria used when investigating shear behaviour of textiles before wrinkles appear. The shear locking data obtained for uO-APT fabrics were compared with those obtained for Saertex industrial fabrics, and were tabulated in Appendix F. Shear force curves and average shear force data for both types of fabrics were also included and tabulated in Appendix E and Appendix G respectively. Both results were analysed and compared using three Taguchi plans that were presented in Chapter 4.

6.3.2 Effect of number of layers on in-plane shear behaviour

The effect of the number of layers on in-plane shear behaviour of uO-AOT fabrics was analysed from results of groups A4 and A5 samples. Group A4 shear samples made from uO-APT fabrics were manufactured from 8 layers yarns while group A5 shear samples featured 12 layers of yarns. Shear force curves for both groups presented in Appendix E showed similar in-plane shear behaviour.

Shear locking angle values listed in Appendix F for samples featuring 12 layers yarns ranged between 56° and 59° for the first cycle, and between 60° and 62° for the fourth cycle, while for samples featured 8 layers of yarns, shear locking angles ranged between 58° and 60° for the first cycle and ranged between 60 and 62 ° for the fourth cycle.

Shear force data presented in Appendix G showed that the average shear force for samples featuring 12 layers of yarns ranged between 22 N and 28 N for the first cycle and between 12 N and 16 N for the fourth cycle, while for samples featured 8 layers of yarns the average shear force ranged between 11 N and 20 N for the first cycle and between 8 N and 18 N for the fourth cycle.

The effect of the number of layers on the in-plane shear behaviour of uO-APT samples was also investigated in Chapter 4 using Taguchi analysis. The analysis revealed a similar conclusion, that number of layers had no significant influence on the in-plane shear behaviour of uO-APT fabrics.

6.3.3 Effect of type of fabric on in-plane shear behaviour

The effect of the type of fabric was analysed from the results of groups A6 and B6 samples. Groups A6 and B6 samples shared the same features except for the type fabric. Shear force curves for both groups presented in Appendix E show differences in in-plane shear behaviour.

The effect of the type of fabric on the shear behaviour was investigated in Chapter 4 using Taguchi analysis. The analysis showed that the type of fabric has a major influence on the in-plane shear behaviour. This was expected as both fabrics are assembled differently.

6.3.4 Effect of stitching setups on in-plane shear behaviour

The effect of R-45 vs. R+45 stitching directions was analysed using groups A4 and A5 samples. Shear force curves for both groups presented in Appendix E show similar in-plane shear behaviour.

Shear locking angle values listed in Appendix F for sub-group A4/R-45 samples ranged between 58° and 60° for the first cycle, and between 60° and 62° for the fourth cycle, while for sub-group A4/R+45 samples, shear locking angles were about 58.5° for the first cycle and about 61° for the fourth cycle. For sub-group A5/R-45 samples shear locking angles ranged between 56° and 58.5° for the first cycle and ranged between 60° and 61° for the fourth cycle. For sub-group A5/R+45 samples, shear locking angles were about 58° for the first cycle and ranged between 60.5° and 61.5° for the fourth cycle.

Shear force data presented in Appendix G show that the average shear force for sub-group A4/R-45 samples ranged between 11 N and 20 N for the first cycle, and between 5 N and 18 N for the fourth cycle, while for sub-group A4/R+45 samples the average shear force ranged between 13 N and 16 N for the first cycle, and between 10 N and 12 N for the fourth cycle.

Results from both stitching setups were in the same range. Similar findings were reached when comparing both stitching configurations for sub-groups A5/R-45 and A5/R+45. The effect of R-45 and R+45 stitch directions was also investigated in Chapter 4 using Taguchi analysis. The analysis revealed that R-45 and R+45 stitching directions had limited effect on the in-plane shear behaviour of uO-APT fabrics. This was expected as both stitching directions have the same shear setup effect.

The effect of R0 vs. R90 stitching setups was analysed using groups A6 and B6 samples. Shear force curves for both groups presented in Appendix E show differences in in-plane shear behaviour.

Shear locking angle values listed in Appendix F for sub-group A6/R0 samples ranged between 58° and 60° for the first cycle, and between 61° and 63° for the fourth cycle, while for sub-group A6/R90 samples shear locking angles ranged between 55° and 57° for the first cycle and between 59° and 61° for the fourth cycle. For sub-group B6/R0 samples, shear locking angles were about 58.5° for the first cycle and about 61.5° for the fourth cycle, while for sub-group B6/R90 samples, shear locking angles ranged between 34° and 36° for the first cycle and it is ranged between 45° and 46° for the fourth cycle. Results

showed strong differences in shear locking angles between R0 and R90 setups in both groups.

Shear force data presented in Appendix G show that the average shear force for sub-group A6/R0 samples ranged between 35 N and 66 N for the first cycle, and between 8 N and 12 N for the fourth cycle, while for sub-group A6/R90 samples average shear force ranged between 16 N and 20 N for the first cycle and ranged between 5 and 6 N for the fourth cycle.

Differences in results between R0 and R90 stitching setups related mainly to the direction of force applied on stitching lines during shear tests. Stitching lines at R0 setup aligned horizontally which mean stitching lines were under compression load while in R90 setup stitching lines were under tension load.

Similar findings were obtained when comparing shear forces for both stitching configurations of sub-group B6/R0 and B6/R90. The effect of R0 and R90 stitch directions was also investigated in Chapter 4 using Taguchi analysis. The analysis also reveals that R0 and R90 stitching setups had strong effect on the in-plane shear behaviour for both types of fabrics. This was expected as both stitching setups exposed to different applied force.

Stitching setups R-45 and R+45 show better in-plane shear behaviour than R0 and R90, which suggested that the former stitching directions should be used in assembling uO-APT fabrics if the ability to shear is to be promoted. It should be noted that R-45/R+45 stitching

directions related to the orientation of the sample within the shear rig, equivalent to 0°/90° stitching directions.

6.3.5 Effect of cycling on in-plane shear behaviour

The effect of cycles was very clear in all shear force curves presented in Appendix E. Shear locking angles and average shear force data listed in Appendix F and G respectively show the effect of cycles on the in-plane shear behaviour for both types of reinforcement fabrics, for all different stitching setups. All curves and results show lower shear locking angles and higher shear forces in the first cycle than in the three following shear cycles. This was expected as most of stitching failure occurred in the first cycle. It is worth noting, here again, that R-45/R+45 stitching setups were the stitching configurations least affected by cycles, of all shear tests.

6.4 IRT tests

An innovative non-destructive infrared thermography test procedure was conducted on samples made of dry thick fabrics of two different types. The test procedure used an infrared camera to capture images of the samples after being excited using a source of heat. All samples tested with this IRT test procedure were subjected either to bending or shearing. The method was used for identifying any flaws that may already exist in samples after being manufactured, or any type of defects that may arise in samples after being subjected to bending or shearing. Defects and flaws in samples appeared in IR images as

area of higher temperatures. These areas were further analysed by converting the IR images to binary images.

6.4.1 IR and binary images

IRT tests resulted in recording IR images that contained information about temperatures on the surface of the sample. IR images were converted to binary images using MATLAB 7.0 software. The resulting images and data for samples subjected to bending were included in Appendices H and I, while for samples subjected to shear they were included in Appendices K and L.

Binary images were used for calculating a percentage of white area that corresponds to high temperature zone in the IR images. Values of percentage of white area for samples subjected to bending were included in Appendix J, while for samples subjected to shear they were included in Appendix M.

6.4.2 Identifying thickness differences using IRT test

When samples made from different numbers of layers were exposed to a source of heat with the same exposure time pulse, different temperatures were captured on IR images for both types of reinforcement fabrics and for both groups of samples that were subjected to bending or shear. Figure 6-1 (left) shows an IR image for sample A4/R-45/S1 made from uO-APT fabric featuring 8 layers. Figure 6-1 (right) shows an IR image for sample A5/R-45/S1 made from uO-APT fabric featuring 12 layers. Both IR images were captured at 15 seconds pulse exposure time. *AVG* temperature were at 33°C for sample A4/R-45/S1 and at

29°C for sample A5/R-45/S; values are listed in Appendix L. As the thickness of samples increased, lower average temperature were recorded with the infrared camera. Although differences in numbers of layers between groups A4 and A5 were 2 layers, small differences still could be captured by the infrared camera.

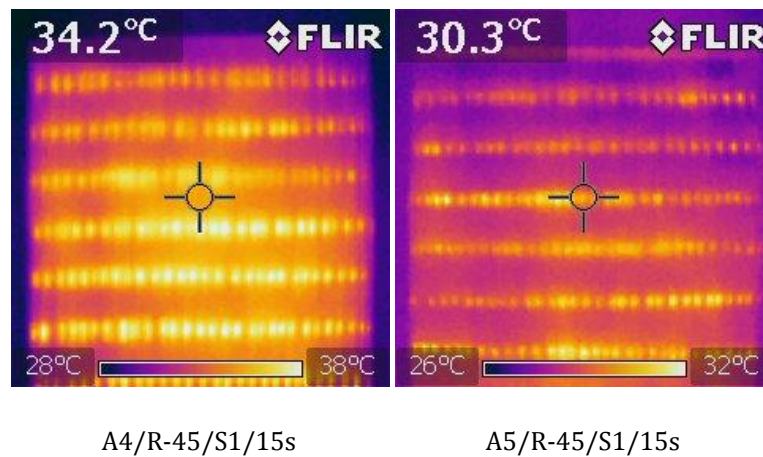


Figure 6-1: IR images for two samples made from uO-APT fabrics featuring different number of layers.

The first conclusion is the ability of IRT test to identify thickness differences between samples made from the same type of fabric. The Taguchi analysis conducted in Chapter 5 analysed different number of layers at different exposure time pulses. .

6.4.3 Identifying types of reinforcement fabric using IRT tests

Images for samples subjected to bending presented in Appendix H, and in Appendix K for those which were subjected to shear, highlight different structural details. Figure 6-2 shows IR images for samples made from different types of reinforcement fabrics. IR images captured different details on samples made from uO-APT fabrics, Figure 6-2 (left), compared with samples made from Saertex industrial fabrics, Figure 6-2 (right).

The analysis conducted in Chapter 5 also shows that the type of reinforcement fabric has a very strong effect on IR and binary image data. This leads to the conclusion that IRT procedure has the ability to identify different fabric types.

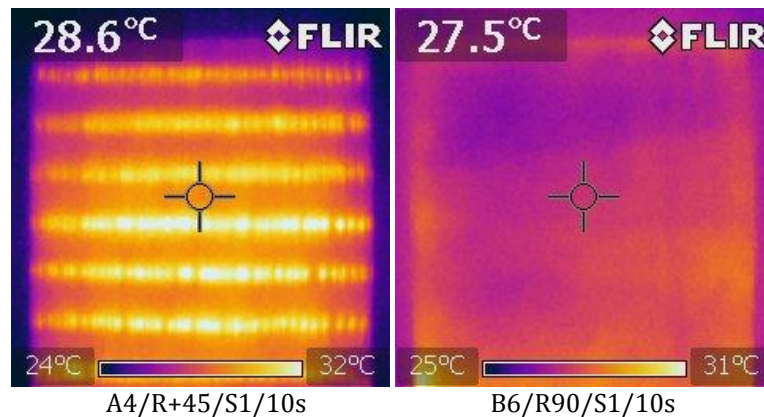


Figure 6-2: IR images for samples made from different types of fabrics.

6.4.4 Identifying fibre distributions using IRT test

By examining images for samples subjected to bending presented in Appendix H, fibre distributions within samples made from the same type of reinforcement fabric and featuring the same number of layers and same exposure time pulse could be identified in IR images and binary images. The same conclusion can be made by examining images for samples subjected to shear that are presented in Appendix K. This shows the ability of the method to identify defects through the thickness, invisible to eye inspection.

IRT tests were also able to identify different fibre distributions within a sample. Figure 6-3 shows IR images and corresponding binary images for samples A1/45/R0/S2 and A1/45/R0/S3. Both samples are from the same sub-group A1/45/R0. Binary image in Figure 6-3 (left) shows that white area within sample A1/45/R0/S2 corresponds to less

fibre distribution at that area than surrounding area. In Figure 6-3 (right), binary images of A1/45/R0/S3 sample shows that the middle area has more fibres than the surrounding area appeared in white.

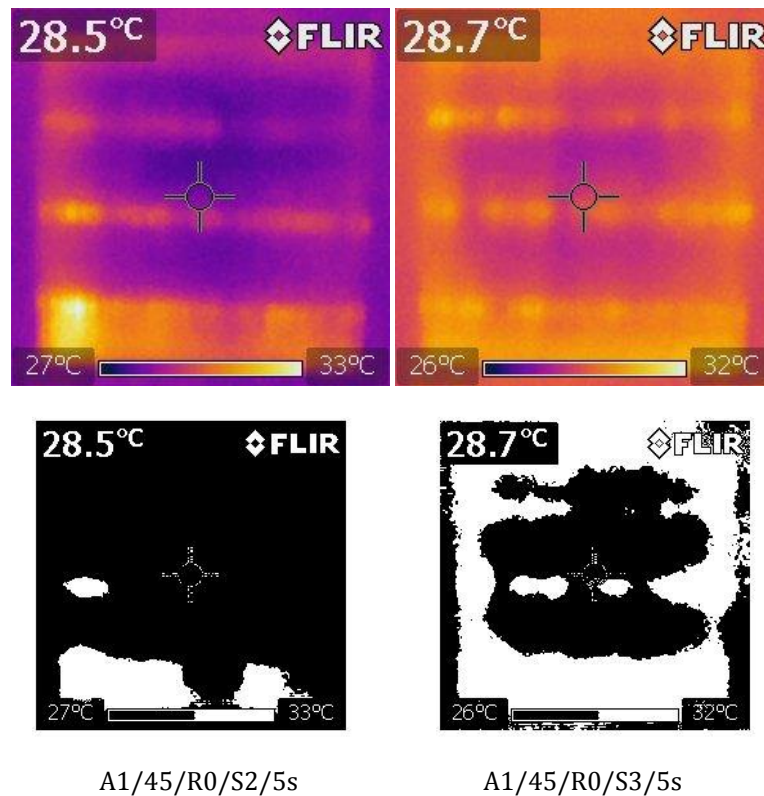


Figure 6-3: IR and corresponding binary images showing fibre distributions.

6.4.5 Identifying stitching defects using IRT test

Stitching lines in samples were visible in IR images presented in Appendix H and K. They were mostly recognized as areas of higher temperatures. Figure 6-4 (top) shows IR images for samples from different type of fabrics with different stitching setups. IR images were able to identify stitching orientations and defects within the stitches. These stitching defects can be highlighted by converting IR images to binary images as shown in Figure 6-4

(bottom). Defects in stitching lines appeared in binary image of type A samples as white strips. As these white strips became wider around stitching lines, defects became more severe. Such stitching defects did not appear in binary images of type B samples. This is related to the different stitching assembly methods used with Saertex industrial samples.

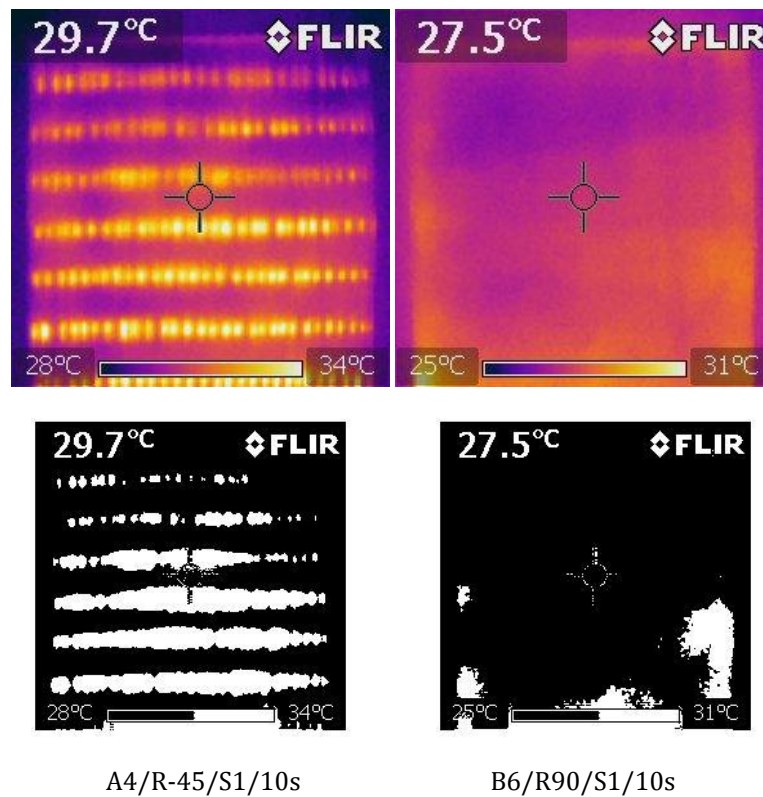


Figure 6-4: IR images and corresponding binary images identify stitching lines in uO-APT sample (left),
absence of stitching lines in Saertex sample (right).

Infrared thermography was also able to identify failure that might occur in stitching threads for those samples made from uO-APT fabrics. By examining images of samples subjected to bending and made from uO-APT fabrics presented in Appendix H, stitching threads showed no sign of failure.

By examining images of samples subjected to in-plane shear and made from uO-APT fabrics presented in Appendix K, stitching threads showed no sign of failure for R-45, R+45 and R0 setups in contrary to R90 setup.

6.5 Summary of conclusions

General conclusions that were made in this work relating to bending tests, shear tests and IRT tests are summarised as follows:

- Shear tests and analysis show that uO-APT fabrics could be sheared up to about 55°. Shear tests done with different stitching orientations proved that R-45 and R+45 gave the best results.
- IRT tests proved the feasibility of using the technique in textile inspection. Using this non-destructive method, small differences in thickness, stitching defects and differences in fibre distributions could be identified.
- The bending apparatus design proved the possibility of measuring low bending moments needed to bend thick fabrics onto a single curvature. The measured bending moments ranged between 0 and 500 Nmm.
- Bending tests were conducted on samples made from uO-APT fabrics that featured 8 and 12 layers; analyses conducted on the results showed the ability of uO-APT fabrics to bend on a radius of 50 mm without buckling or stitch failure. Samples showed no signs of damage when tested 3 to 4 cycles.

- All stitching directions can be used without major influence on the bending behaviour.
- Analysis showed that type of fabric has a major influence on the in-plane shear.
- Analysis revealed that number of layers, 8 or 12, had no significant influence on in-plane shear.
- The stitching type is a crucial factor that affects the ability of fabrics to shear and drape.
- IRT tests showed the ability to identify thickness differences between samples made from the same type of fabric.
- IRT tests highlighted the need for improvements of the uOttawa stitching process.
- IRT procedure has the ability to identify different fabric types.
- IRT tests showed the ability to identify different fibre distributions within the same sample.
- Binary images obtained from IR images have the ability to capture stitching thread failures.

6.6 Future work

Further investigations in different aspects resulting from this work are worth conducting, some of which are listed here.

- The effect of different radii on bending could be investigated. The bending apparatus is able to test curvatures from about of 25 mm and up to about 100 mm.

- Radii sizes are limited by the current bending rig design. A new design that may enable smaller radii would be worth investigating.
- The infrared thermography setup used in this work featured portable elements. IRT tests should be performed using better equipment.
- The stitching type is a crucial factor that affects the ability of fabrics to bend and drape
- IRT tests done on uO-APT fabrics highlighted the need for improvements of the stitching process.

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Appendix A

Bending apparatus

A.1 Design dimensions of parts

Design dimensions for all part of the bending apparatus assembly shown in Figure 3-7are detailed in this appendix.

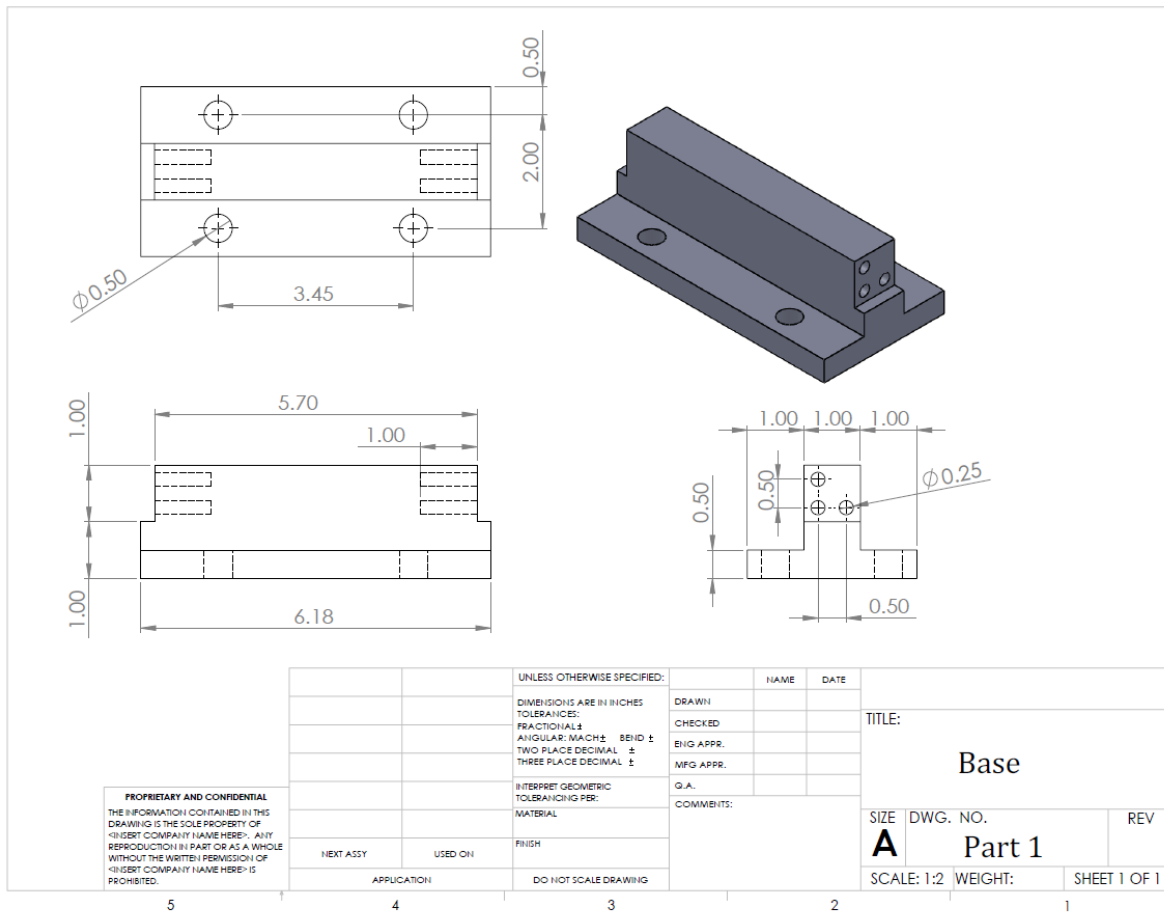


Figure A-1: Draw showing the dimensions of the base.

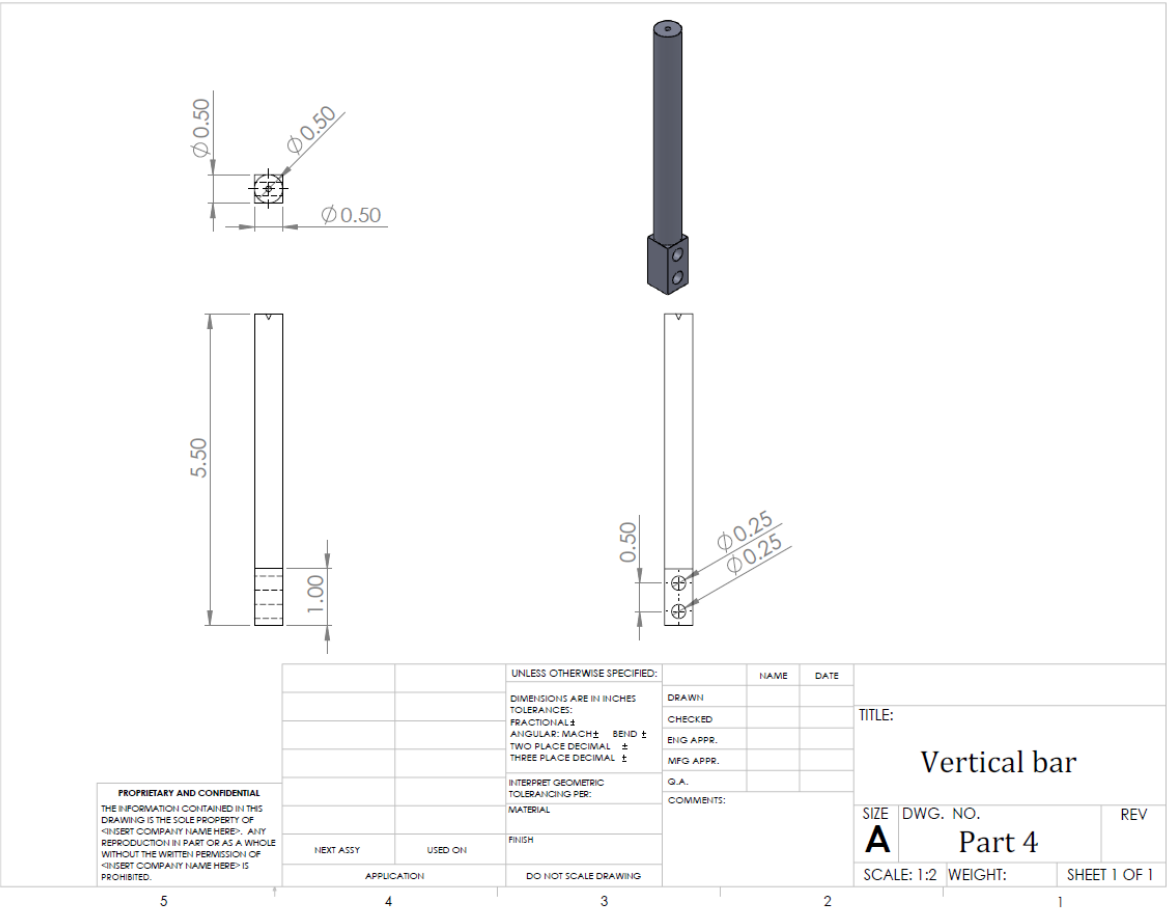


Figure A-4: Draw showing the dimensions of the vertical bar.

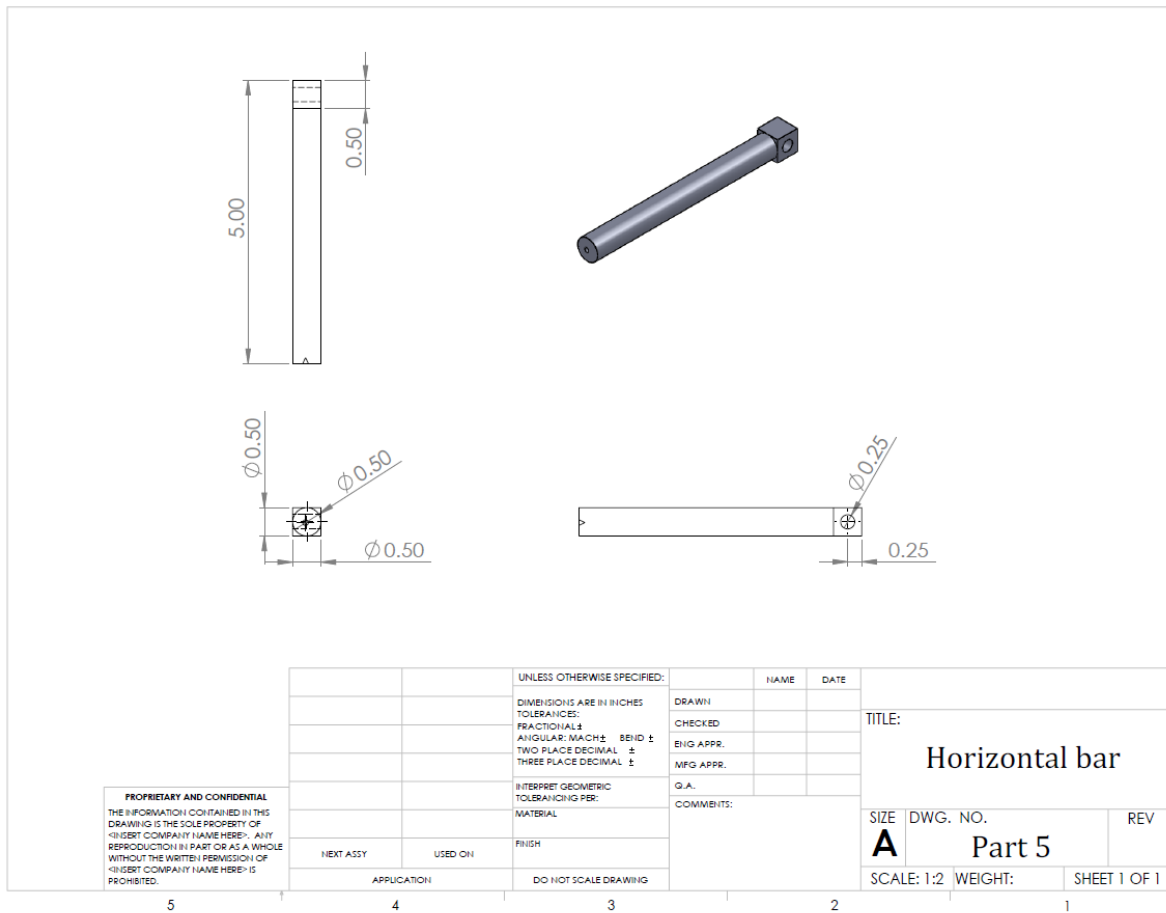


Figure A-5: Draw showing the dimensions of the horizontal bar.

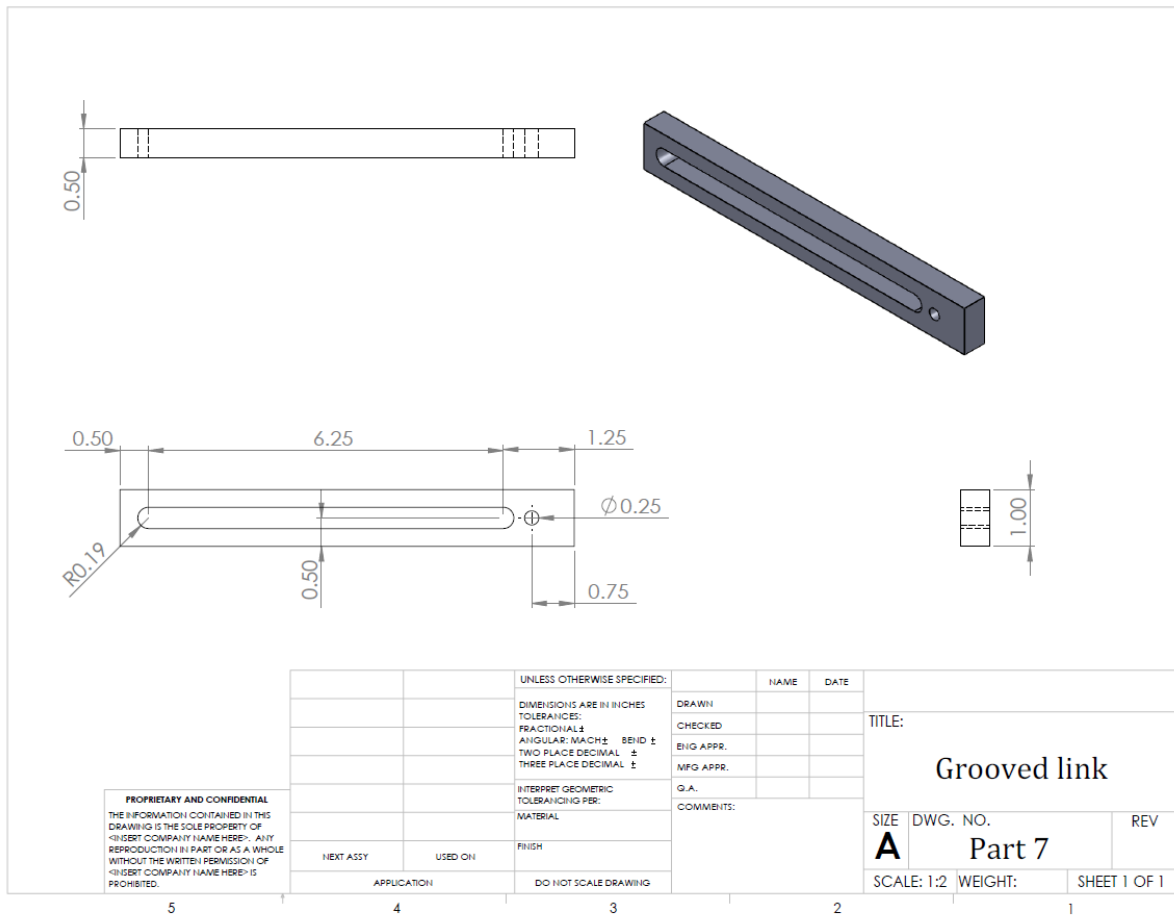


Figure A-7: Draw showing the dimensions of the grooved link.

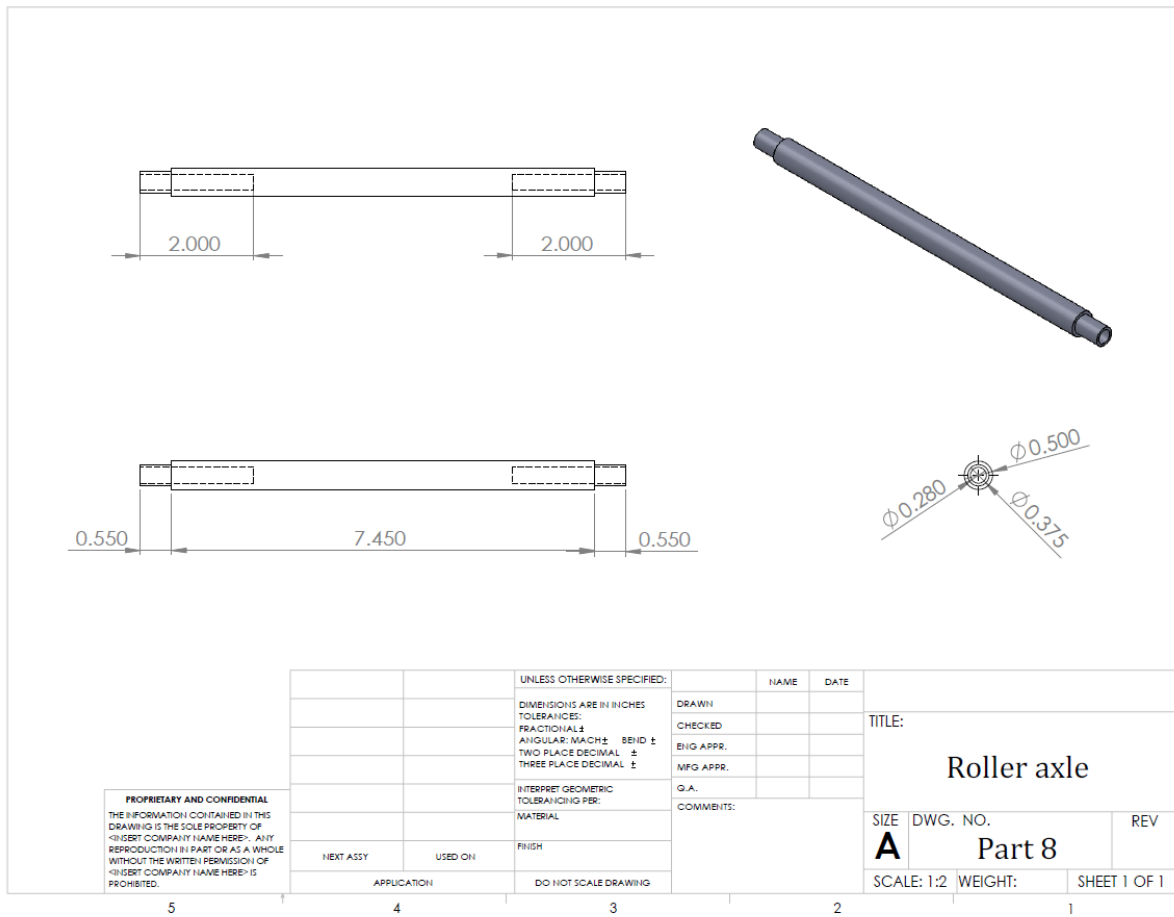


Figure A-8: Draw showing the dimensions of the roller axle.

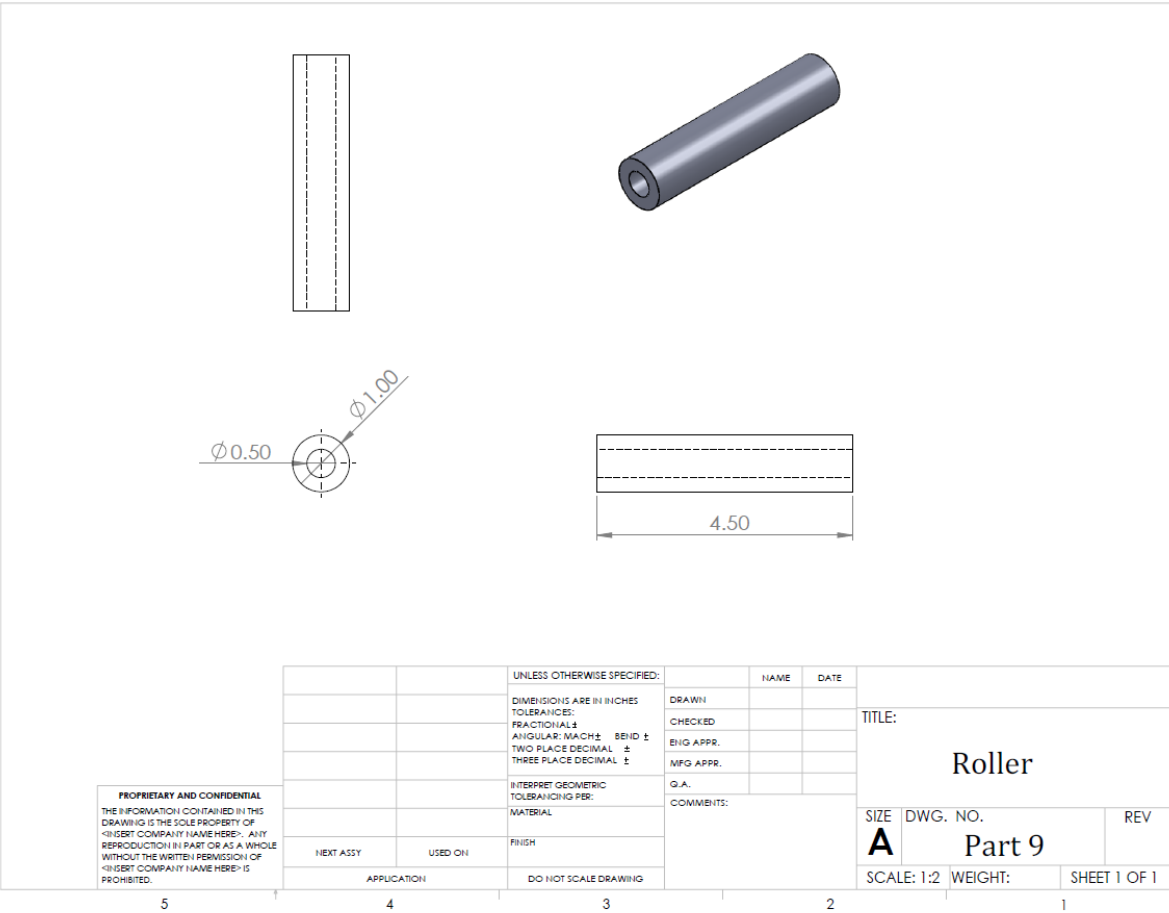


Figure A-9: Draw showing the dimensions of the roller.

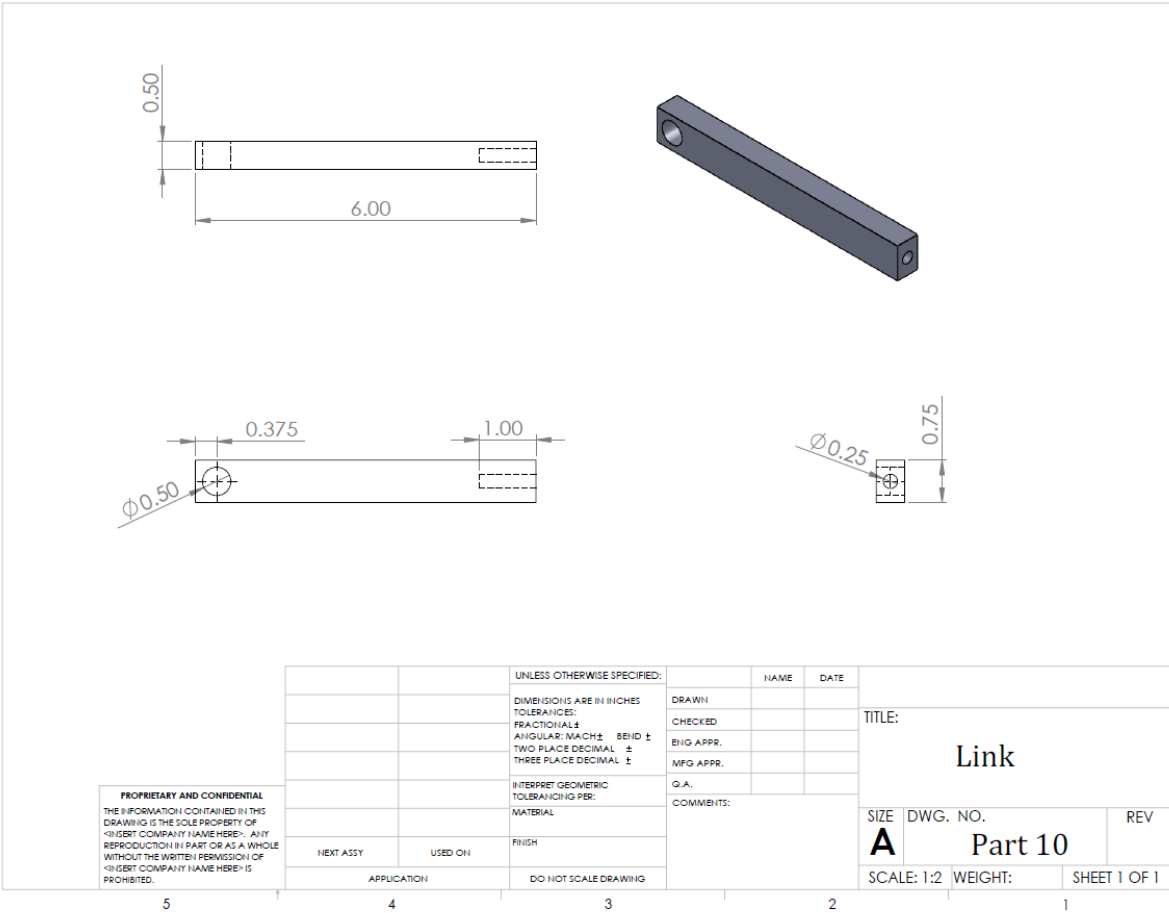


Figure A-10: Draw showing the dimensions of the link.

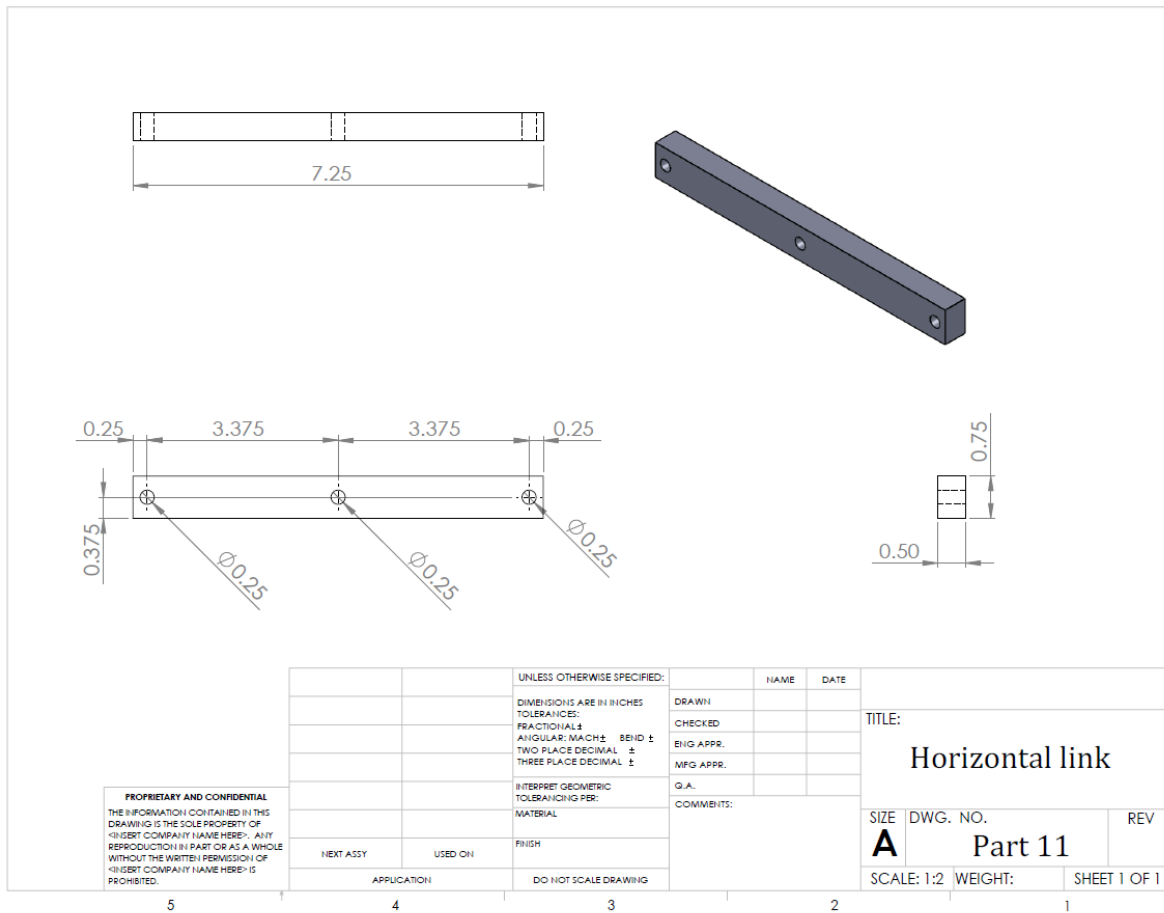


Figure A-11: Draw showing the dimensions of the horizontal link.

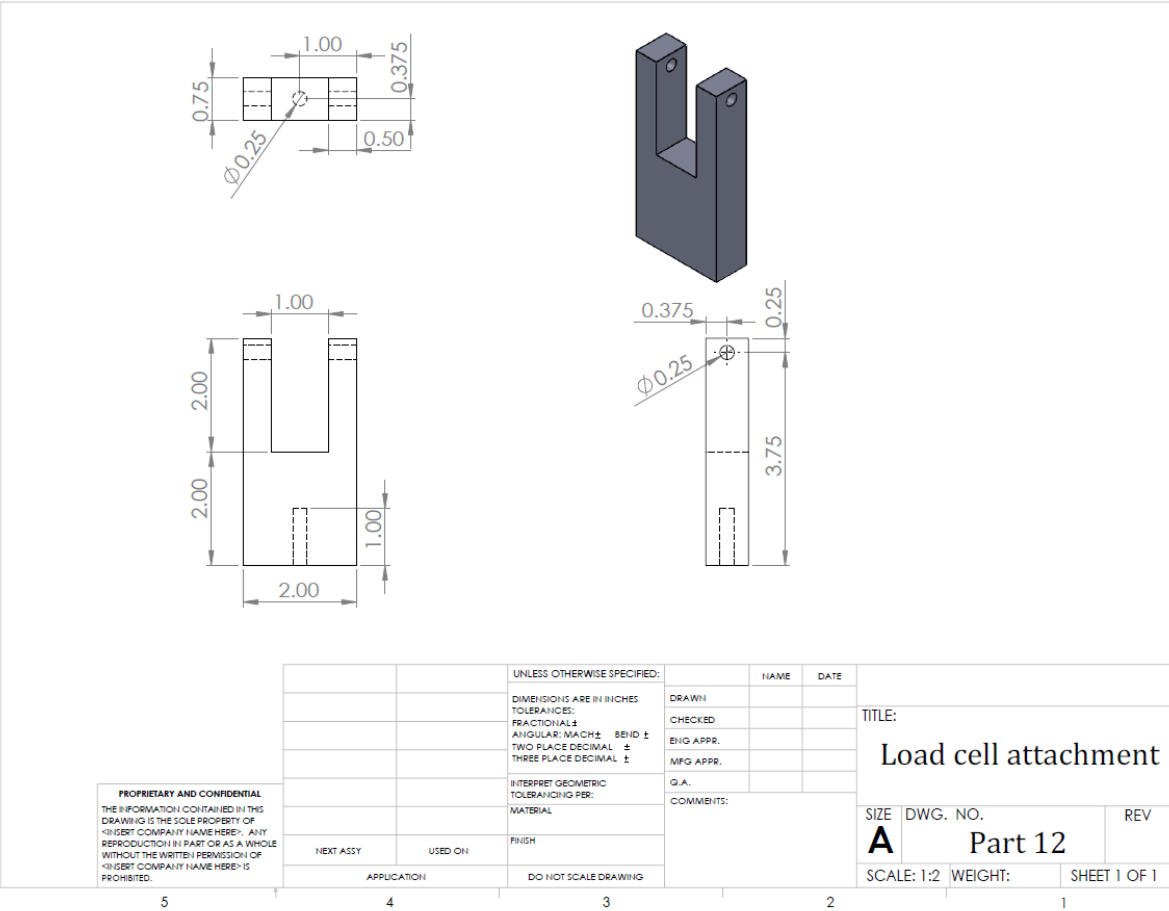


Figure A-12: Draw showing the dimensions of the load cell attachment.

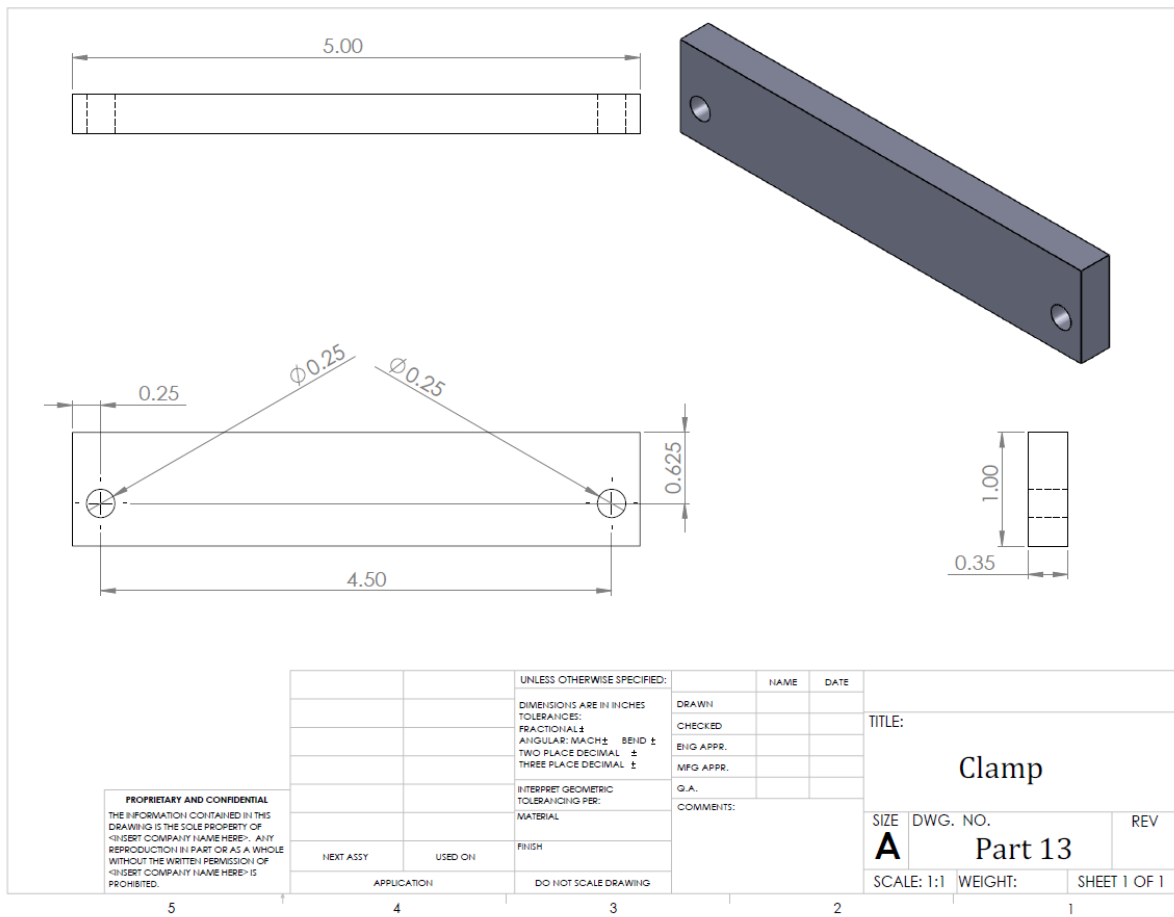


Figure A-13: Draw showing the dimensions of the clamp.

A.2 Design dimensions of spacers

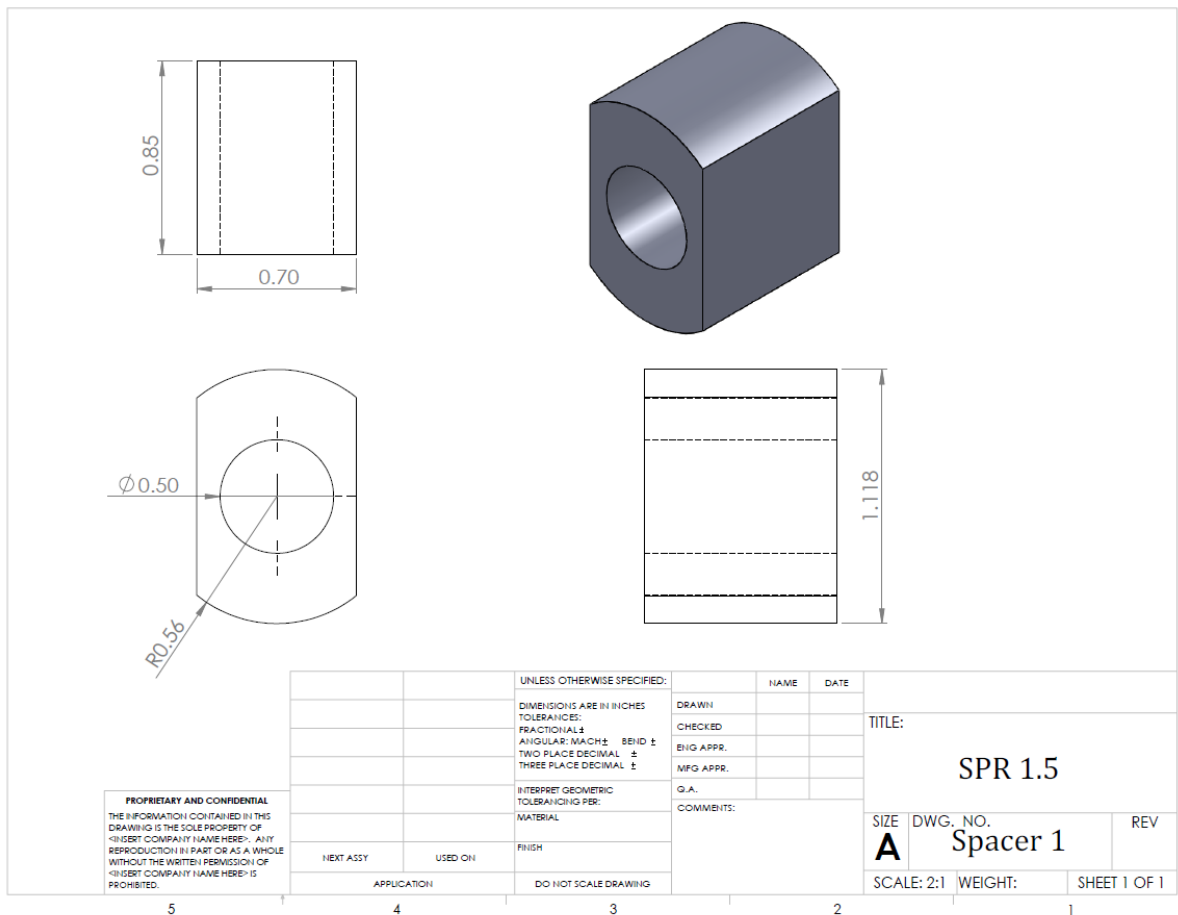


Figure A-14: Draw showing the dimensions of spacer 1.5 mm.

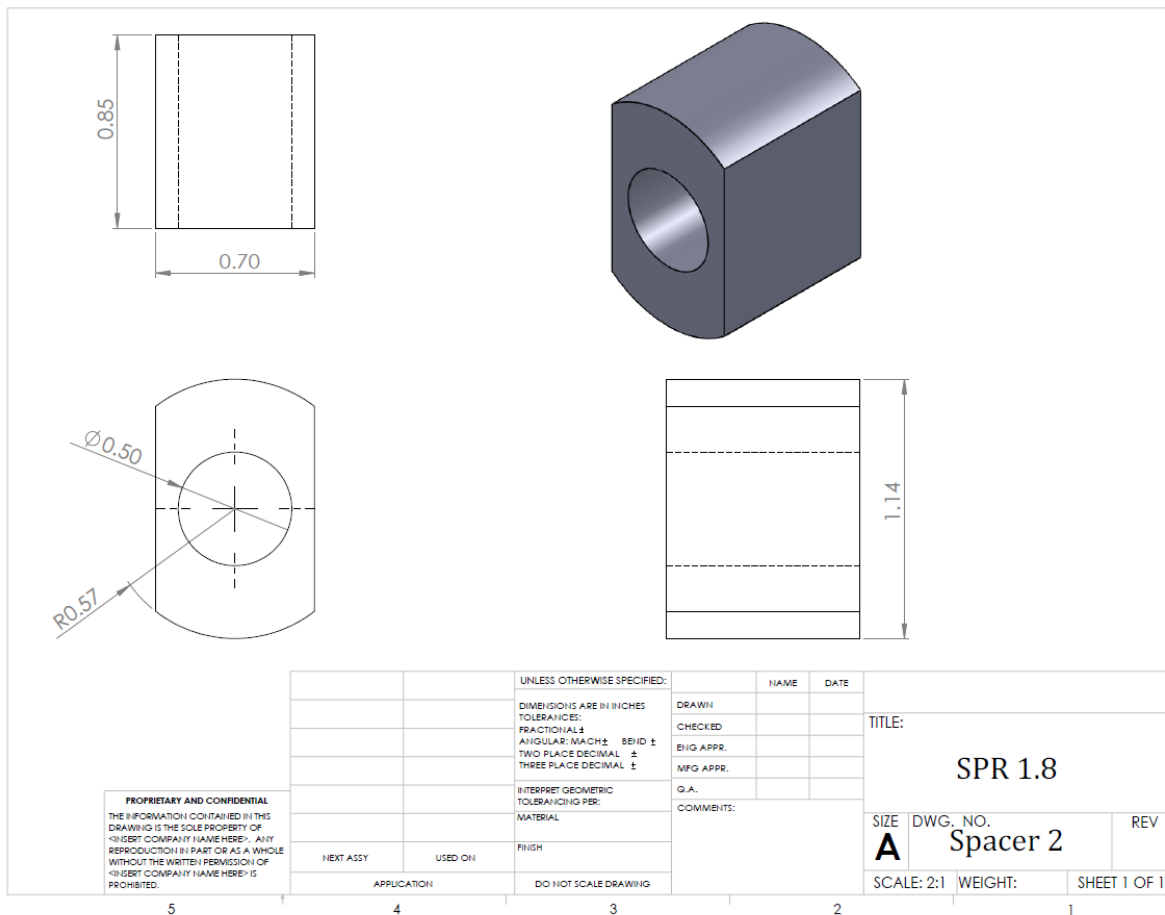


Figure A-15: Draw showing the dimensions of spacer 1.8 mm.

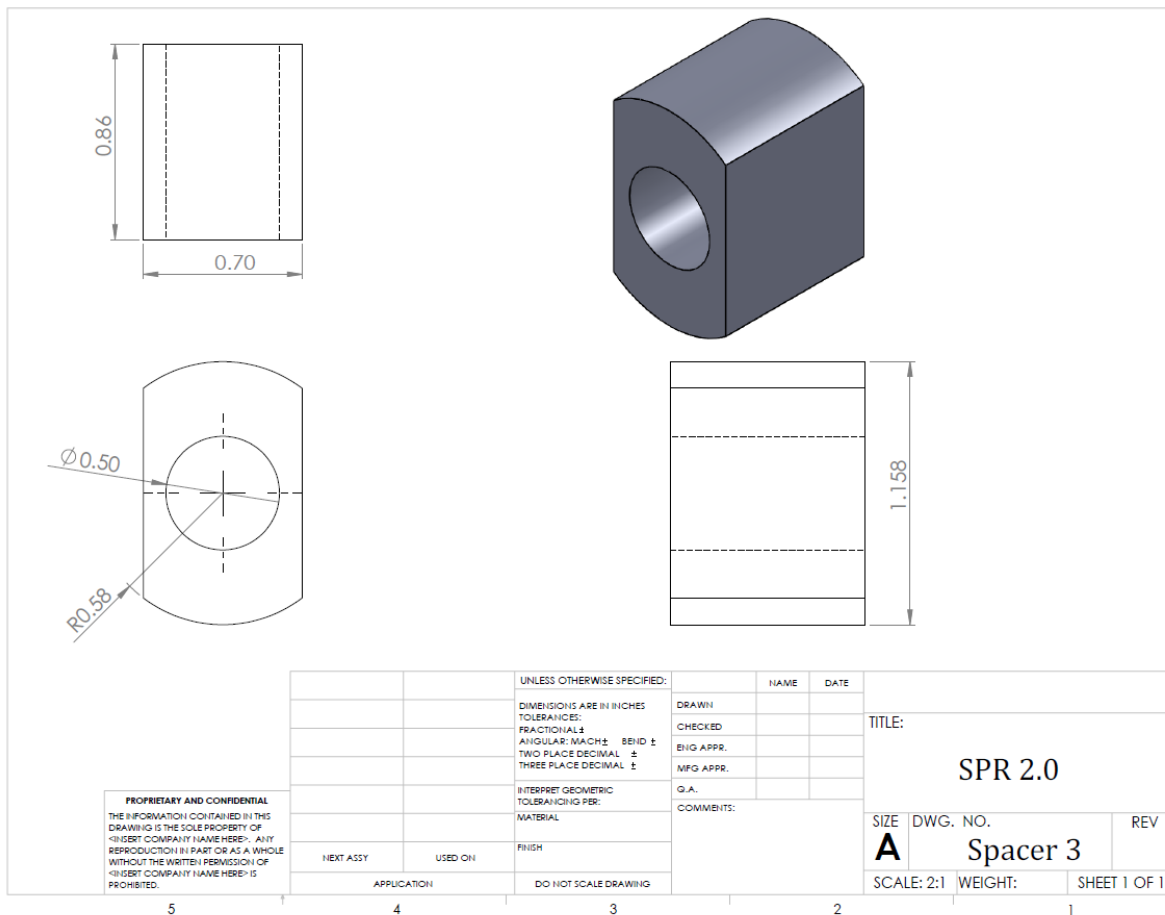


Figure A-16: Draw showing the dimensions of spacer 2.0 mm.

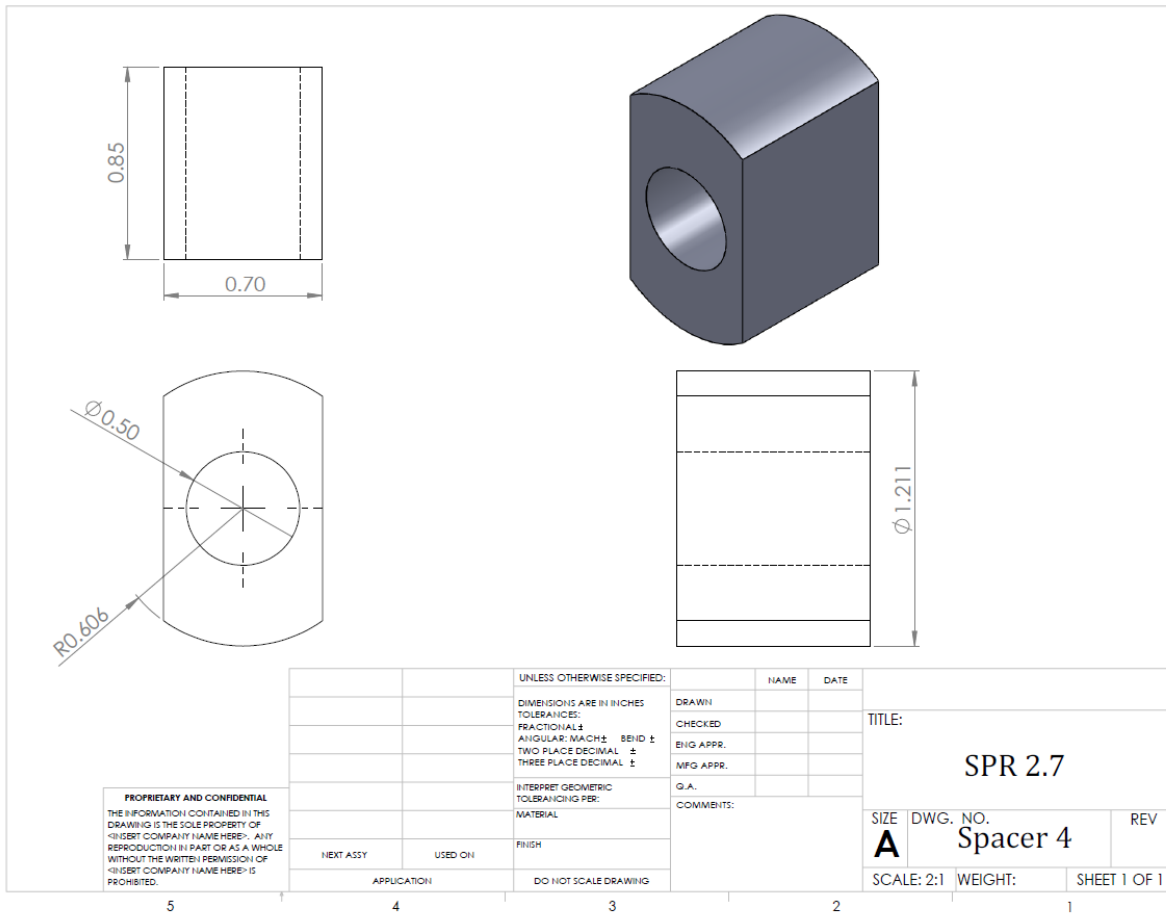


Figure A-17: Draw showing the dimensions of spacer 2.7 mm.

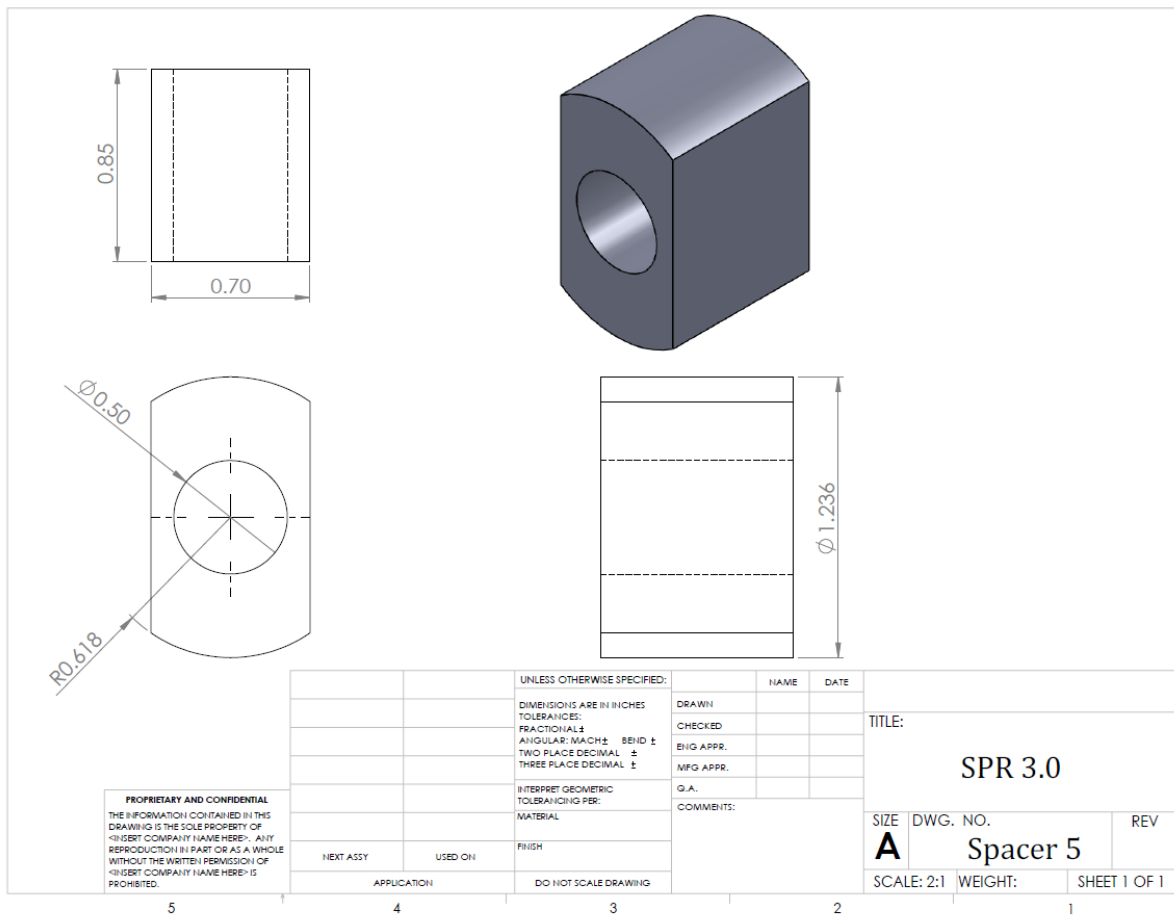


Figure A-18: Draw showing the dimensions of spacer 3.0 mm.

Appendix B

Angle calculations

B.1 Introduction

Values of α , θ and φ during bending test can be obtained from the recorded displacements for each spacer thickness accordingly. For each spacer the corresponding R and H is measured. L is the length of the link and has a constant value of 255 mm.

B.2 SPR 1.5

For a spacer thickness of 1.5 mm the measured R , H and the constant length L substituted in equations 3.16 to 3.20 and the corresponding α , θ and φ values can be then calculated. The result values for spacer 1.5 mm are listed in Table B-1.

Table B-1: Values of α , θ and φ during bending test for spacer thickness of 1.5 mm,
 $R = 65$ mm, $H = 313$ mm and $L=255$ mm.

D (mm)	$\cos (\alpha)$	$\alpha(^{\circ})$	$\sin (\theta)$	$\theta(^{\circ})$	$\cos (\theta)$	$\varphi(^{\circ})$
0	-0.866	150.035	0.407	24.011	0.913	5.954
1	-0.847	147.939	0.434	25.712	0.901	6.349
2	-0.829	145.964	0.459	27.318	0.888	6.718
3	-0.810	144.092	0.482	28.845	0.876	7.064
4	-0.791	142.305	0.505	30.305	0.863	7.390
5	-0.773	140.594	0.526	31.707	0.851	7.699
6	-0.754	138.948	0.546	33.059	0.838	7.993
7	-0.736	137.360	0.564	34.367	0.825	8.273
8	-0.717	135.823	0.583	35.636	0.813	8.541
9	-0.699	134.333	0.600	36.870	0.800	8.797
10	-0.681	132.884	0.617	38.073	0.787	9.044
11	-0.662	131.473	0.633	39.247	0.774	9.280
12	-0.644	130.096	0.648	40.395	0.762	9.508
13	-0.626	128.751	0.663	41.521	0.749	9.728
14	-0.608	127.436	0.677	42.624	0.736	9.940
15	-0.590	126.147	0.691	43.708	0.723	10.145
16	-0.572	124.884	0.704	44.774	0.710	10.342
17	-0.554	123.644	0.717	45.823	0.697	10.534
18	-0.536	122.425	0.730	46.856	0.684	10.719
19	-0.518	121.227	0.742	47.875	0.671	10.898
20	-0.501	120.048	0.753	48.881	0.658	11.071
21	-0.483	118.887	0.765	49.874	0.644	11.239
22	-0.465	117.742	0.776	50.856	0.631	11.402
23	-0.448	116.613	0.786	51.827	0.618	11.560
24	-0.430	115.499	0.796	52.788	0.605	11.713
25	-0.413	114.399	0.806	53.740	0.591	11.861
26	-0.396	113.313	0.816	54.683	0.578	12.005
27	-0.378	112.238	0.825	55.618	0.565	12.144
28	-0.361	111.176	0.834	56.545	0.551	12.279
29	-0.344	110.125	0.843	57.465	0.538	12.410
30	-0.327	109.08	0.8515	58.379	0.5243	12.536

B.3 SPR 1.8

Similarly, for a spacer thickness of 1.8 mm the values listed in Table B-2.

Table B-2: Values of α , θ and ϕ during bending test for spacer thickness of 1.8 mm,
 $R = 65.29$ mm, $H = 313.5$ mm and $L=255$ mm.

D (mm)	$\cos(\alpha)$	$\alpha(^{\circ})$	$\sin(\theta)$	$\theta(^{\circ})$	$\cos(\theta)$	$\phi(^{\circ})$
0	-0.871	150.547	0.400	23.575	0.917	5.878
1	-0.852	148.425	0.427	25.294	0.904	6.281
2	-0.833	146.431	0.453	26.914	0.892	6.655
3	-0.815	144.542	0.476	28.452	0.879	7.006
4	-0.796	142.742	0.499	29.920	0.867	7.337
5	-0.777	141.020	0.520	31.330	0.854	7.651
6	-0.759	139.364	0.540	32.688	0.842	7.948
7	-0.740	137.767	0.559	34.001	0.829	8.232
8	-0.722	136.223	0.577	35.274	0.816	8.503
9	-0.704	134.726	0.595	36.511	0.804	8.762
10	-0.685	133.272	0.612	37.716	0.791	9.012
11	-0.667	131.856	0.628	38.893	0.778	9.251
12	-0.649	130.476	0.643	40.043	0.766	9.481
13	-0.631	129.127	0.658	41.169	0.753	9.703
14	-0.613	127.809	0.673	42.274	0.740	9.918
15	-0.595	126.517	0.687	43.358	0.727	10.124
16	-0.577	125.252	0.700	44.424	0.714	10.324
17	-0.559	124.009	0.713	45.473	0.701	10.518
18	-0.542	122.789	0.725	46.506	0.688	10.704
19	-0.524	121.590	0.738	47.525	0.675	10.886
20	-0.506	120.409	0.749	48.530	0.662	11.061
21	-0.489	119.247	0.761	49.522	0.649	11.231
22	-0.471	118.101	0.772	50.503	0.636	11.395
23	-0.454	116.972	0.782	51.473	0.623	11.555
24	-0.436	115.858	0.793	52.433	0.610	11.709
25	-0.419	114.758	0.803	53.383	0.596	11.859
26	-0.401	113.671	0.812	54.325	0.583	12.005
27	-0.384	112.597	0.822	55.258	0.570	12.145
28	-0.367	111.535	0.831	56.183	0.557	12.282
29	-0.350	110.484	0.840	57.102	0.543	12.414
30	-0.333	109.44	0.8482	58.013	0.5297	12.543

B.4 SPR 2.0

For a spacer thickness of 2.0 mm the values the values listed in Table B-3.

Table B-3: Values of α , θ and ϕ during bending test for spacer thickness of 2.0 mm,
 $R = 65.5$ mm, $H = 314$ mm and $L=255$ mm.

D (mm)	$\cos(\alpha)$	$\alpha(^{\circ})$	$\sin(\theta)$	$\theta(^{\circ})$	$\cos(\theta)$	$\phi(^{\circ})$
0	-0.877	151.228	0.391	23.010	0.920	5.763
1	-0.858	149.067	0.419	24.758	0.908	6.175
2	-0.839	147.041	0.445	26.401	0.896	6.558
3	-0.820	145.126	0.469	27.958	0.883	6.916
4	-0.802	143.304	0.492	29.442	0.871	7.254
5	-0.783	141.563	0.513	30.865	0.858	7.572
6	-0.765	139.891	0.533	32.234	0.846	7.875
7	-0.746	138.280	0.553	33.557	0.833	8.163
8	-0.728	136.724	0.571	34.838	0.821	8.438
9	-0.710	135.216	0.589	36.083	0.808	8.701
10	-0.692	133.752	0.606	37.295	0.796	8.954
11	-0.673	132.327	0.622	38.476	0.783	9.196
12	-0.655	130.939	0.638	39.631	0.770	9.430
13	-0.637	129.584	0.653	40.762	0.757	9.655
14	-0.619	128.259	0.667	41.870	0.745	9.872
15	-0.601	126.962	0.681	42.957	0.732	10.081
16	-0.583	125.691	0.695	44.026	0.719	10.283
17	-0.566	124.444	0.708	45.077	0.706	10.479
18	-0.548	123.219	0.721	46.113	0.693	10.668
19	-0.530	122.016	0.733	47.133	0.680	10.851
20	-0.513	120.832	0.745	48.139	0.667	11.029
21	-0.495	119.666	0.756	49.133	0.654	11.201
22	-0.477	118.518	0.767	50.115	0.641	11.367
23	-0.460	117.386	0.778	51.085	0.628	11.529
24	-0.443	116.269	0.788	52.045	0.615	11.685
25	-0.425	115.167	0.799	52.996	0.602	11.837
26	-0.408	114.078	0.808	53.937	0.589	11.984
27	-0.391	113.003	0.818	54.871	0.575	12.127
28	-0.374	111.939	0.827	55.796	0.562	12.265
29	-0.357	110.887	0.836	56.714	0.549	12.399
30	-0.339	109.85	0.8446	57.625	0.5355	12.529

B.5 SPR 2.7

For a spacer thickness of 2.7 mm the values the values listed in Table B-4.

Table B-4: Values of α , θ and ϕ during bending test for spacer thickness of 2.7 mm,
 $R = 66.18$ mm, $H = 315$ mm and $L=255$ mm.

D (mm)	$\cos(\alpha)$	$\alpha(^{\circ})$	$\sin(\theta)$	$\theta(^{\circ})$	$\cos(\theta)$	$\phi(^{\circ})$
0	-0.884	152.069	0.379	22.283	0.925	5.648
1	-0.865	149.869	0.408	24.058	0.913	6.073
2	-0.846	147.812	0.434	25.721	0.901	6.467
3	-0.828	145.872	0.459	27.293	0.889	6.835
4	-0.809	144.030	0.482	28.790	0.876	7.180
5	-0.791	142.272	0.503	30.222	0.864	7.506
6	-0.773	140.587	0.524	31.598	0.852	7.815
7	-0.754	138.965	0.544	32.926	0.839	8.110
8	-0.736	137.399	0.562	34.211	0.827	8.390
9	-0.718	135.883	0.580	35.458	0.815	8.659
10	-0.700	134.413	0.597	36.671	0.802	8.917
11	-0.682	132.983	0.614	37.853	0.790	9.164
12	-0.664	131.590	0.629	39.008	0.777	9.402
13	-0.646	130.231	0.645	40.138	0.764	9.631
14	-0.628	128.903	0.659	41.245	0.752	9.852
15	-0.610	127.604	0.673	42.331	0.739	10.065
16	-0.592	126.331	0.687	43.398	0.727	10.271
17	-0.575	125.083	0.700	44.446	0.714	10.471
18	-0.557	123.858	0.713	45.479	0.701	10.664
19	-0.540	122.654	0.725	46.496	0.688	10.850
20	-0.522	121.470	0.737	47.499	0.676	11.031
21	-0.505	120.305	0.749	48.489	0.663	11.206
22	-0.487	119.157	0.760	49.467	0.650	11.376
23	-0.470	118.026	0.771	50.433	0.637	11.541
24	-0.453	116.911	0.781	51.389	0.624	11.700
25	-0.435	115.810	0.792	52.335	0.611	11.855
26	-0.418	114.723	0.801	53.271	0.598	12.006
27	-0.401	113.649	0.811	54.199	0.585	12.151
28	-0.384	112.588	0.820	55.119	0.572	12.293
29	-0.367	111.539	0.829	56.032	0.559	12.430
30	-0.35	110.5	0.8381	56.937	0.5456	12.563

B.6 SPR 3.0

For a spacer thickness of 3.0 mm the values the values listed in Table B-5.

Table B-5: Values of α , θ and φ during bending test for spacer thickness of 3.0 mm,
 $R = 66.5$ mm, $H = 315.5$ mm and $L=255$ mm.

D (mm)	$\cos(\alpha)$	$\alpha(^{\circ})$	$\sin(\theta)$	$\theta(^{\circ})$	$\cos(\theta)$	$\varphi(^{\circ})$
0	-0.887	152.537	0.373	21.885	0.928	5.578
1	-0.869	150.311	0.402	23.677	0.916	6.011
2	-0.850	148.235	0.428	25.354	0.904	6.412
3	-0.832	146.280	0.453	26.936	0.892	6.784
4	-0.813	144.425	0.476	28.440	0.879	7.134
5	-0.795	142.657	0.498	29.879	0.867	7.465
6	-0.777	140.963	0.519	31.260	0.855	7.777
7	-0.759	139.333	0.539	32.592	0.843	8.075
8	-0.740	137.761	0.557	33.880	0.830	8.359
9	-0.722	136.240	0.575	35.129	0.818	8.630
10	-0.704	134.765	0.593	36.344	0.805	8.891
11	-0.686	133.331	0.609	37.528	0.793	9.141
12	-0.668	131.935	0.625	38.684	0.781	9.381
13	-0.650	130.573	0.640	39.814	0.768	9.612
14	-0.633	129.243	0.655	40.921	0.756	9.836
15	-0.615	127.942	0.669	42.007	0.743	10.051
16	-0.597	126.667	0.683	43.074	0.730	10.259
17	-0.580	125.418	0.696	44.122	0.718	10.460
18	-0.562	124.192	0.709	45.153	0.705	10.655
19	-0.544	122.987	0.721	46.169	0.693	10.844
20	-0.527	121.803	0.733	47.171	0.680	11.026
21	-0.510	120.637	0.745	48.160	0.667	11.203
22	-0.492	119.489	0.756	49.136	0.654	11.375
23	-0.475	118.358	0.767	50.101	0.641	11.541
24	-0.458	117.243	0.778	51.055	0.629	11.702
25	-0.441	116.142	0.788	51.999	0.616	11.859
26	-0.423	115.056	0.798	52.934	0.603	12.010
27	-0.406	113.982	0.808	53.860	0.590	12.158
28	-0.389	112.922	0.817	54.778	0.577	12.301
29	-0.373	111.873	0.826	55.688	0.564	12.439
30	-0.356	110.84	0.8348	56.591	0.5506	12.574

Appendix C

Bending moment curves

C.1 Introduction

All bending moment curves result from bending tests conducted on both types of preforms are presented here. The curves represent the relation between the bending moment M_B and the bending rig angle θ .

C.2 UO-APT Samples

Bending moment curves result from bending tests conducted on type A samples for groups A1, A2 and A3 which they were prepared from uo-APT preforms are presented here.

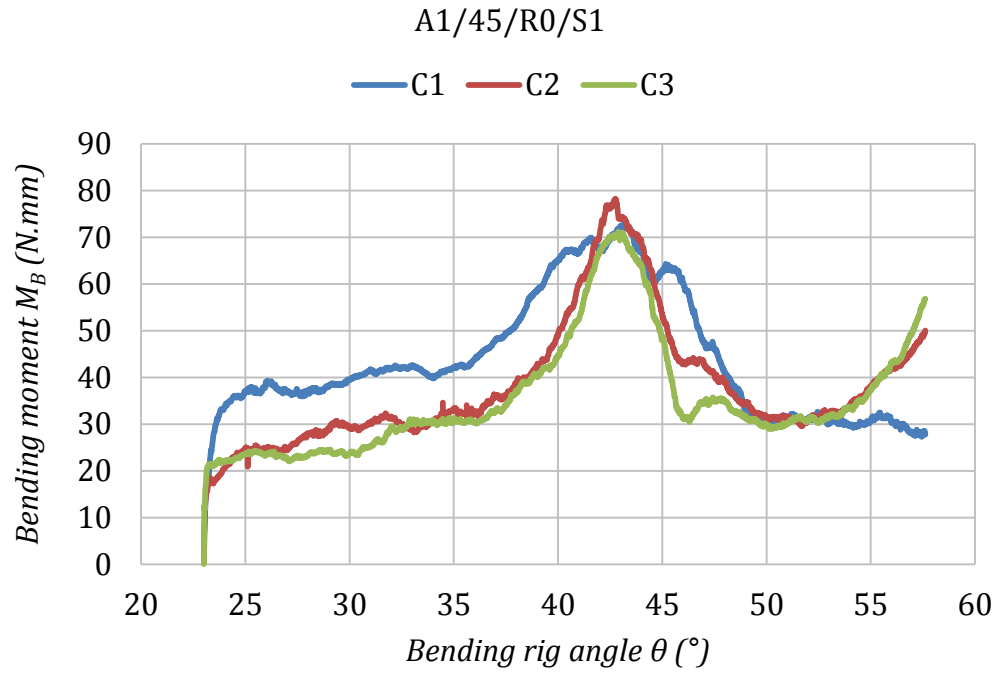


Figure C-1: Bending moment curves resulting from testing of sample A1/45/R0/S1.

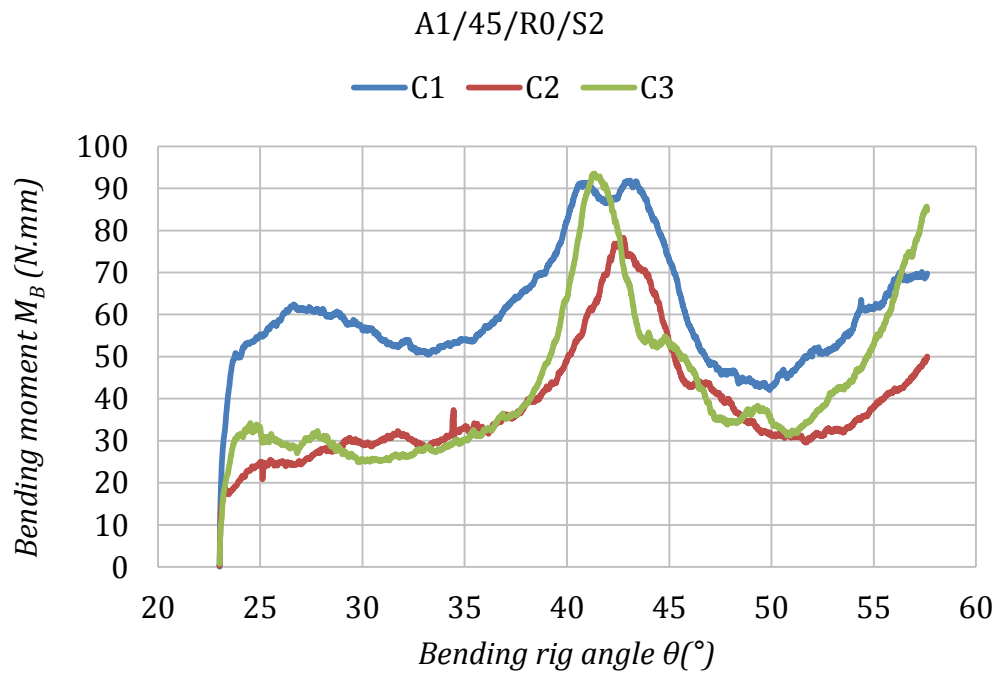


Figure C-2: Bending moment curves resulting from testing of sample A1/45/R0/S2.

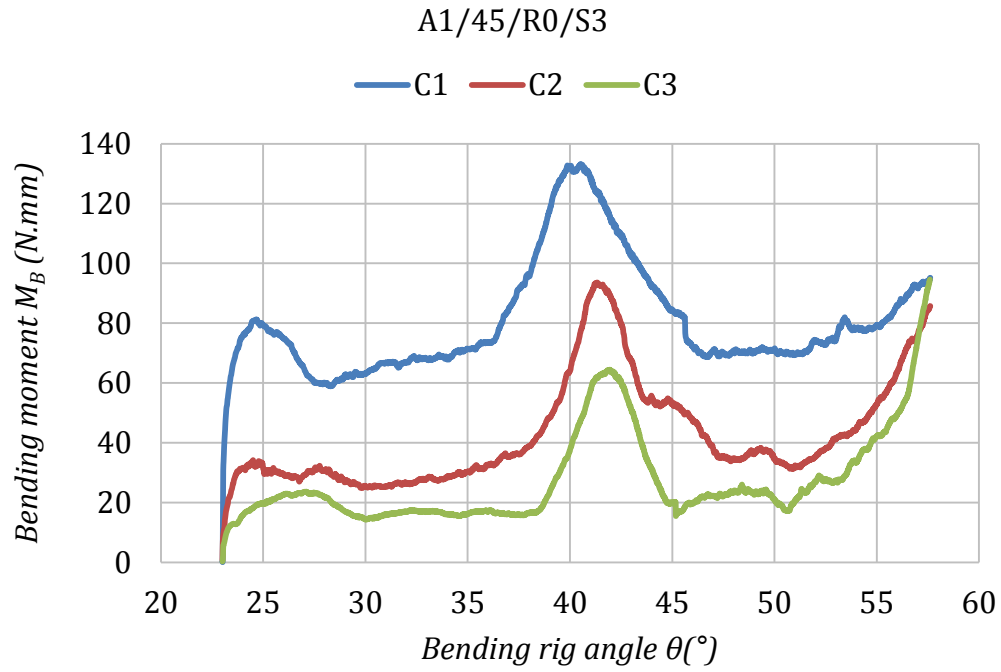


Figure C-3: Bending moment curves resulting from testing of sample A1/45/R0/S3.

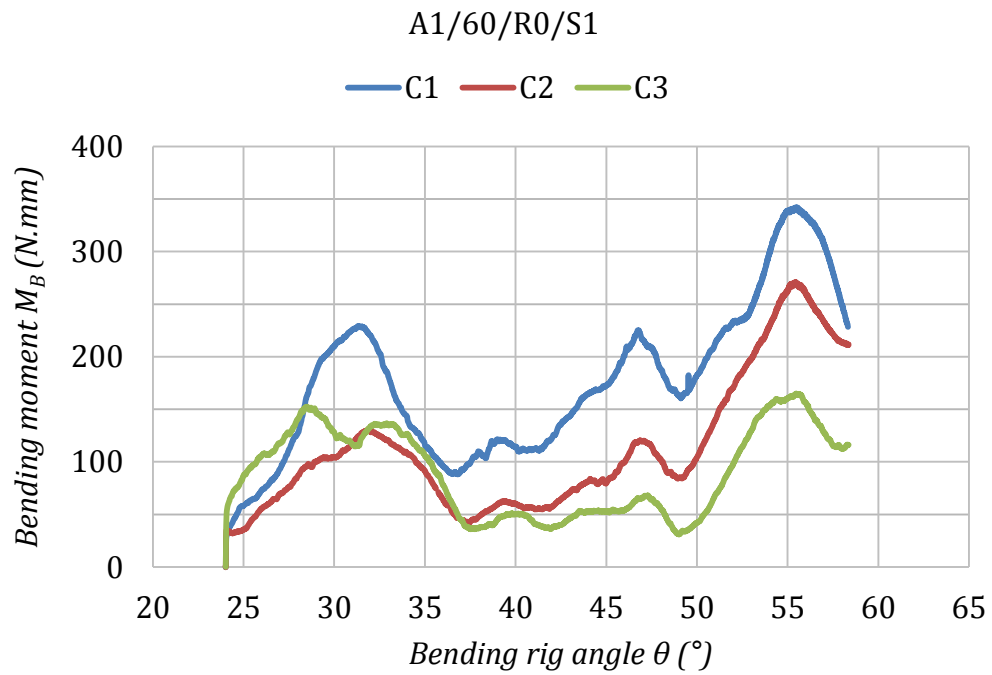


Figure C-4: Bending moment curves resulting from testing of sample A1/60/R0/S1.

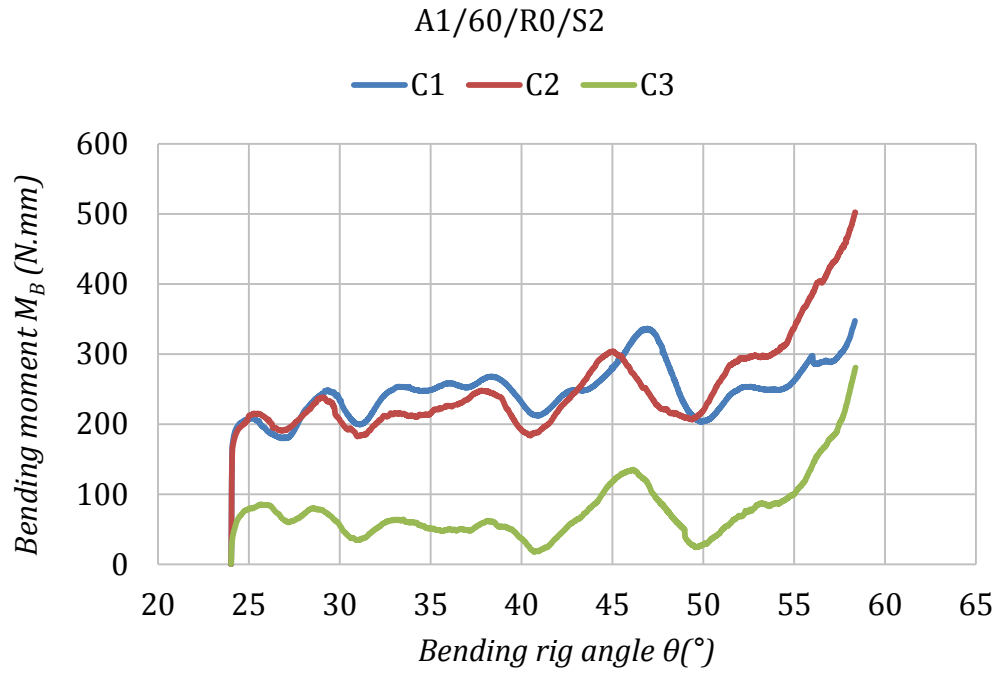


Figure C-5: Bending moment curves resulting from testing of sample A1/60/R0/S2.

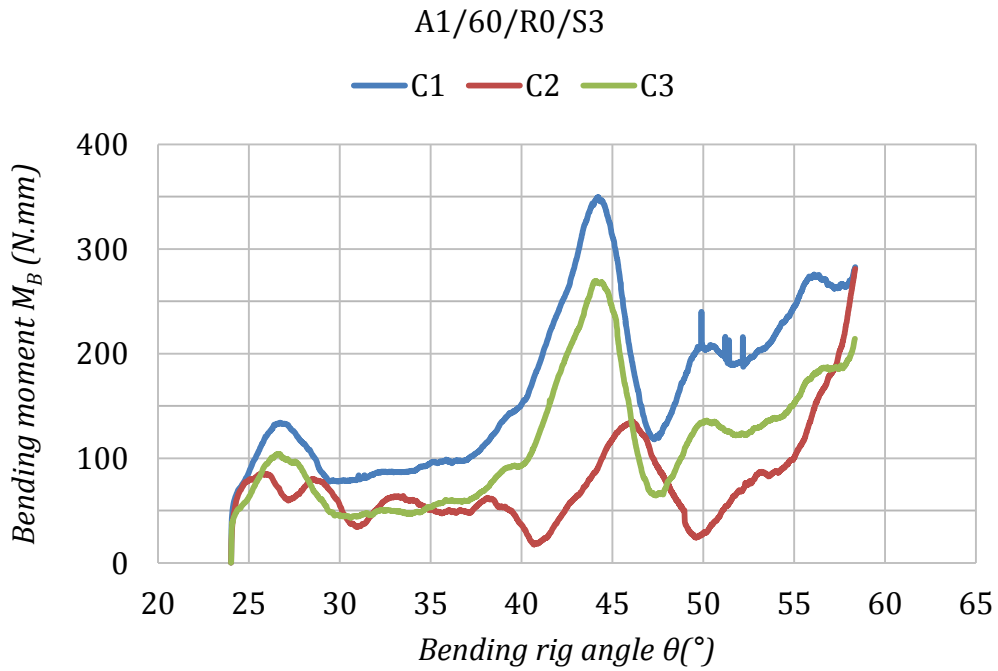


Figure C-6: Bending moment curves resulting from testing of sample A1/60/R0/S3.

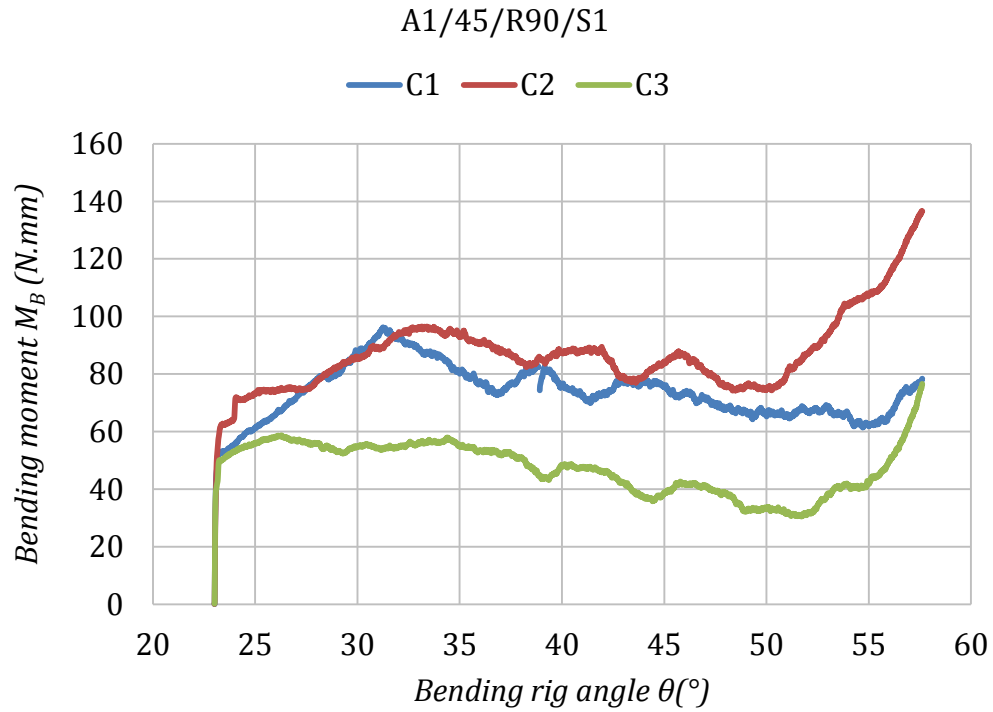


Figure C-7: Bending moment curves resulting from testing of sample A1/45/R90/S1.

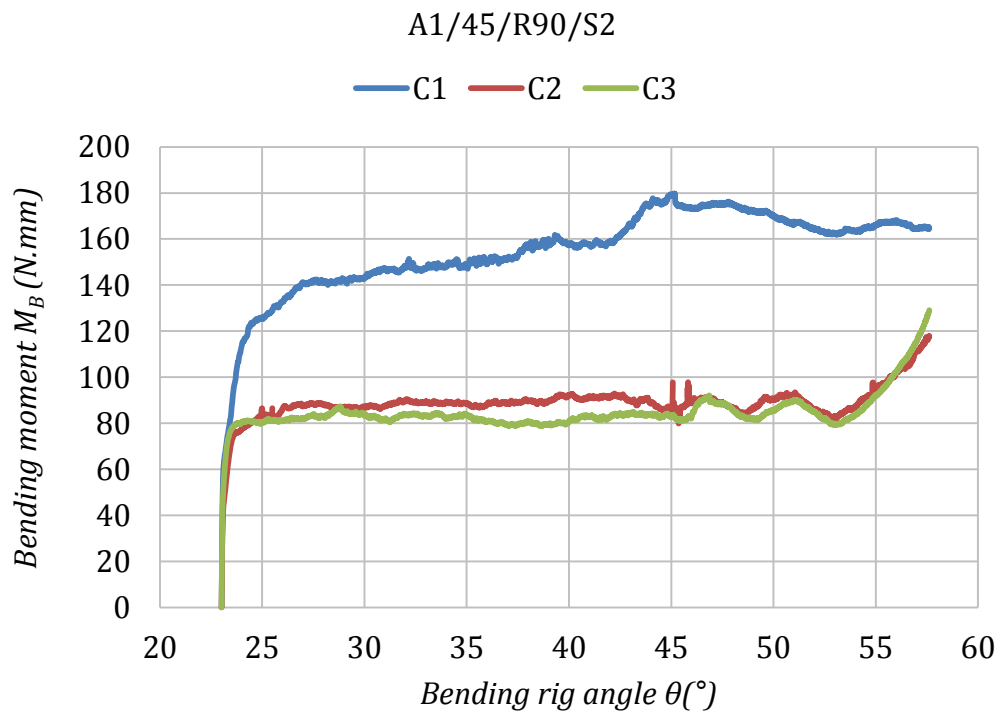


Figure C-8: Bending moment curves resulting from testing of sample A1/45/R90/S2.

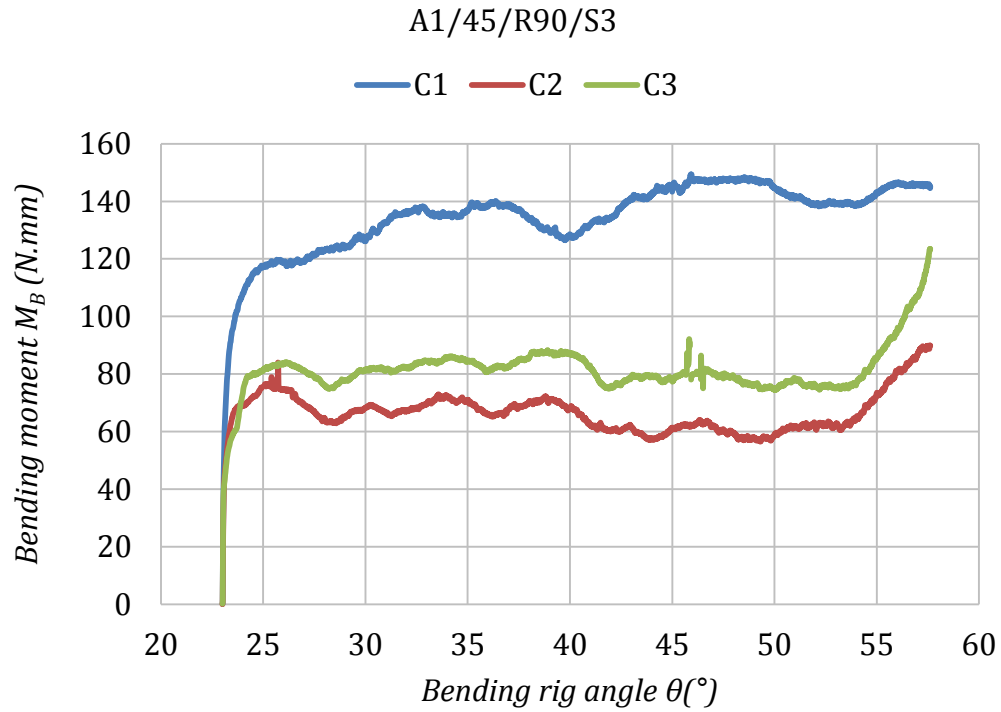


Figure C-9: Bending moment curves resulting from testing of sample A1/45/R90/S3.

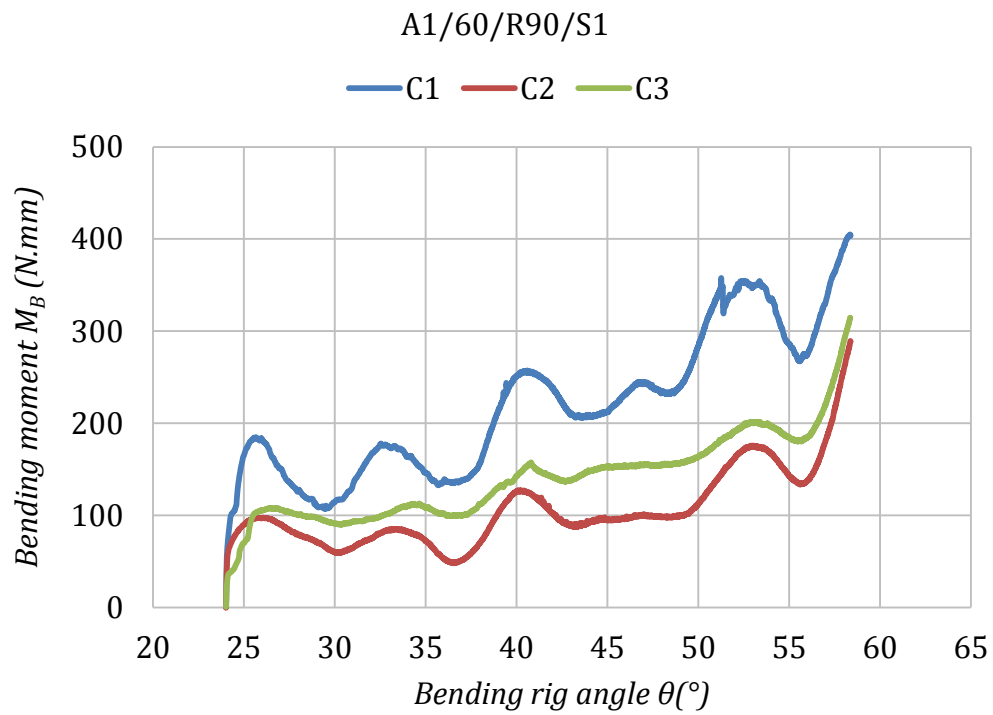


Figure C-10: Bending moment curves resulting from testing of sample A1/60/R90/S1.

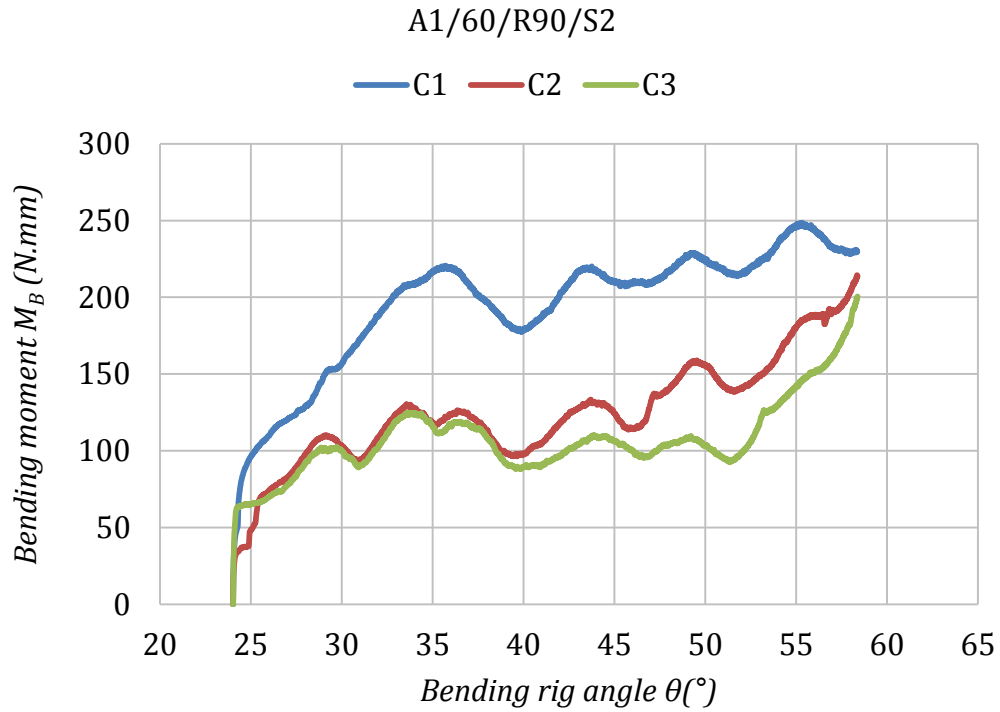


Figure C-11: Bending moment curves resulting from testing of sample A1/60/R90/S2.

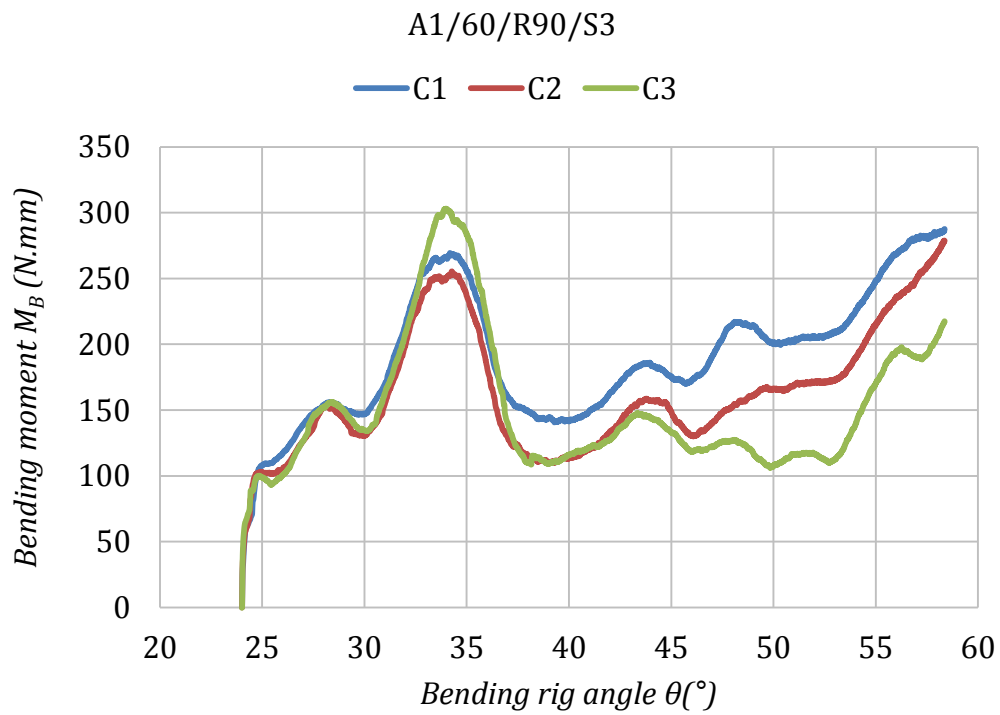


Figure C-12: Bending moment curves resulting from testing of sample A1/60/R90/S3.

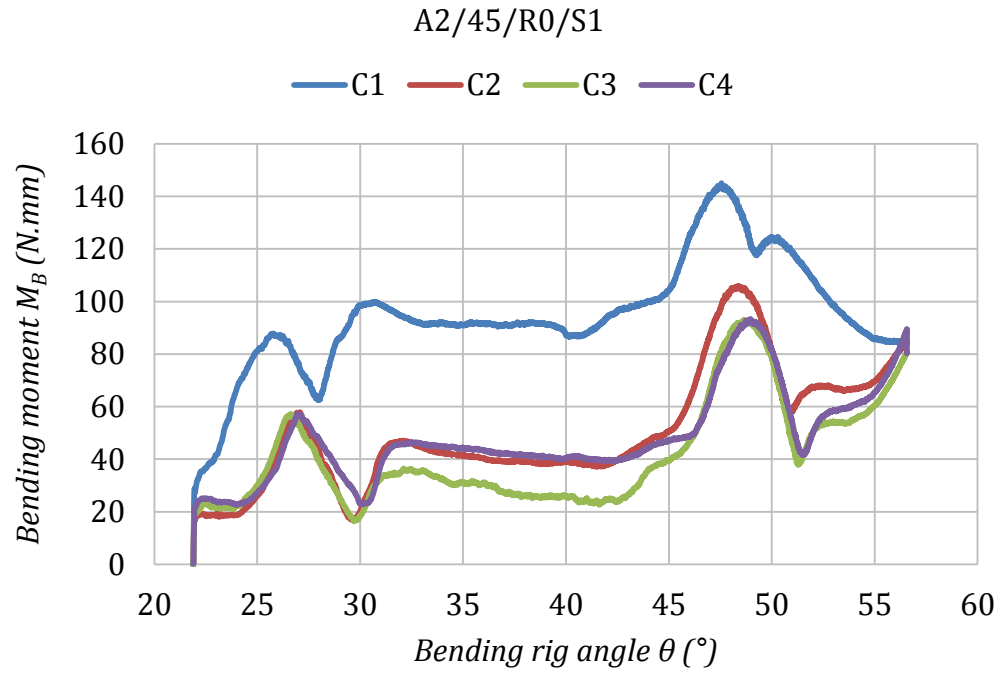


Figure C-13: Bending moment curves resulting from testing of sample A2/45/R0/S1.

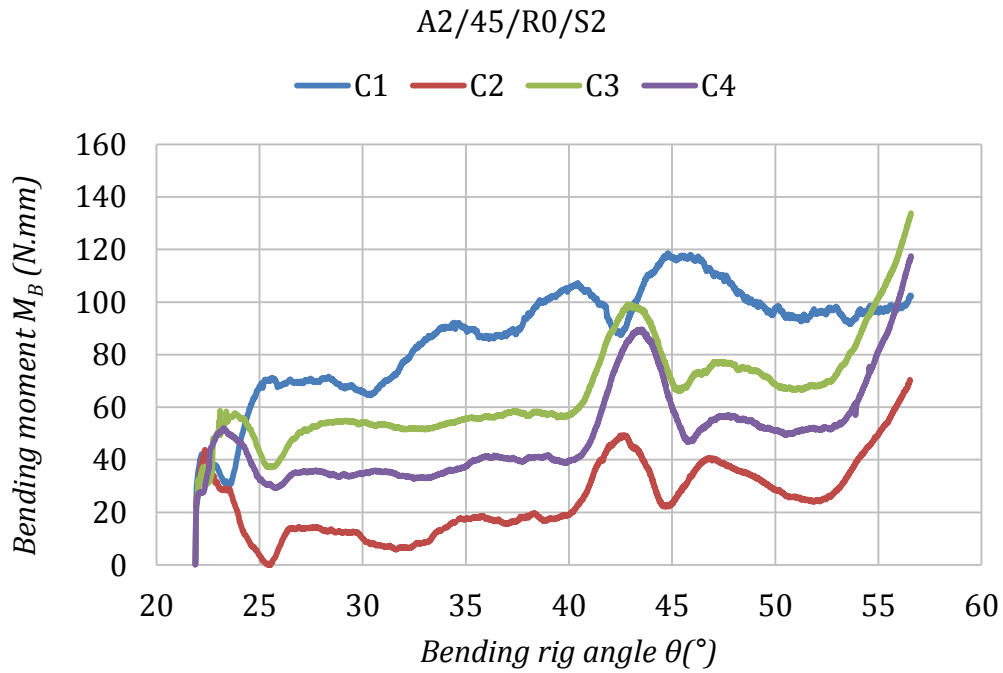


Figure C-14: Bending moment curves resulting from testing of sample A2/45/R0/S2.

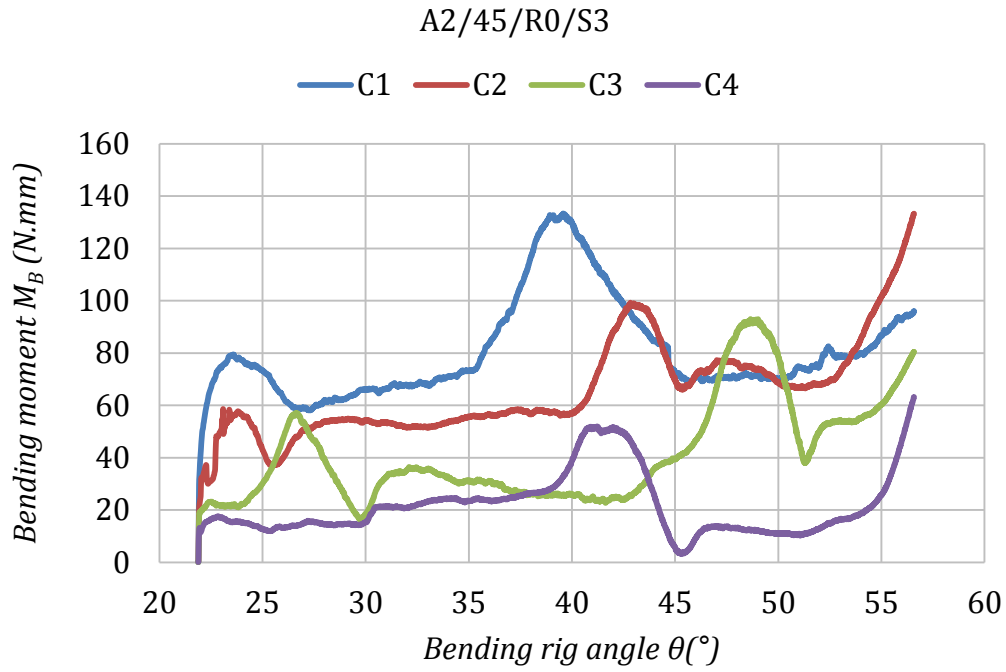


Figure C-15: Bending moment curves resulting from testing of sample A2/45/R0/S3.

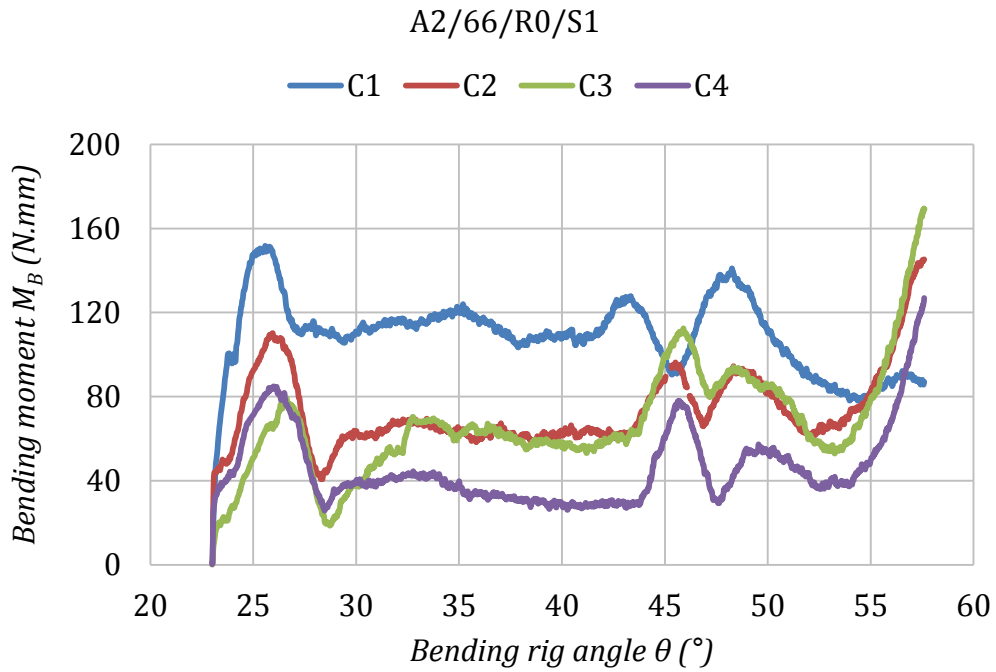


Figure C-16: Bending moment curves resulting from testing of sample A2/66/R0/S1.

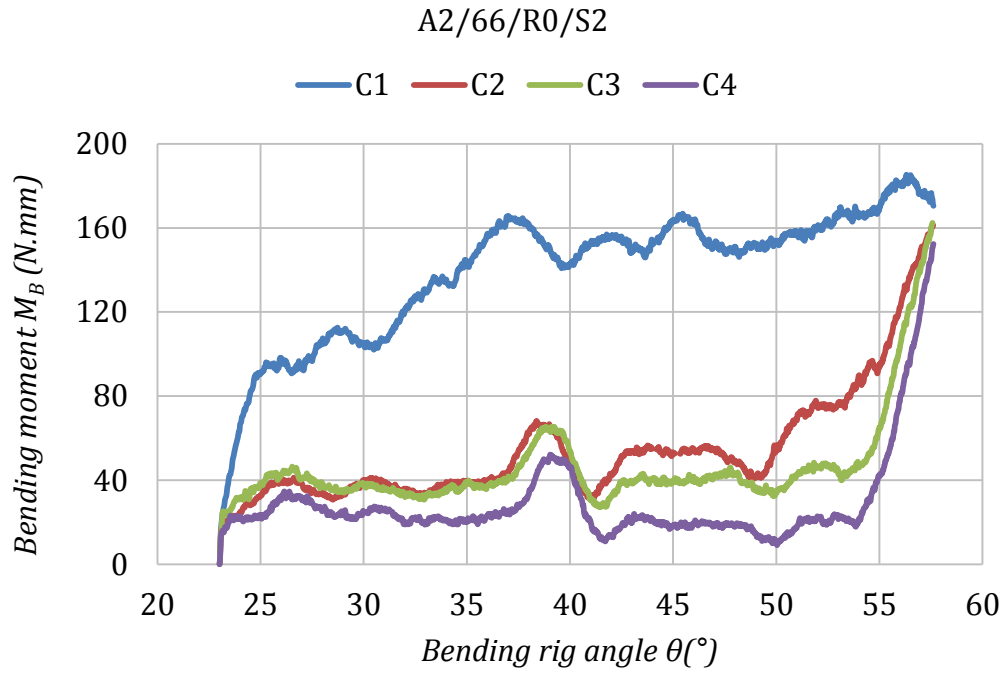


Figure C-17: Bending moment curves resulting from testing of sample A2/66/R0/S2.

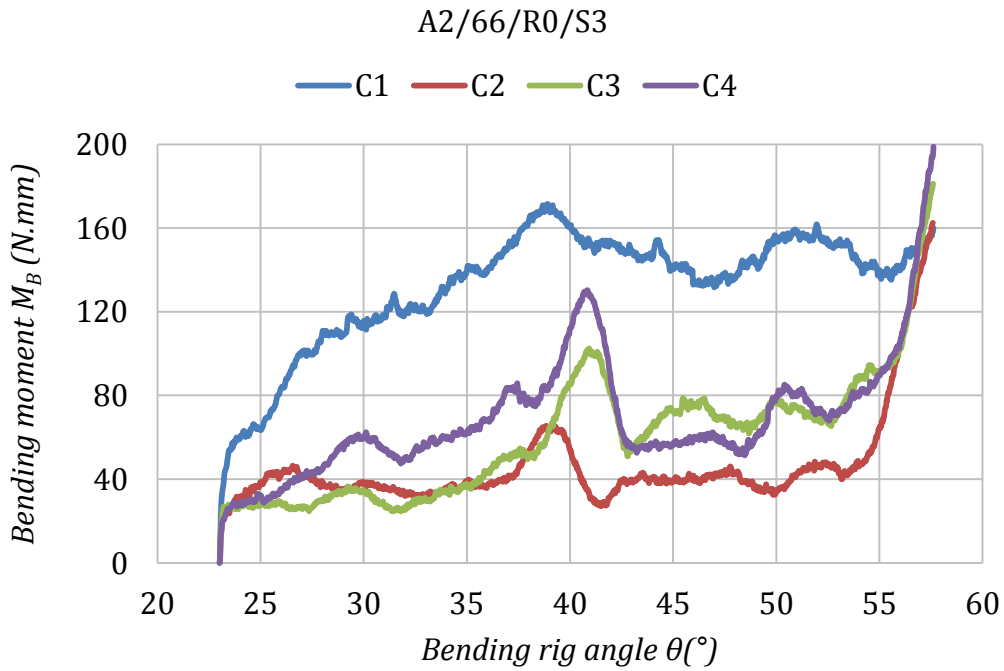


Figure C-18: Bending moment curves resulting from testing of sample A2/66/R0/S3.

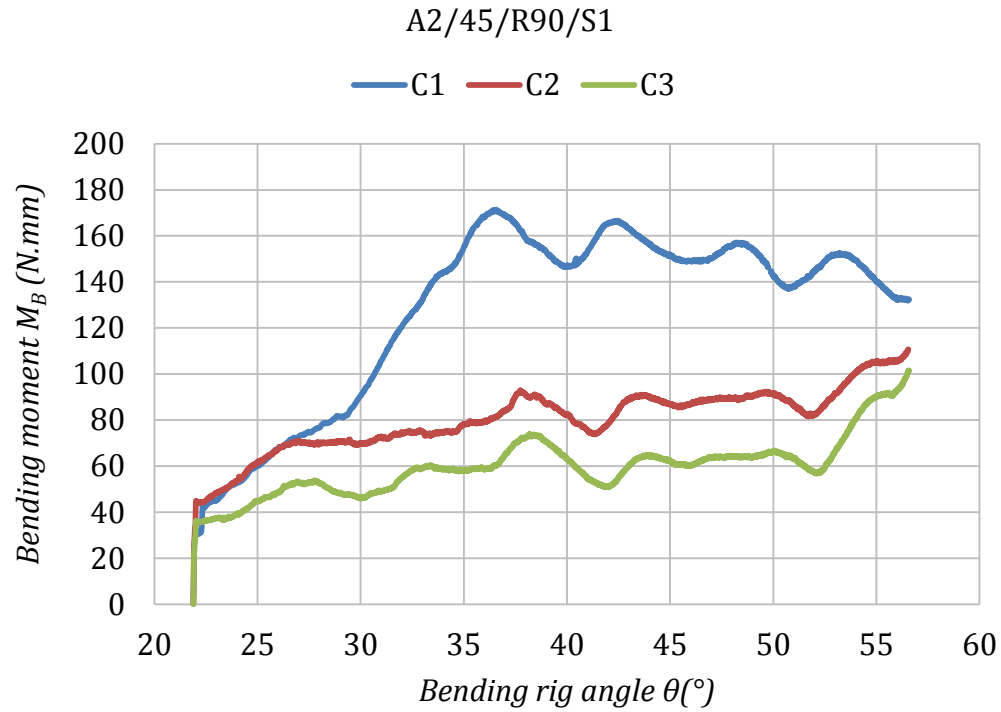


Figure C-19: Bending moment curves resulting from testing of sample A2/45/R90/S1.

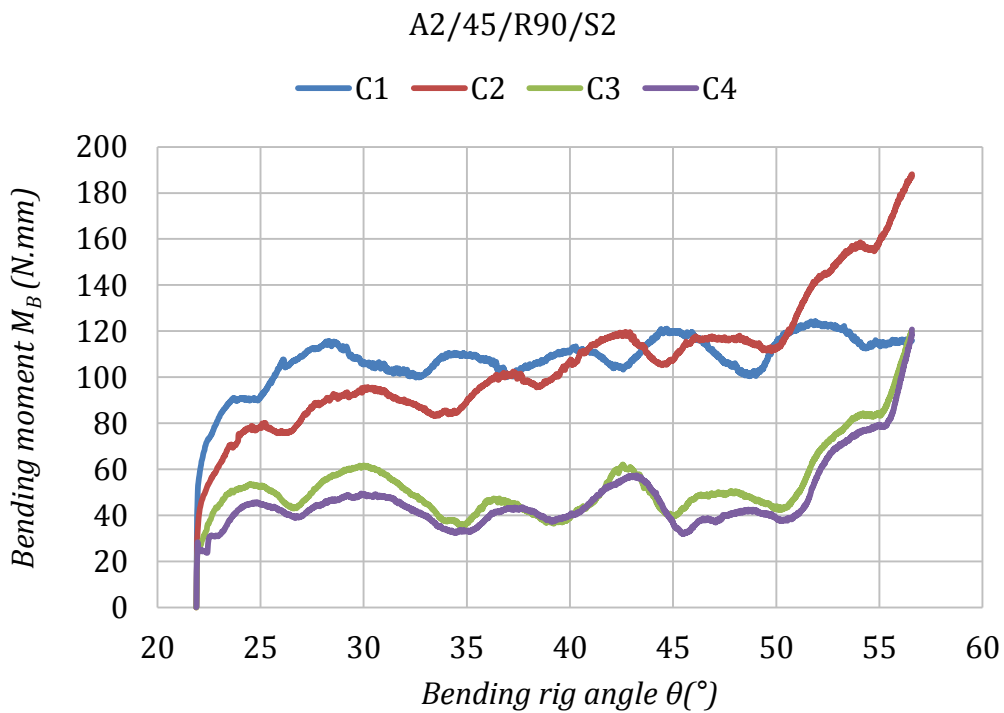


Figure C-20: Bending moment curves resulting from testing of sample A2/45/R90/S2.

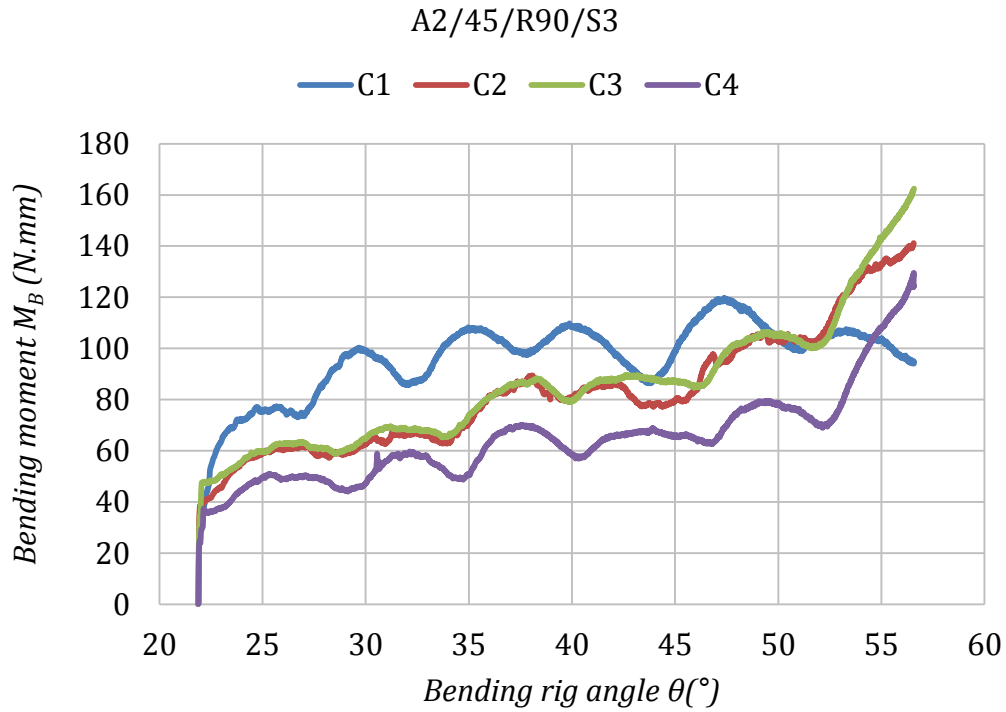


Figure C-21: Bending moment curves resulting from testing of sample A2/45/R90/S3.

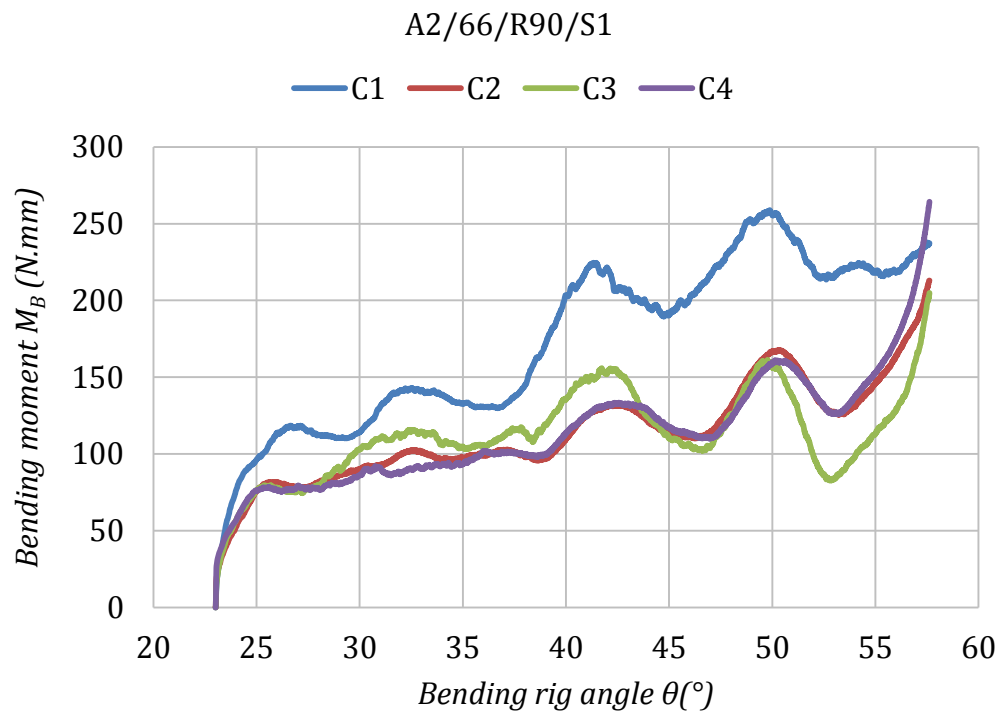


Figure C-22: Bending moment curves resulting from testing of sample A2/66/R90/S1.

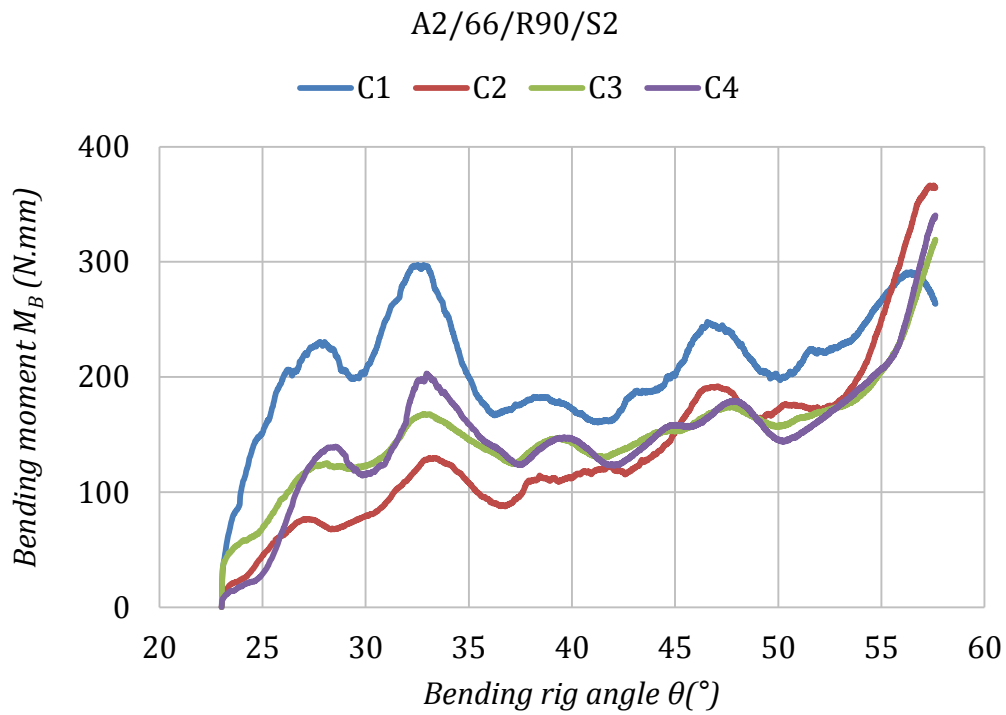


Figure C-23: Bending moment curves resulting from testing of sample A2/66/R90/S2.

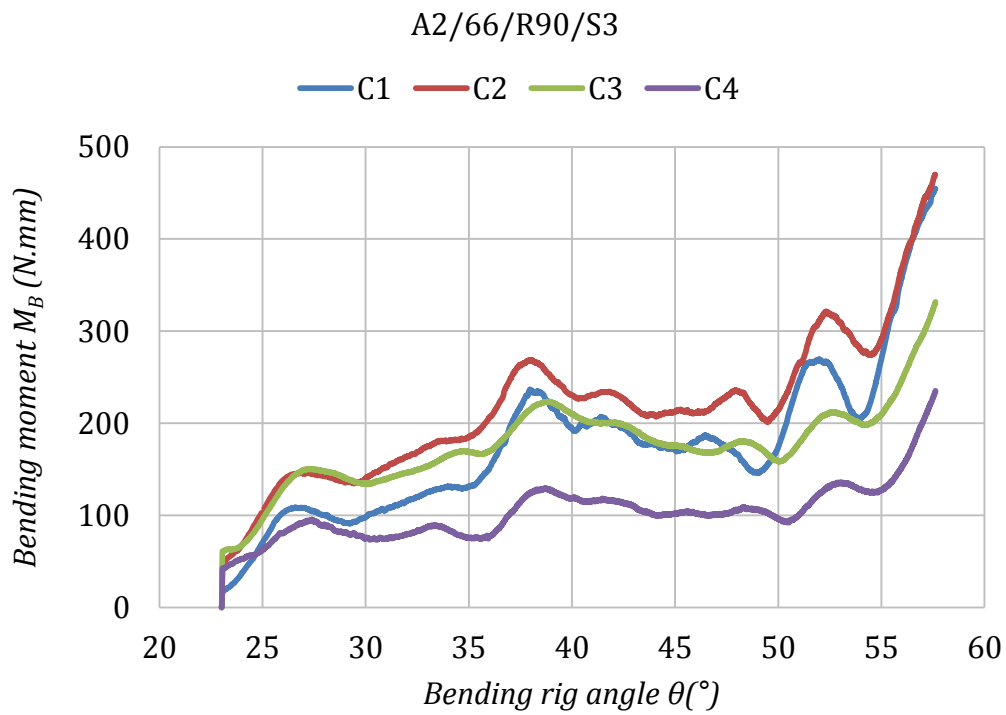


Figure C-24: Bending moment curves resulting from testing of sample A2/66/R90/S3.

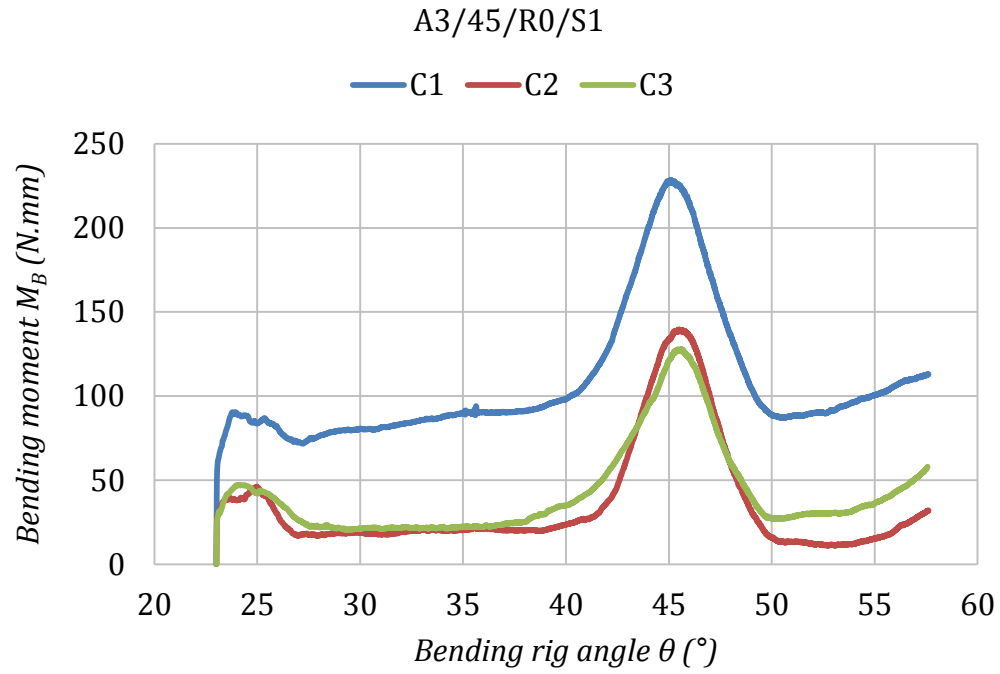


Figure C-25: Bending moment curves resulting from testing of sample A3/45/R0/S1.

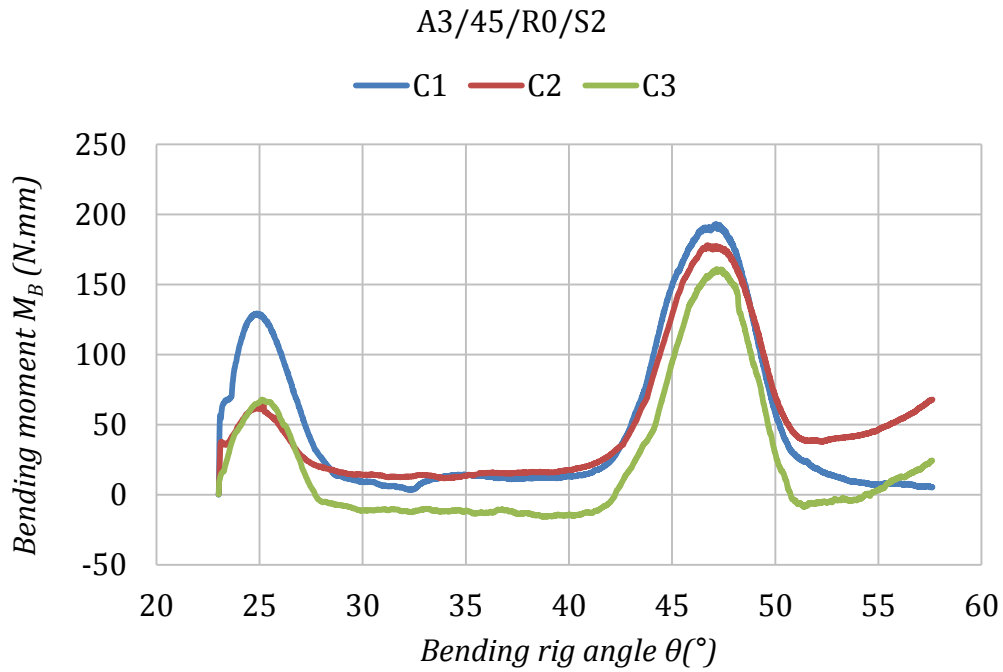


Figure C-26: Bending moment curves resulting from testing of sample A3/45/R0/S2.

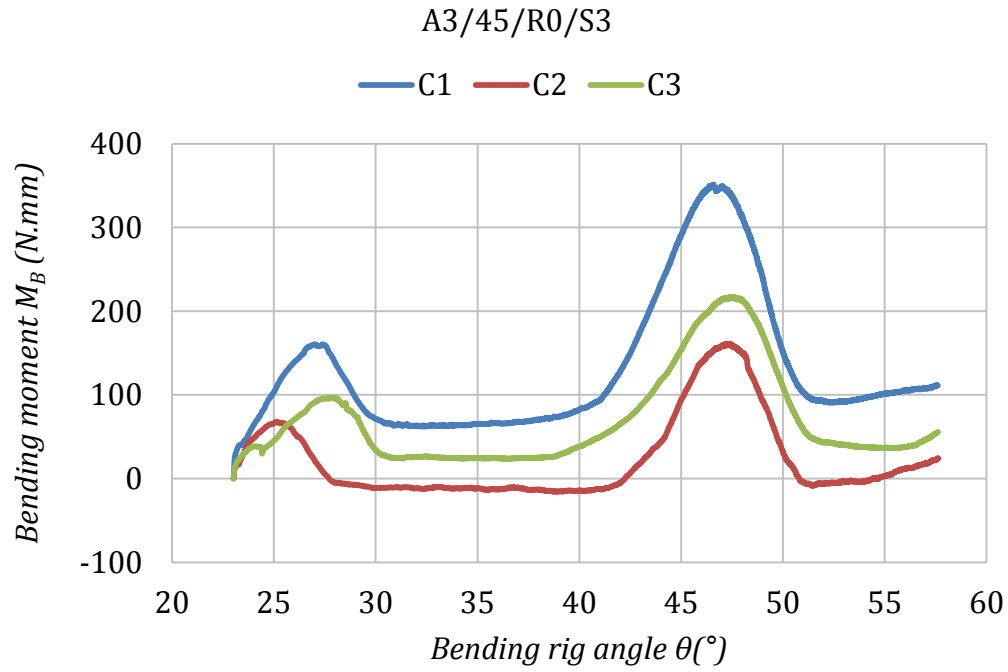


Figure C-27: Bending moment curves resulting from testing of sample A3/45/R0/S3.

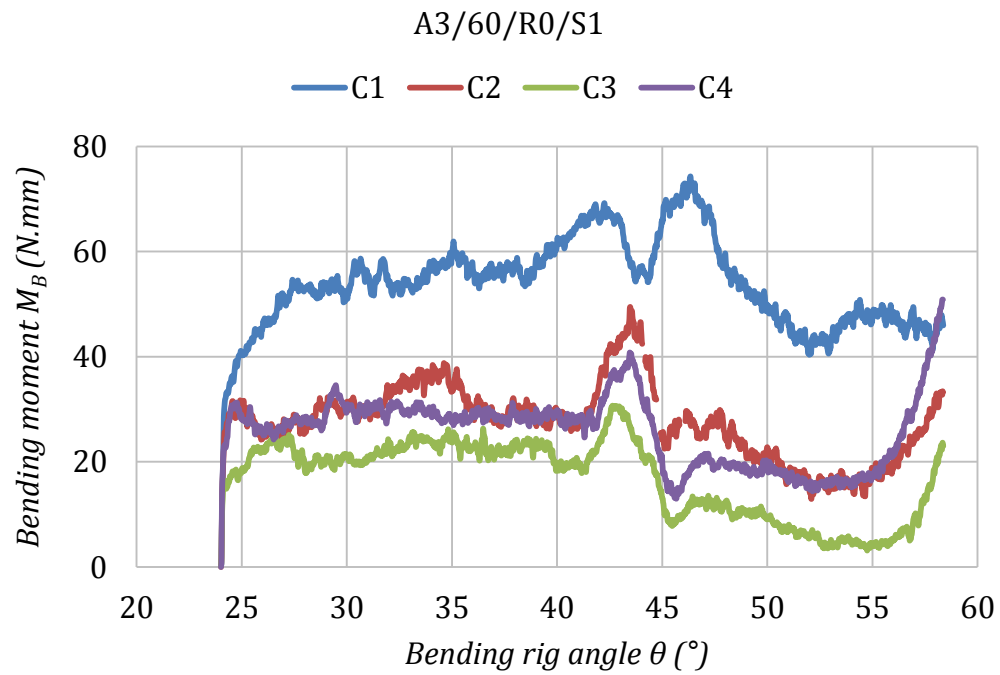


Figure C-28: Bending moment curves resulting from testing of sample A3/60/R0/S1.

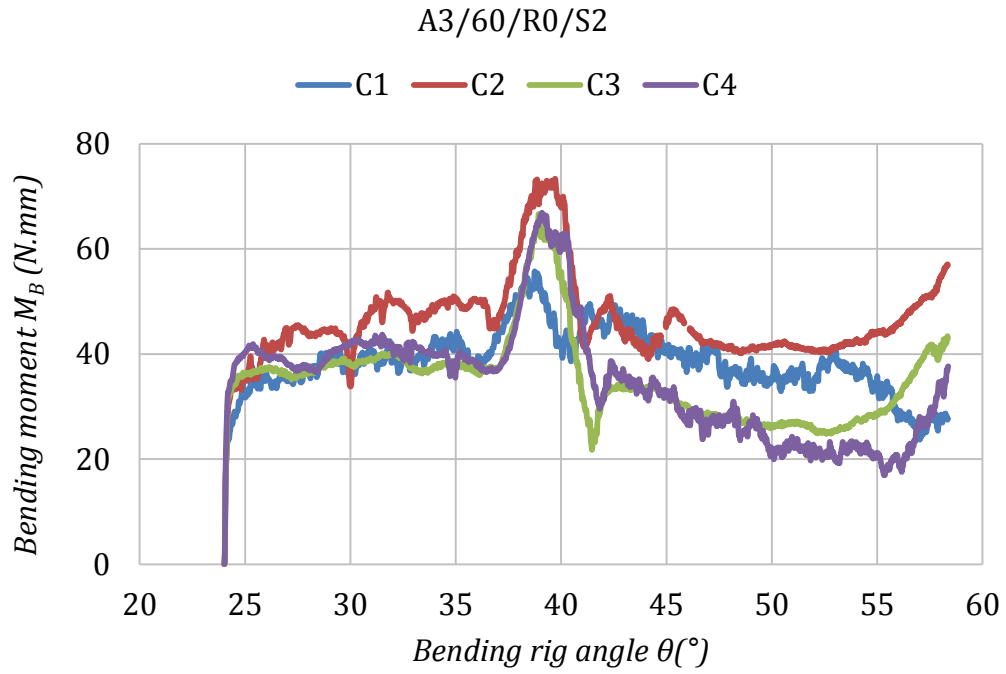


Figure C-29: Bending moment curves resulting from testing of sample A3/60/R0/S2.

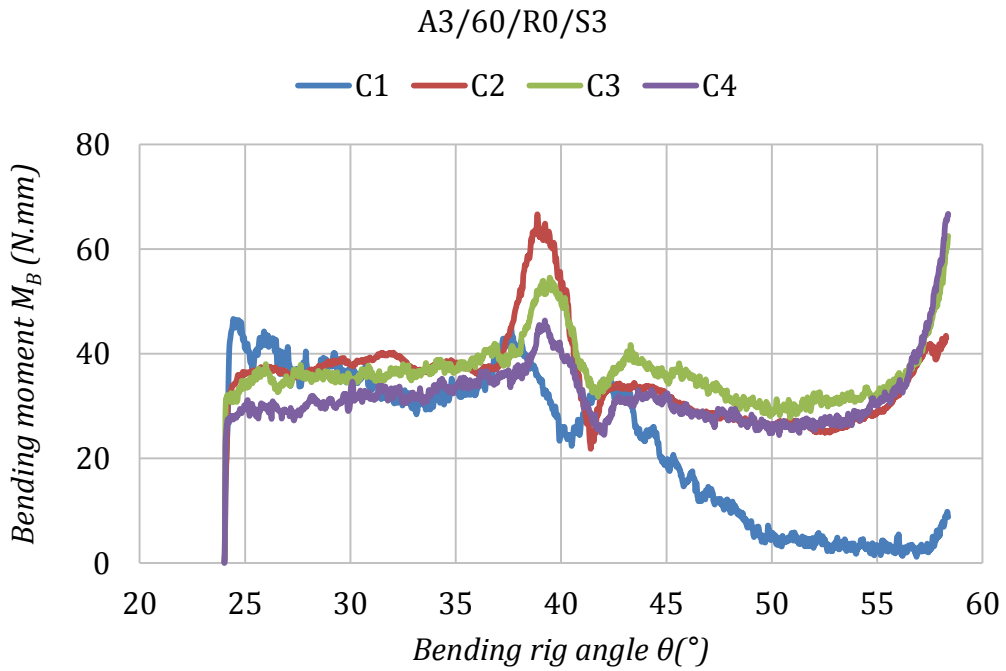


Figure C-30: Bending moment curves resulting from testing of sample A3/60/R0/S3.

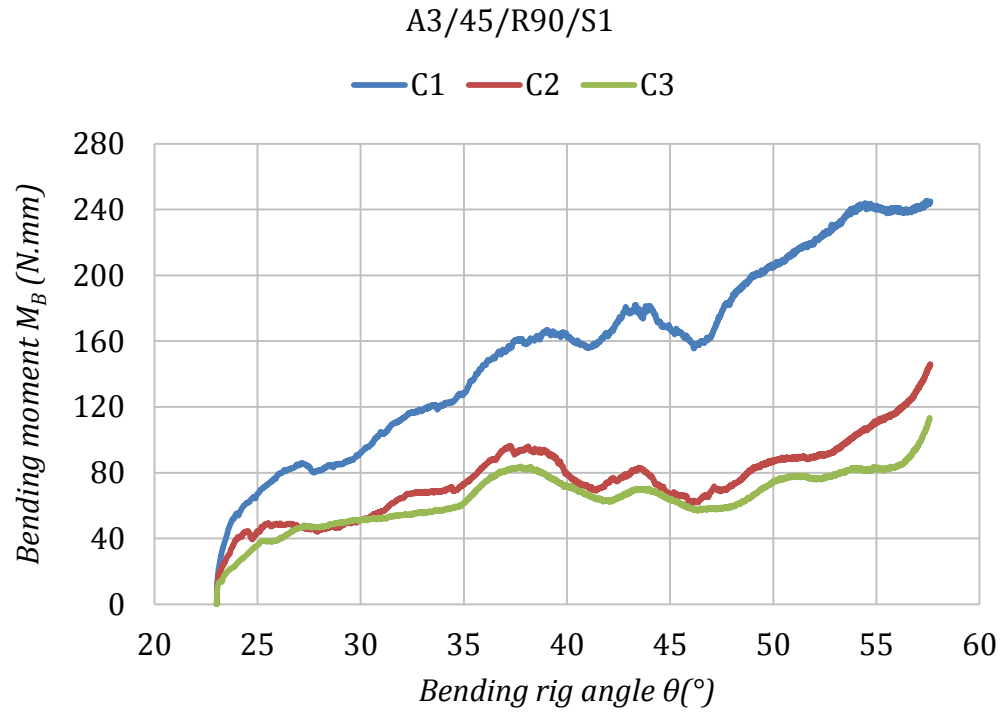


Figure C-31: Bending moment curves resulting from testing of sample A3/45/R90/S1.

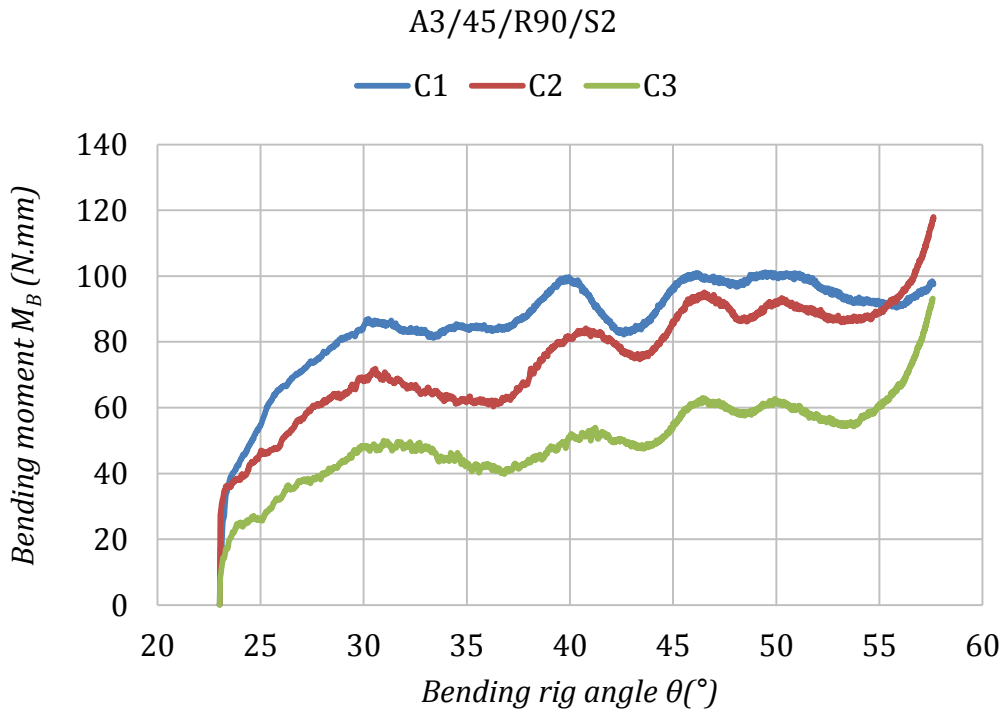


Figure C-32: Bending moment curves resulting from testing of sample A3/45/R90/S2.

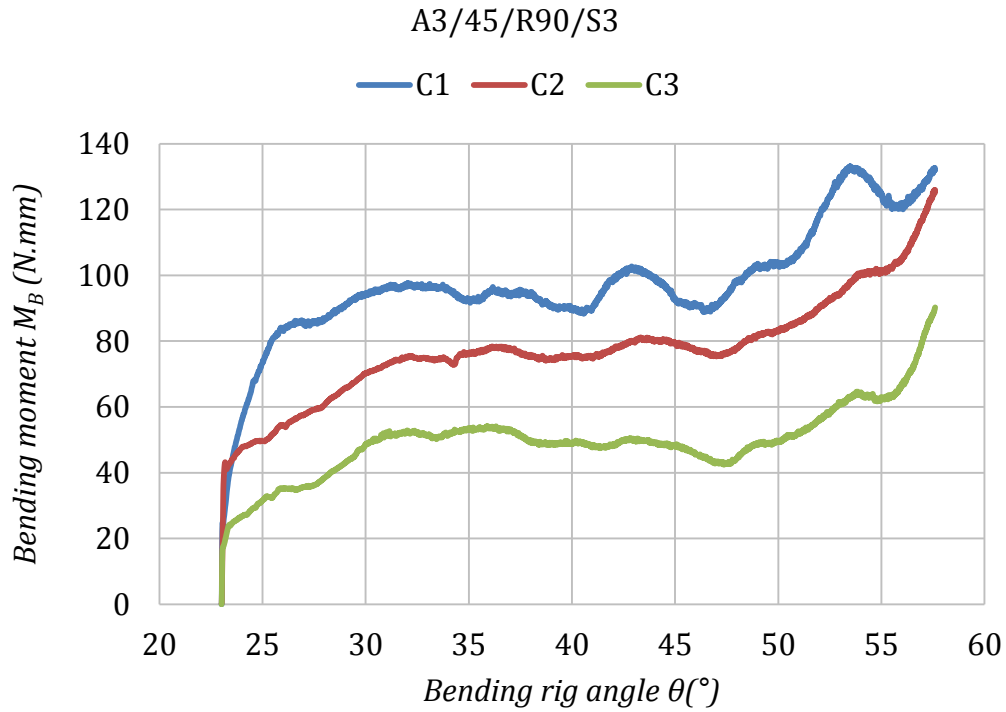


Figure C-33: Bending moment curves resulting from testing of sample A3/45/R90/S3.

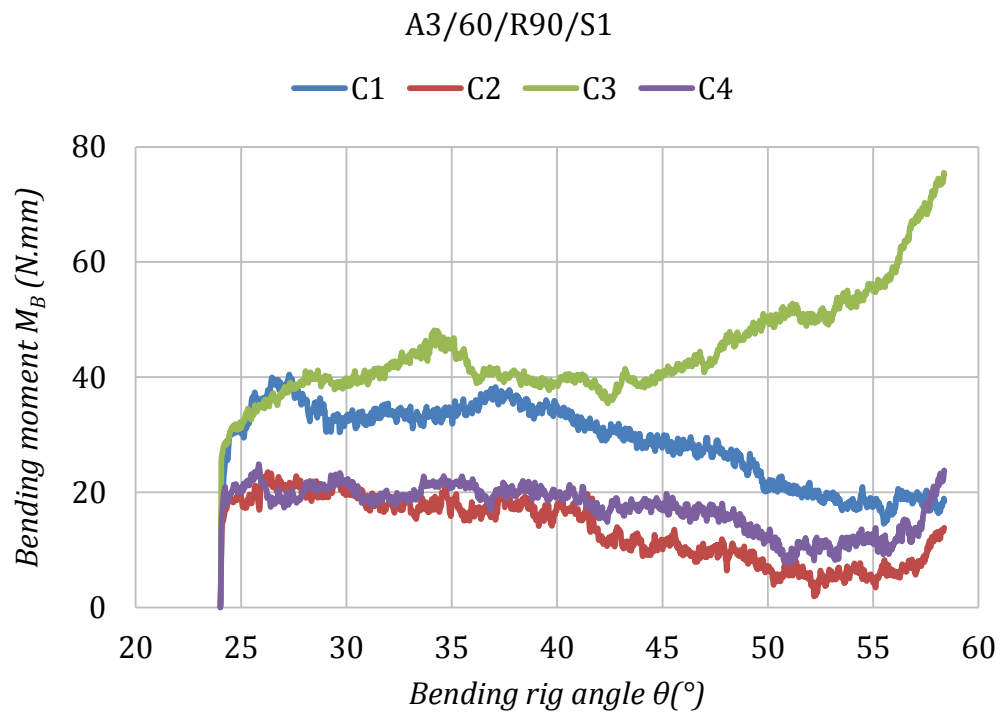


Figure C-34: Bending moment curves resulting from testing of sample A3/60/R90/S1.

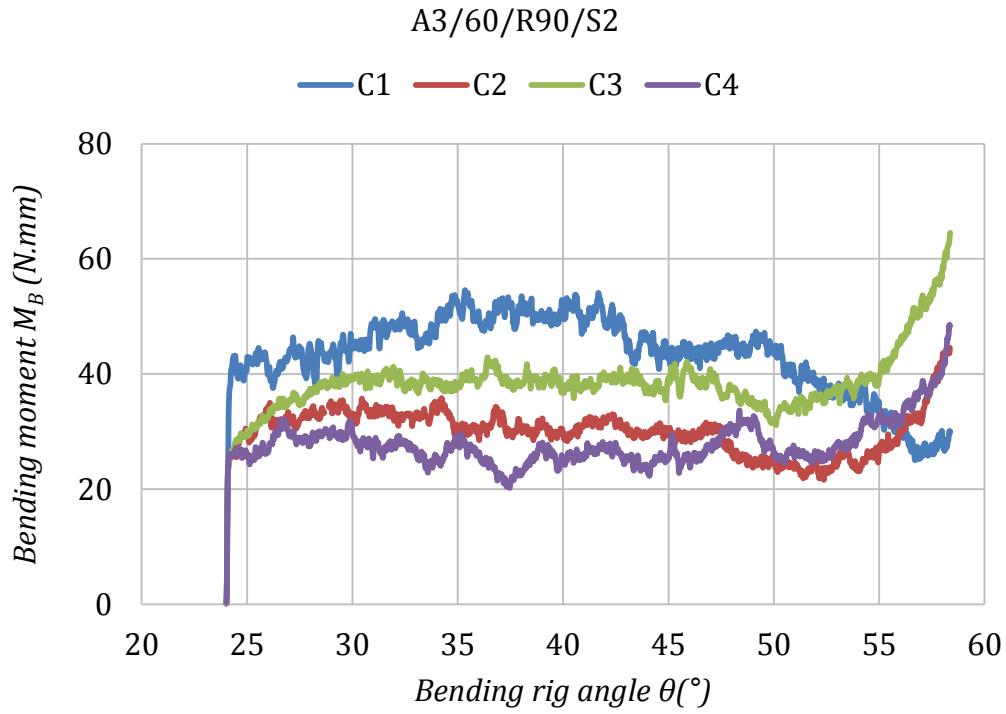


Figure C-35: Bending moment curves resulting from testing of sample A3/60/R90/S2.

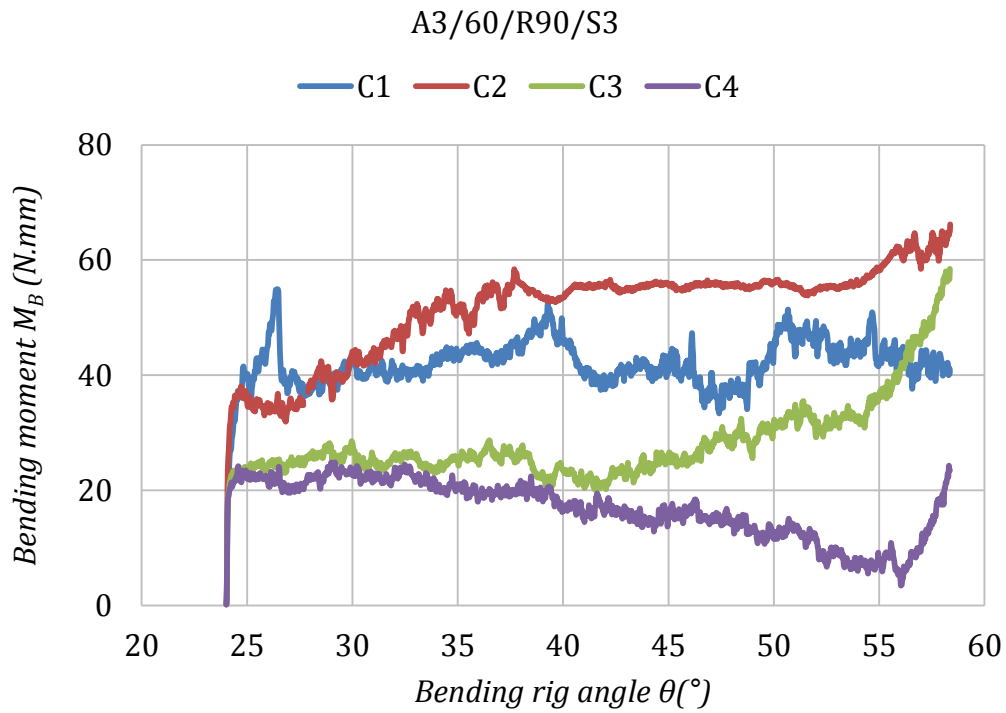


Figure C-36: Bending moment curves resulting from testing of sample A3/60/R90/S3.

C.3 Saertex Samples

Bending moment curves result from bending tests conducted on type B samples for groups B1, B2 and B3 which they were prepared from Saertex industrial preforms are presented here.

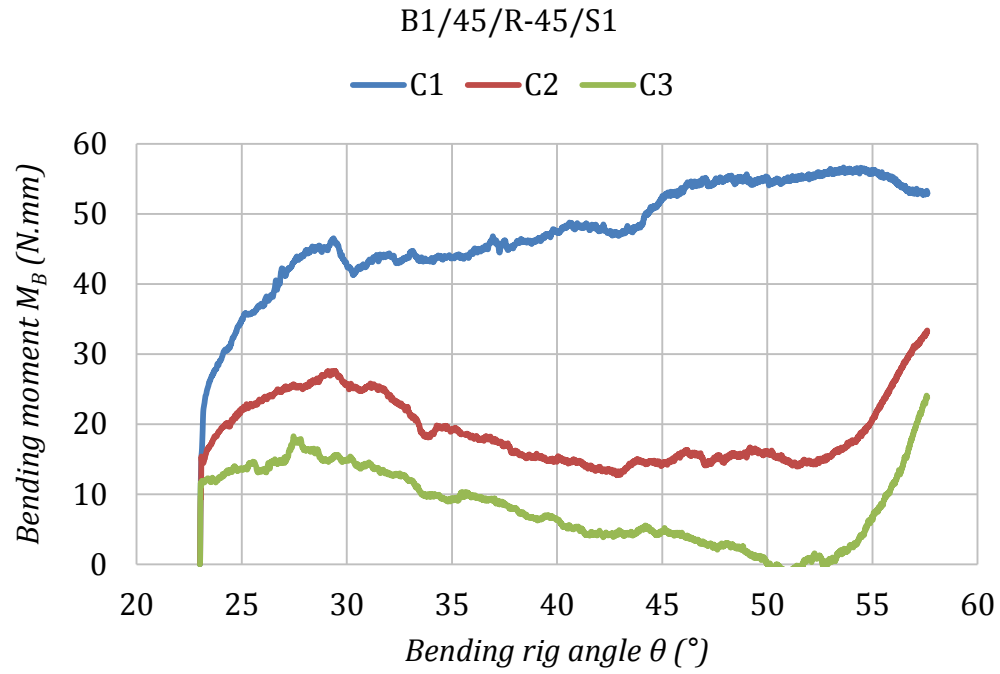


Figure C-37: Bending moment curves resulting from testing of sample B1/45/R-45/S1.

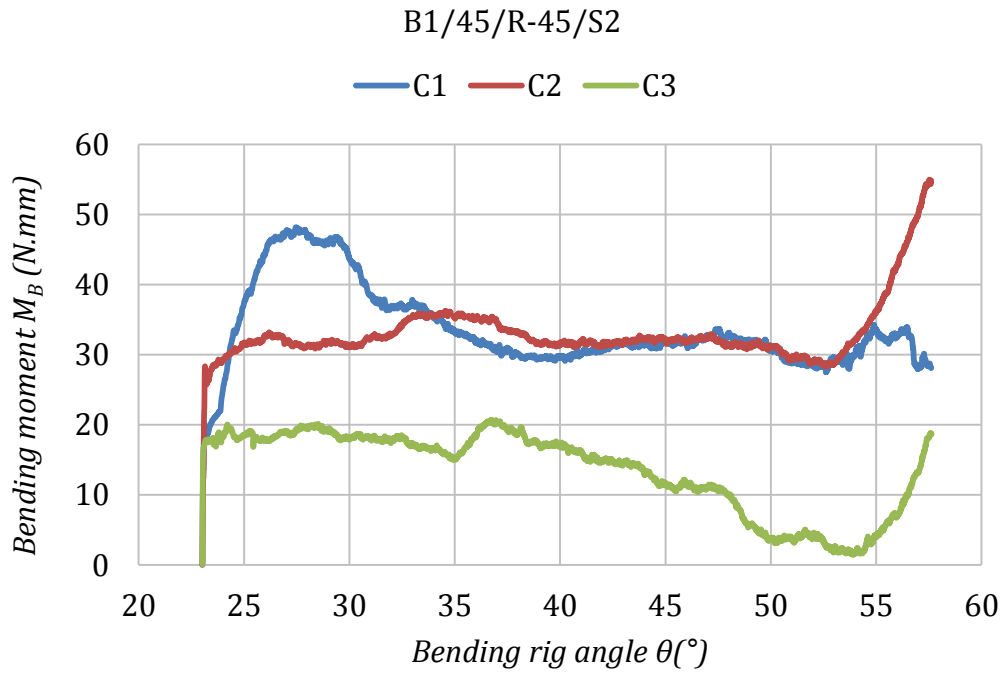


Figure C-38: Bending moment curves resulting from testing of sample B1/45/R-45/S2.

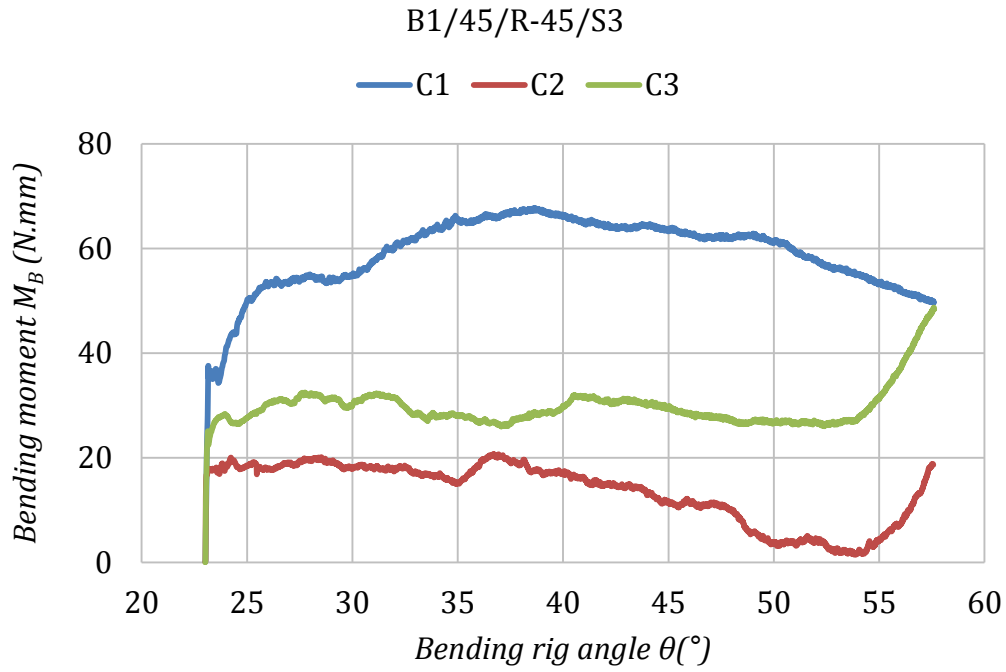


Figure C-39: Bending moment curves resulting from testing of sample B1/45/R-45/S3.

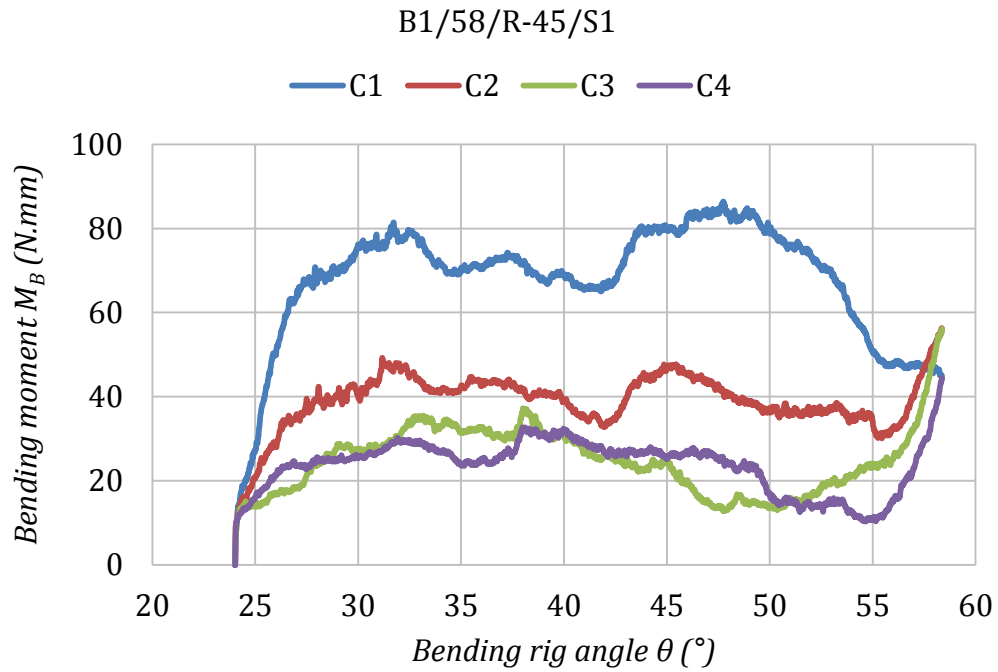


Figure C-40: Bending moment curves resulting from testing of sample B1/58/R-45/S1.

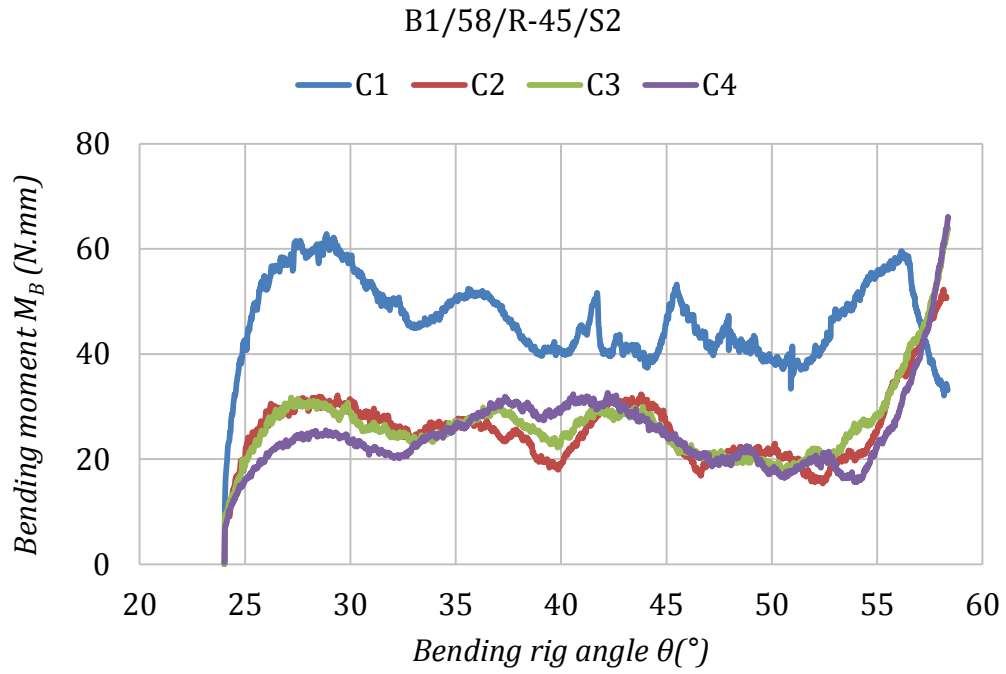


Figure C-41: Bending moment curves resulting from testing of sample B1/58/R-45/S2.

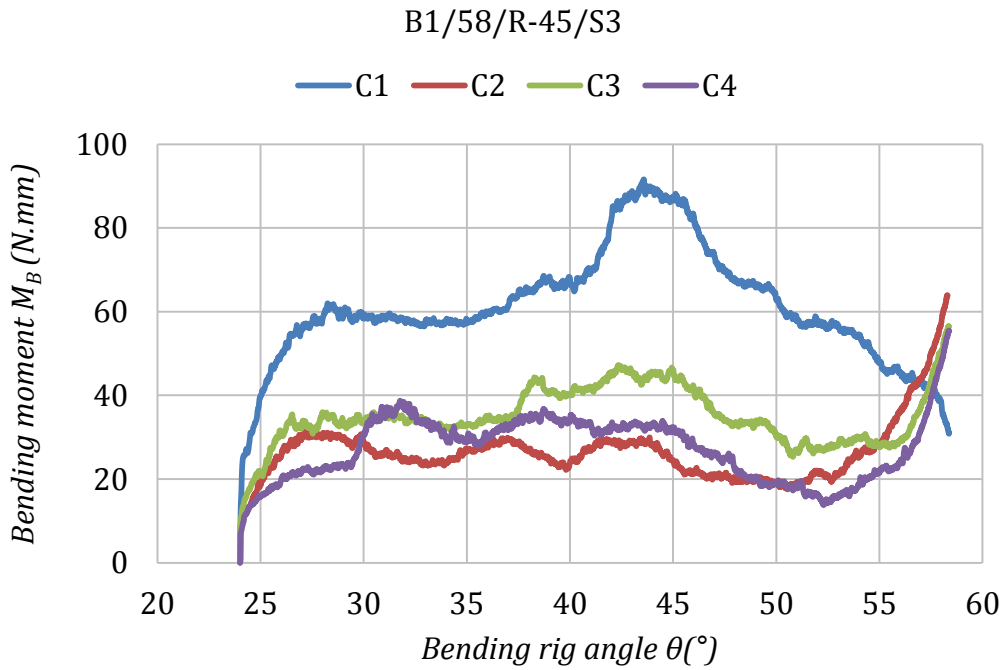


Figure C-42: Bending moment curves resulting from testing of sample B1/58/R-45/S3.

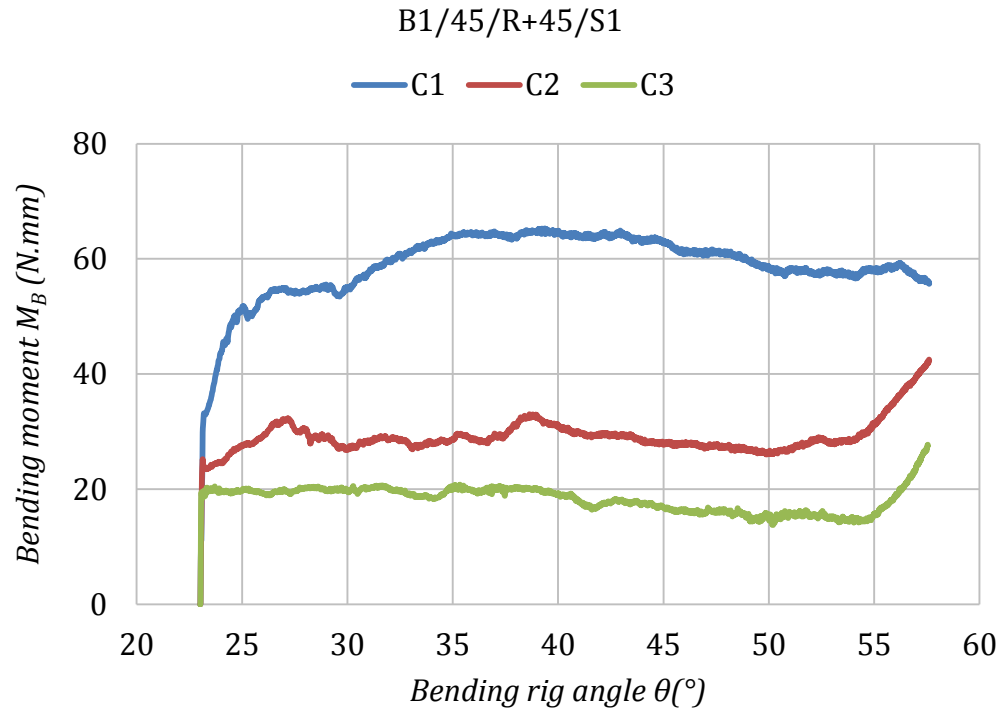


Figure C-43: Bending moment curves resulting from testing of sample B1/45/R+45/S1.

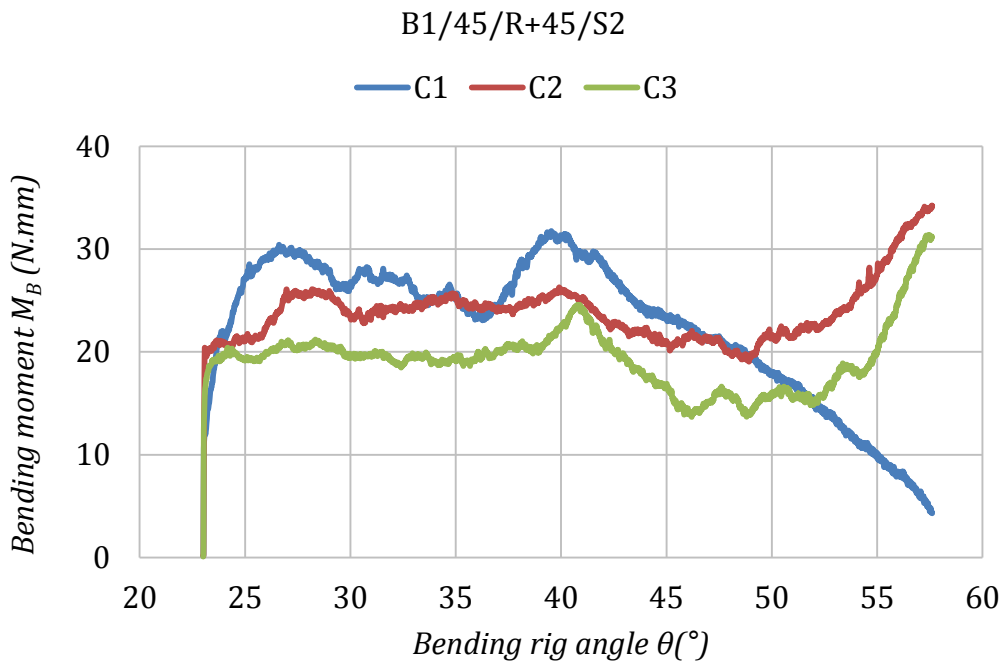


Figure C-44: Bending moment curves resulting from testing of sample B1/45/R+45/S2.

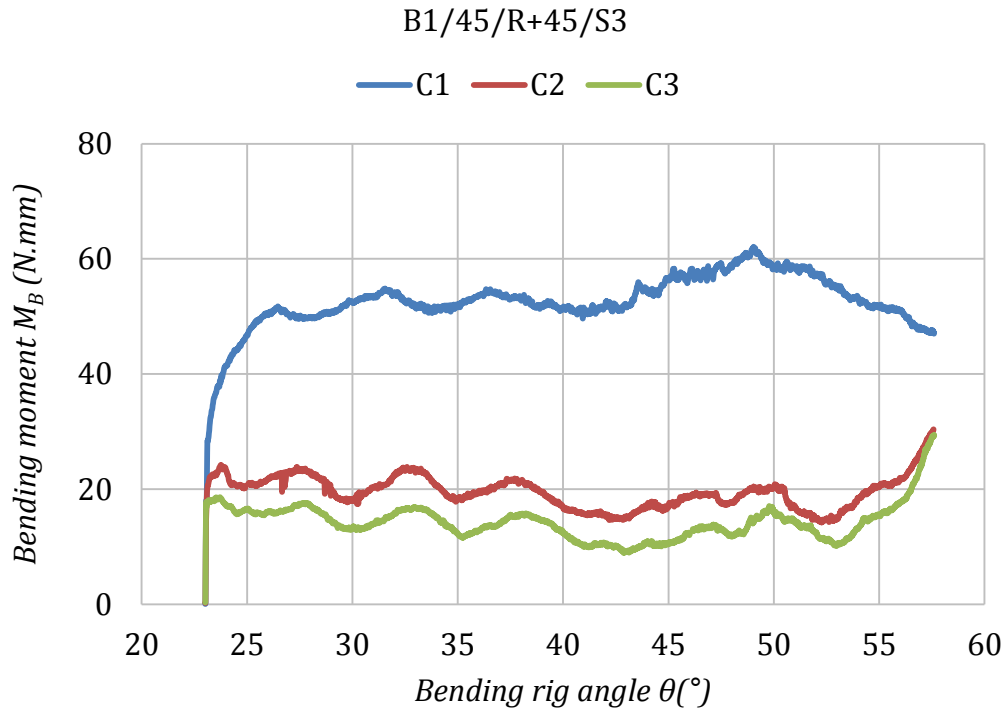


Figure C-45: Bending moment curves resulting from testing of sample B1/45/R+45/S3.

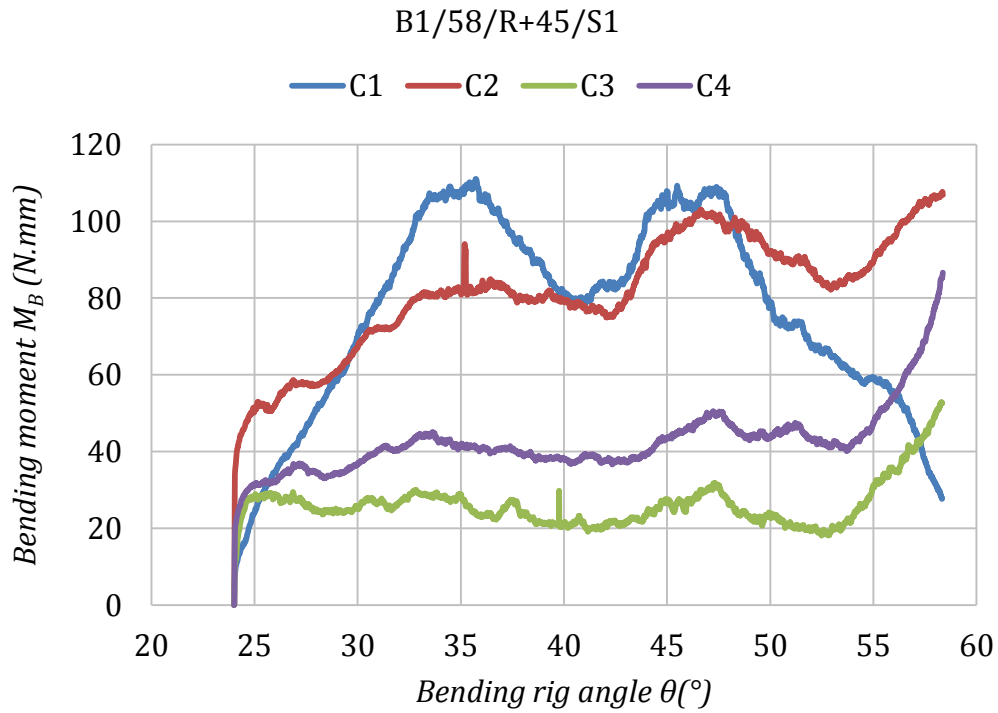


Figure C-46: Bending moment curves resulting from testing of sample B1/58/R+45/S1.

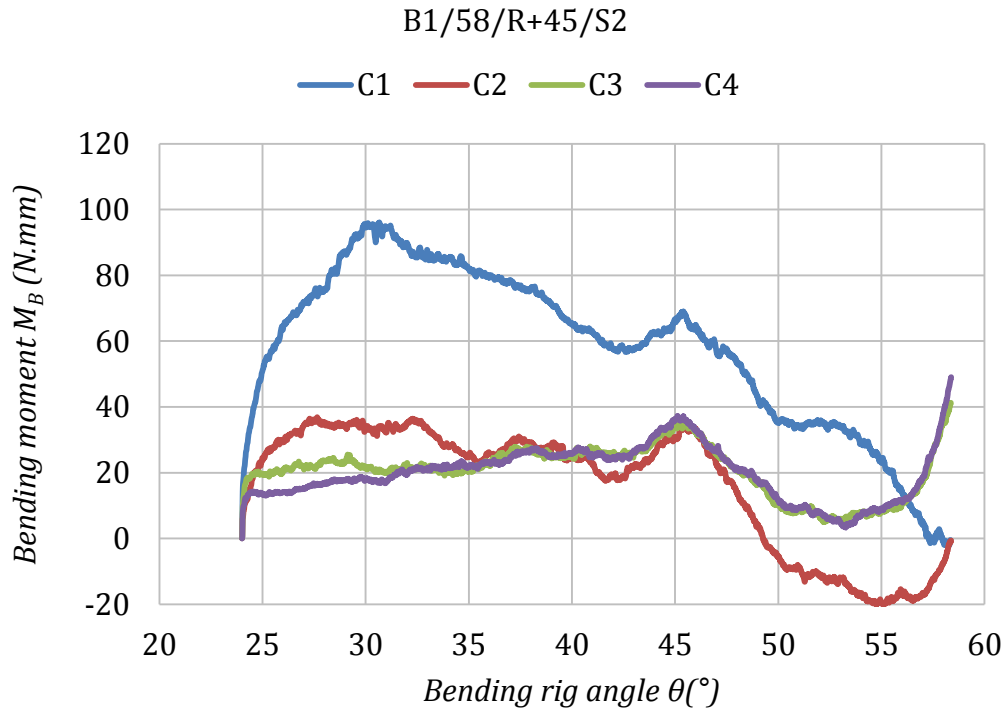


Figure C-47: Bending moment curves resulting from testing of sample B1/58/R+45/S2.

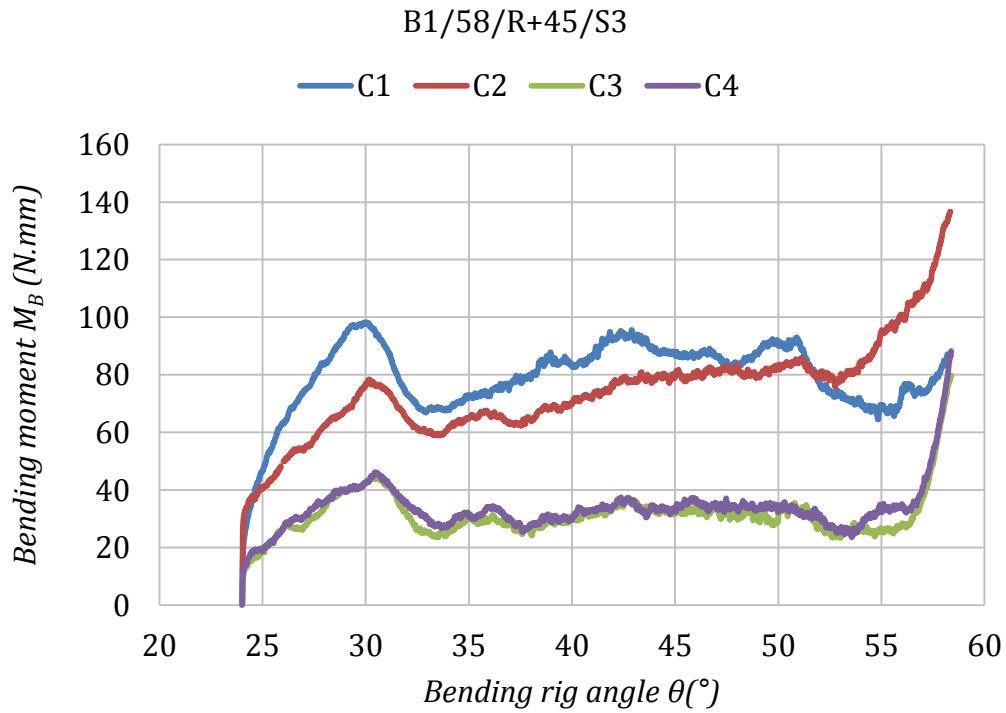


Figure C-48: Bending moment curves resulting from testing of sample B1/58/R+45/S3.

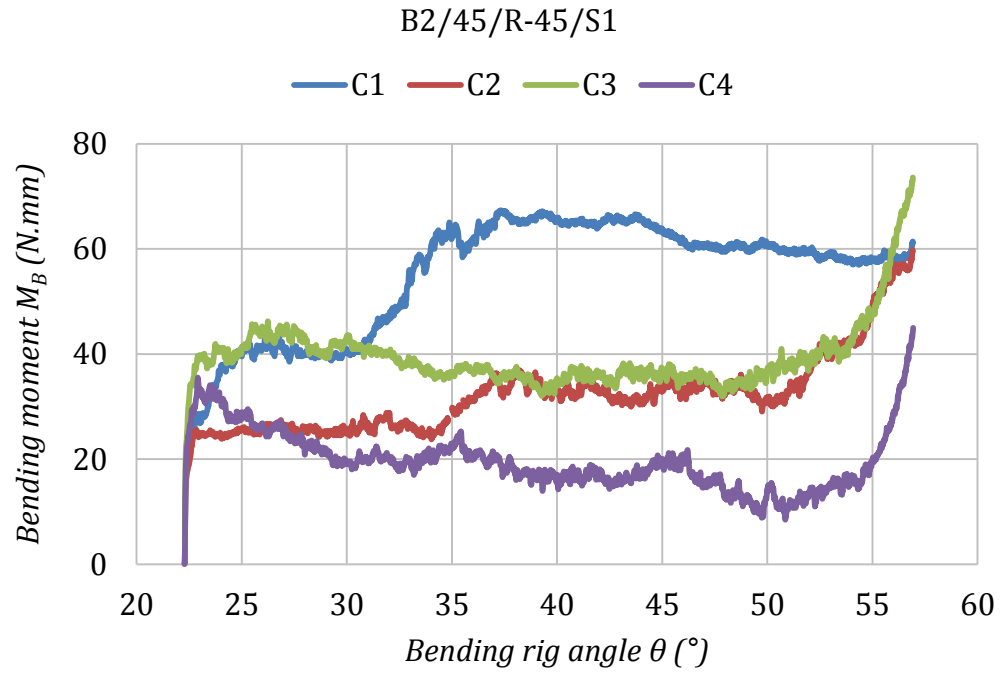


Figure C-49: Bending moment curves resulting from testing of sample B2/45/R-45/S1.

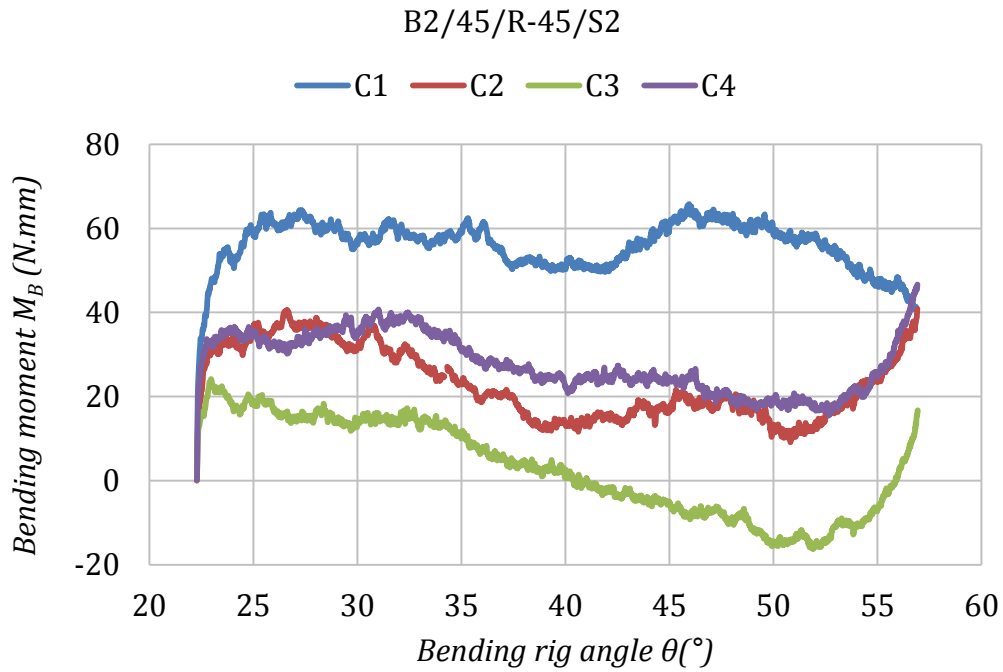


Figure C-50: Bending moment curves resulting from testing of sample B2/45/R-45/S2.

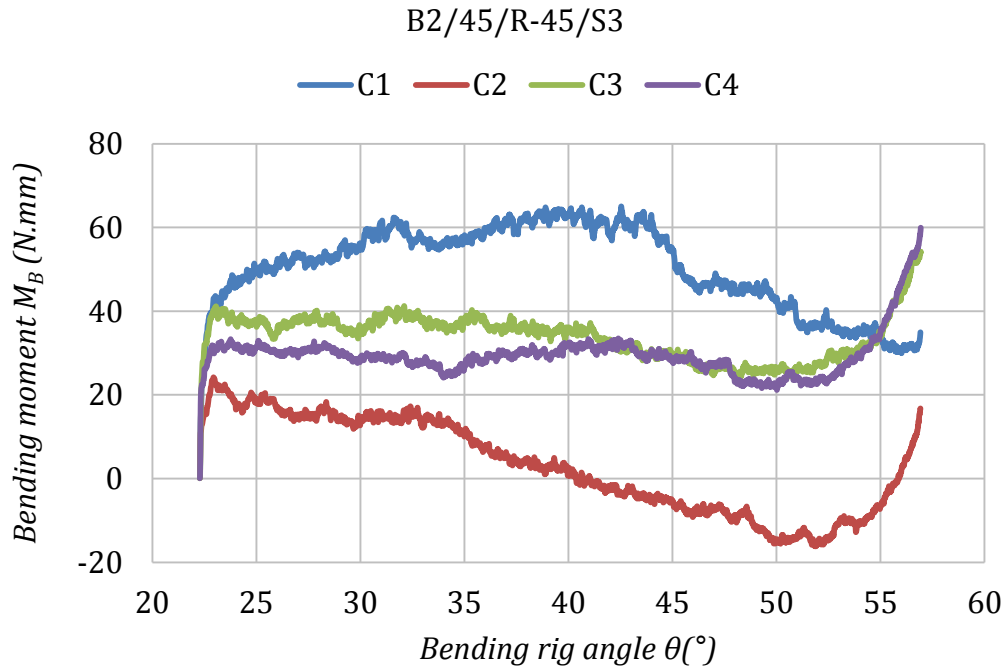


Figure C-51: Bending moment curves resulting from testing of sample B2/45/R-45/S3.

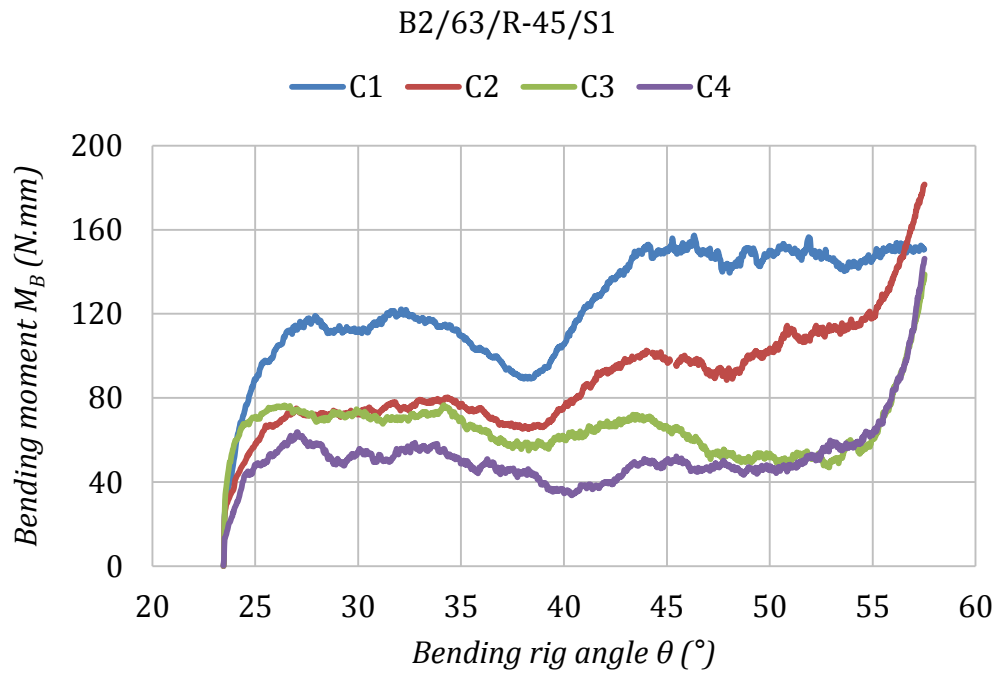


Figure C-52: Bending moment curves resulting from testing of sample B2/63/R-45/S1.

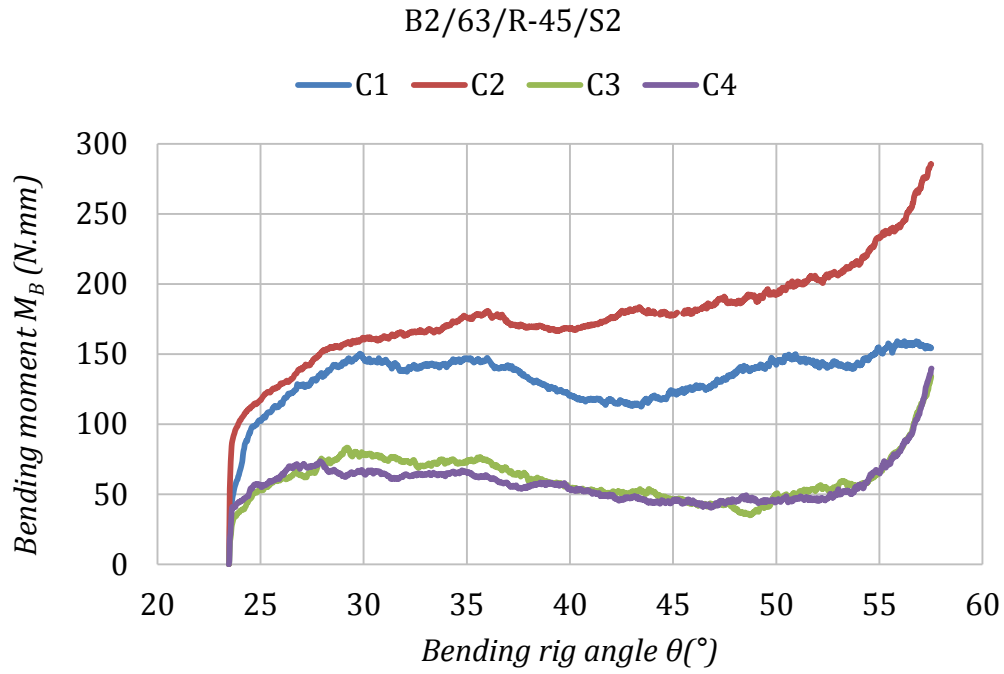


Figure C-53: Bending moment curves resulting from testing of sample B2/63/R-45/S2.

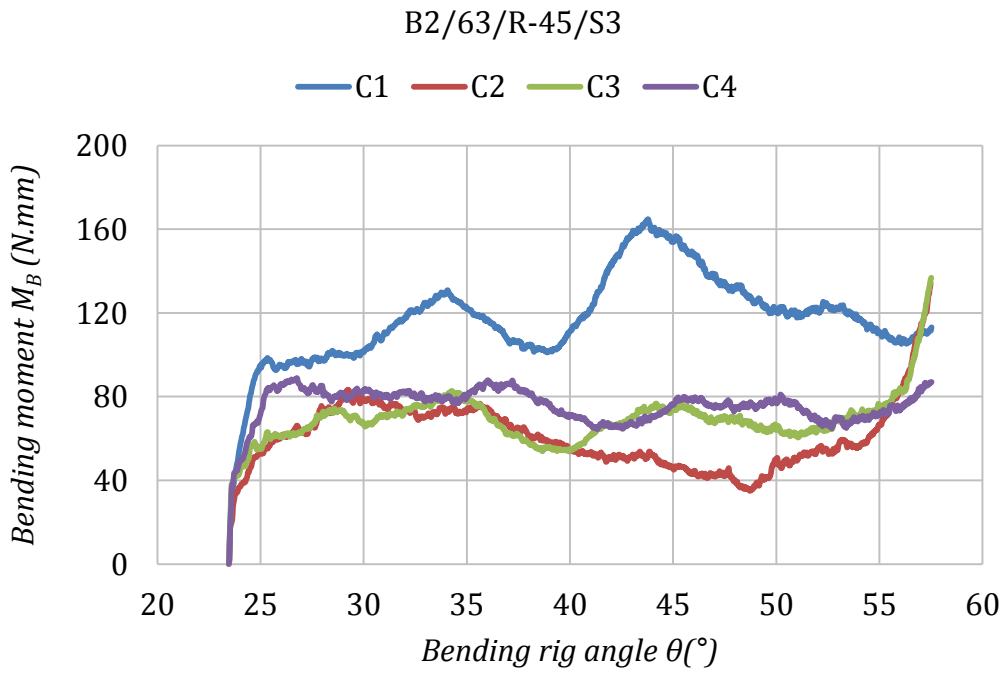


Figure C-54: Bending moment curves resulting from testing of sample B2/63/R-45/S3.

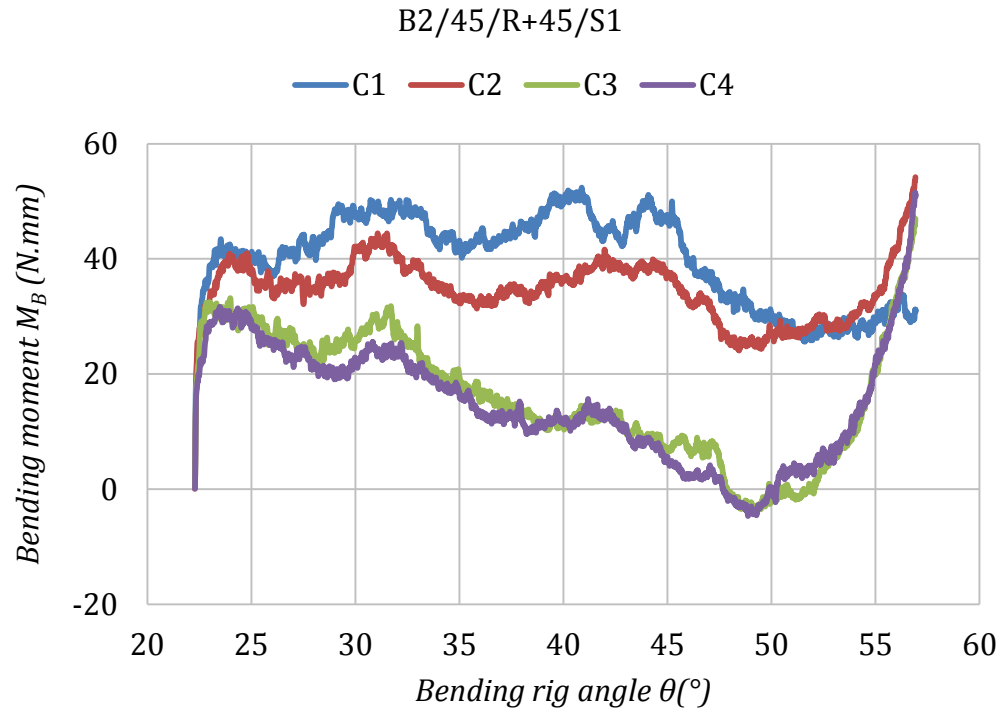


Figure C-55: Bending moment curves resulting from testing of sample B2/45/R+45/S1.

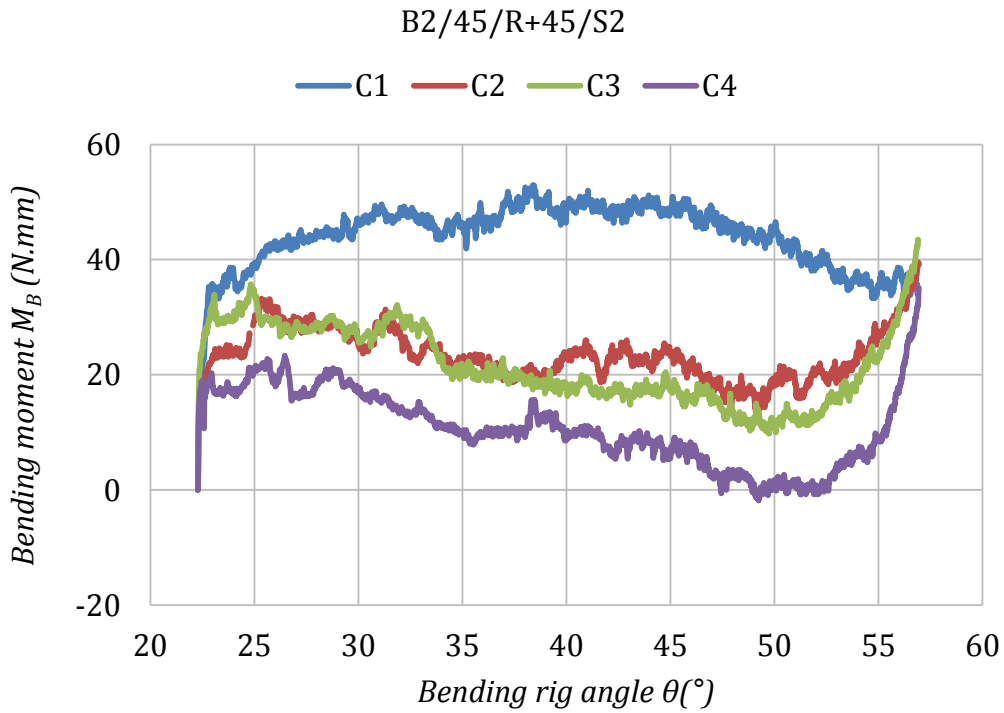


Figure C-56: Bending moment curves resulting from testing of sample B2/45/R+45/S2.

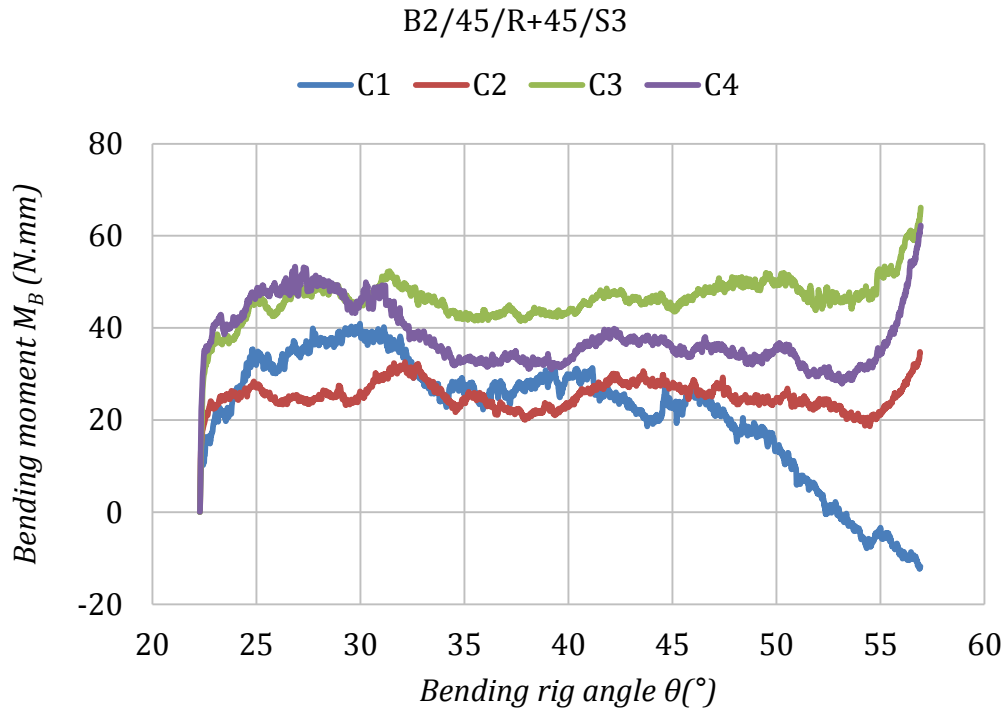


Figure C-57: Bending moment curves resulting from testing of sample B2/45/R+45/S3.

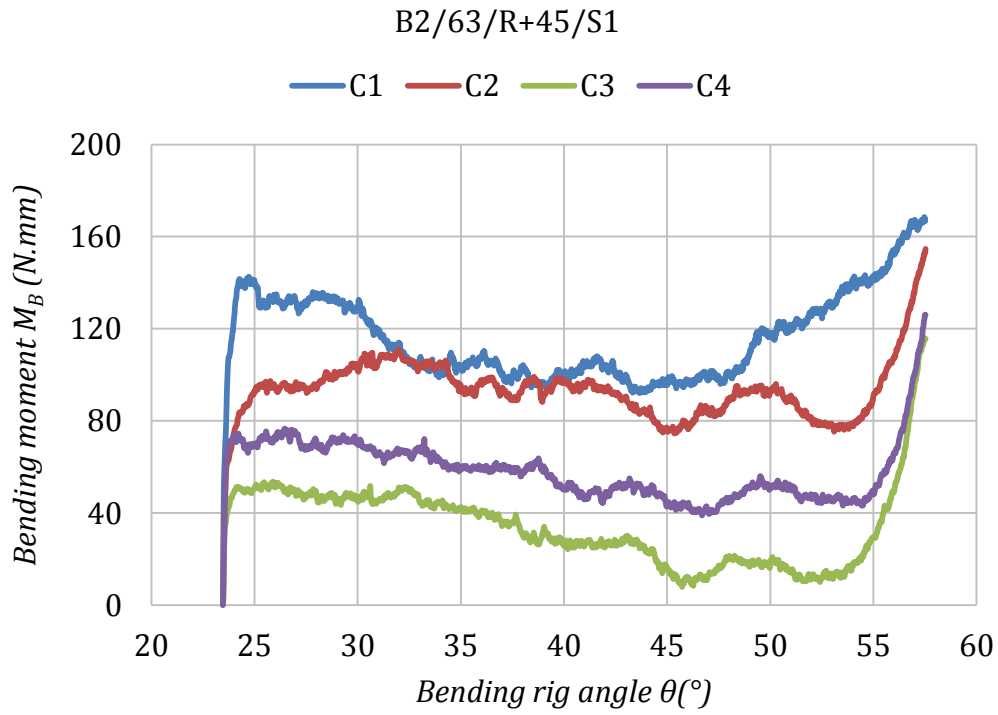


Figure C-58: Bending moment curves resulting from testing of sample B2/63/R+45/S1.

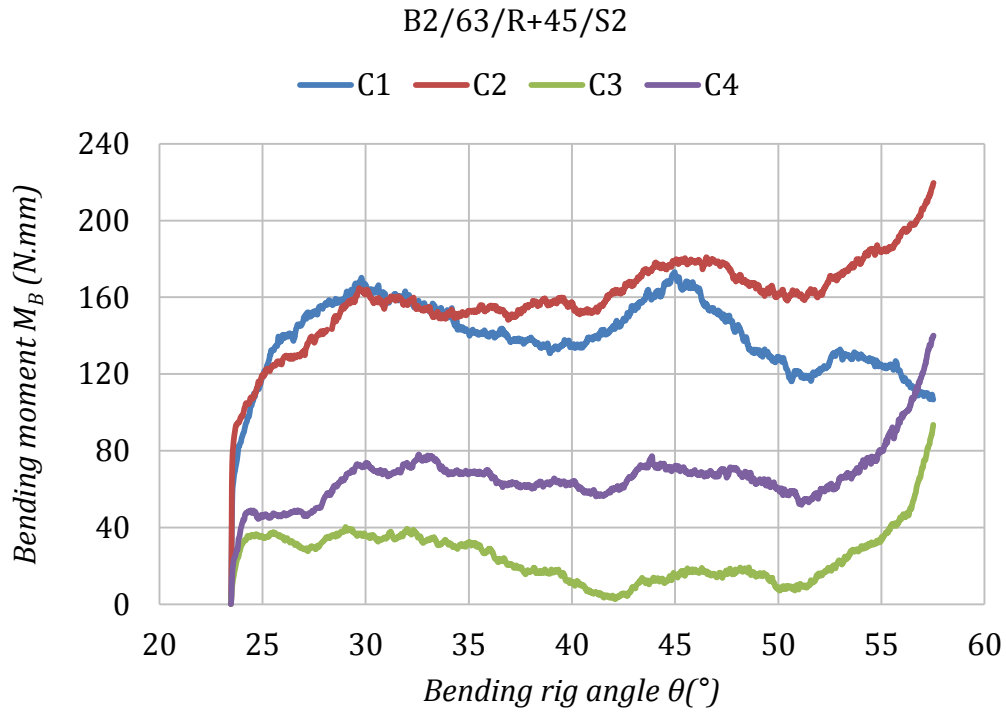


Figure C-59: Bending moment curves resulting from testing of sample B2/63/R+45/S2.

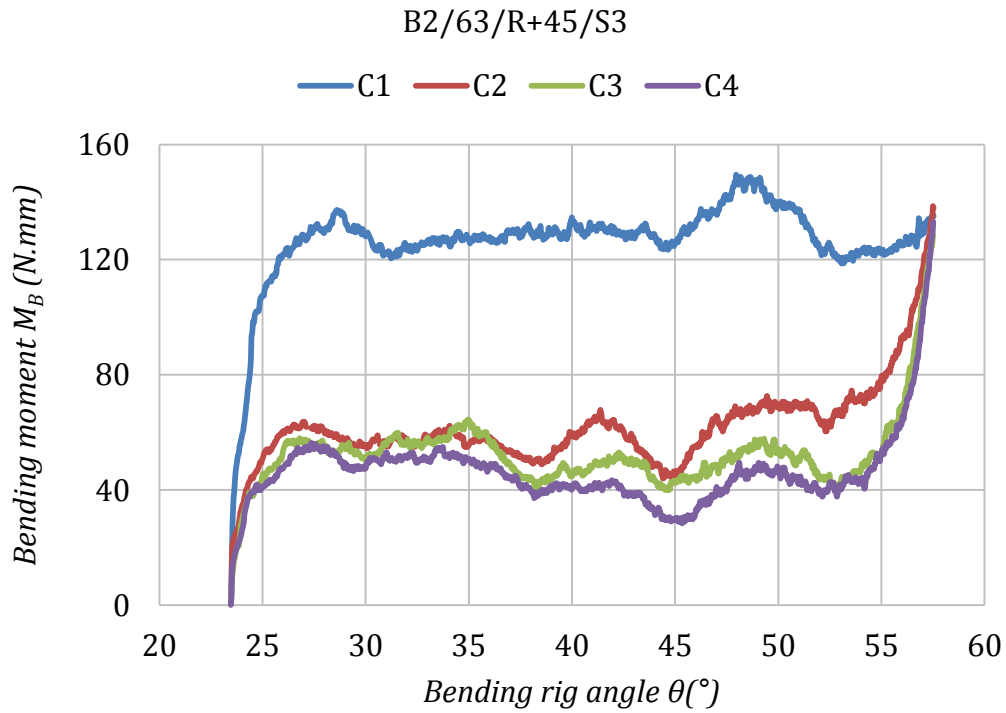


Figure C-60: Bending moment curves resulting from testing of sample B2/63/R+45/S3.

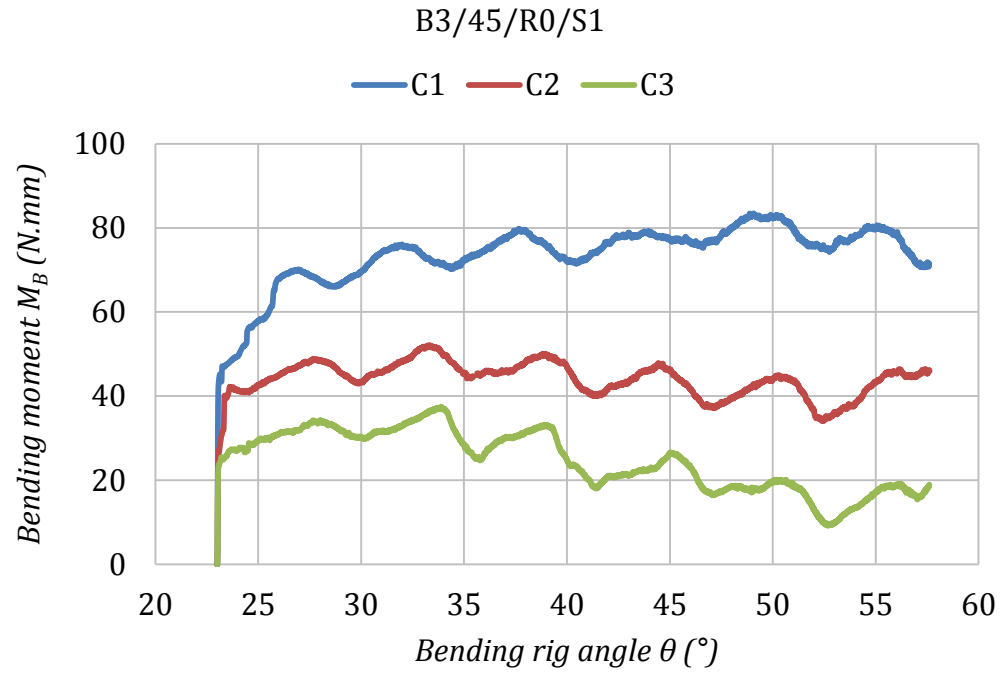


Figure C-61: Bending moment curves resulting from testing of sample B3/45/R0/S1.

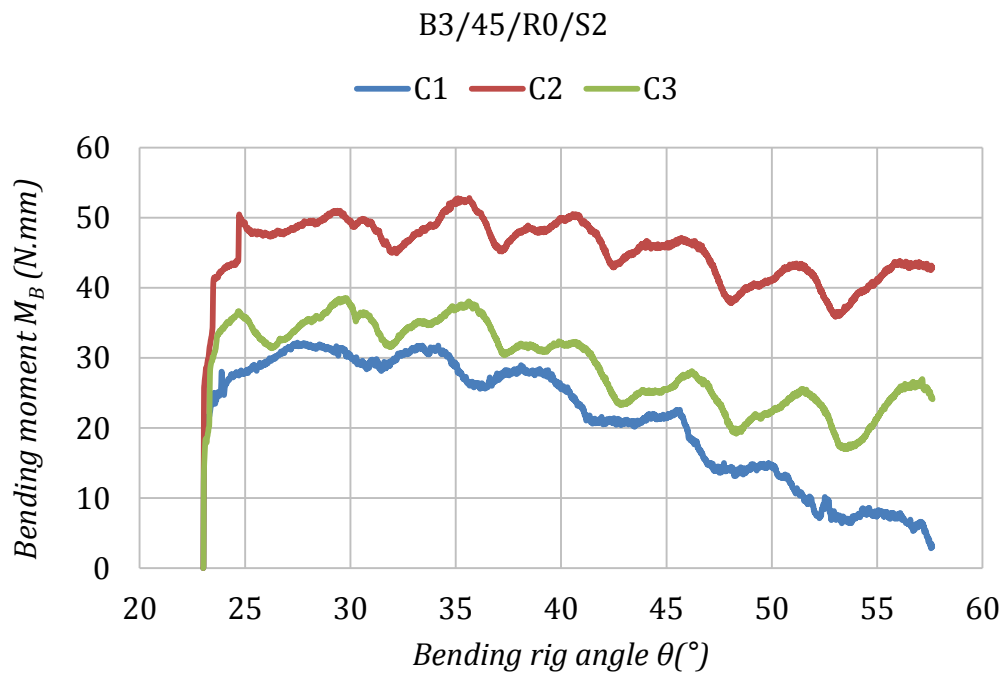


Figure C-62: Bending moment curves resulting from testing of sample B3/45/R0/S2.

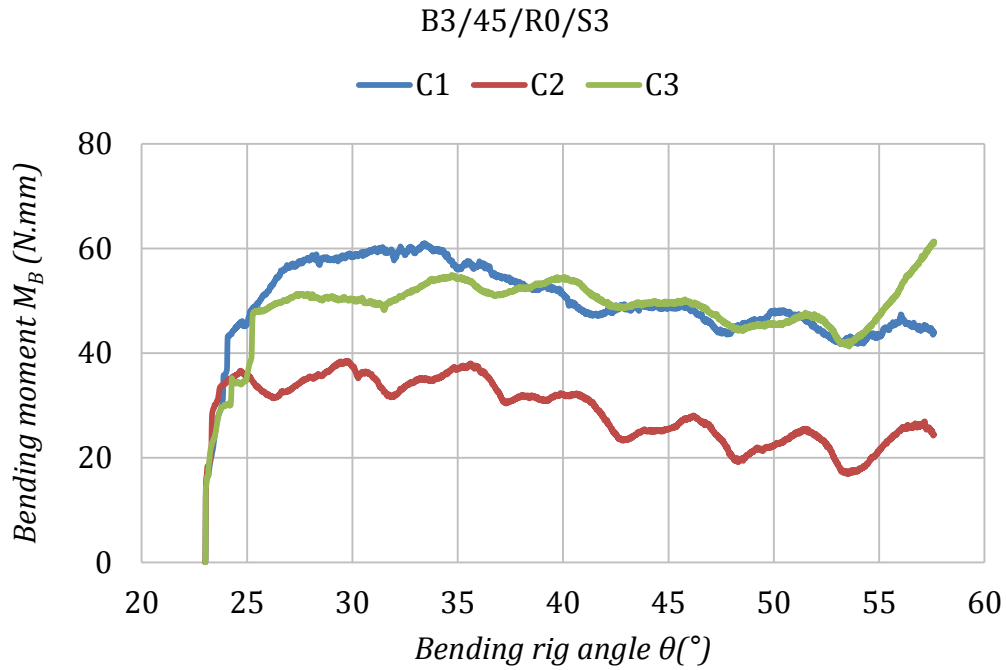


Figure C-63: Bending moment curves resulting from testing of sample B3/45/R0/S3.

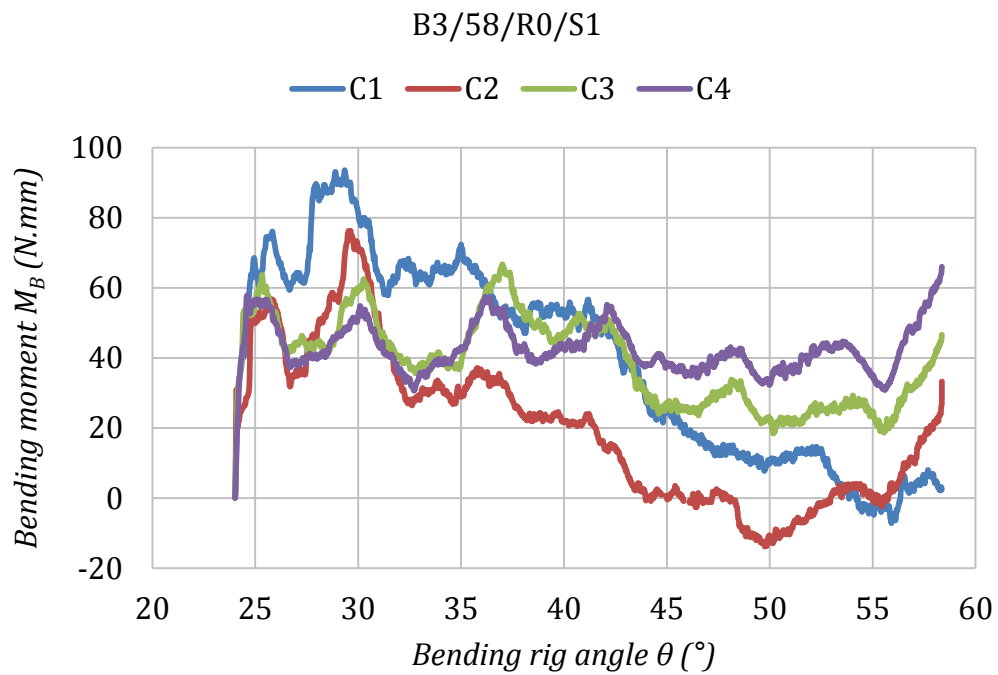


Figure C-64: Bending moment curves resulting from testing of sample B3/58/R0/S1.

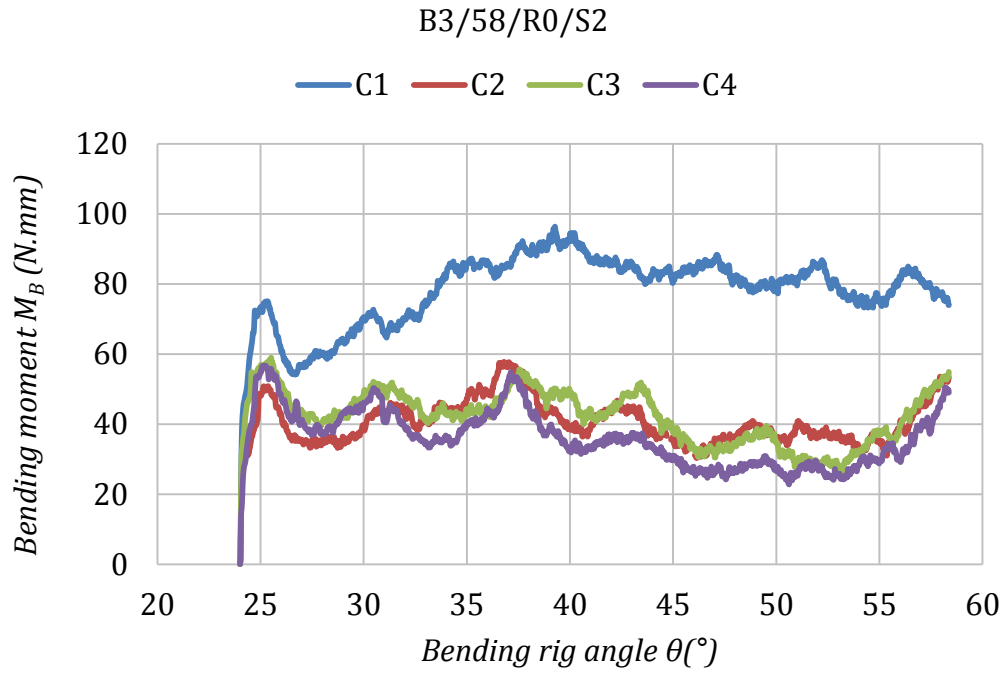


Figure C-65: Bending moment curves resulting from testing of sample B3/58/R0/S2.

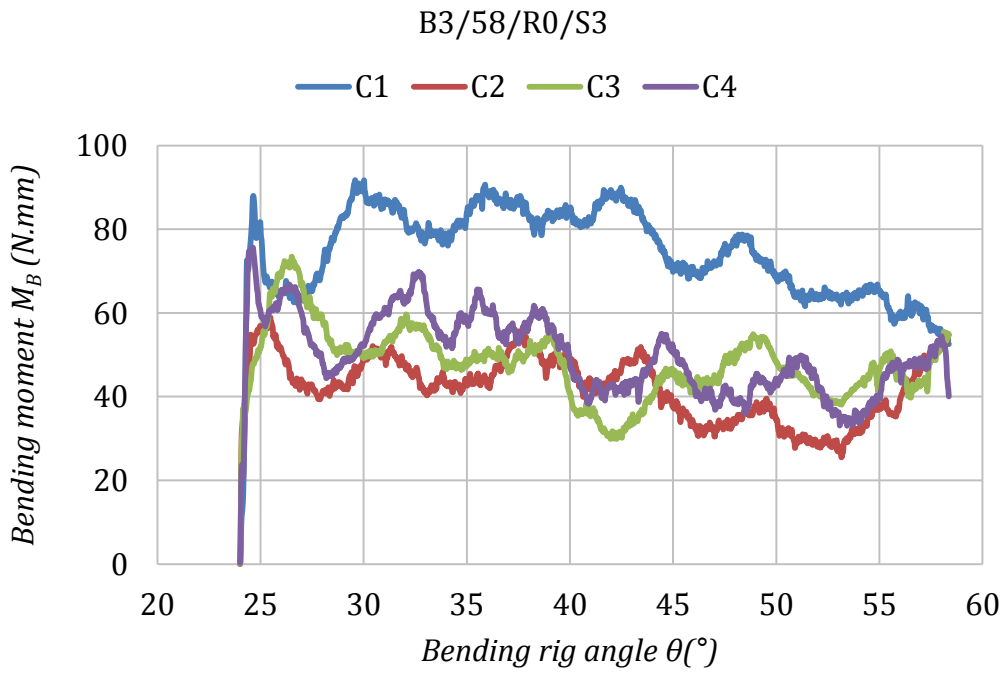


Figure C-66: Bending moment curves resulting from testing of sample B3/58/R0/S3.

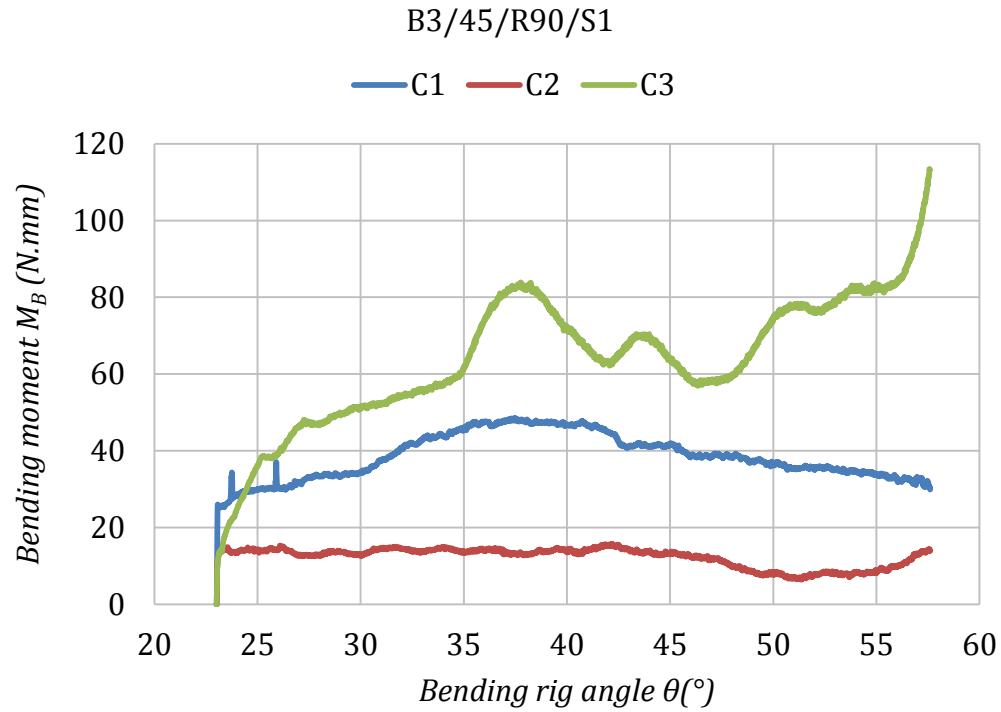


Figure C-67: Bending moment curves resulting from testing of sample B3/45/R90/S1.

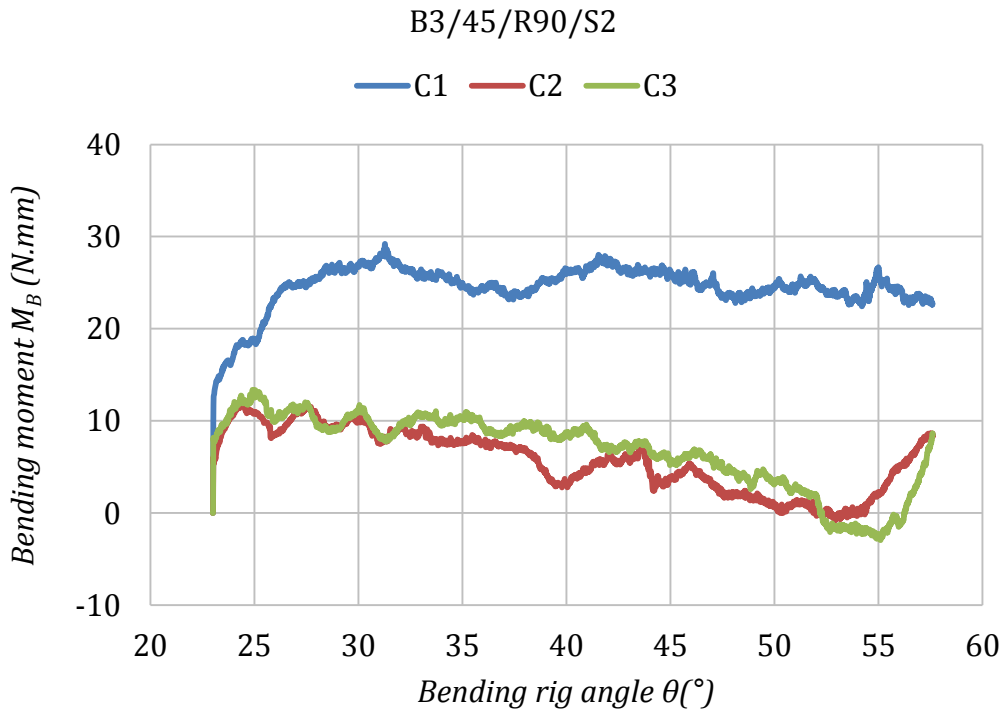


Figure C-68: Bending moment curves resulting from testing of sample B3/45/R90/S2.

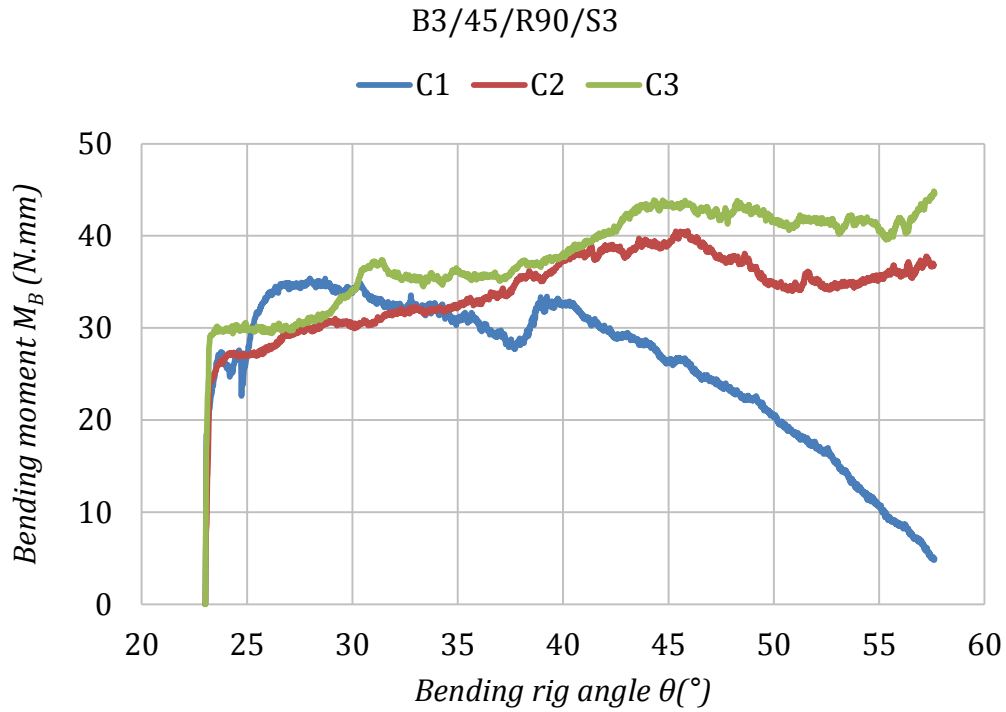


Figure C-69: Bending moment curves resulting from testing of sample B3/45/R90/S3.

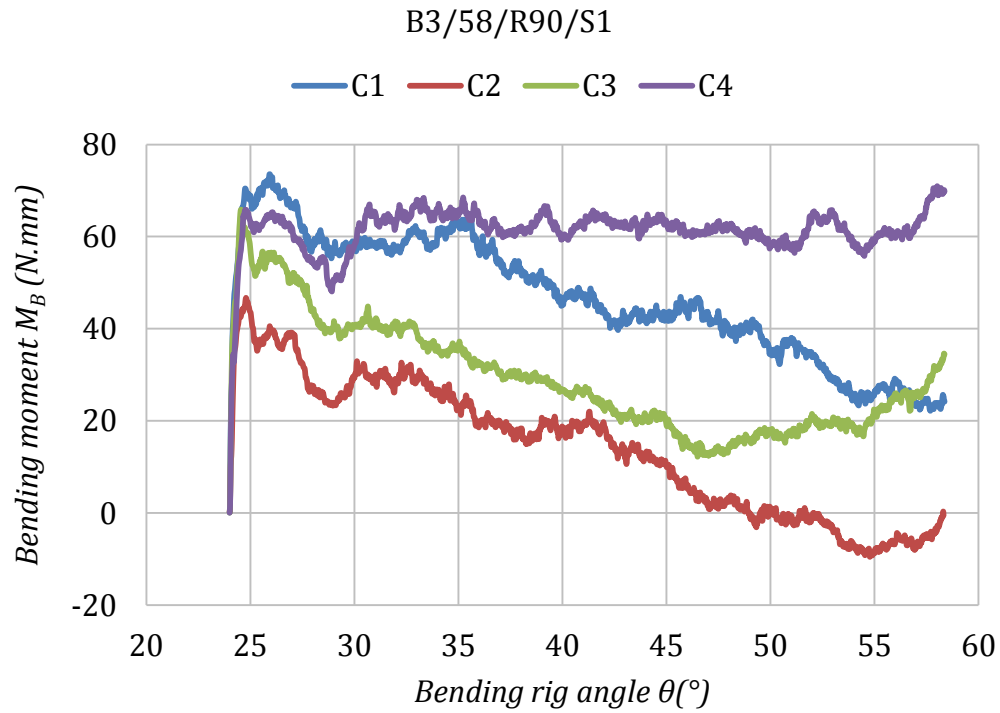


Figure C-70: Bending moment curves resulting from testing of sample B3/58/R90/S1.

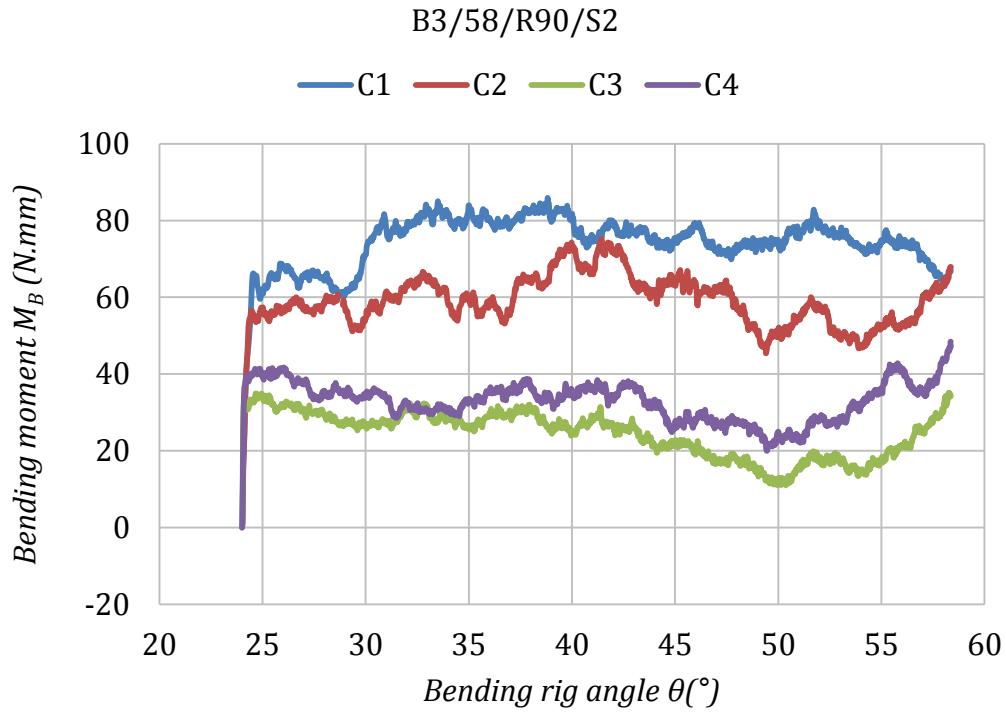


Figure C-71: Bending moment curves resulting from testing of sample B3/58/R90/S2.

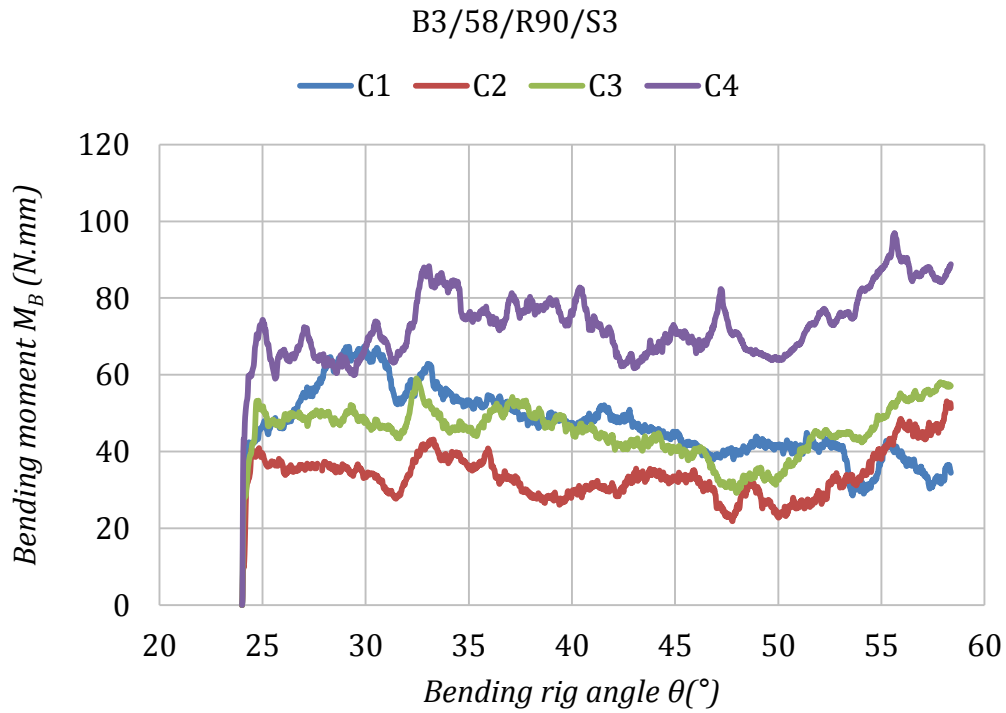


Figure C-72: Bending moment curves resulting from testing of sample B3/58/R90/S3.

Appendix D

Bending moment data

D.1 UO-APT Samples

The average (*AVG*) and the standard deviation (*STDEV*) values obtained from the bending moment curves for all samples which were made from uo-APT preforms are presented here.

Table D-1: Average and standard deviation bending moment values obtained for group A1 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
								AVG		STD		
								C1	C3	C1	C3	
uO-APT	A1	8 parallel yarn arrays - [90/0/90/0] _s	Along 0° in reinforcement	A1/45	R0	2.0	S1	45.81	36.34	13.39	12.50	0.44
							S2	61.04	42.31	14.15	16.64	0.45
							S3	81.54	26.10	19.34	12.46	0.43
				A1/60		1.5	S1	177.88	85.38	64.66	42.90	0.60
							S2	248.38	66.87	32.46	28.11	0.63
							S3	170.84	113.24	72.79	58.21	0.60
				A1/45	R90	2.0	S1	74.60	45.19	8.04	8.56	0.46
							S2	159.19	83.49	12.24	2.86	0.44
							S3	136.97	80.28	7.90	3.76	0.43
				A1/60		1.5	S1	222.57	141.13	70.55	33.71	0.60
							S2	202.40	106.04	29.55	14.90	0.61
							S3	190.84	148.63	37.44	49.87	0.64

Table D-2: Average and standard deviation bending moment values obtained for group A2 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
								AVG		STD		
								C1	C3	C1	C3	
uO-APT	A2	12 parallel yarn arrays – [90/0/90/0/90/0] _s	Along 0° in reinforcement	A2/45	R0	3.0	S1	100.62	42.34	17.77	19.72	0.45
							S2	92.29	65.17	15.38	13.48	0.45
							S3	81.51	31.03	19.45	13.02	0.45
				A2/66		2.0	S1	110.73	67.08	15.40	17.73	0.66
							S2	144.42	41.17	21.46	7.56	0.65
							S3	139.17	59.43	20.26	21.52	0.67
				A2/45	R90	3.0	S1	140.46	59.68	25.64	7.60	0.45
							S2	109.88	50.40	7.43	10.27	0.46
							S3	99.67	85.12	10.98	16.93	0.44
				A2/66		2.0	S1	183.43	115.25	47.26	22.49	0.68
							S2	211.56	149.47	33.30	22.65	0.68
							S3	174.06	177.54	49.61	25.96	0.67

Table D-3: Average and standard deviation bending moment values obtained for group A3 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
								AVG		STD		
								C1	C3	C1	C3	
uO-APT	A3	8 parallel yarn arrays - [90/0/90/0] _s	Along 45° in reinforcement	A3/45	R0	2.0	S1	112.27	43.94	42.72	29.64	0.45
							S2	52.53	24.37	60.01	53.77	0.47
							S3	140.83	77.26	89.05	60.51	0.47
				A3/60		1.5	S1	55.51	16.32	7.62	7.70	0.60
							S2	40.00	34.44	4.76	8.78	0.59
							S3	22.20	35.83	13.73	5.20	0.59
				A3/45	R90	2.0	S1	161.32	65.71	46.62	11.83	0.46
							S2	89.76	50.66	9.05	7.88	0.45
							S3	99.30	49.64	12.46	6.49	0.45
				A3/60		1.5	S1	28.88	43.90	6.40	5.57	0.59
							S2	44.68	37.83	5.31	2.13	0.59
							S3	42.56	27.19	3.60	4.05	0.60

D.2 Saertex Samples

The average (*AVG*) and the standard deviation (*STDEV*) values obtained from the bending moment curves for all samples which were made from Saertex industrial preforms are presented here.

Table D-4: Average and standard deviation bending moment values obtained for group B1 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
							AVG		STD			
							C1	C3	C1	C3		
Saertex industrial reinforcement	B1	3 layers - [(0/90)] ₃	Along 45° in reinforcement	B1/45	R-45	2.0	S1	49.00	6.58	5.43	5.02	0.44
							S2	33.58	12.70	5.28	6.06	0.44
							S3	61.02	28.79	4.49	1.83	0.44
				B1/58		1.5	S1	72.34	23.72	8.69	6.86	0.60
							S2	46.41	24.74	6.32	3.62	0.59
							S3	64.98	35.39	11.15	5.80	0.56
				B1/45	R+45	2.0	S1	60.32	17.71	3.59	2.03	0.43
							S2	23.31	18.47	5.69	2.46	0.43
							S3	54.10	13.38	3.13	2.14	0.43
				B1/58		1.5	S1	83.03	24.36	20.19	3.15	0.58
							S2	61.95	20.67	19.47	7.85	0.57
							S3	81.68	30.74	9.44	4.58	0.57

Table D-5: Average and standard deviation bending moment values obtained for group B2 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
								AVG		STD		
								C1	C3	C1	C3	
Saertex industrial reinforcement	B2	4 layers - [(0/90)] ₄	Along 45° in reinforcement	B2/45	R-45	2.7	S1	57.91	37.94	8.55	3.33	0.42
							S2	57.07	26.08	6.61	10.72	0.42
							S3	51.74	32.42	9.35	4.65	0.42
				B2/63		1.8	S1	128.18	62.26	20.60	8.26	0.62
							S2	134.05	57.86	11.61	11.88	0.63
							S3	122.37	67.89	17.76	6.42	0.63
				B2/45	R+45	2.7	S1	40.23	12.54	8.03	9.49	0.43
							S2	45.35	19.52	4.17	5.67	0.43
							S3	22.17	46.57	11.88	2.51	0.42
				B2/63		1.8	S1	112.02	28.79	14.67	13.47	0.61
							S2	143.27	20.93	14.17	10.17	0.62
							S3	129.68	50.52	6.98	5.43	0.62

Table D-6: Average and standard deviation bending moment values obtained for group B3 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Stitching setup	SPR (mm)	Sample	Bending moment M_B (N.mm)				v_f
								AVG		STD		
								C1	C3	C1	C3	
Saertex industrial reinforcement	B3	3 layers - [(0/90)] ₃	Along 45° in reinforcement	B3/45	R0	2.0	S1	75.52	24.06	4.56	7.31	0.43
							S2	21.37	28.38	8.13	6.01	0.42
							S3	50.67	49.10	5.60	3.36	0.43
				B3/58		1.5	S1	39.87	38.24	26.44	12.47	0.60
							S2	79.78	40.99	8.80	7.59	0.58
							S3	76.27	47.21	8.62	8.19	0.56
				B3/45	R90	2.0	S1	39.76	65.71	5.18	11.83	0.43
							S2	25.07	6.50	1.42	3.92	0.44
							S3	26.76	38.67	6.68	4.04	0.43
				B3/58		1.5	S1	47.21	27.24	11.68	11.22	0.59
							S2	75.58	23.36	5.22	6.03	0.57
							S3	47.45	43.90	8.40	5.87	0.57

Appendix E

Shear force curves

E.1 Introduction

Shear force curves result from all shear tests conducted on samples prepared from uo-APT preforms (type A) and Saertex industrial preforms (type B) samples are presented here.

The curves represent the relation between the shear force F_s and the shear angle γ .

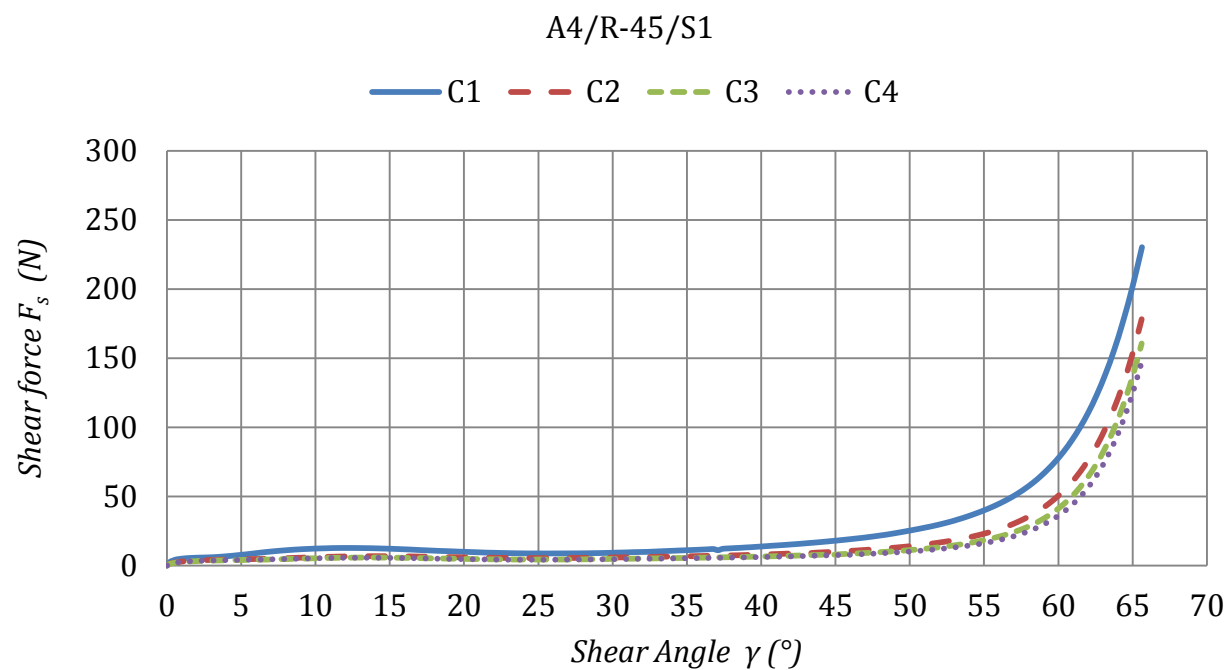


Figure E-1: Shear force curves resulting from testing of sample A4/R-45/ S1.

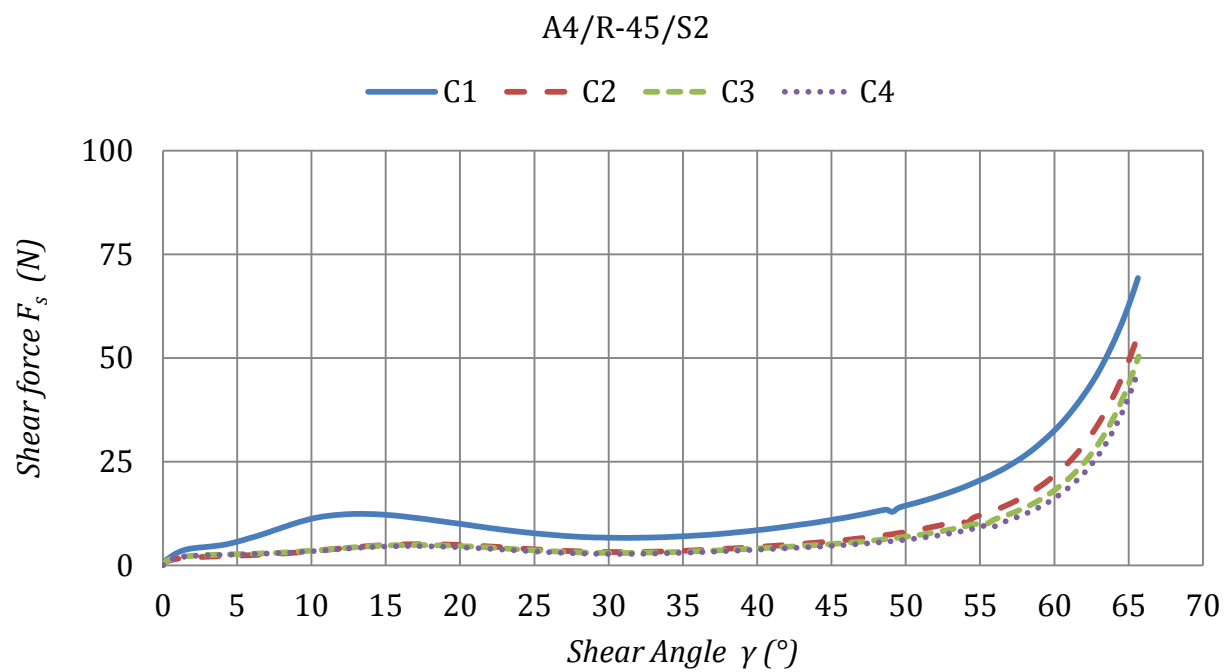


Figure E-2: Shear force curves resulting from testing of sample A4/R-45/S2.

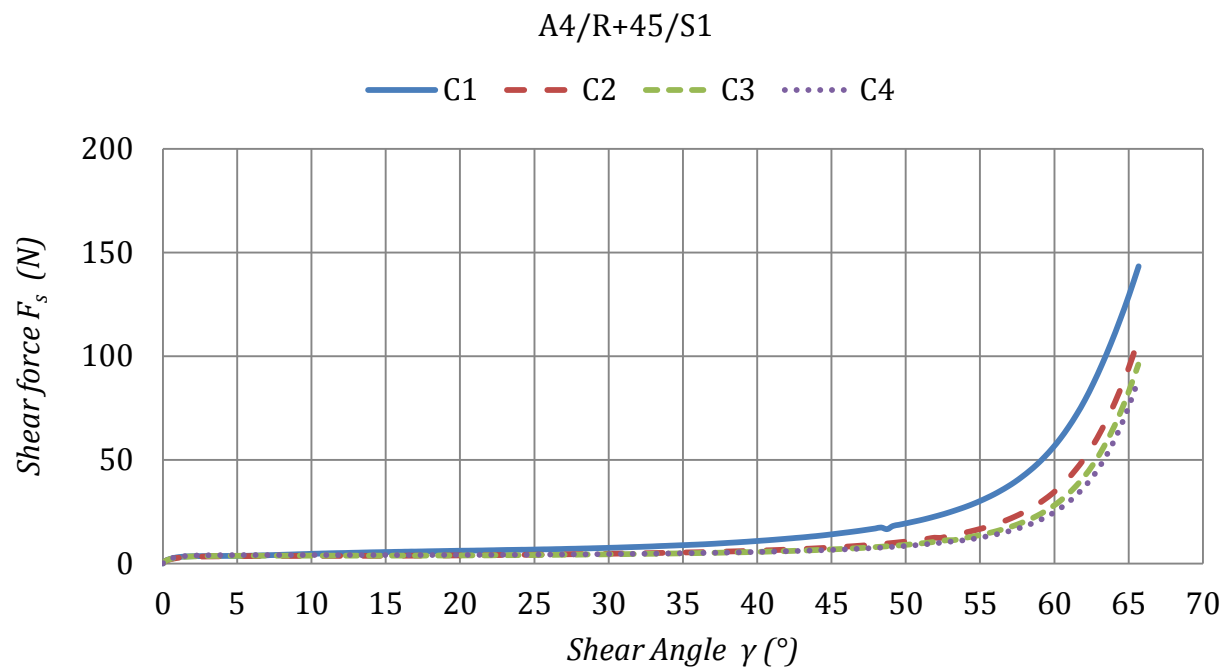


Figure E-3: Shear force curves resulting from testing of sample A4/R+45/ S1.

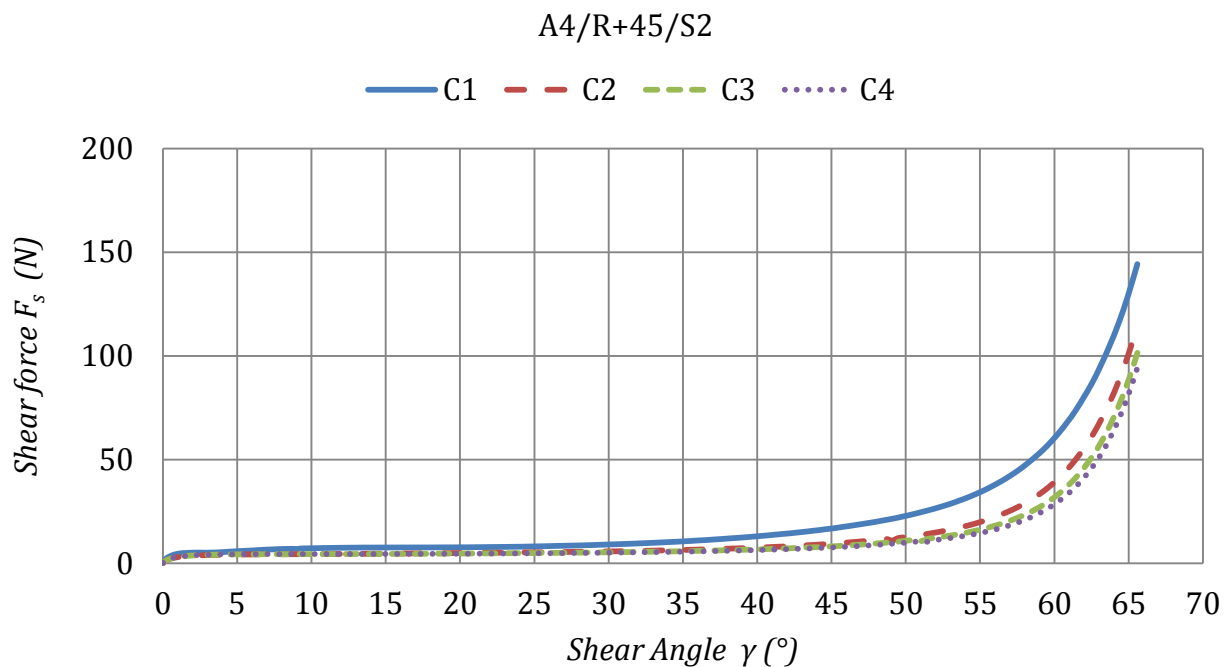


Figure E-4: Shear force curves resulting from testing of sample A4/R+45/S2.

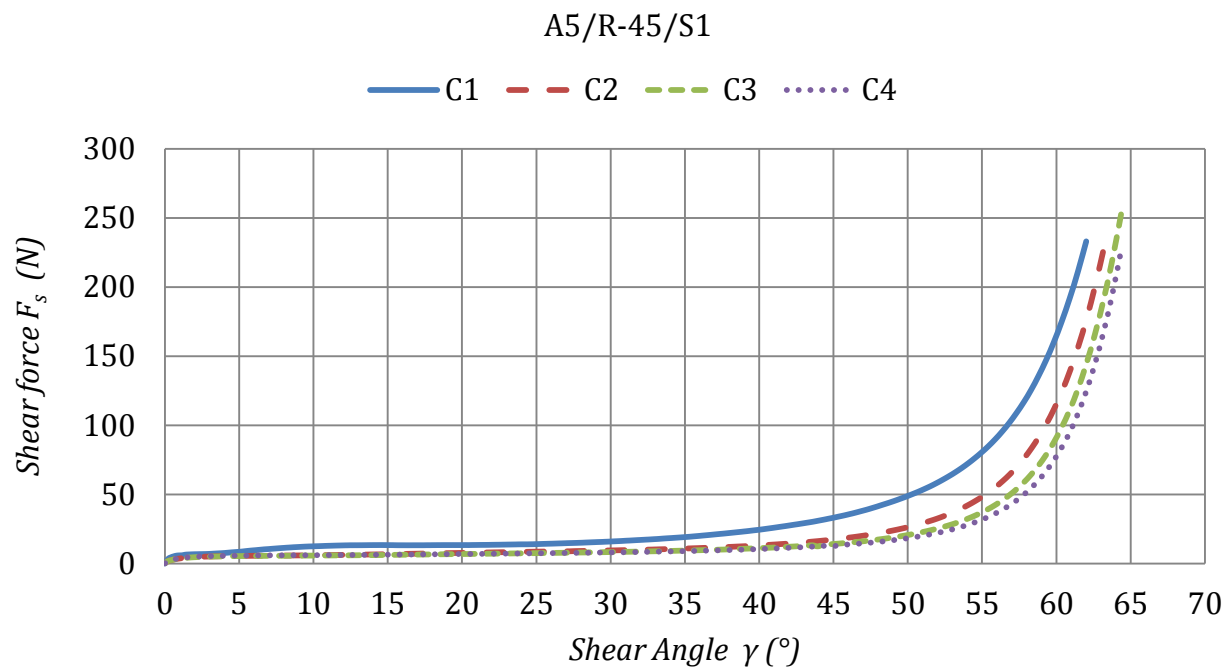


Figure E-5: Shear force curves resulting from testing of sample A5/R-45/S1.

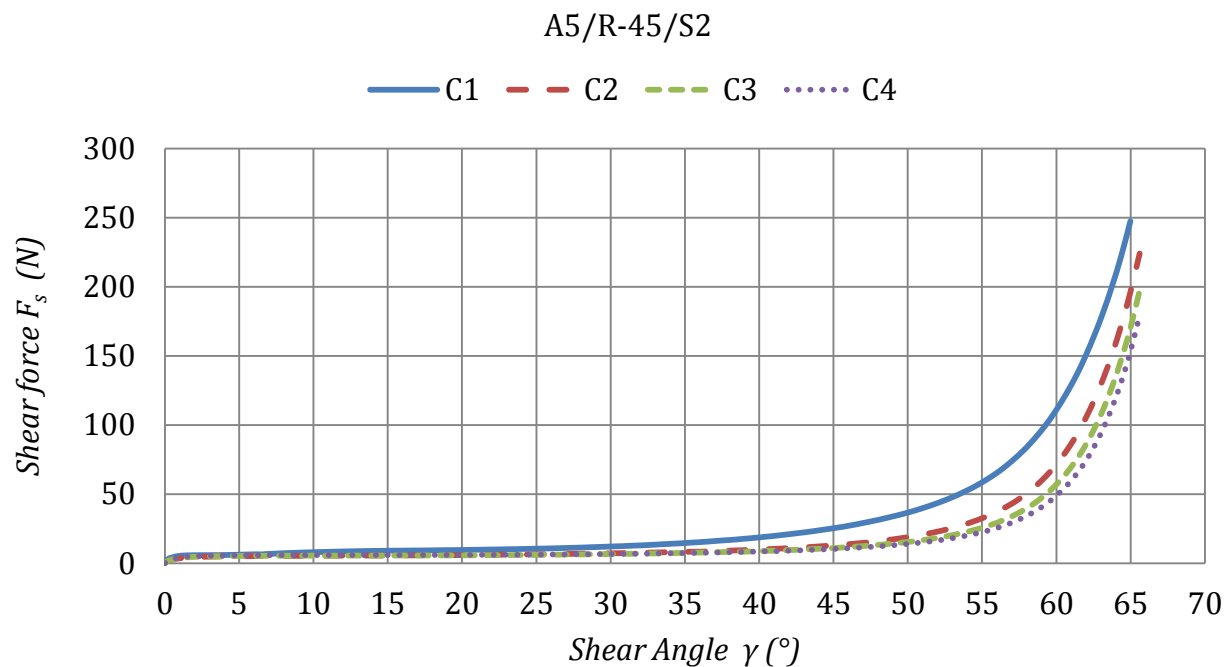


Figure E-6: Shear force curves resulting from testing of sample A5/R-45/S2.

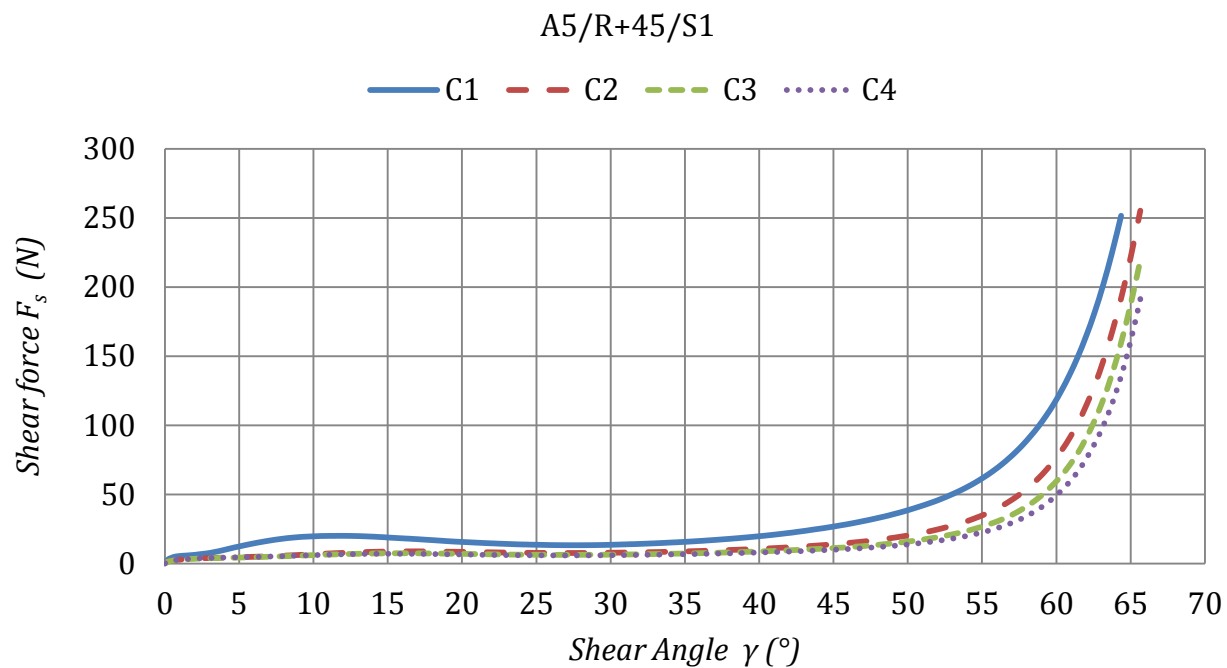


Figure E-7: Shear force curves resulting from testing of sample A5/R+45/S1.

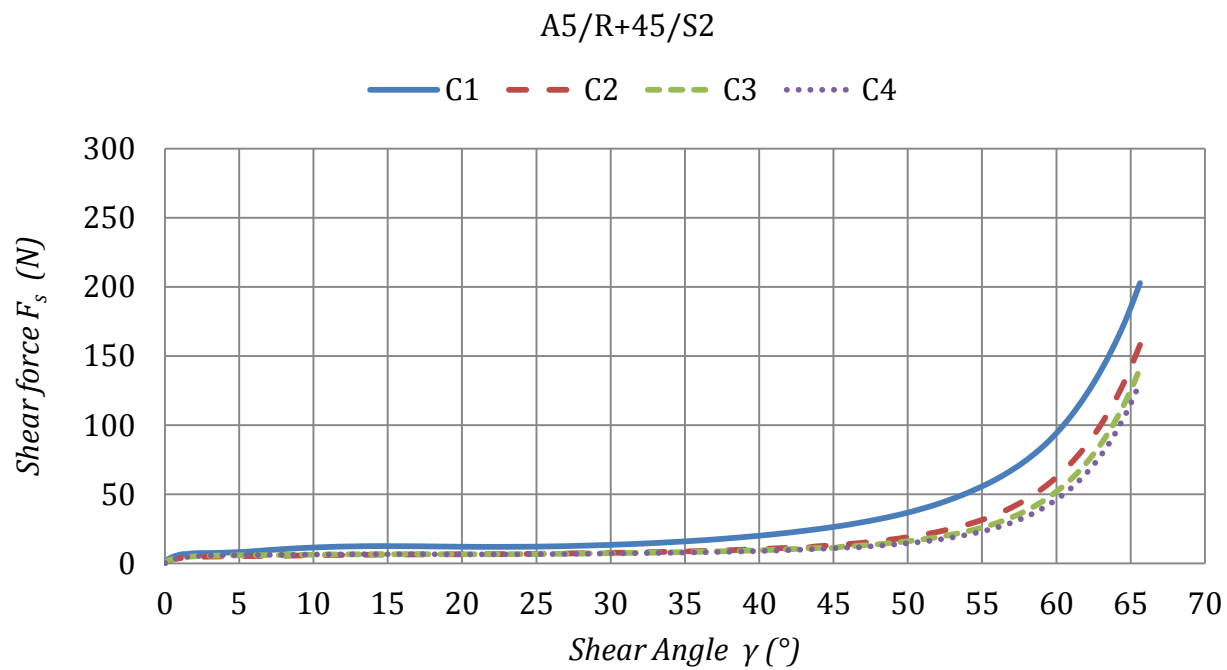


Figure E-8: Shear force curves resulting from testing of sample A5/R+45/S2.

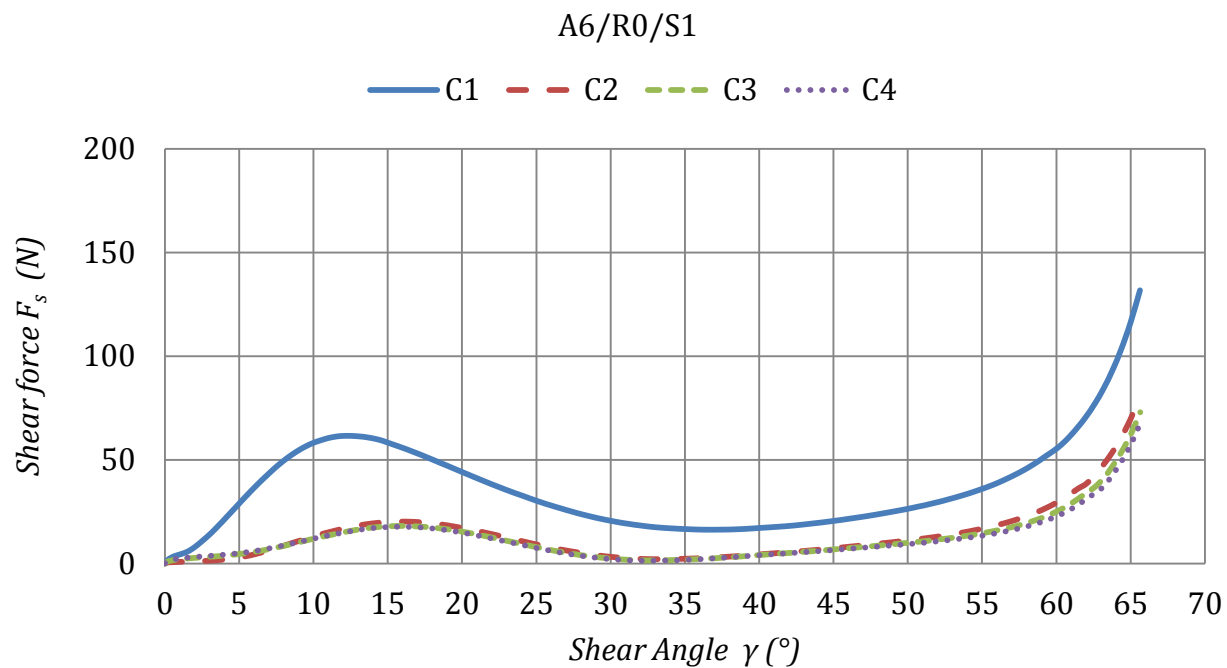


Figure E-9: Shear force curves resulting from testing of sample A6/R0/ S1.

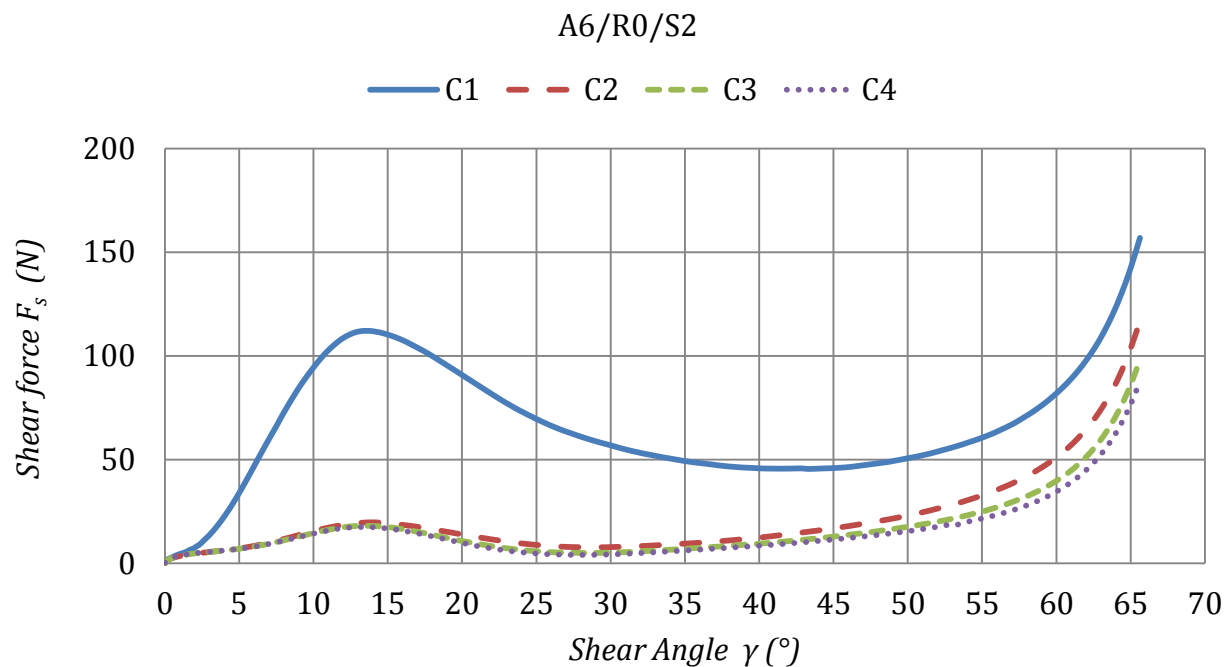


Figure E-10: Shear force curves resulting from testing of sample A6/R0/S2.

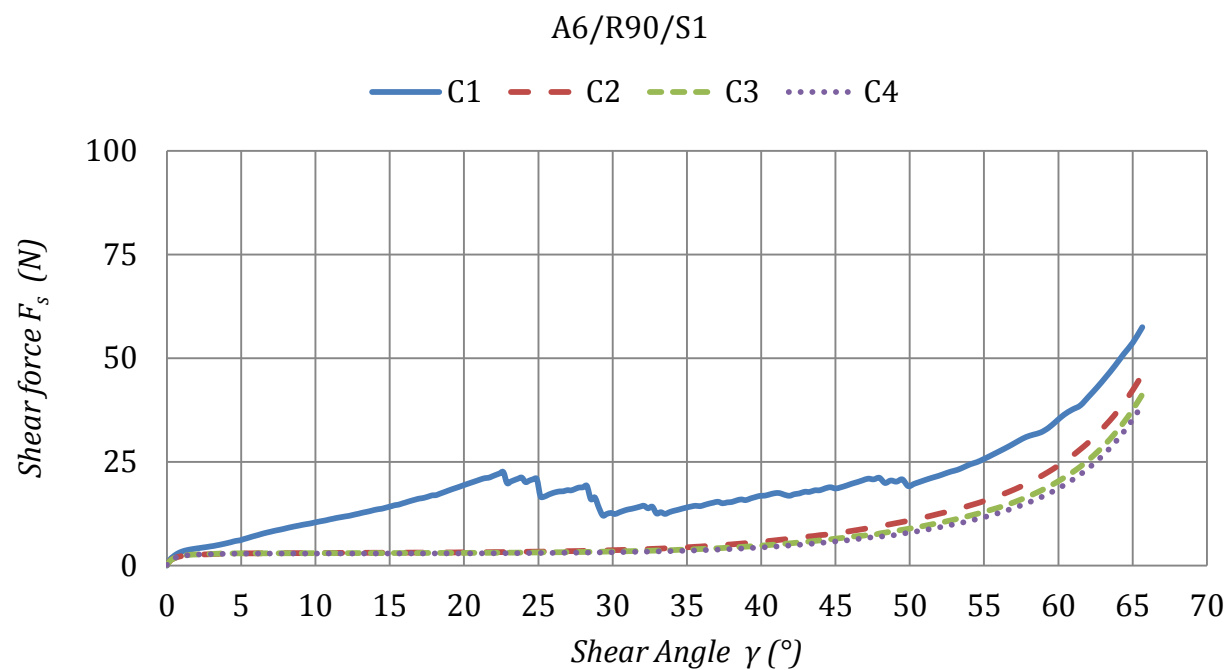


Figure E-11: Shear force curves resulting from testing of sample A6/R90/ S1.

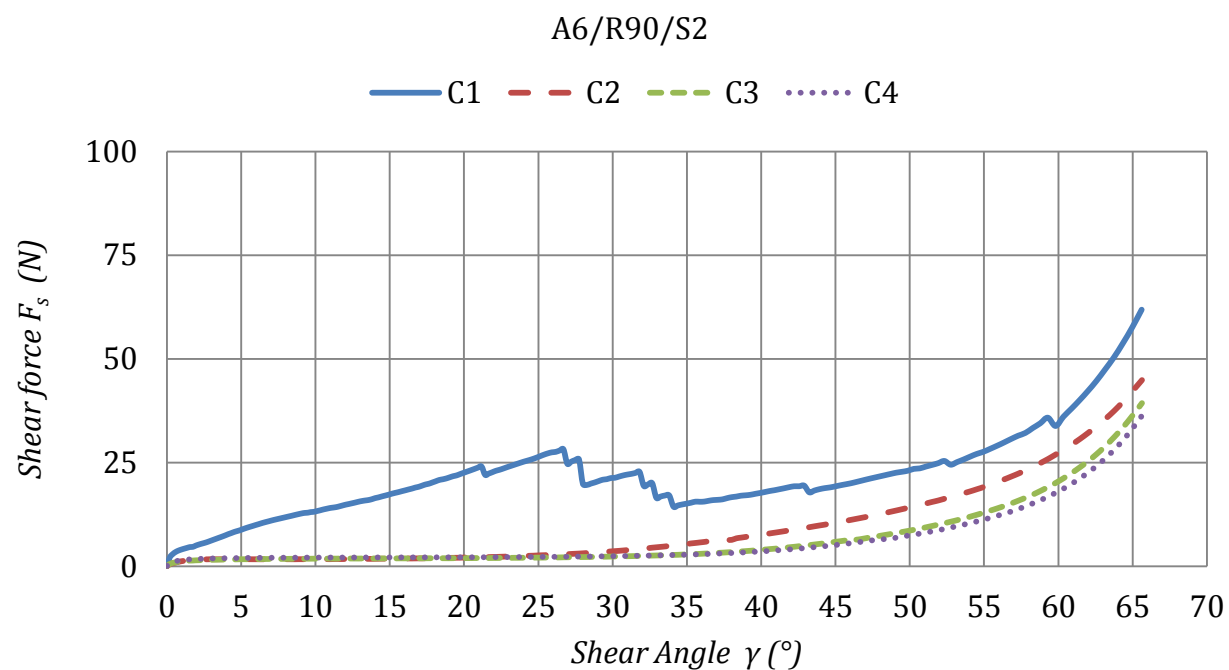


Figure E-12: Shear force curves resulting from testing of sample A6/R90/S2.

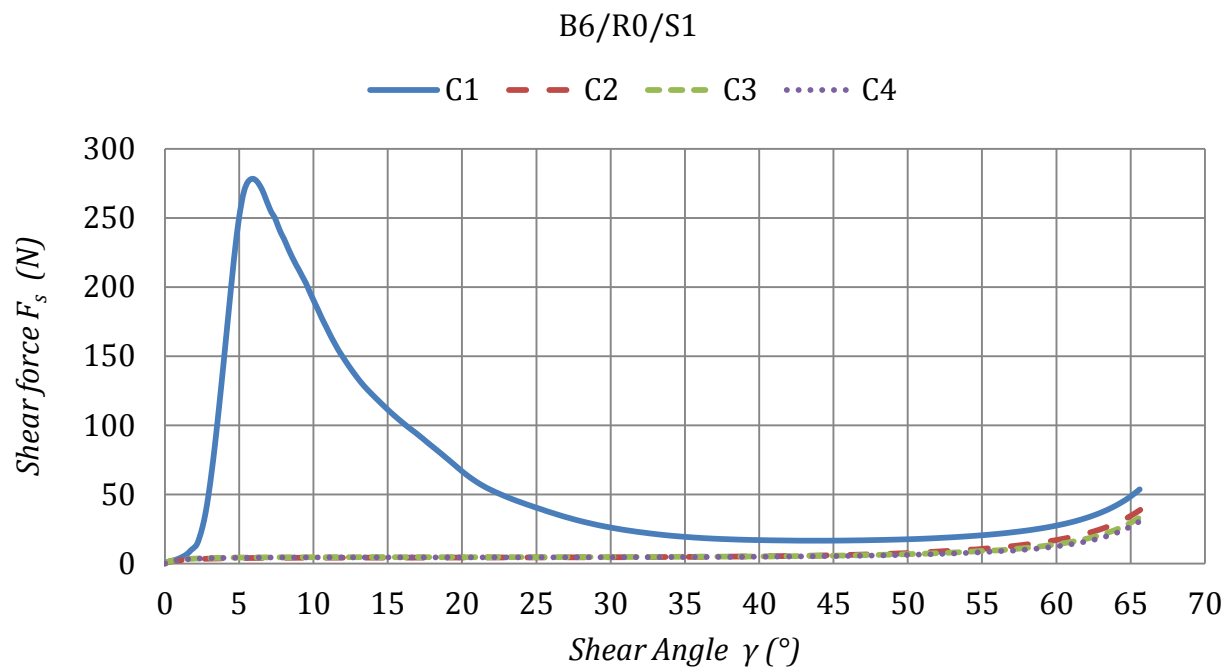


Figure E-13: Shear force curves resulting from testing of sample B6/R0/S1.

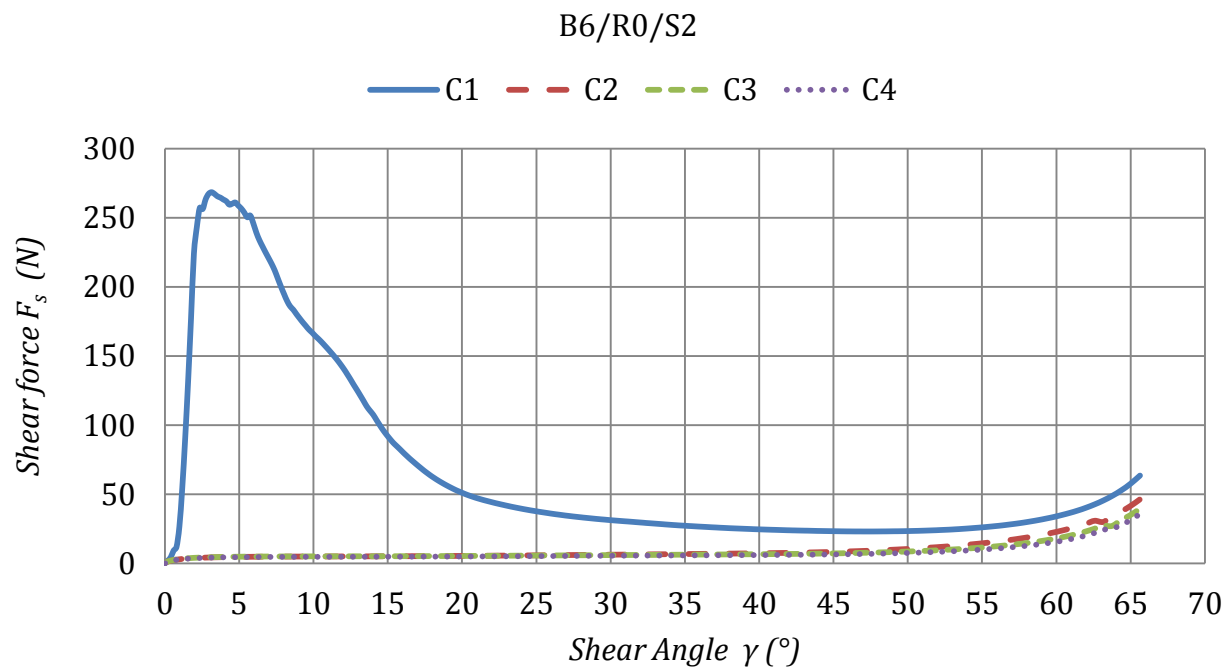


Figure E-14: Shear force curves resulting from testing of sample B6/R0/S2.

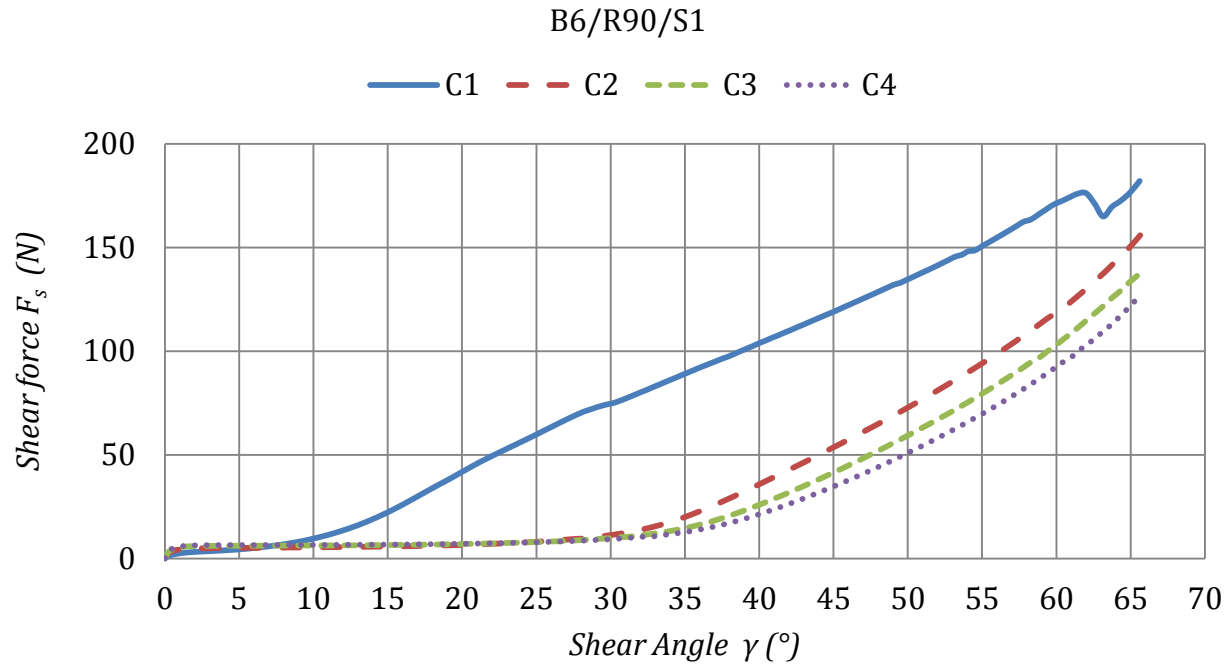


Figure E-15: Shear force curves resulting from testing of sample B6/R90/S1.

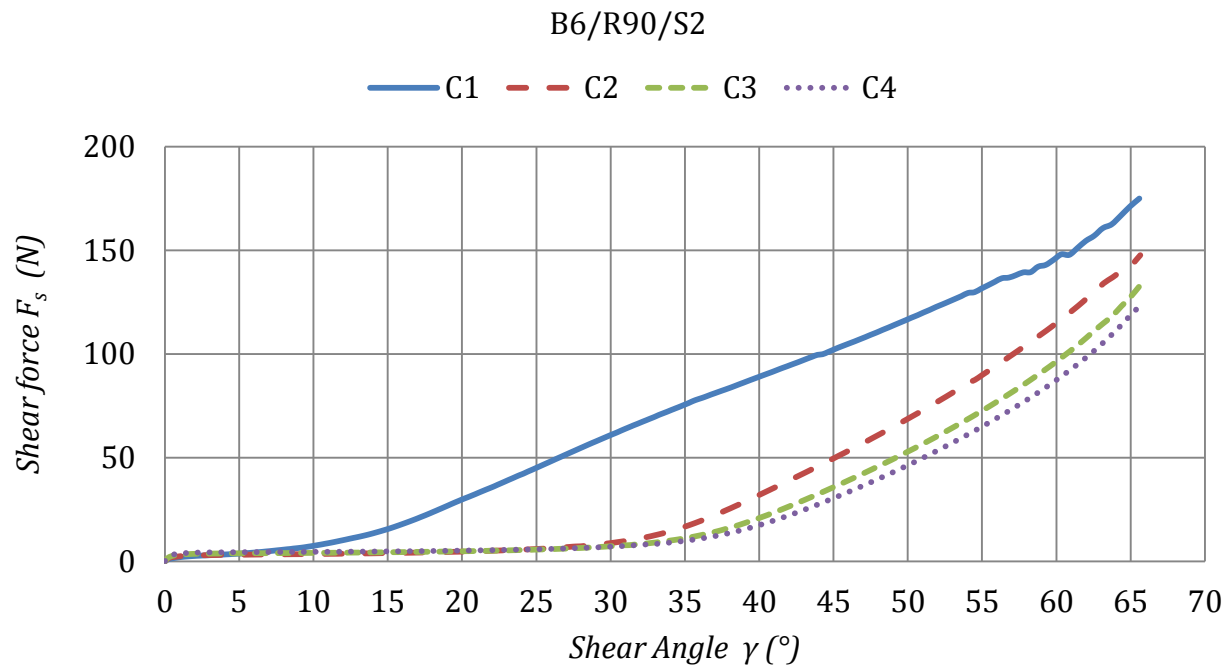


Figure E-16: Shear force curves resulting from testing of sample B6/R90/S2.

Appendix F

Shear locking angle data

F.1 UO-APT Samples

The values of the shear locking angle (γ_L) obtained from the shear curves for all samples which were made from uo-APT preforms are presented here.

Table F-1: Shear locking angles obtained for group A4 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear locking angle γ_L ($^\circ$)</i>			
							C1	C2	C3	C4
uO-APT	A4	8 parallel yarn arrays - [90/0/90/0] _s	Along 0° in reinforcement	R-45	2.0	S1	60	60.5	61	61.5
						S2	58.5	59.5	60	60.5
				R+45	2.0	S1	58.5	60	60.5	61
						S2	58.5	60	60.5	61

Table F-2: Shear locking angles obtained for group A5 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear locking angle γ_L ($^\circ$)</i>			
							C1	C2	C3	C4
uO-APT	A5	12 parallel yarn arrays – [90/0/90/0/90/0]s	Along 0° in reinforcement	R-45	3.0	S1	56	58	59	60
						S2	58.5	60	60.5	61
				R+45	3.0	S1	58	60	61	61.5
						S2	58	59	60	60.5

Table F-3: Shear locking angles obtained for group A6 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear locking angle γ_L ($^\circ$)</i>			
							C1	C2	C3	C4
uO-APT	A6	8 parallel yarn arrays - [90/0/90/0] _s	Along 45° in reinforcement	R0	2.0	S1	59.5	61.5	62	62.5
						S2	58	60	61	61.5
				R90	2.0	S1	55	57.5	58.5	59.5
						S2	56.5	59	60	60.5

F.2 Saertex Samples

The values of the shear locking angle obtained from the shear curves for all samples which were made from Saertex industrial preforms are presented here.

Table F-4: Shear locking angles obtained for group B6 samples made from Saertex industrial reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear locking angle γ_L</i> (°)			
							C1	C2	C3	C4
Saertex	B6	3 layers - [(0/90)] ₃	Along 45° in reinforcement	R0	2.0	S1	58.5	60.5	61	61.5
						S2	58.5	60.5	61	61.5
				R90	2.0	S1	36	41	43.5	46
						S2	34	40	43.5	45.5

Appendix G

Shear force data

G.1 UO-APT Samples

The average (*AVG*) and the standard deviation (*STD*) values of the shear force obtained from the shear curves for all samples which were made from uo-APT preforms are presented here.

Table G-1: Average and standard deviation shear force values obtained for group A4 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear force F_s (N)</i>			
							<i>AVG</i>		<i>STD</i>	
							C1	C4	C1	C4
uO-APT	A4	8 parallel yarn arrays - [90/0/90/0] _s	Along 0° in reinforcement	R-45	2.0	S1	19.88	9.73	29.93	17.50
						S2	11.59	5.22	9.51	5.80
				R+45	2.0	S1	13.47	7.46	20.46	10.55
						S2	15.52	8.25	20.36	11.51

Table G-2: Average and standard deviation shear force values obtained for group A5 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear force F_s (N)</i>			
							<i>AVG</i>		<i>STD</i>	
							C1	C4	C1	C4
uO-APT	A5	12 parallel yarn arrays - [90/0/90/0/90/0] _s	Along 0° in reinforcement	R-45	3.0	S1	26.77	15.30	34.68	28.06
						S2	23.31	12.54	35.97	21.70
				R+45	3.0	S1	27.31	12.54	34.77	22.80
						S2	22.39	12.09	30.38	17.15

Table G-3: Average and standard deviation shear force values obtained for group A6 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear force F_s (N)</i>			
							<i>AVG</i>		<i>STD</i>	
							C1	C4	C1	C4
uO-APT	A6	8 parallel yarn arrays - [90/0/90/0] _s	Along 45° in reinforcement	R0	2.0	S1	35.11	9.96	20.24	8.91
						S2	65.77	12.41	30.86	11.53
				R90	2.0	S1	16.35	5.25	8.94	5.68
						S2	19.22	4.55	9.17	5.63

G.2 Saertex Samples

The average (*AVG*) and the standard deviation (*STD*) values of the shear force obtained from the shear curves for all samples which were made from Saertex industrial preforms are presented here.

Table G-4: Average and standard deviation shear force values obtained for group B6 samples made from Saertex reinforcements.

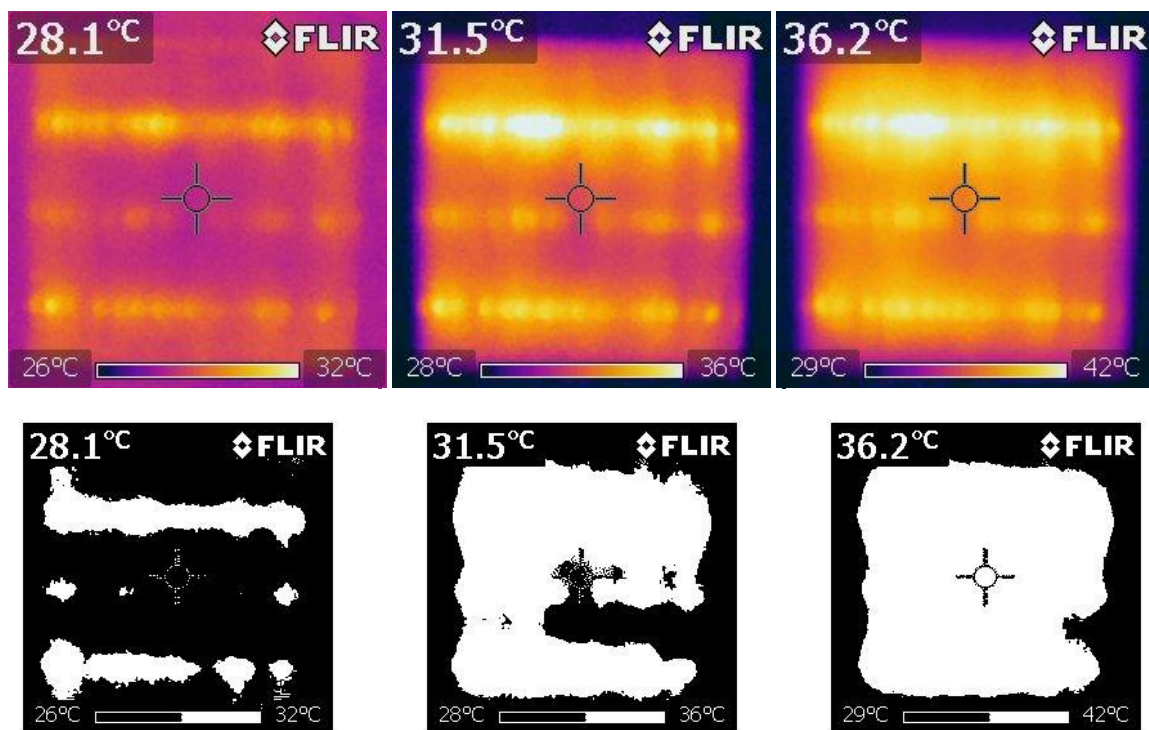
Type	Group	Arrays	Stitching	Stitching setup	Thickness (mm)	Sample	<i>Shear force F_s (N)</i>			
							<i>AVG</i>		<i>STD</i>	
							C1	C4	C1	C4
Saertex	B6	3 layers - [(0/90)] ₃	Along 45° in reinforcement	R0	2.0	S1	72.36	5.55	76.03	4.04
						S2	80.50	6.60	78.11	4.80
				R90	2.0	S1	65.89	21.79	53.83	27.36
						S2	55.24	19.01	48.06	26.52

Appendix H

IR and binary images: Bending samples

H.1 Introduction

All infrared images result from the active IRT tests for all bending samples and corresponding binary images conducted on both types of preforms are presented here. The images represent the temperature distributions after exposure times of 5 seconds, 10 seconds and 15 seconds.

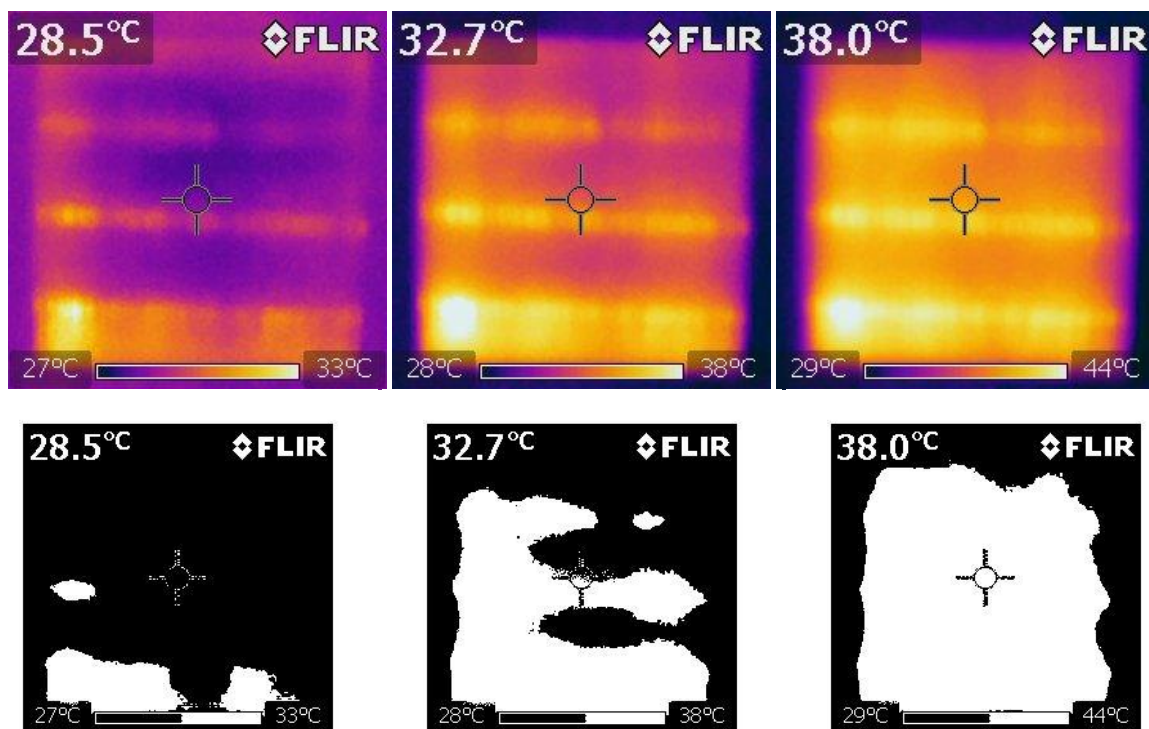


A1/45/R0/S1/5s

A1/45/R0/S1/10s

A1/45/R0/S1/15s

Figure H-1: IR and corresponding binary images obtained for A1/45/R0/S1 sample.

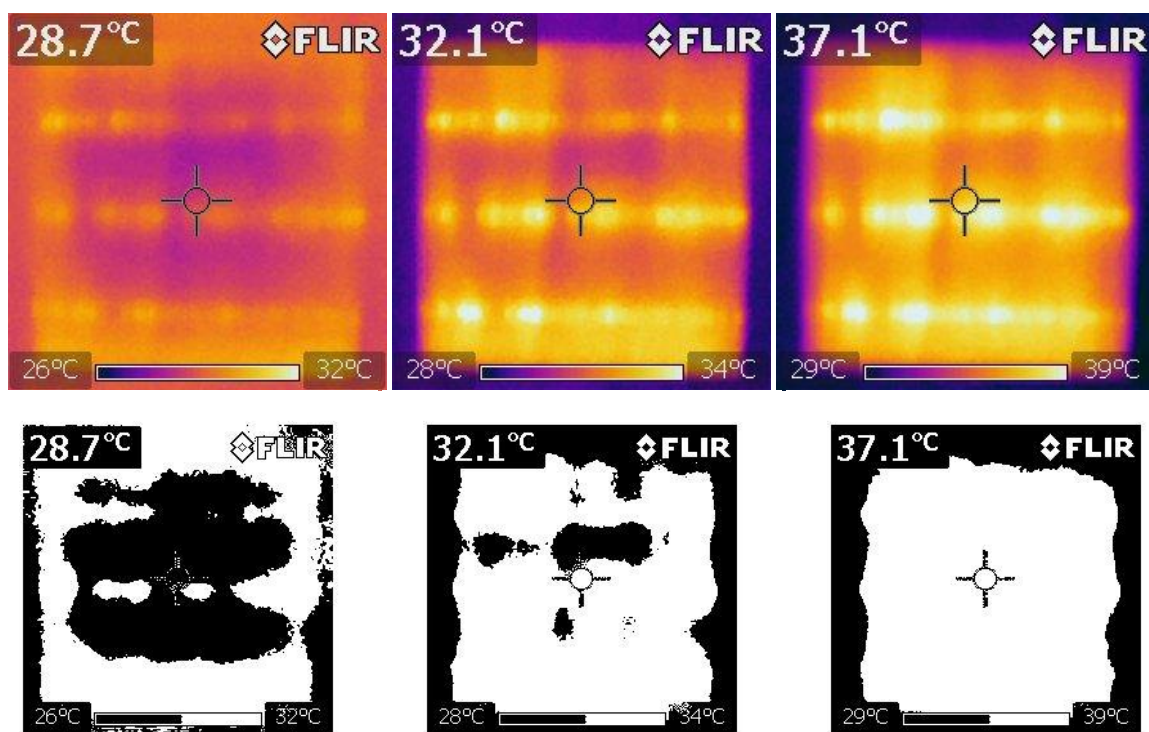


A1/45/R0/S2/5s

A1/45/R0/S2/10s

A1/45/R0/S2/15s

Figure H-2: IR and corresponding binary images obtained for A1/45/R0/S2 sample.

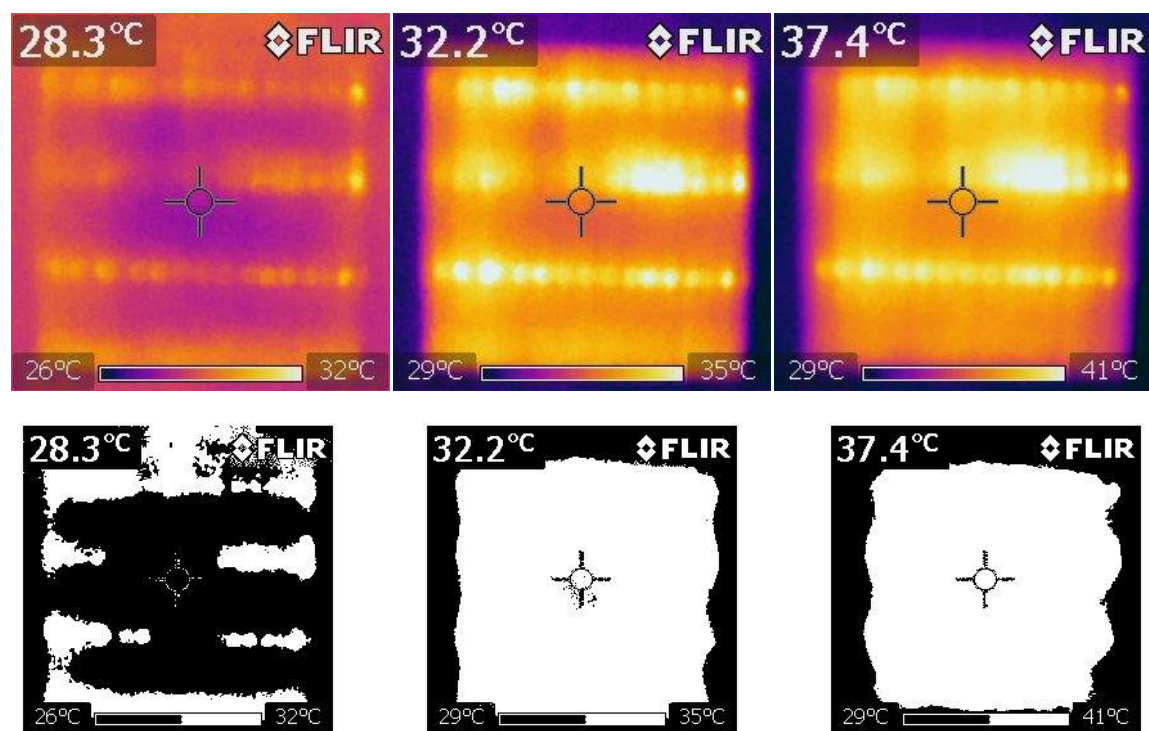


A1/45/R0/S3/5s

A1/45/R0/S3/10s

A1/45/R0/S3/15s

Figure H-3: IR and corresponding binary images obtained for A1/45/R0/S3 sample.

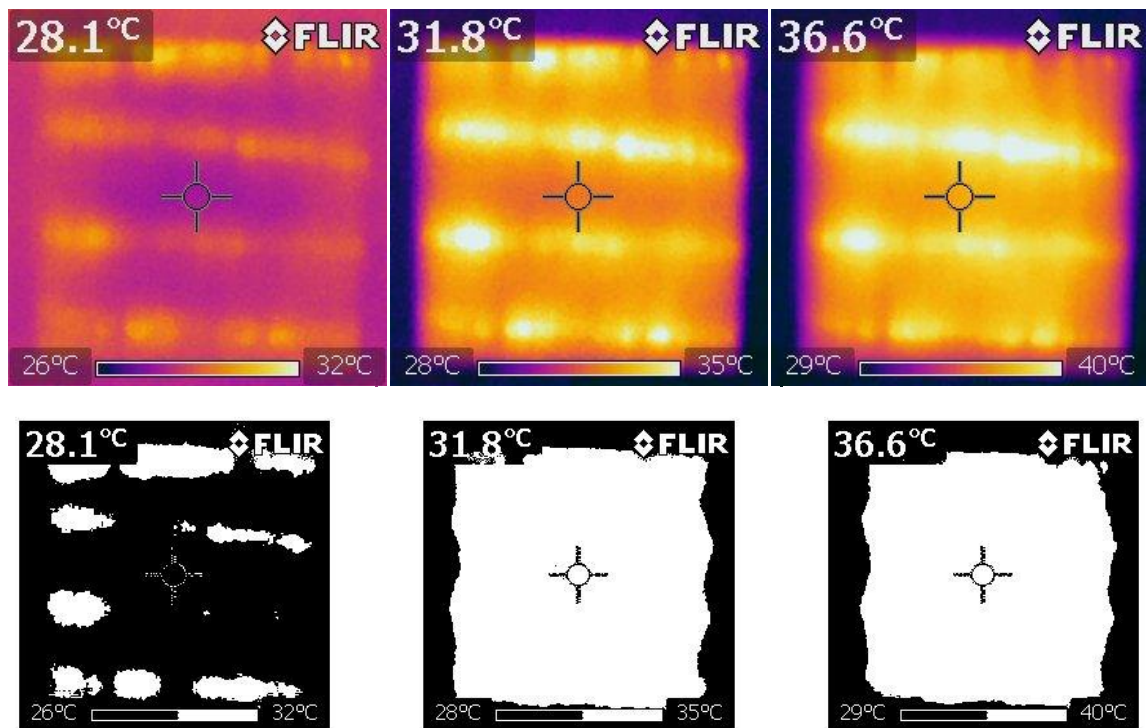


A1/45/R90/S1/5s

A1/45/R90/S1/10s

A1/45/R90/S1/15s

Figure H-4: IR and corresponding binary images obtained for A1/45/R90/S1 sample.

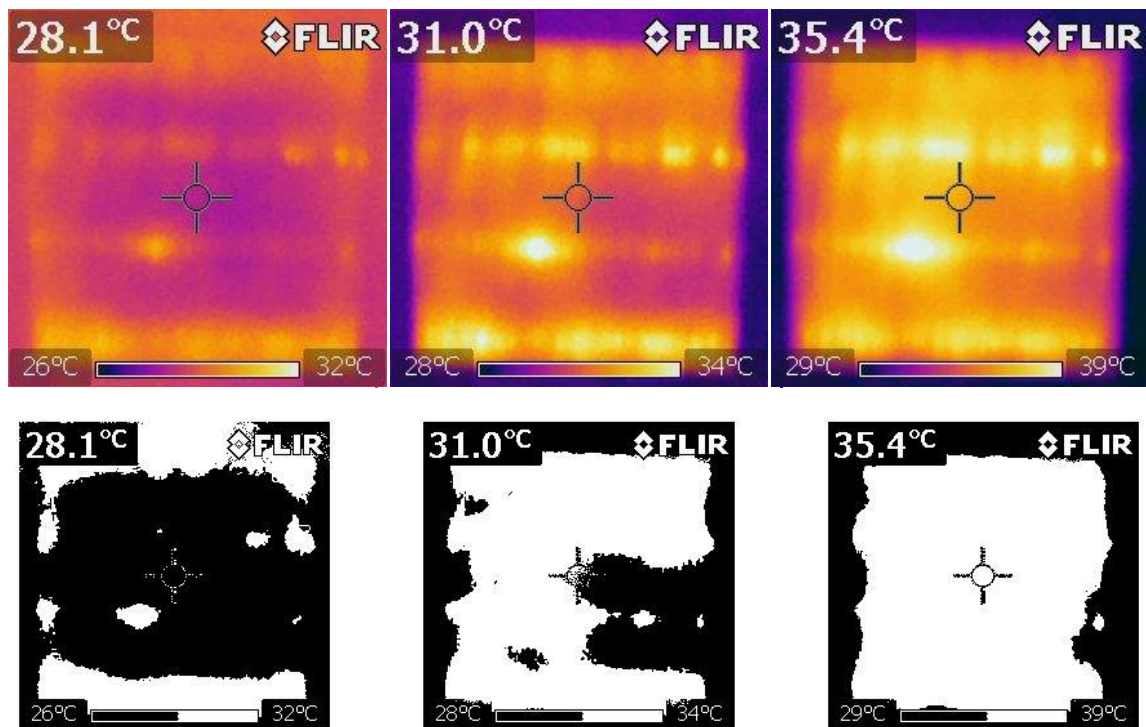


A1/45/R90/S2/5s

A1/45/R90/S2/10s

A1/45/R90/S2/15s

Figure H-5: IR and corresponding binary images obtained for A1/45/R90/S2 sample.

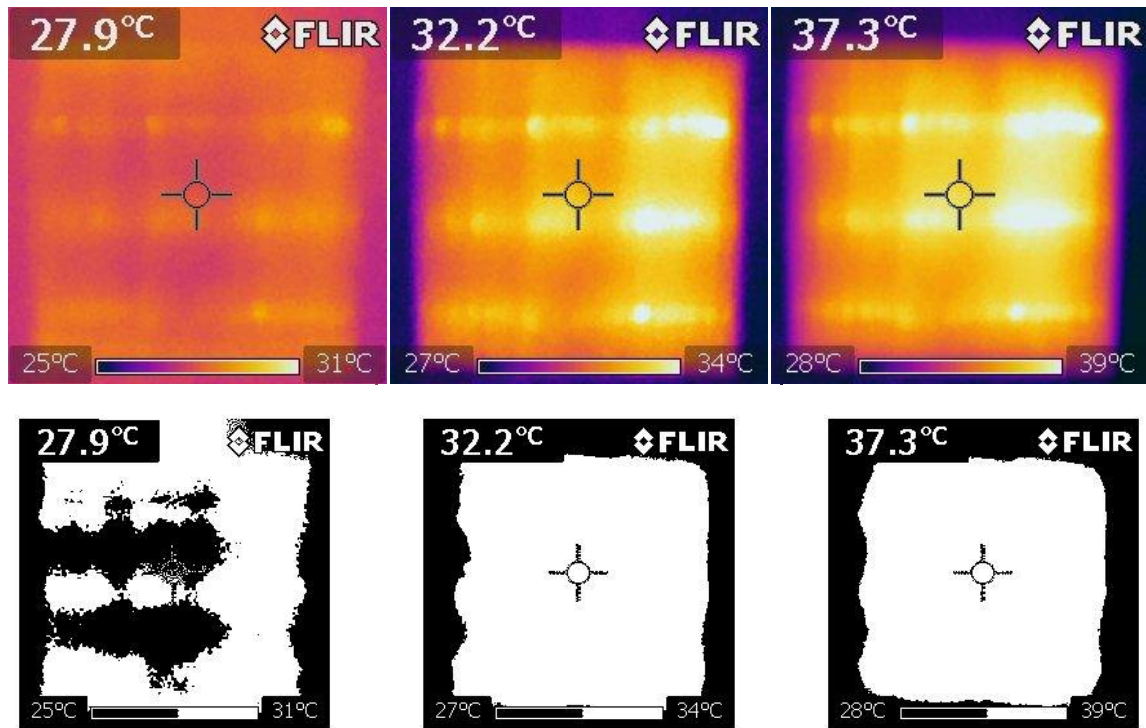


A1/45/R90/S3/5s

A1/45/R90/S3/10s

A1/45/R90/S3/15s

Figure H-6: IR and corresponding binary images obtained for A1/45/R90/S3 sample.

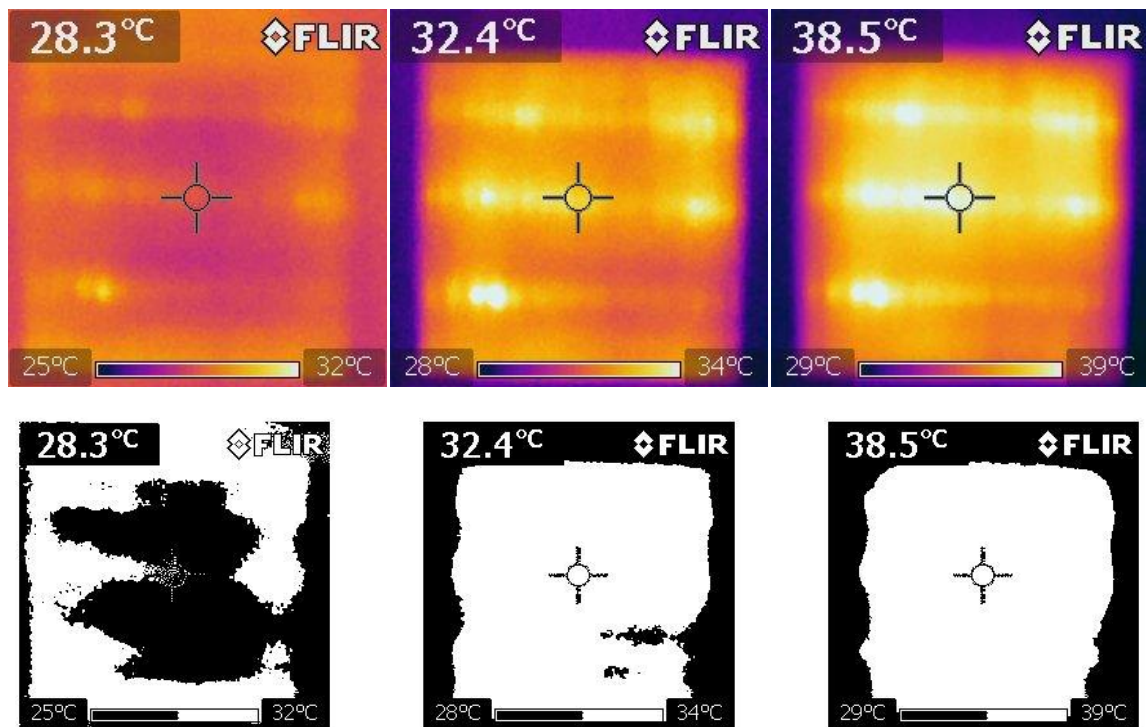


A1/60/R0/S1/5s

A1/60/R0/S1/10s

A1/60/R0/S1/15s

Figure H-7: IR and corresponding binary images obtained for A1/60/R0/S1 sample.

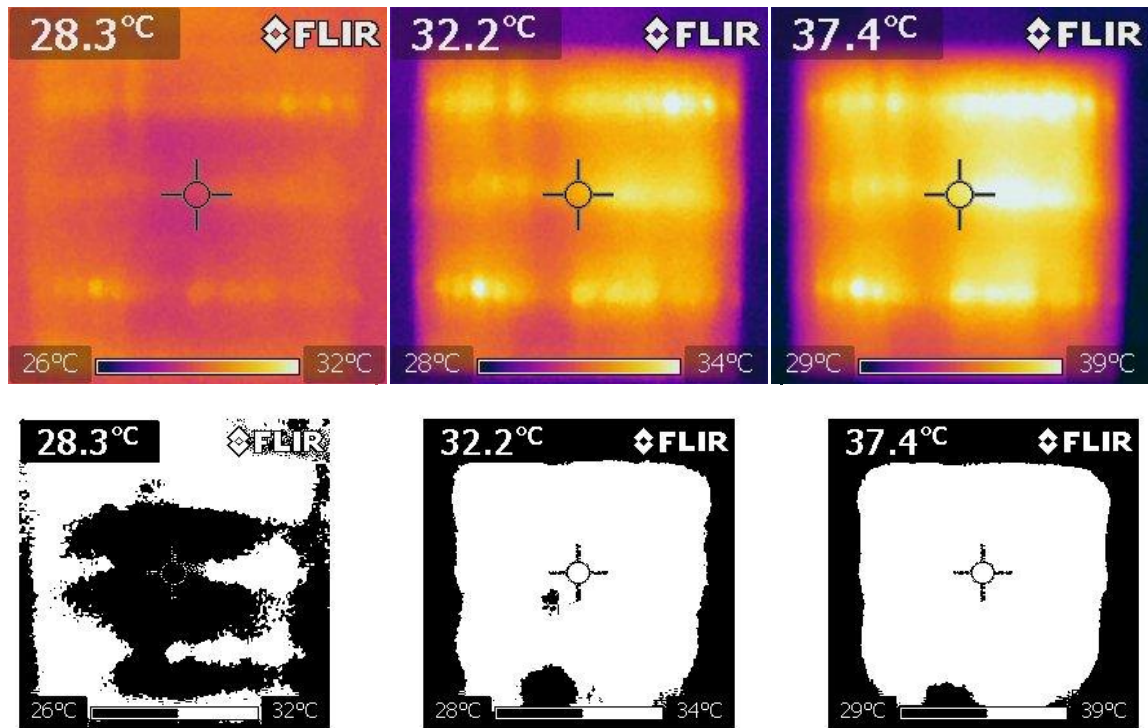


A1/60/R0/S2/5s

A1/60/R0/S2/10s

A1/60/R0/S2/15s

Figure H-8: IR and corresponding binary images obtained for A1/60/R0/S2 sample.

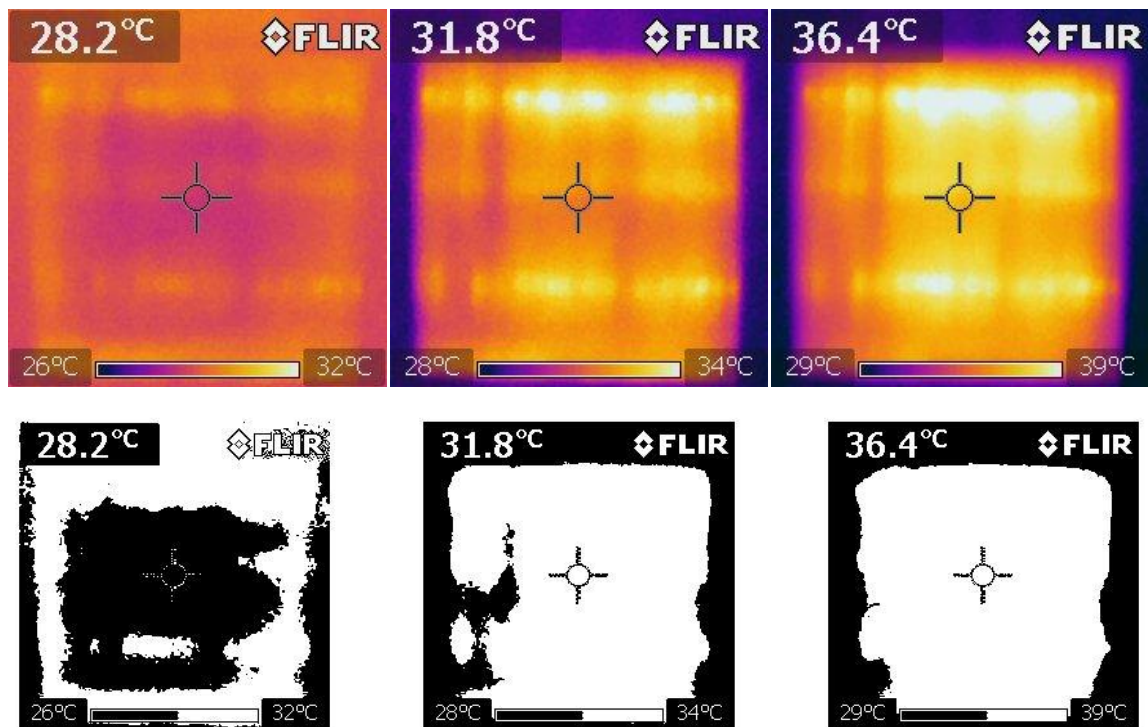


A1/60/R0/S3/5s

A1/60/R0/S3/10s

A1/60/R0/S3/15s

Figure H-9: IR and corresponding binary images obtained for A1/60/R0/S3 sample.

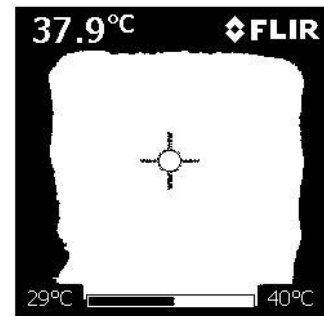
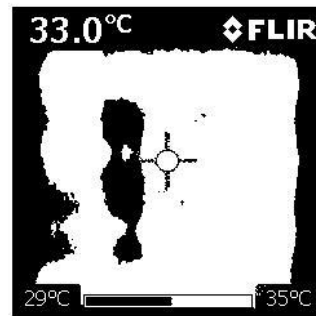
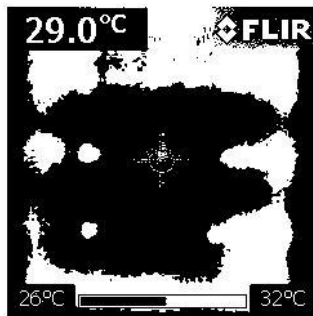
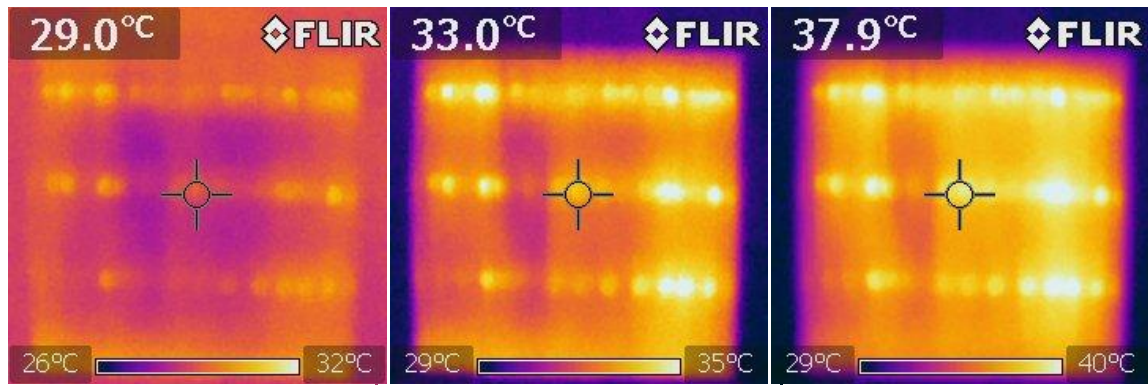


A1/60/R90/S1/5s

A1/60/R90/S1/10s

A1/60/R90/S1/15s

Figure H-10: IR and corresponding binary images obtained for A1/60/R90/S1 sample.

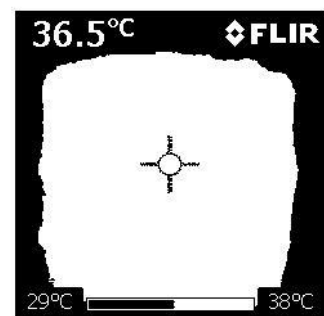
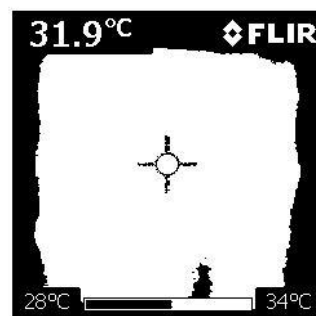
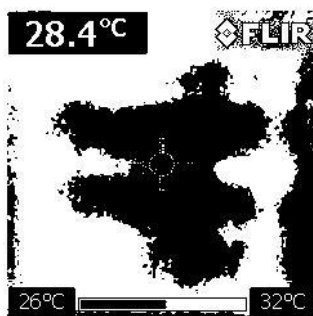
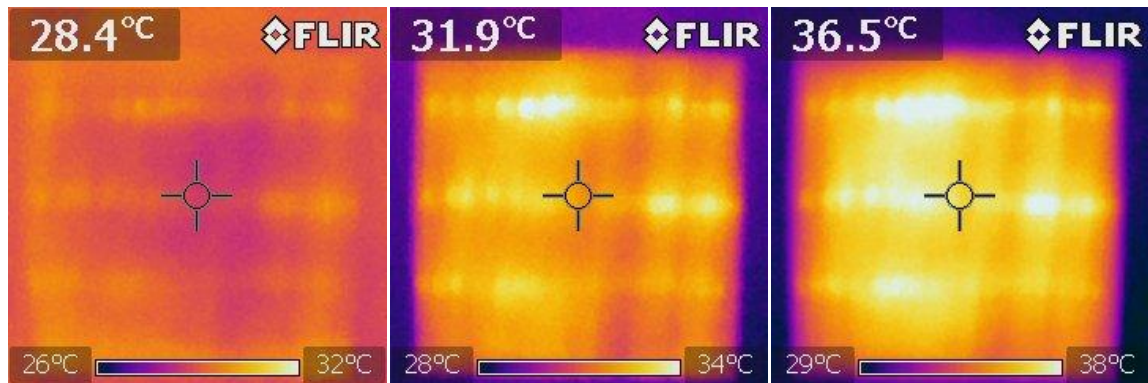


A1/60/R90/S2/5s

A1/60/R90/S2/10s

A1/60/R90/S2/15s

Figure H-11: IR and corresponding binary images obtained for A1/60/R90/S2 sample.

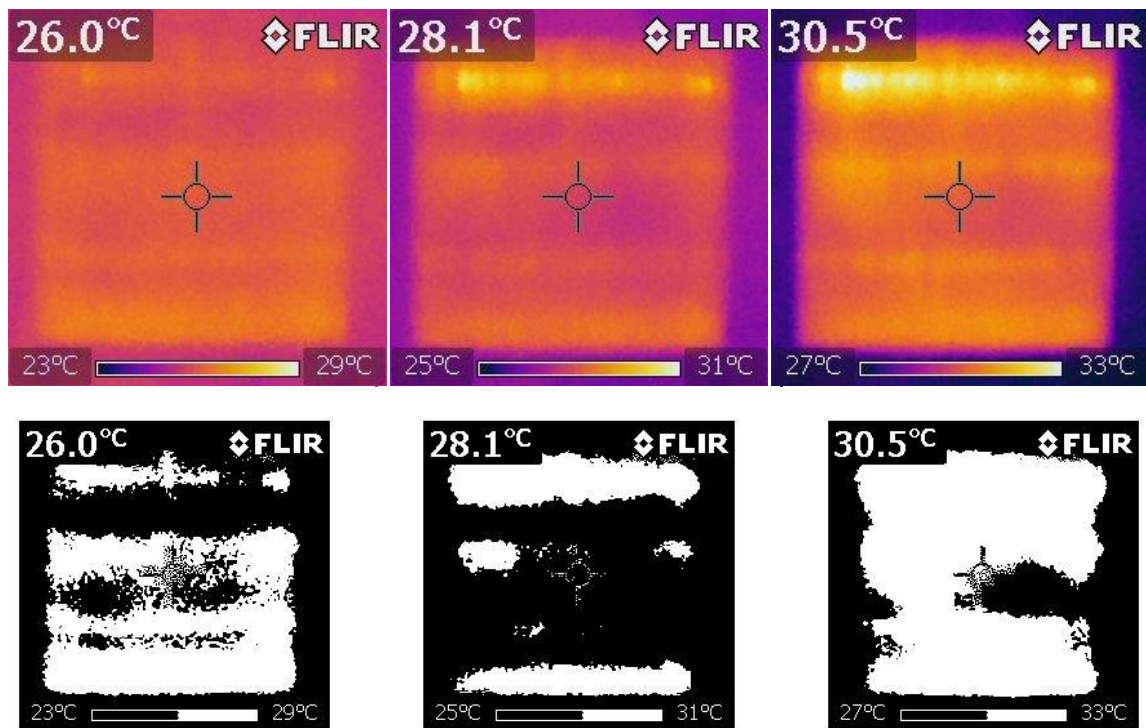


A1/60/R90/S3/5s

A1/60/R90/S3/10s

A1/60/R90/S3/15s

Figure H-12: IR and corresponding binary images obtained for A1/60/R90/S3 sample.

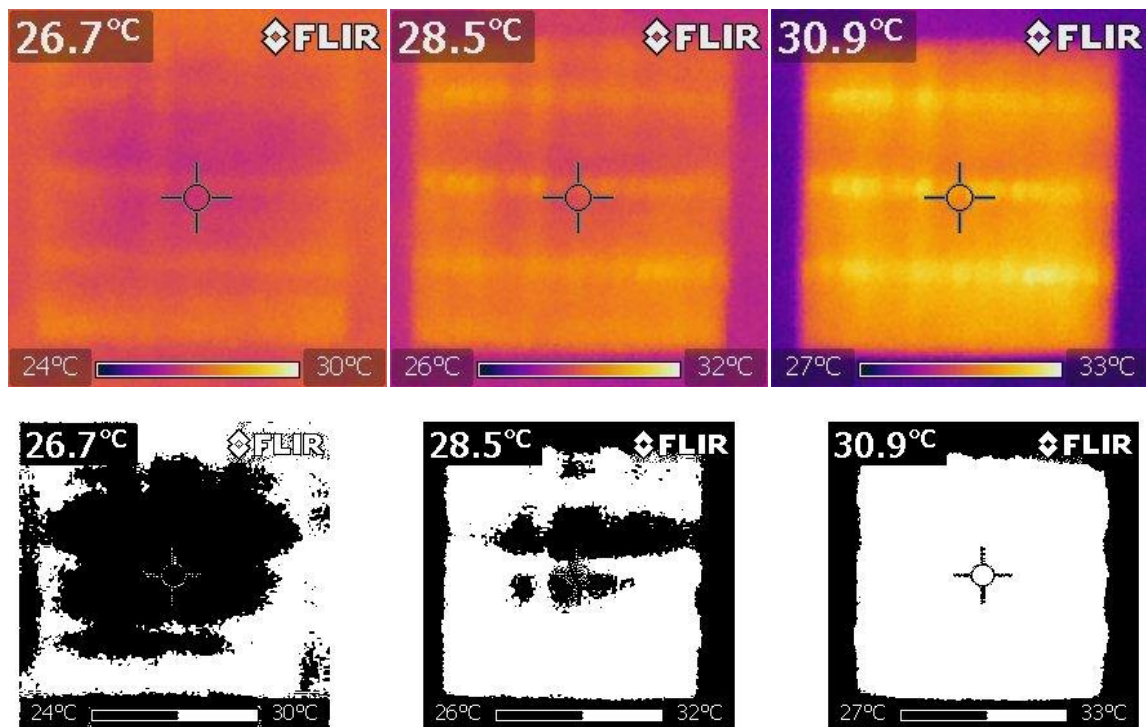


A2/45/R0/S1/5s

A2/45/R0/S1/10s

A2/45/R0/S1/15s

Figure H-13: IR and corresponding binary images obtained for A2/45/R0/S1 sample.

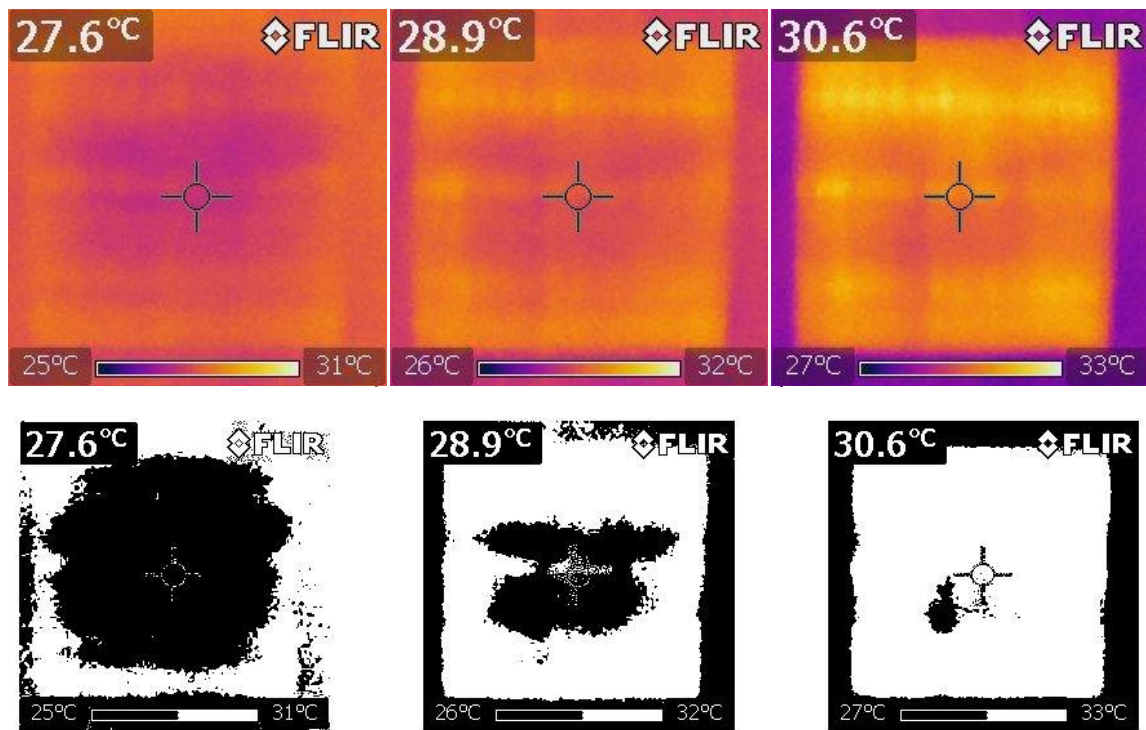


A2/45/R0/S2/5s

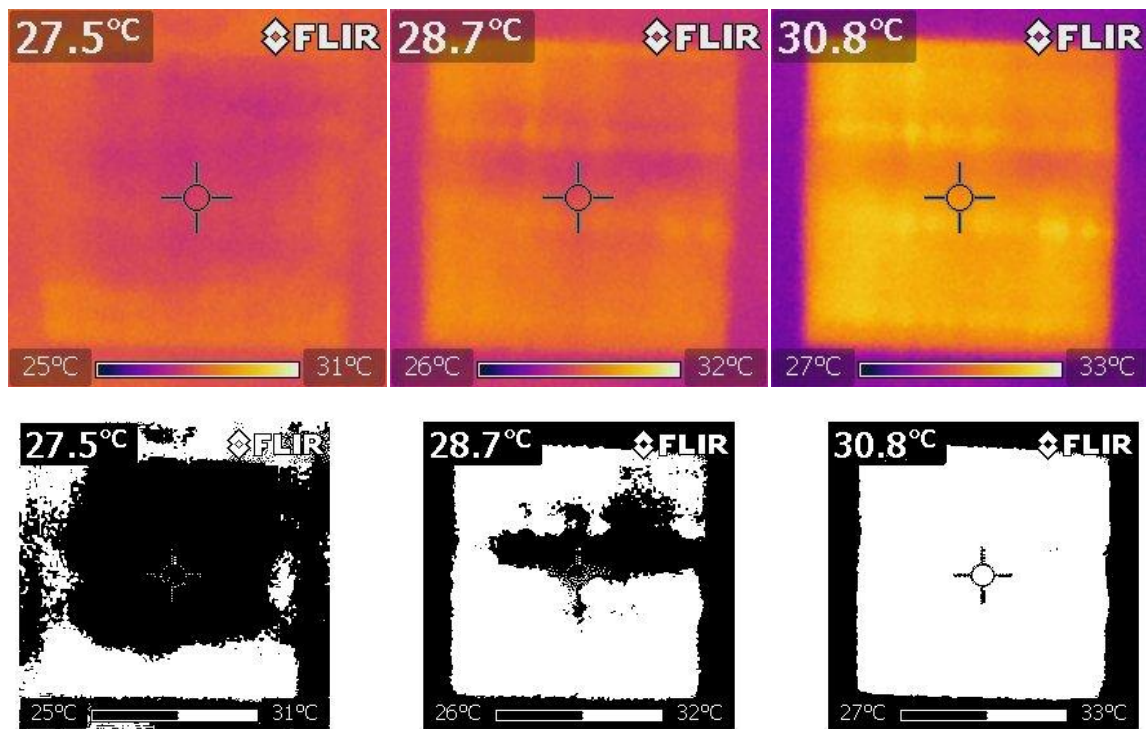
A2/45/R0/S2/10s

A2/45/R0/S2/15s

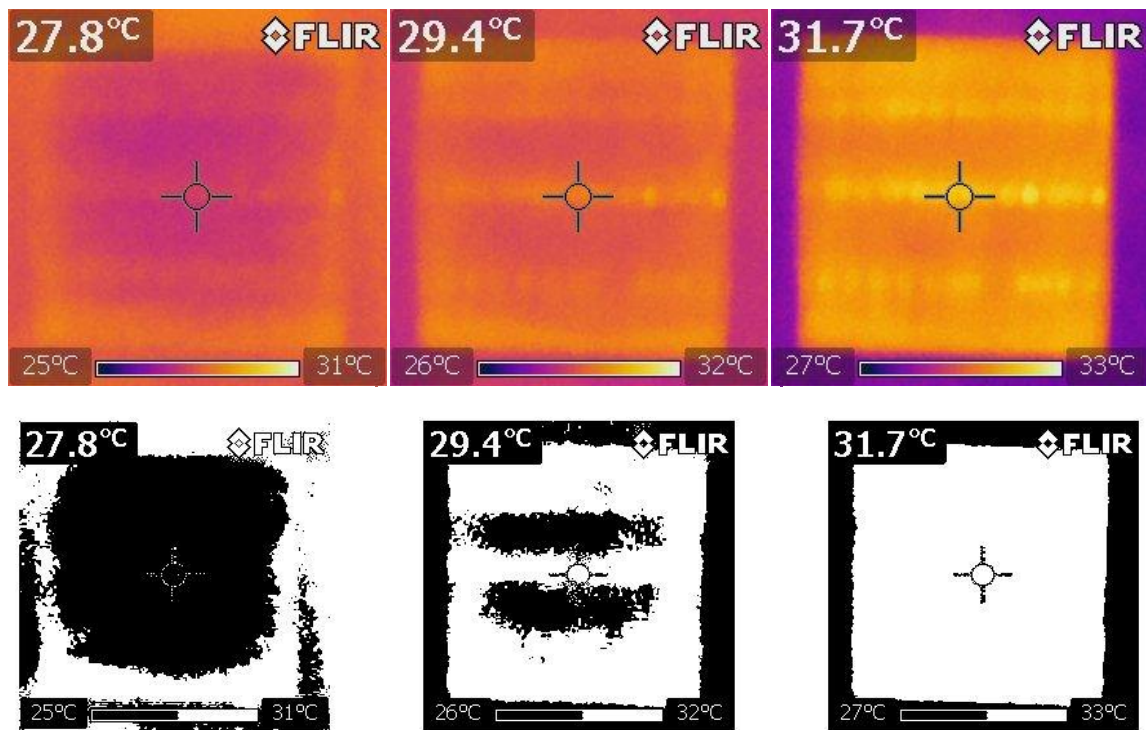
Figure H-14: IR and corresponding binary images obtained for A2/45/R0/S2 sample.



A2/45/R0/S3/5s A2/45/R0/S3/10s A2/45/R0/S3/15s
Figure H-15: IR and corresponding binary images obtained for A2/45/R0/S3 sample.



A2/45/R90/S1/5s A2/45/R90/S1/10s A2/45/R90/S1/15s
Figure H-16: IR and corresponding binary images obtained for A2/45/R90/S1 sample.

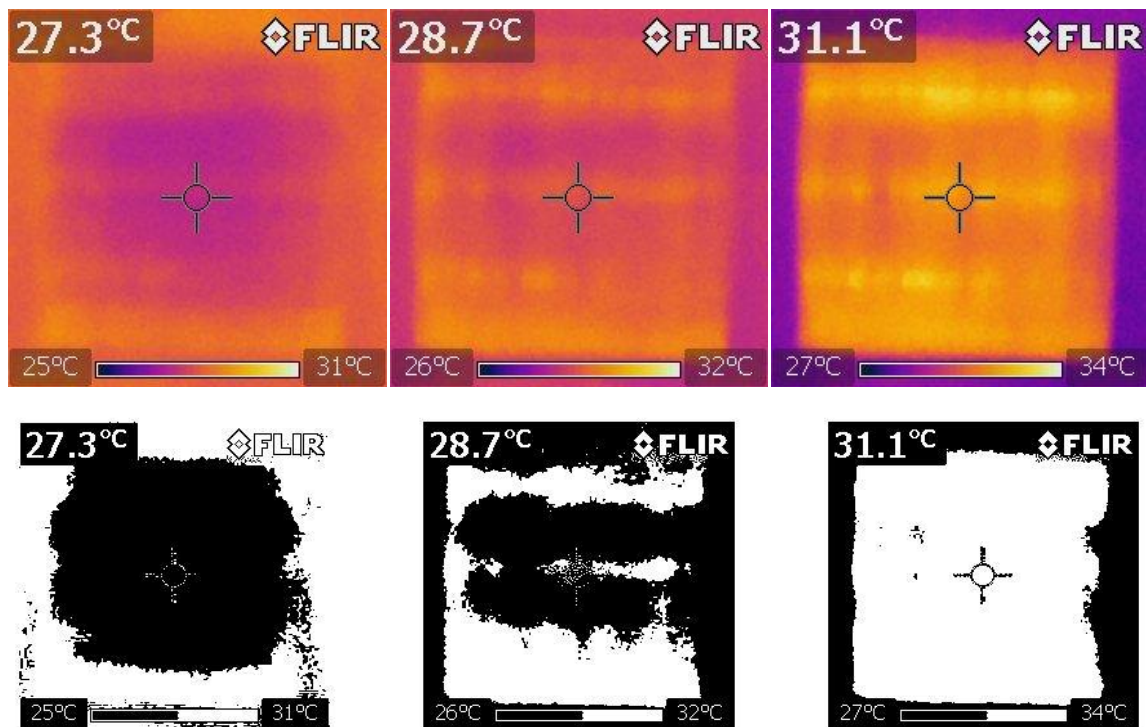


A2/45/R90/S2/5s

A2/45/R90/S2/10s

A2/45/R90/S2/15s

Figure H-17: IR and corresponding binary images obtained for A2/45/R90/S2 sample.

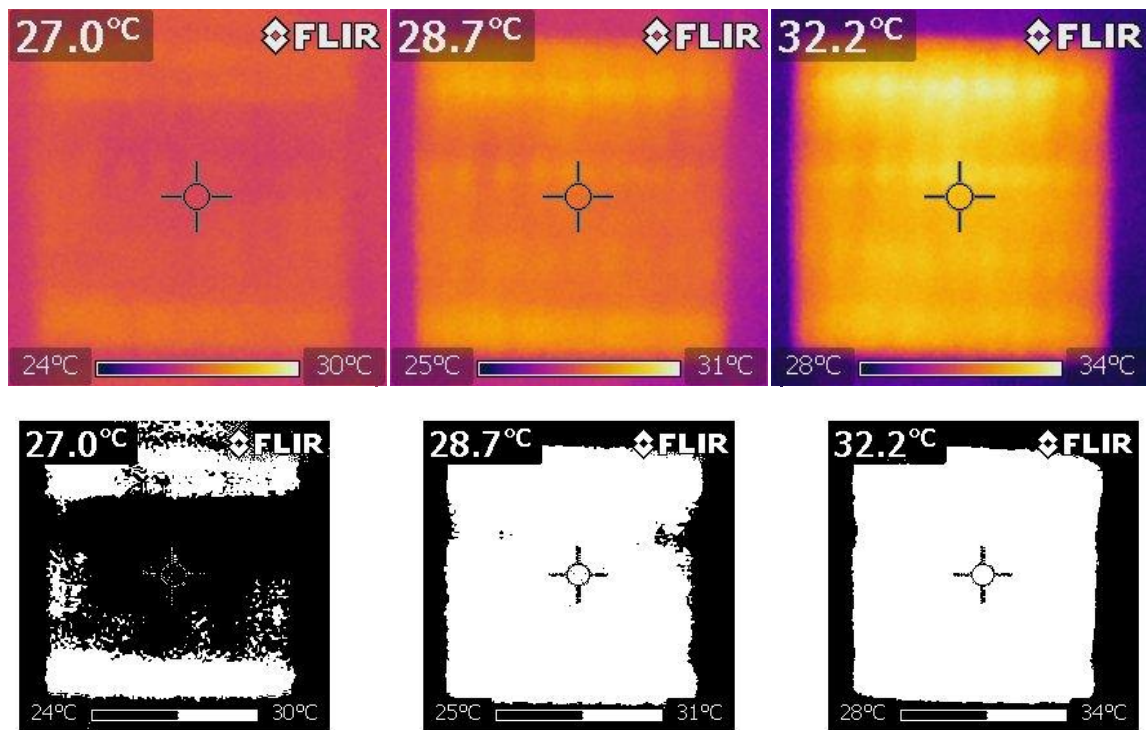


A2/45/R90/S3/5s

A2/45/R90/S3/10s

A2/45/R90/S3/15s

Figure H-18: IR and corresponding binary images obtained for A2/45/R90/S3 sample.

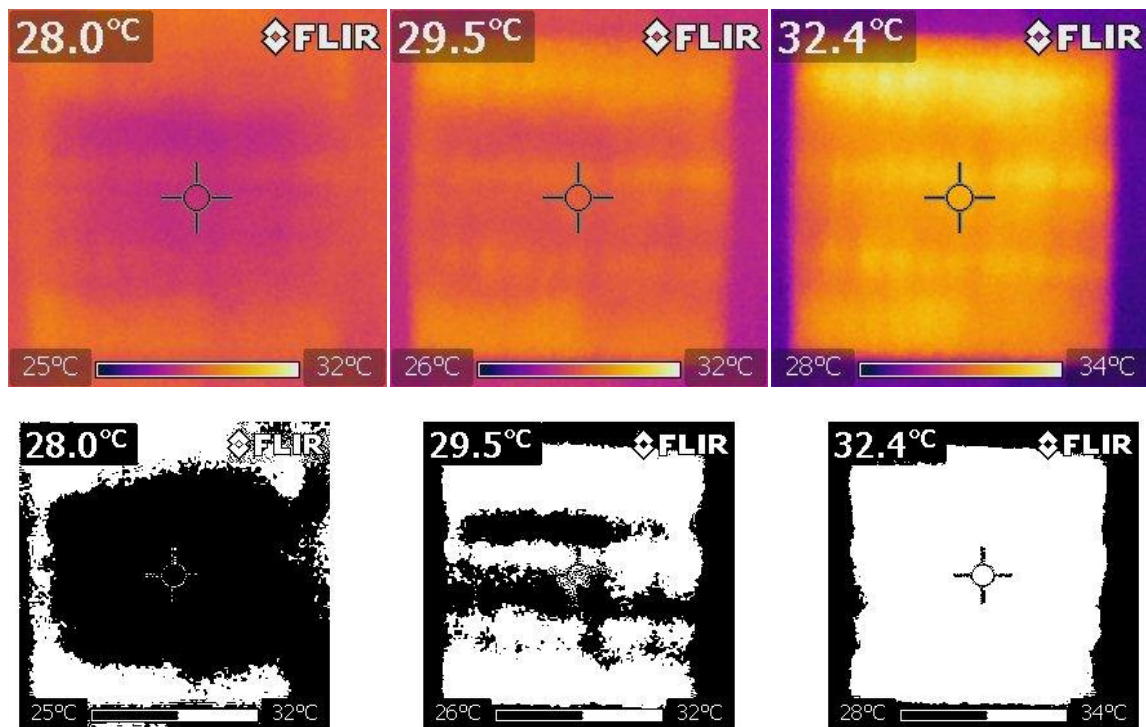


A2/60/R0/S1/5s

A2/60/R0/S1/10s

A2/60/R0/S1/15s

Figure H-19: IR and corresponding binary images obtained for A2/60/R0/S1 sample.

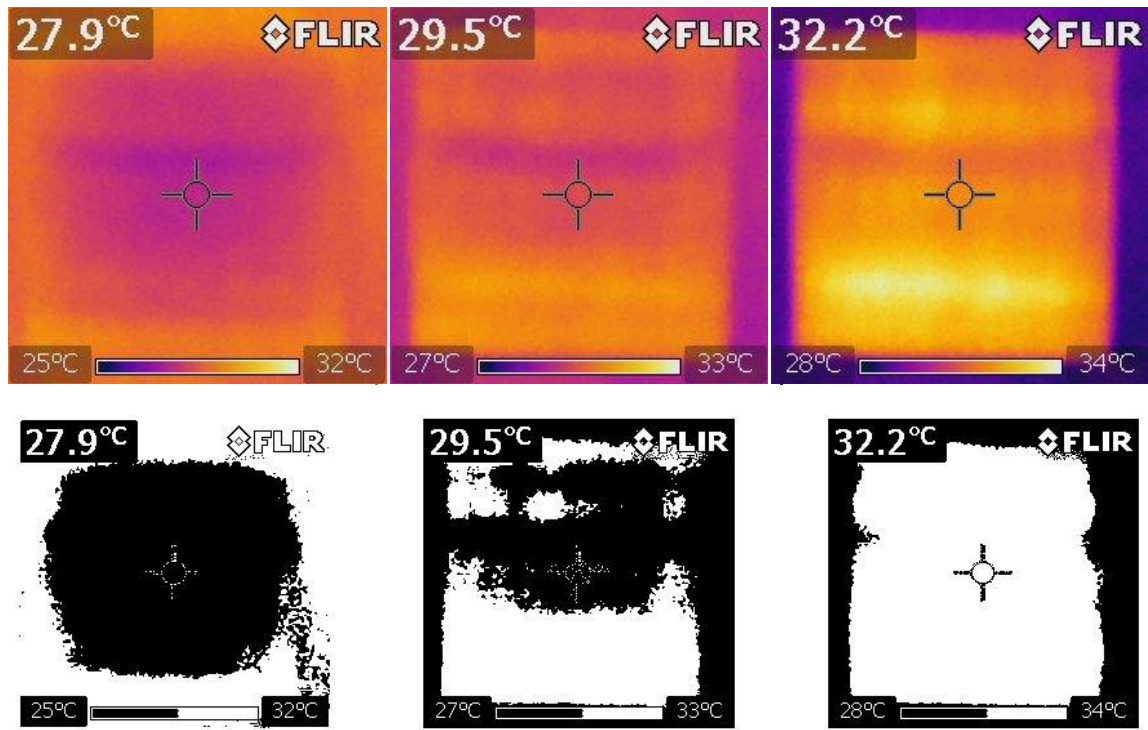


A2/60/R0/S2/5s

A2/60/R0/S2/10s

A2/60/R0/S2/15s

Figure H-20: IR and corresponding binary images obtained for A2/60/R0/S2 sample.

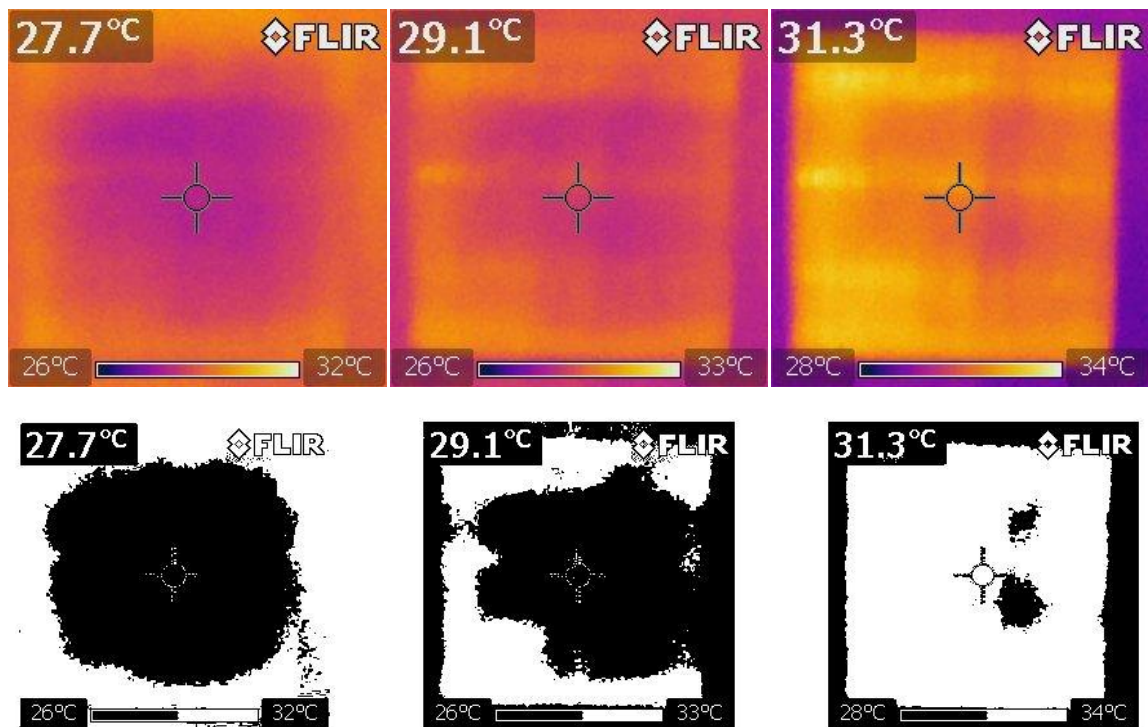


A2/60/R0/S3/5s

A2/60/R0/S3/10s

A2/60/R0/S3/15s

Figure H-21: IR and corresponding binary images obtained for A2/60/R0/S3 sample.

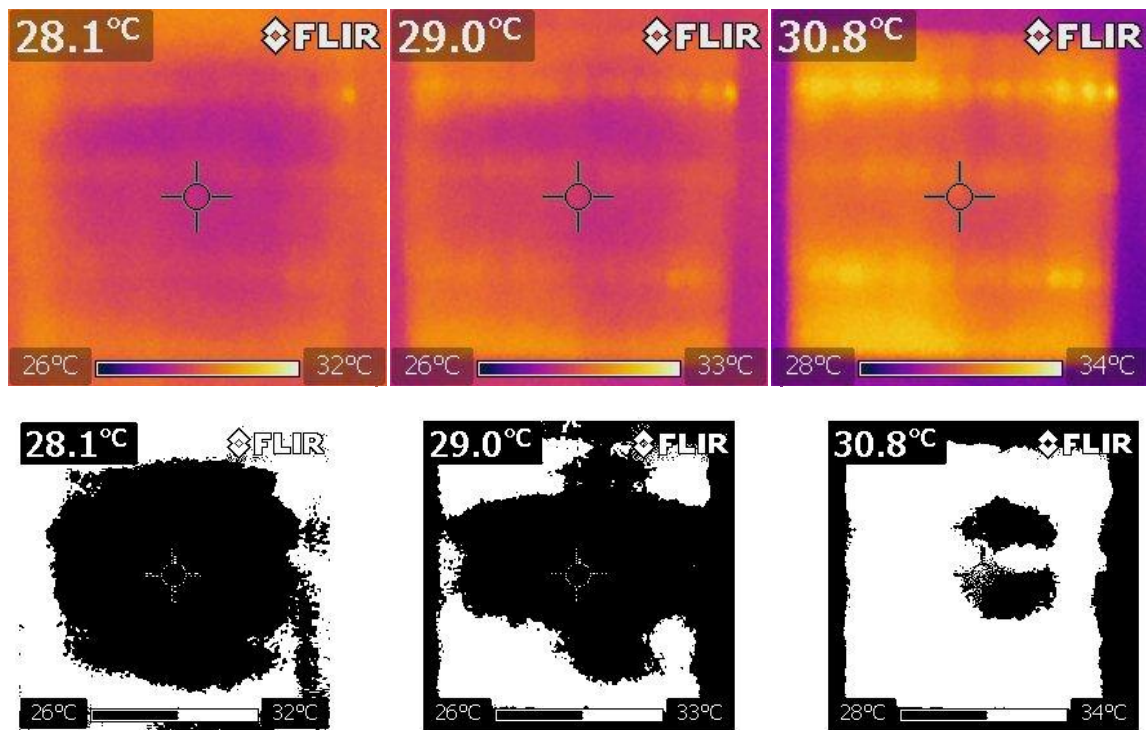


A2/60/R90/S1/5s

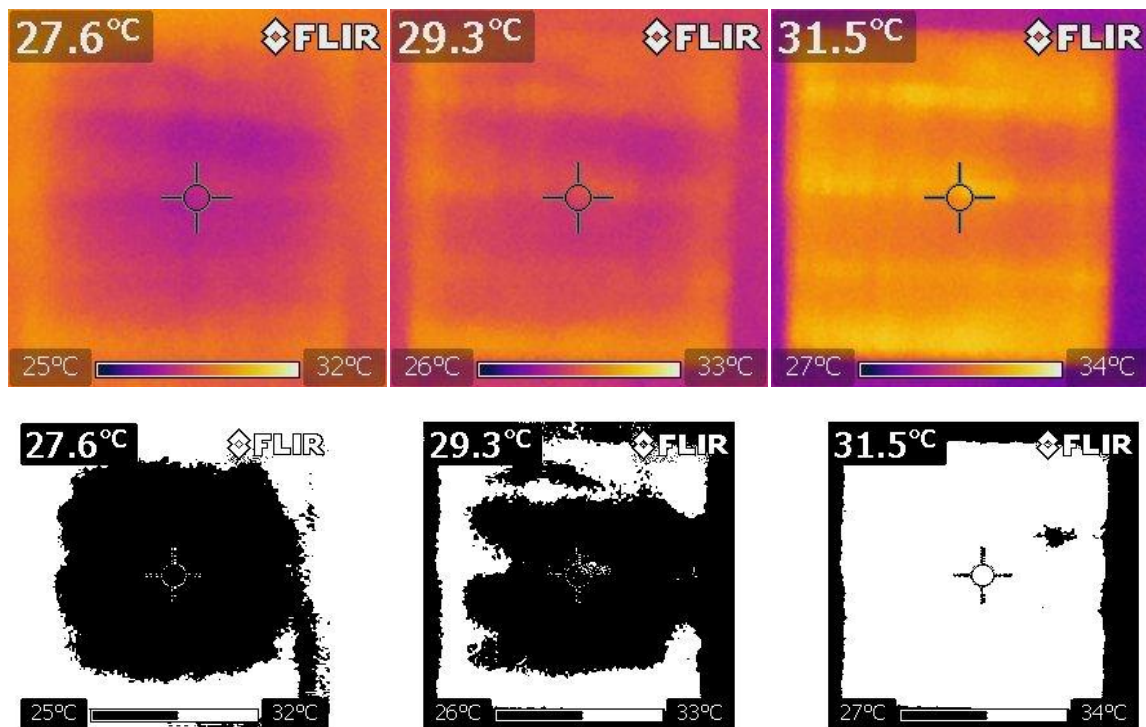
A2/60/R90/S1/10s

A2/60/R90/S1/15s

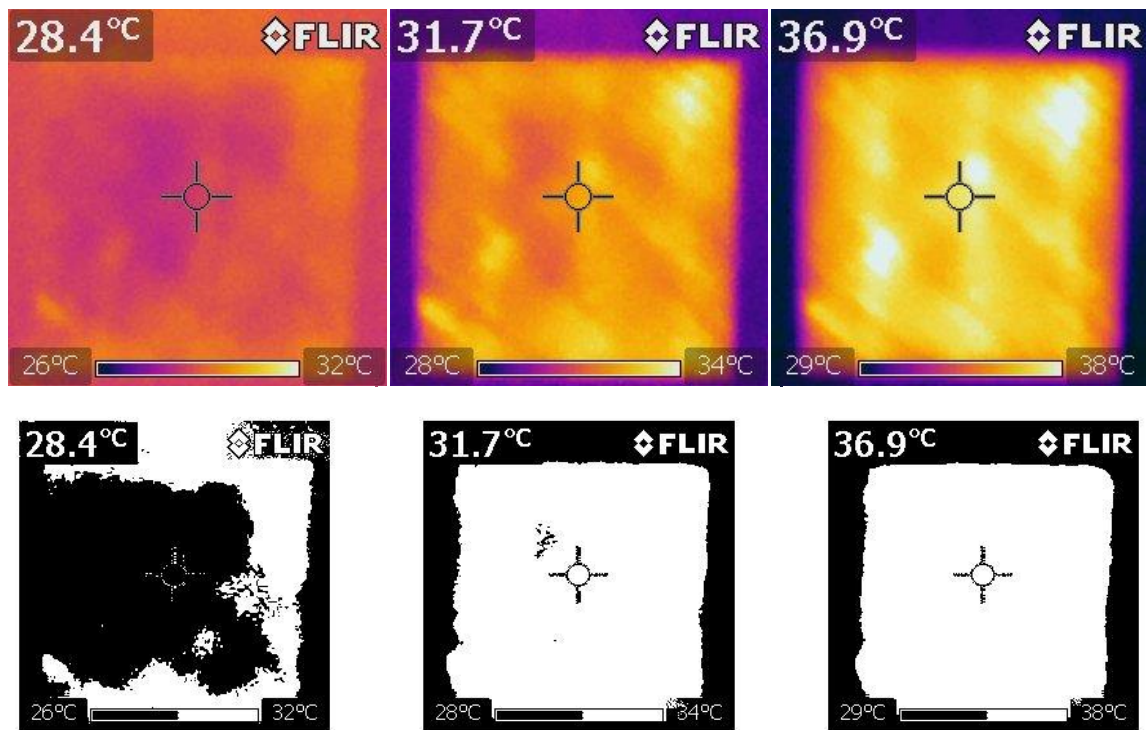
Figure H-22: IR and corresponding binary images obtained for A2/60/R90/S1 sample.



A2/60/R90/S2/5s A2/60/R90/S2/10s A2/60/R90/S2/15s
 Figure H-23: FLIR i7 IR and corresponding binary images obtained for A2/60/R90/S2 sample.



A2/60/R90/S3/5s A2/60/R90/S3/10s A2/60/R90/S3/15s
 Figure H-24: IR and corresponding binary images obtained for A2/60/R90/S3 sample.

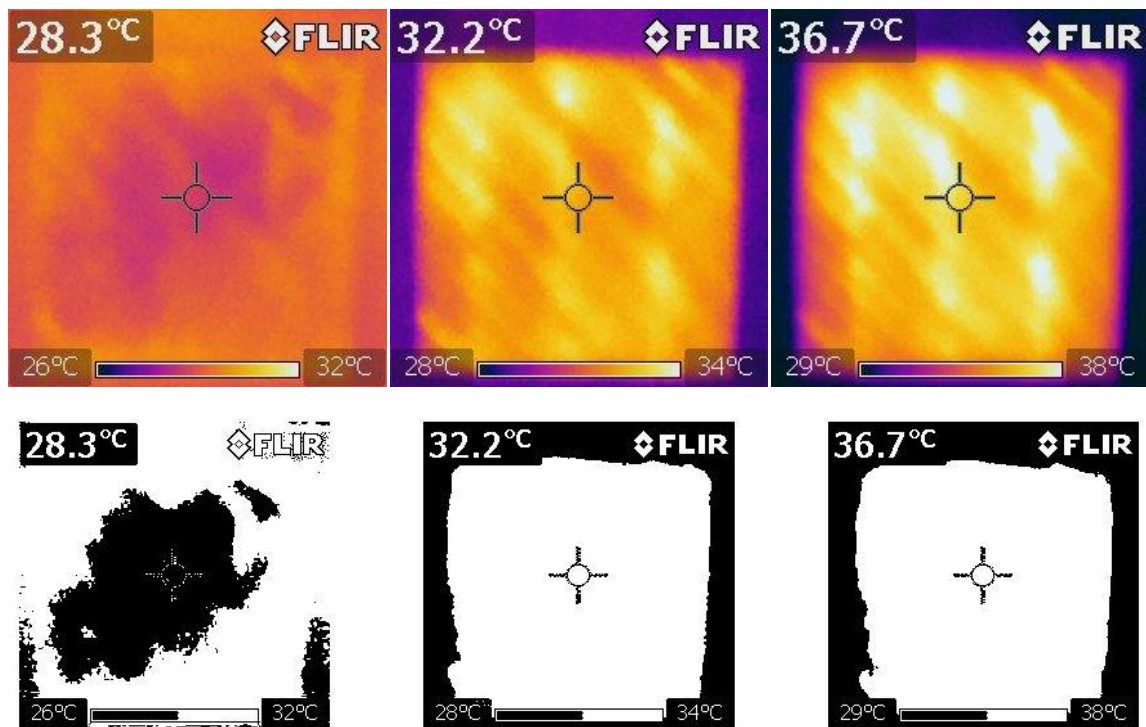


A3/45/R0/S1/5s

A3/45/R0/S1/10s

A3/45/R0/S1/15s

Figure H-25: IR and corresponding binary images obtained for A3/45/R0/S1 sample.

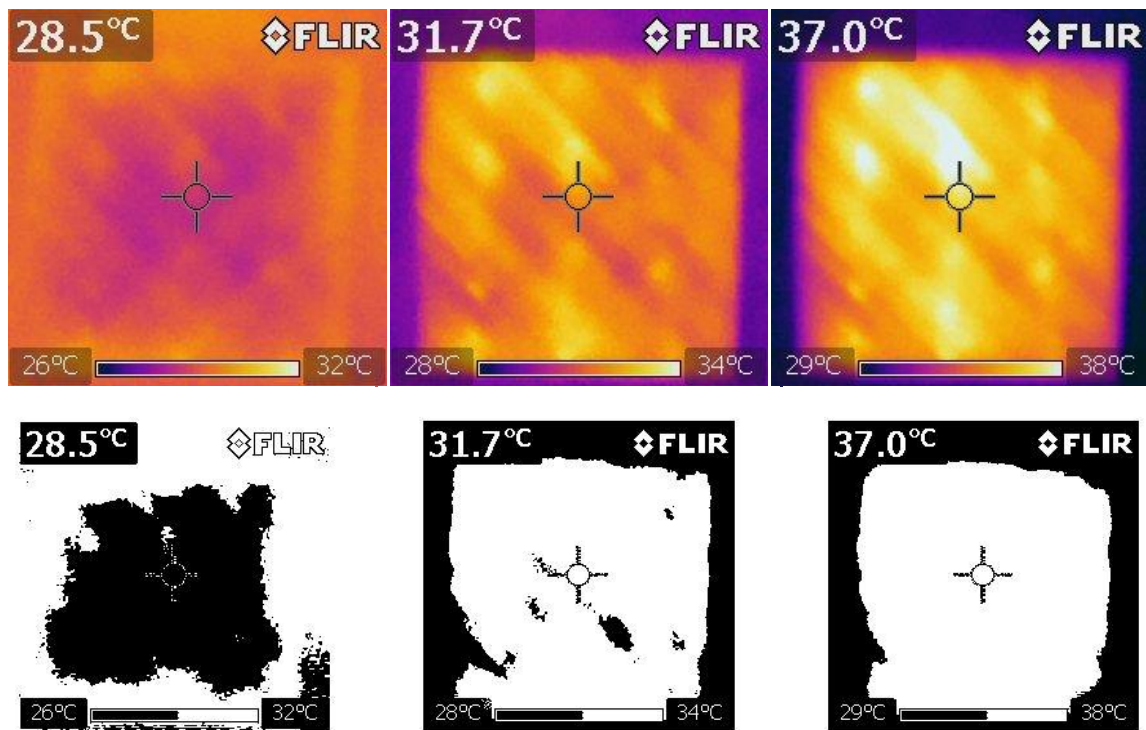


A3/45/R0/S2/5s

A3/45/R0/S2/10s

A3/45/R0/S2/15s

Figure H-26: IR and corresponding binary images obtained for A3/45/R0/S2 sample.

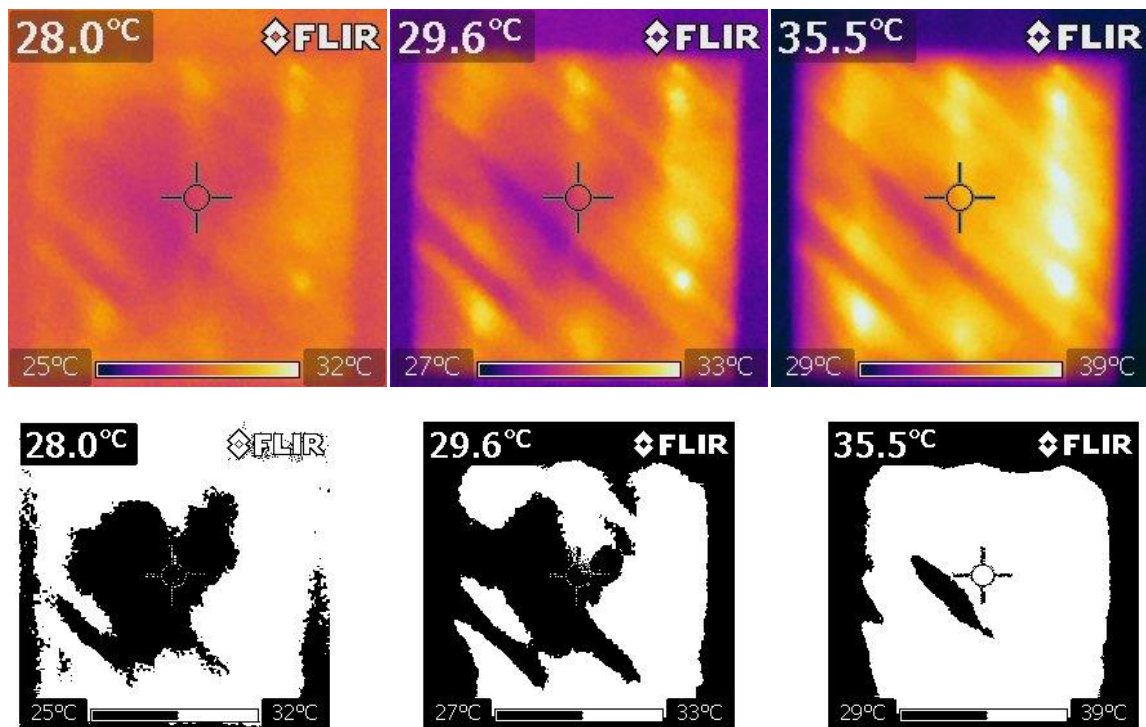


A3/45/R0/S3/5s

A3/45/R0/S3/10s

A3/45/R0/S3/15s

Figure H-27: IR and corresponding binary images obtained for A3/45/R0/S3 sample.

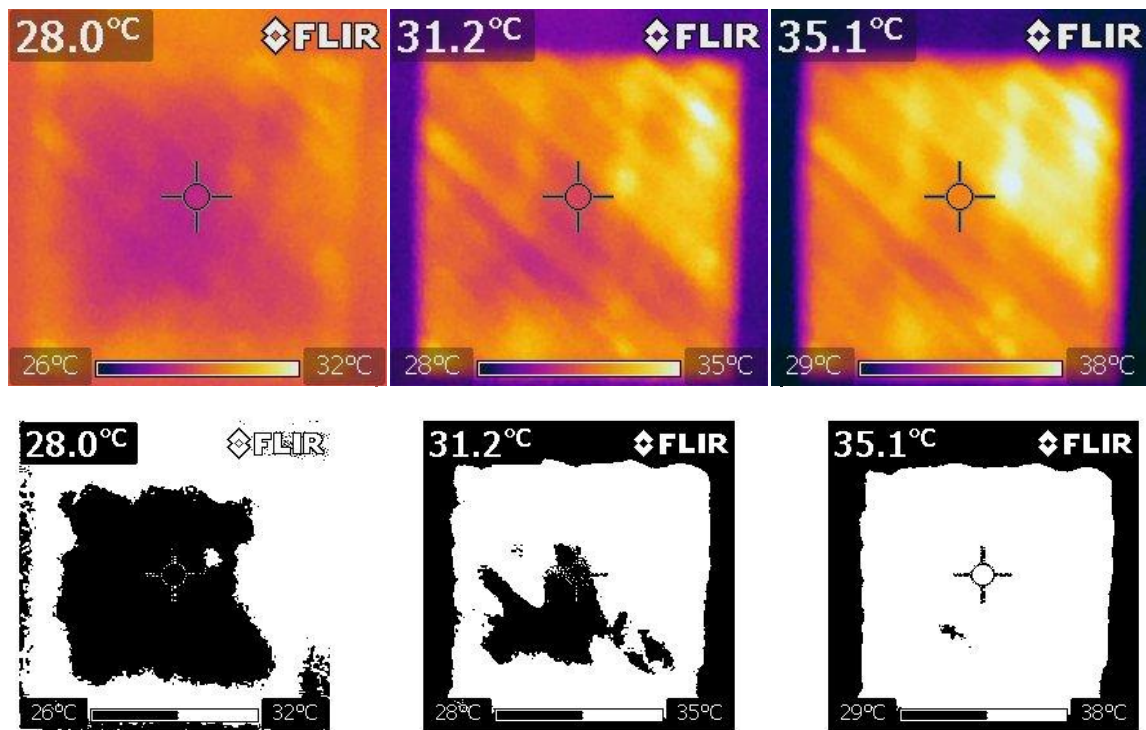


A3/45/R90/S1/5s

A3/45/R90/S1/10s

A3/45/R90/S1/15s

Figure H-28: IR and corresponding binary images obtained for A3/45/R90/S1 sample.

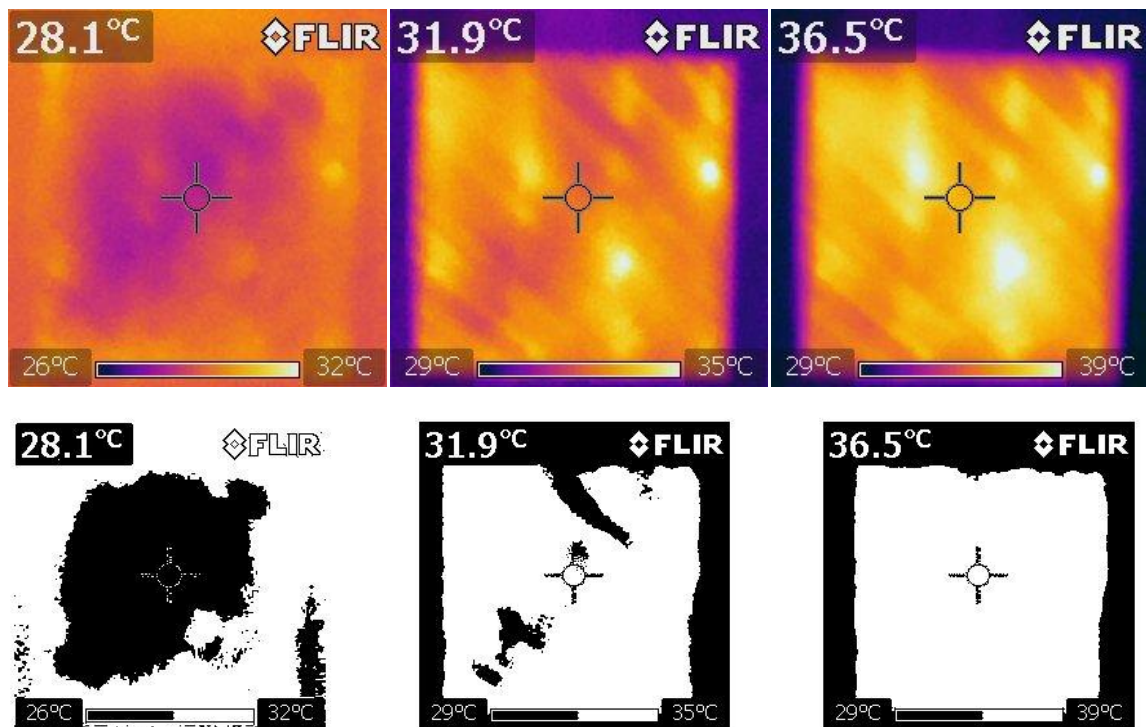


A3/45/R90/S2/5s

A3/45/R90/S2/10s

A3/45/R90/S2/15s

Figure H-29: IR and corresponding binary images obtained for A3/45/R90/S2 sample.

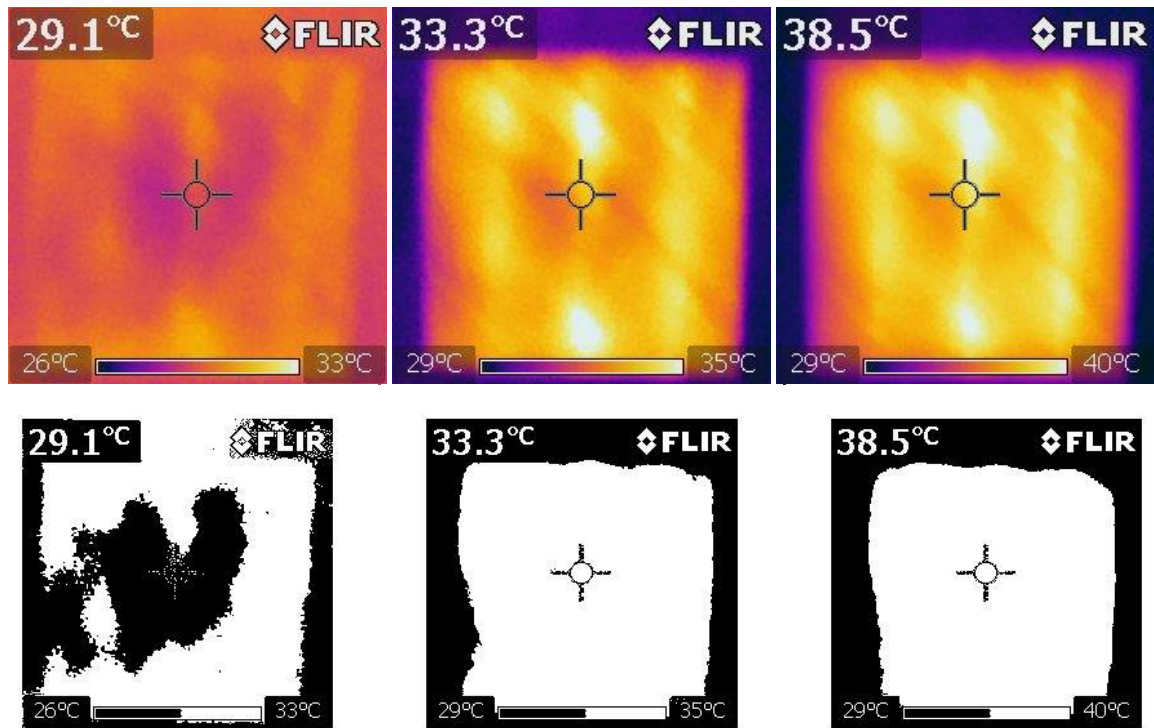


A3/45/R90/S3/5s

A3/45/R90/S3/10s

A3/45/R90/S3/15s

Figure H-30: IR and corresponding binary images obtained for A3/45/R90/S3 sample.

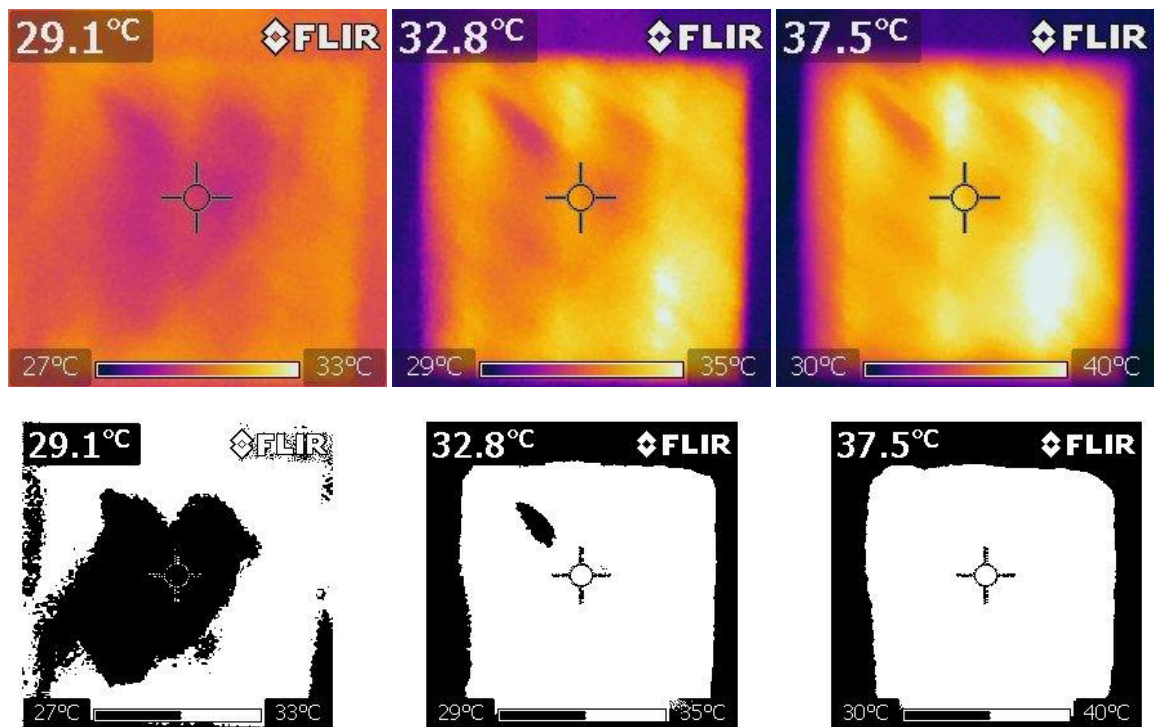


A3/60/R0/S1/5s

A3/60/R0/S1/10s

A3/60/R0/S1/15s

Figure H-31: IR and corresponding binary images obtained for A3/60/R0/S1 sample.

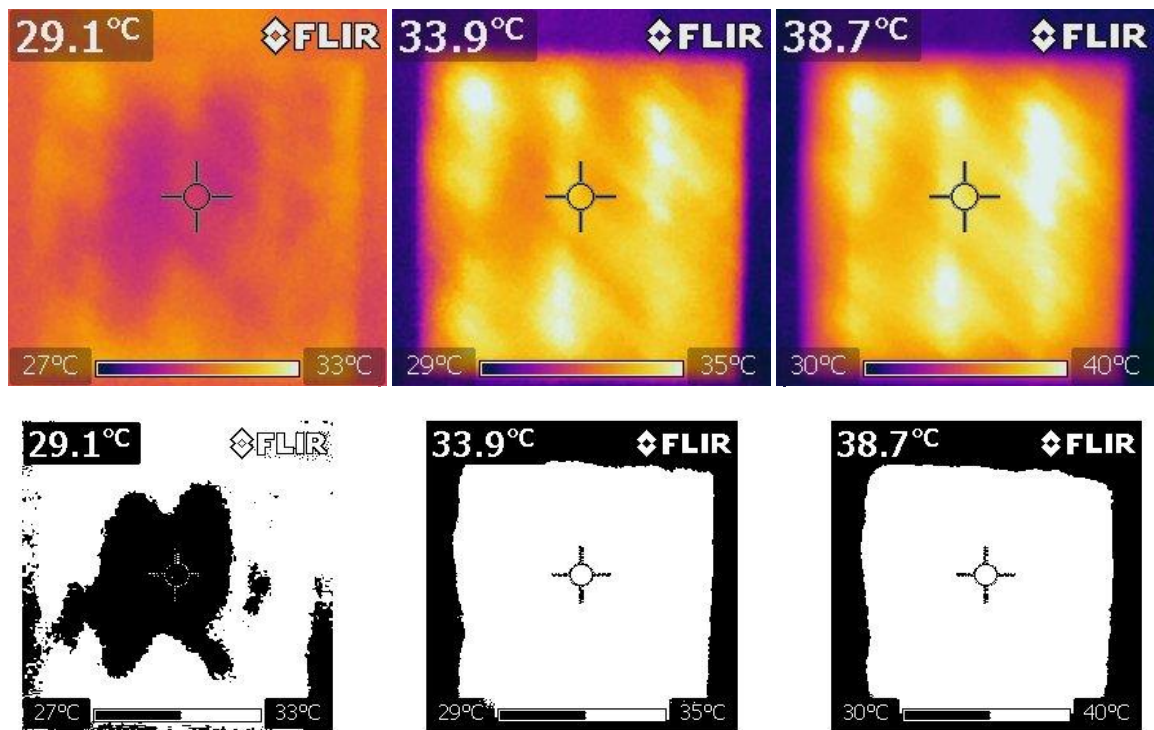


A3/60/R0/S2/5s

A3/60/R0/S2/10s

A3/60/R0/S2/15s

Figure H-32: IR and corresponding binary images obtained for A3/60/R0/S2 sample.

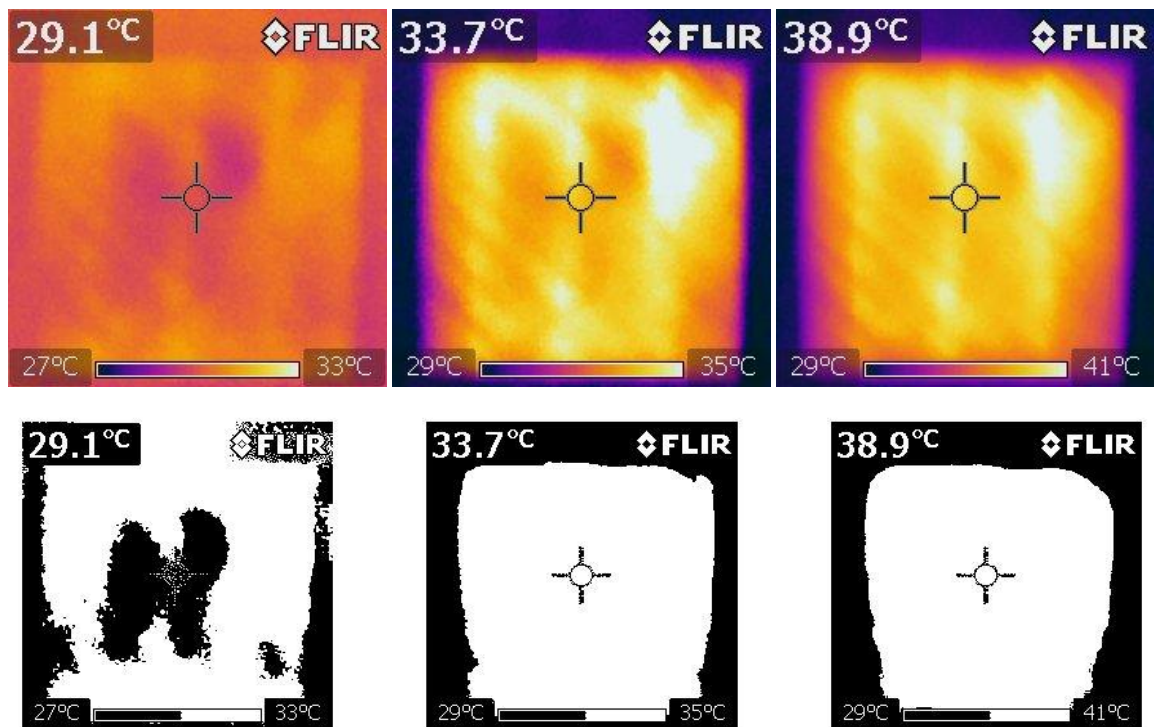


A3/60/R0/S3/5s

A3/60/R0/S3/10s

A3/60/R0/S3/15s

Figure H-33: IR and corresponding binary images obtained for A3/60/R0/S3 sample.

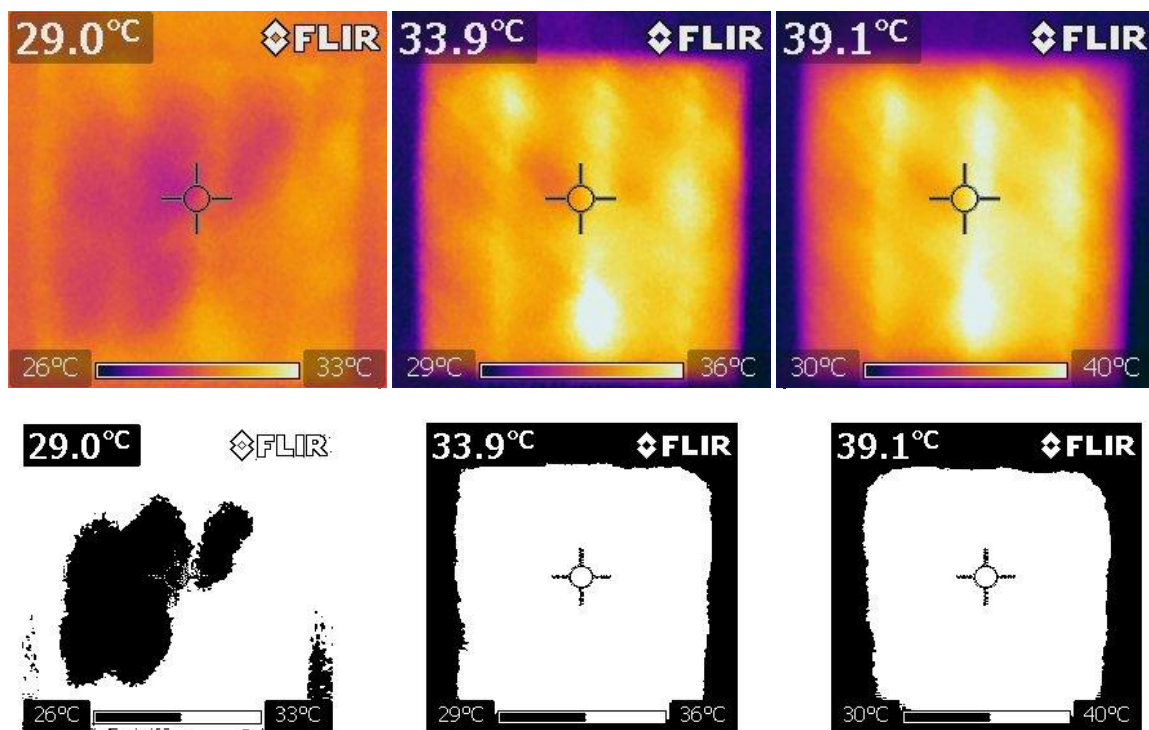


A3/60/R90/S1/5s

A3/60/R90/S1/10s

A3/60/R90/S1/15s

Figure H-34: IR and corresponding binary images obtained for A3/60/R90/S1 sample.

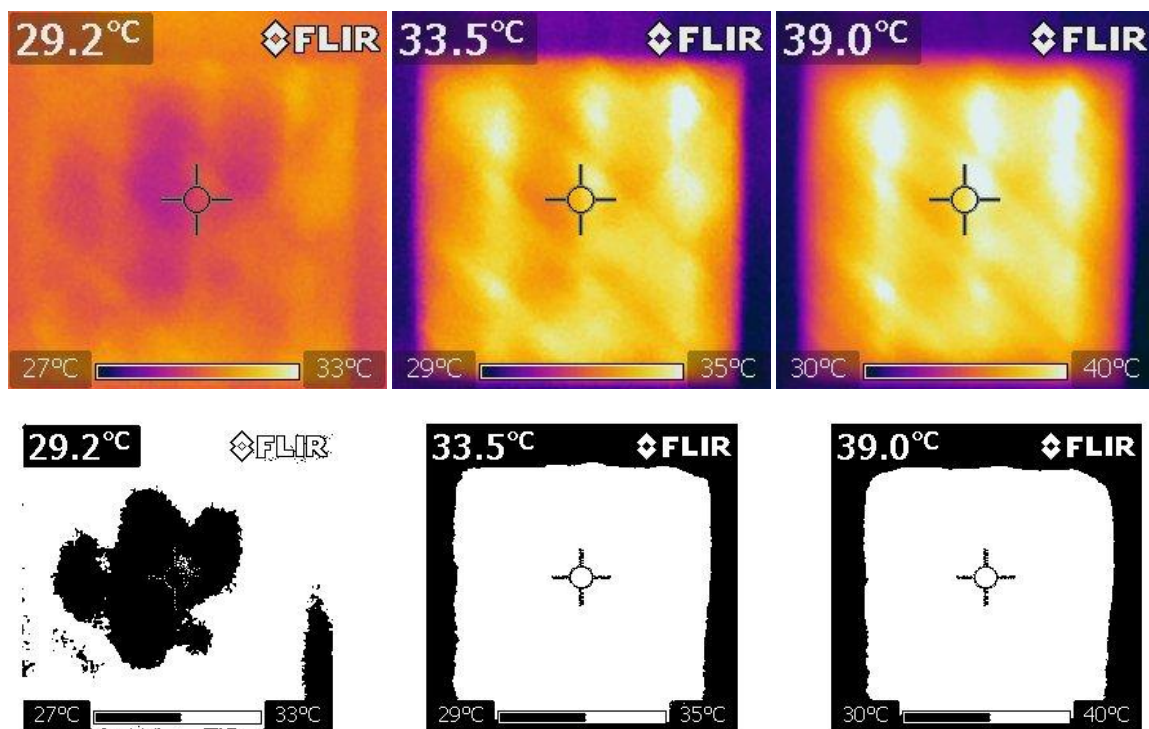


A3/60/R90/S2/5s

A3/60/R90/S2/10s

A3/60/R90/S2/15s

Figure H-35: IR and corresponding binary images obtained for A3/60/R90/S2 sample.

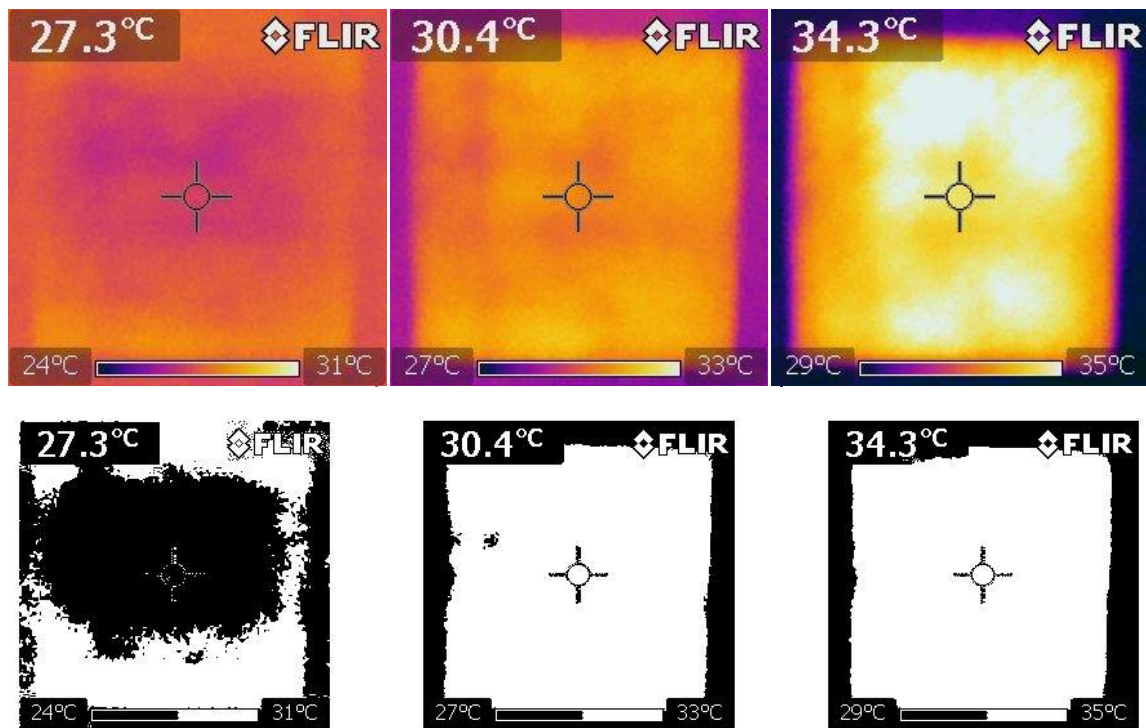


A3/60/R90/S3/5s

A3/60/R90/S3/10s

A3/60/R90/S3/15s

Figure H-36: IR and corresponding binary images obtained for A3/60/R90/S3 sample.

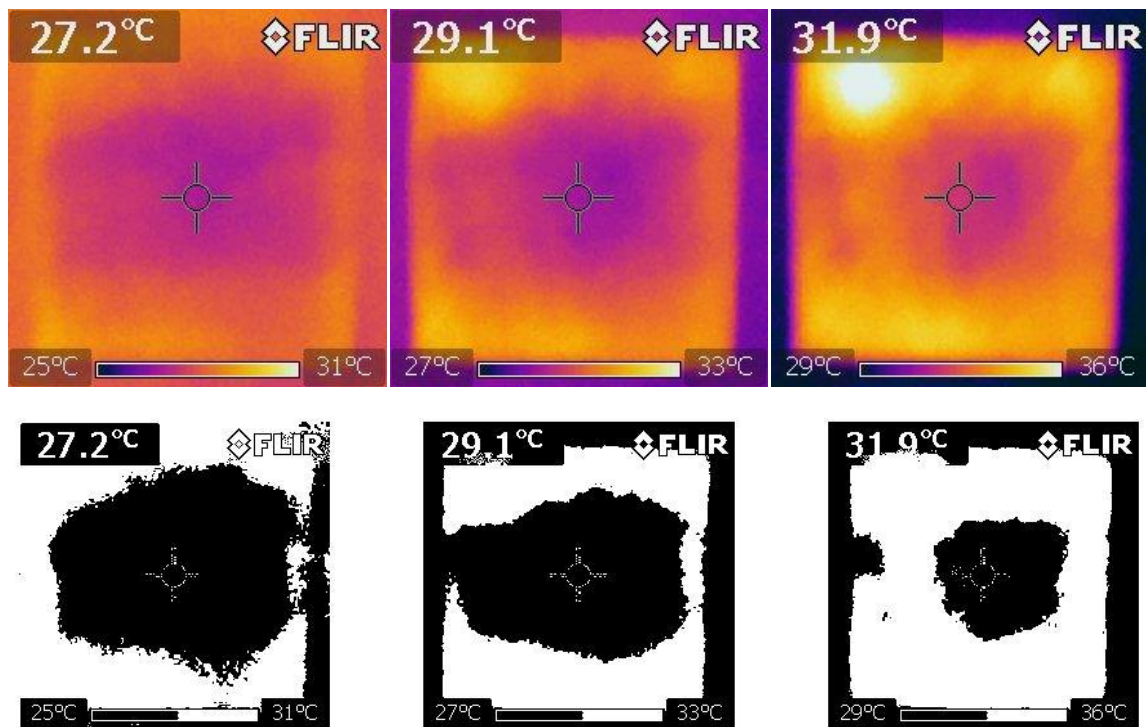


B1/45/R-45/S1/5s

B1/45/ R-45/S1/10s

B1/45/ R-45/S1/15s

Figure H-37: IR and corresponding binary images obtained for B1/45/ R-45/S1 sample.

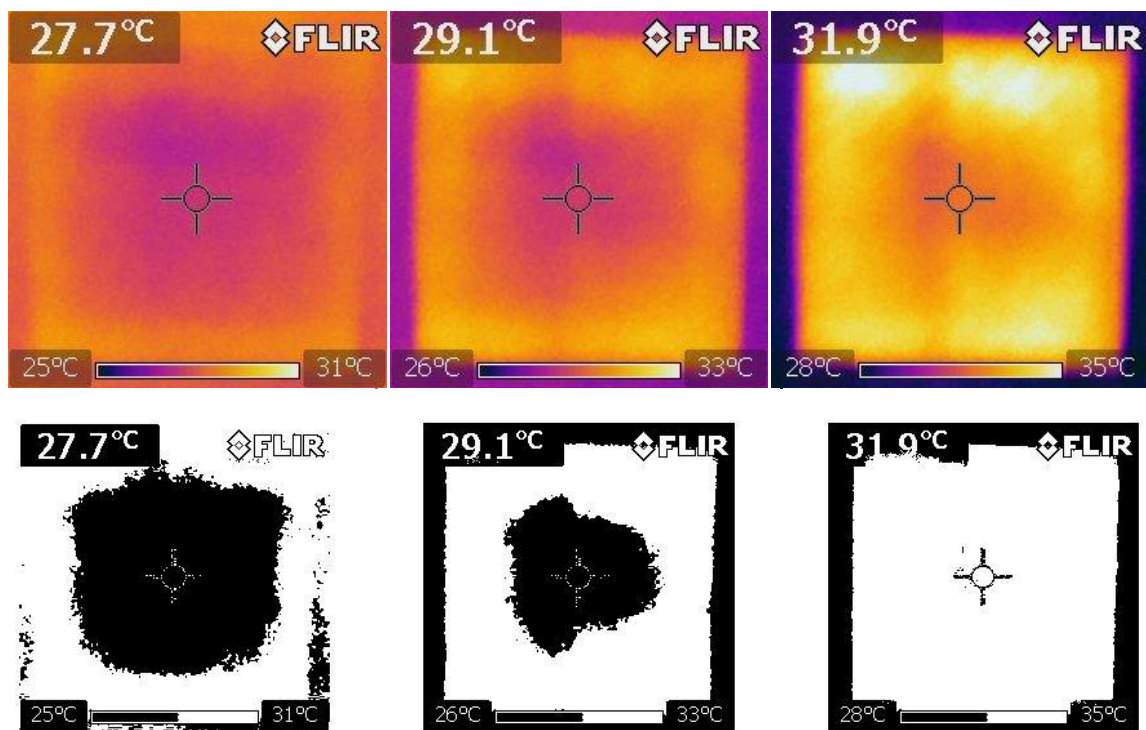


B1/45/R-45/S2/5s

B1/45/R-45/S2/10s

B1/45/R-45/S2/15s

Figure H-38: IR and corresponding binary images obtained for B1/45/R-45/S2 sample.

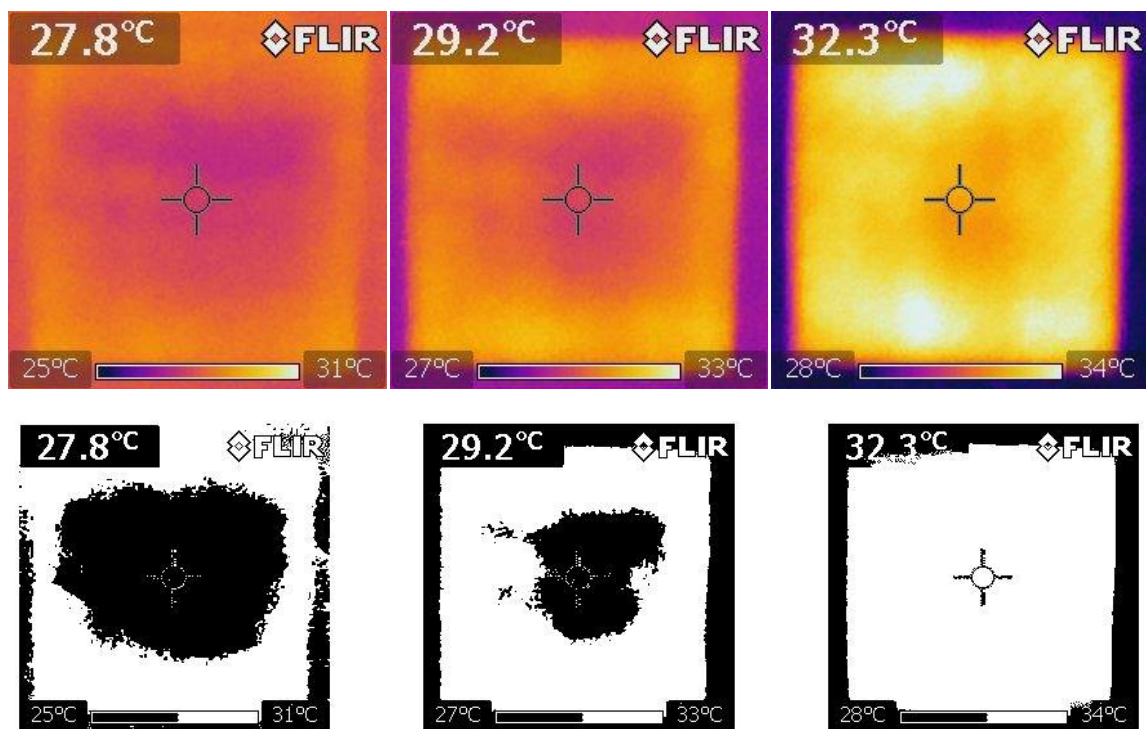


B1/45/R-45/S3/5s

B1/45/R-45/S3/10s

B1/45/R-45/S3/15s

Figure H-39: IR and corresponding binary images obtained for B1/45/R-45/S3 sample.

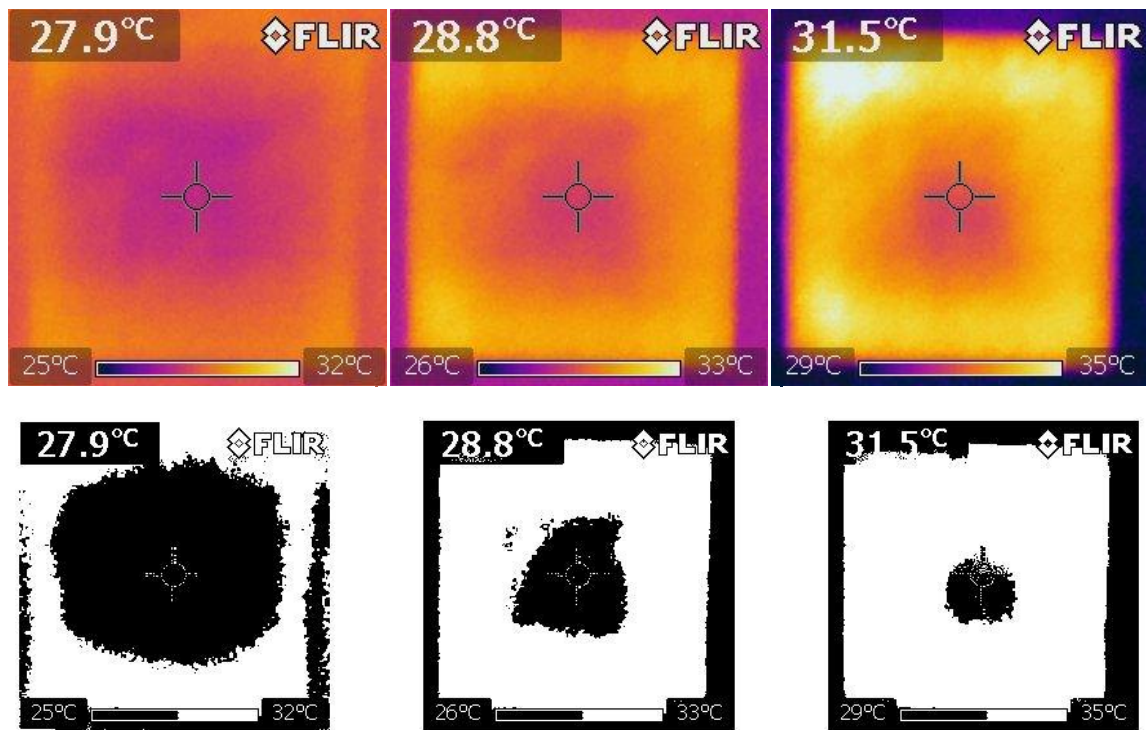


B1/45/R+45/S1/5s

B1/45/R+45/S1/10s

B1/45/R+45/S1/15s

Figure H-40: IR and corresponding binary images obtained for B1/45/R+45/S1 sample.

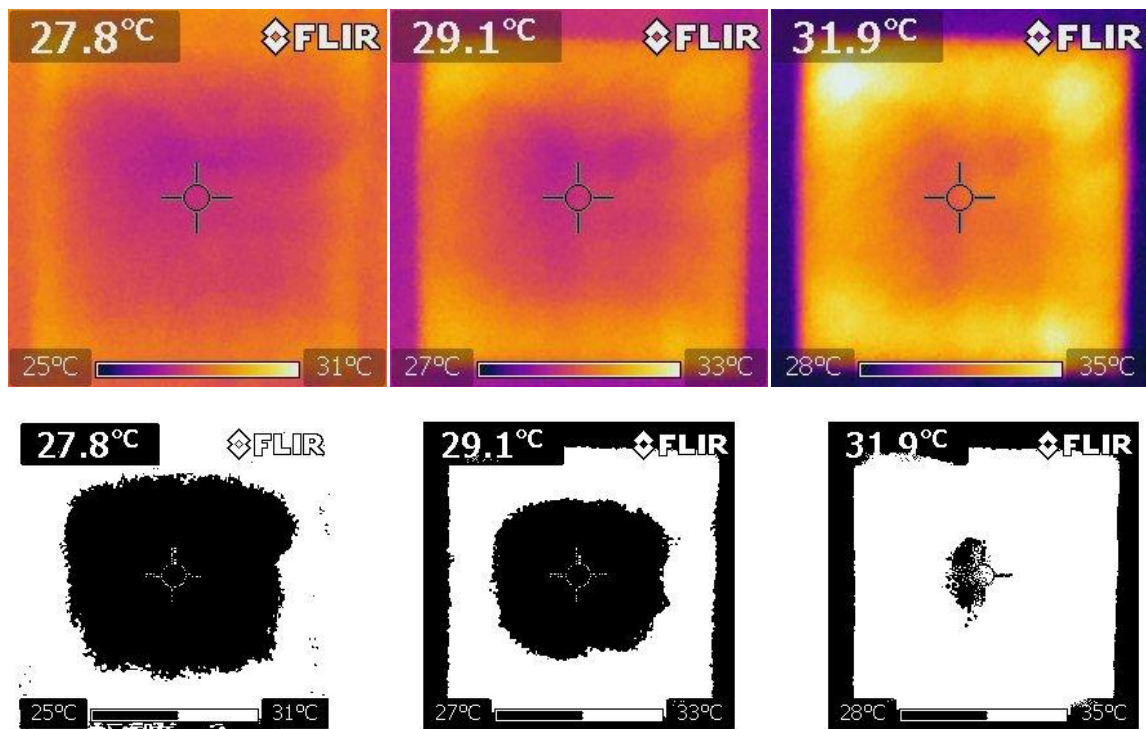


B1/45/R+45/S2/5s

B1/45/R+45/S2/10s

B1/45/R+45/S2/15s

Figure H-41: IR and corresponding binary images obtained for B1/45/R+45/S2 sample.

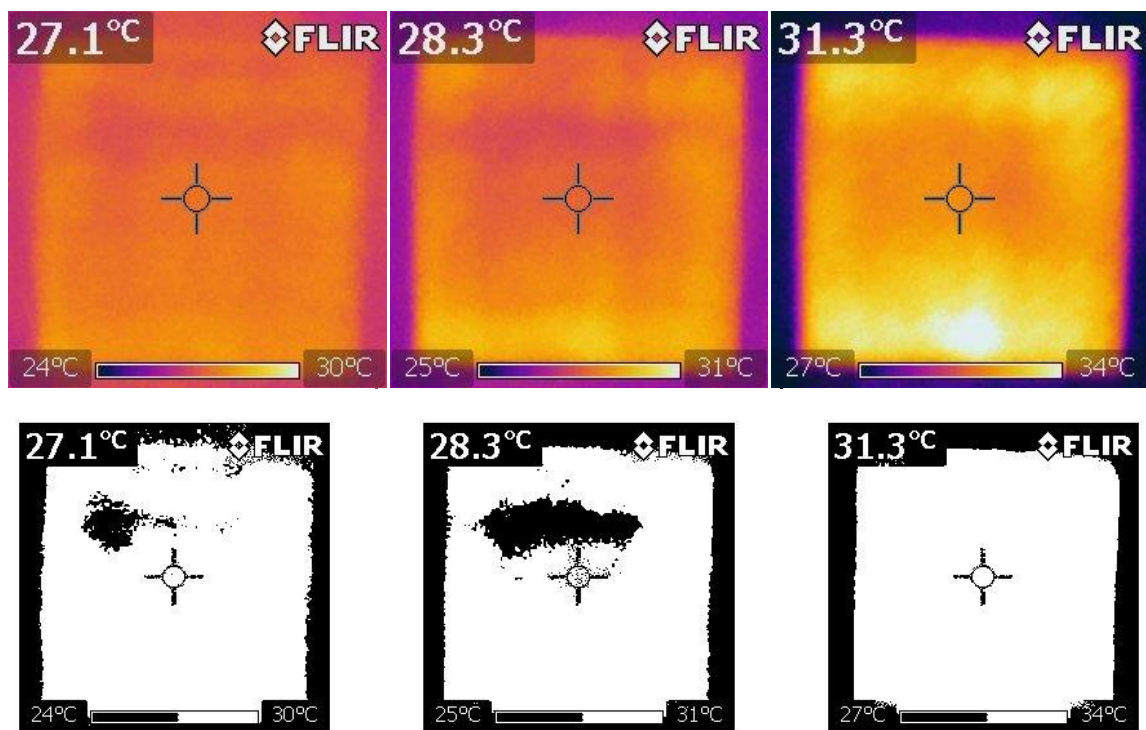


B1/45/R+45/S3/5s

B1/45/R+45/S3/10s

B1/45/R+45/S3/15s

Figure H-42: IR and corresponding binary images obtained for B1/45/R+45/S3 sample.

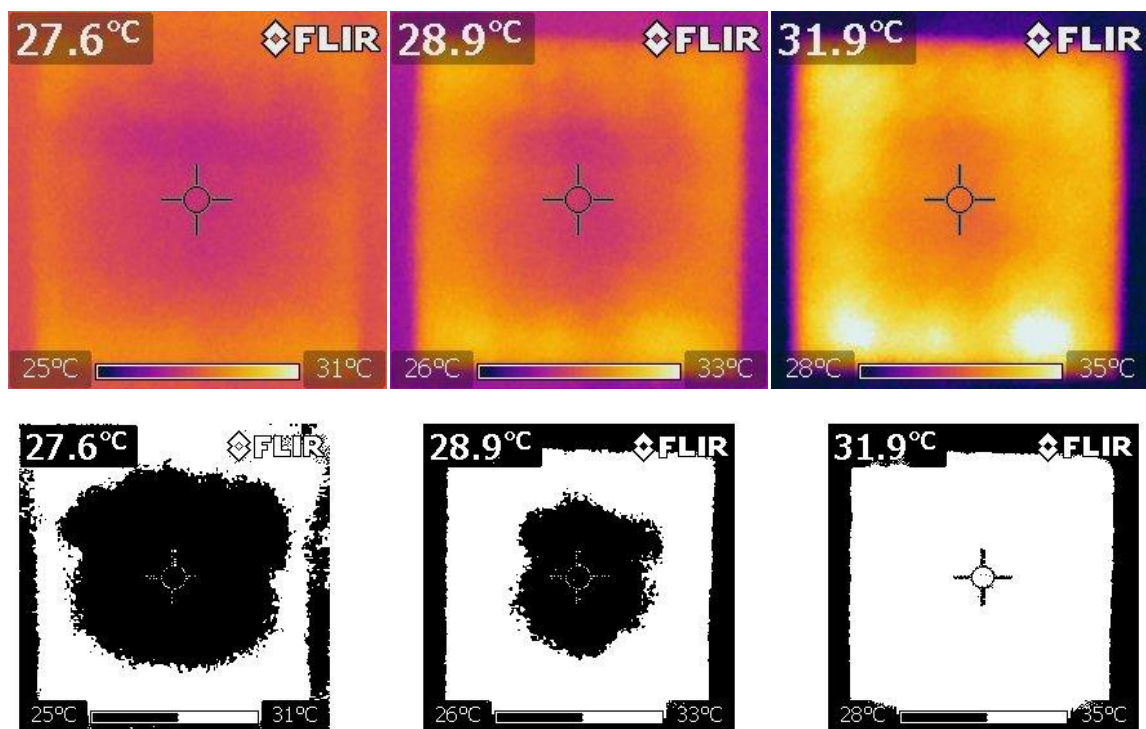


B1/60/R-45/S1/5s

B1/60/R-45/S1/10s

B1/60/R-45/S1/15s

Figure H-43: IR and corresponding binary images obtained for B1/60/R-45/S1 sample.

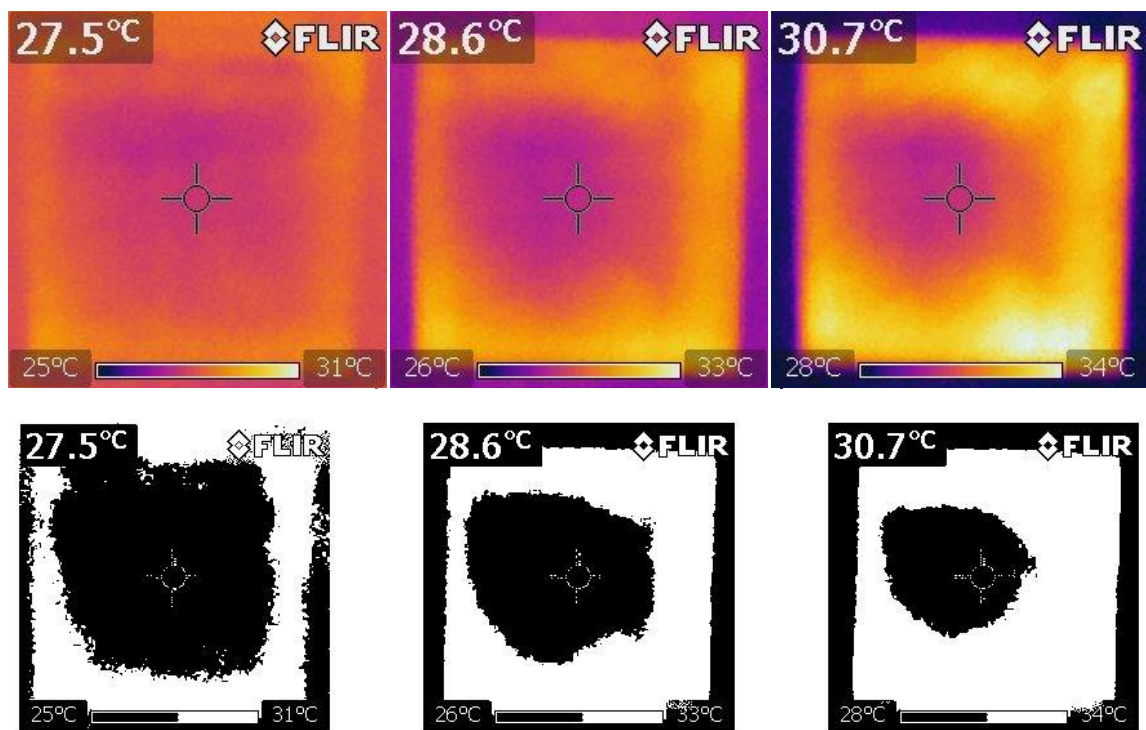


B1/60/R-45/S2/5s

B1/60/R-45/S2/10s

B1/60/R-45/S2/15s

Figure H-44: IR and corresponding binary images obtained for B1/60/R-45/S2 sample.

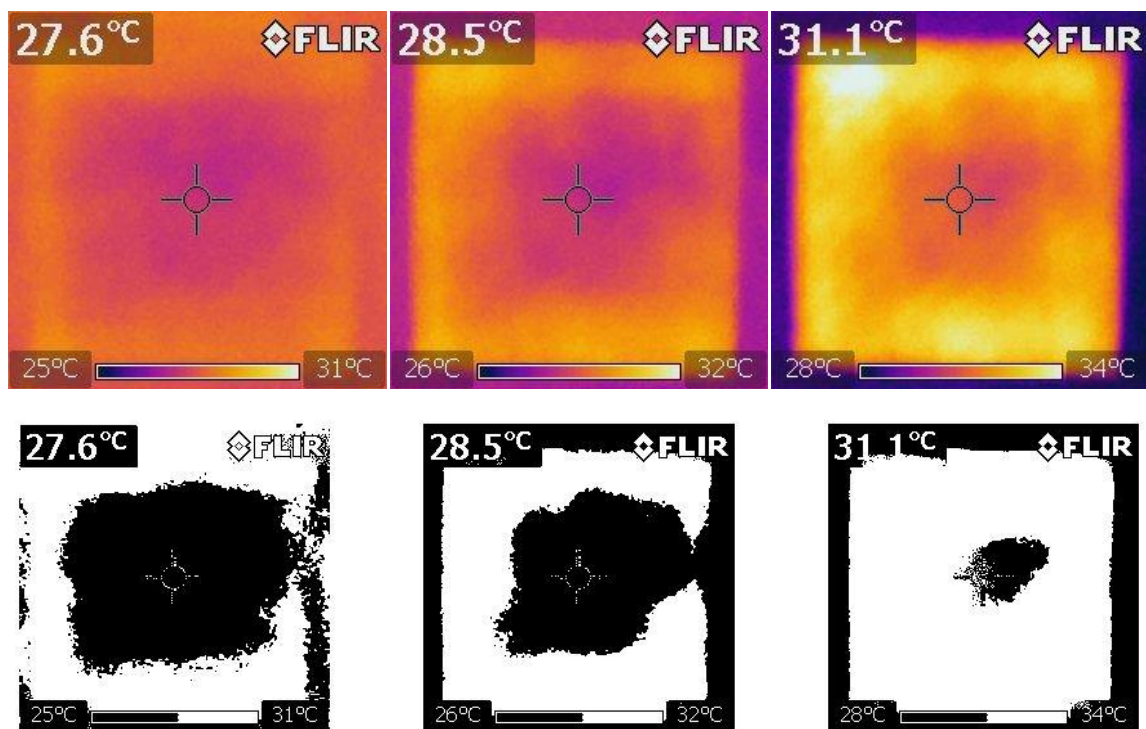


B1/60/R-45/S3/5s

B1/60/R-45/S3/10s

B1/60/R-45/S3/15s

Figure H-45: IR and corresponding binary images obtained for B1/60/R-45/S3 sample.

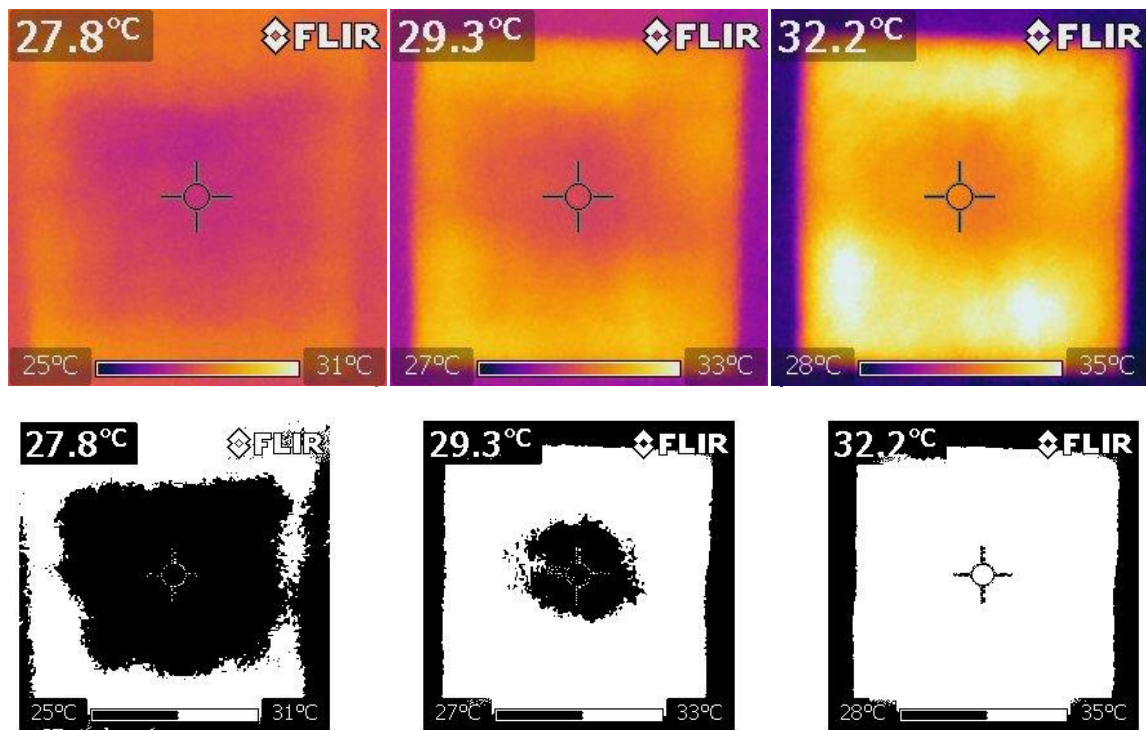


B1/60/R+45/S1/5s

B1/60/R+45/S1/10s

B1/60/R+45/S1/15s

Figure H-46: IR and corresponding binary images obtained for B1/60/R+45/S1 sample.

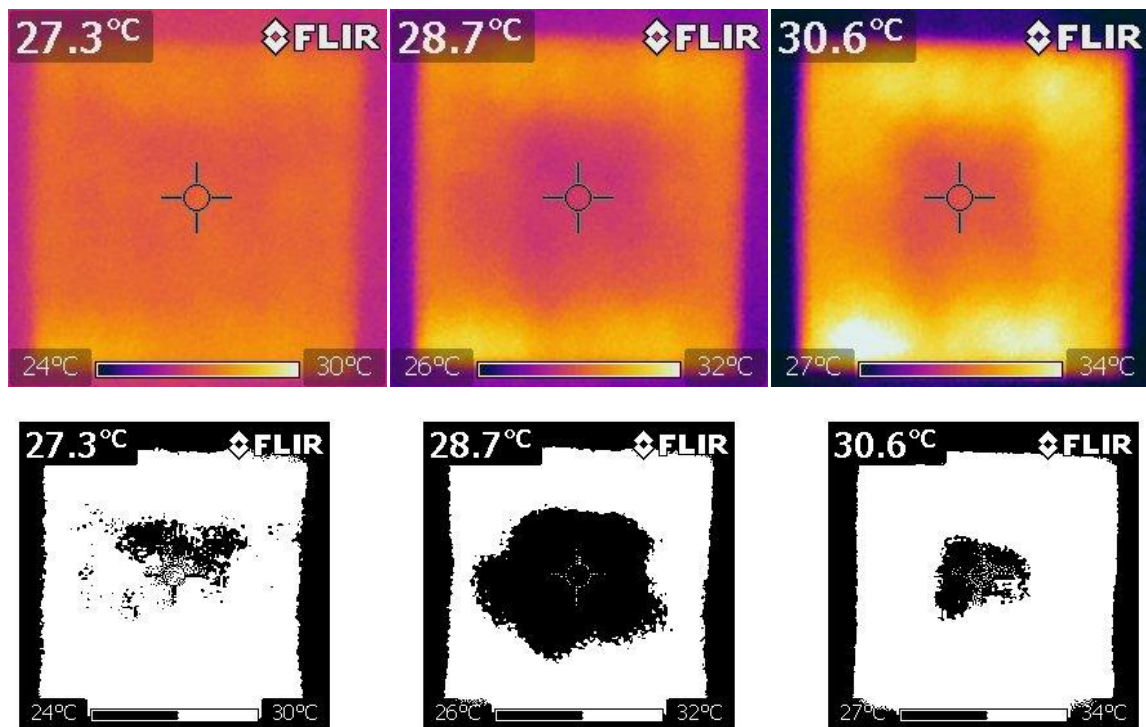


B1/60/R+45/S2/5s

B1/60/R+45/S2/10s

B1/60/R+45/S2/15s

Figure H-47: IR and corresponding binary images obtained for B1/60/R+45/S2 sample.

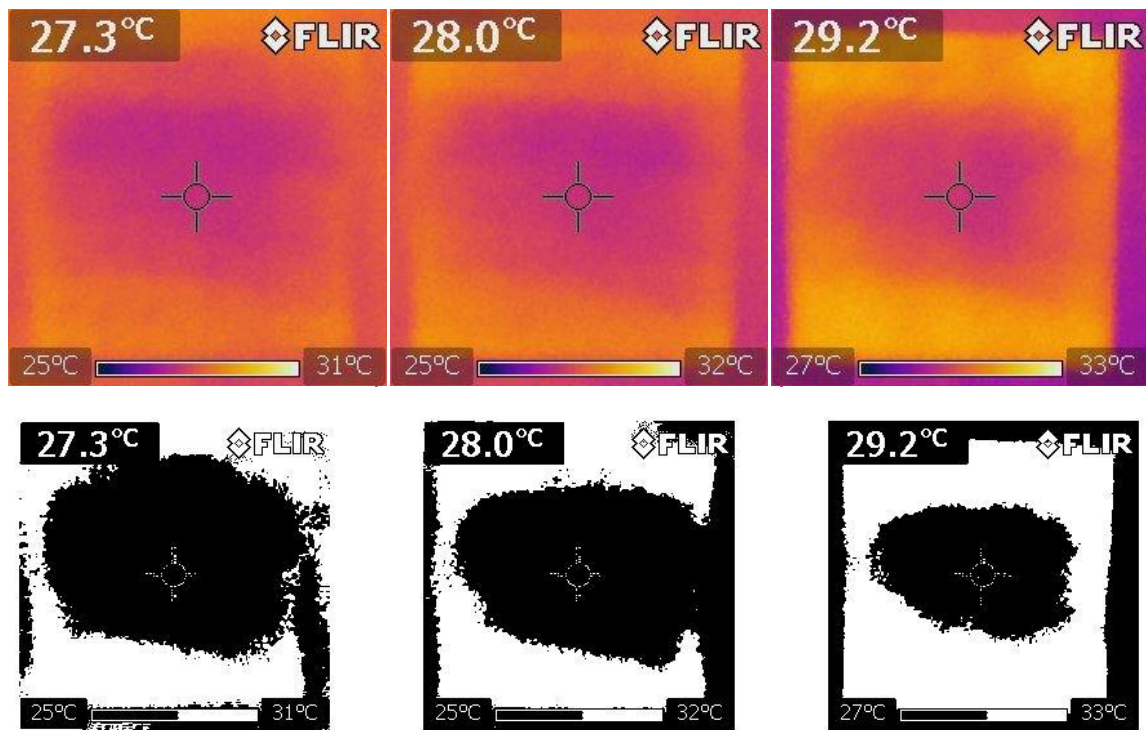


B1/60/R+45/S3/5s

B1/60/R+45/S3/10s

B1/60/R+45/S3/15s

Figure H-48: IR and corresponding binary images obtained for B1/60/R+45/S3 sample.

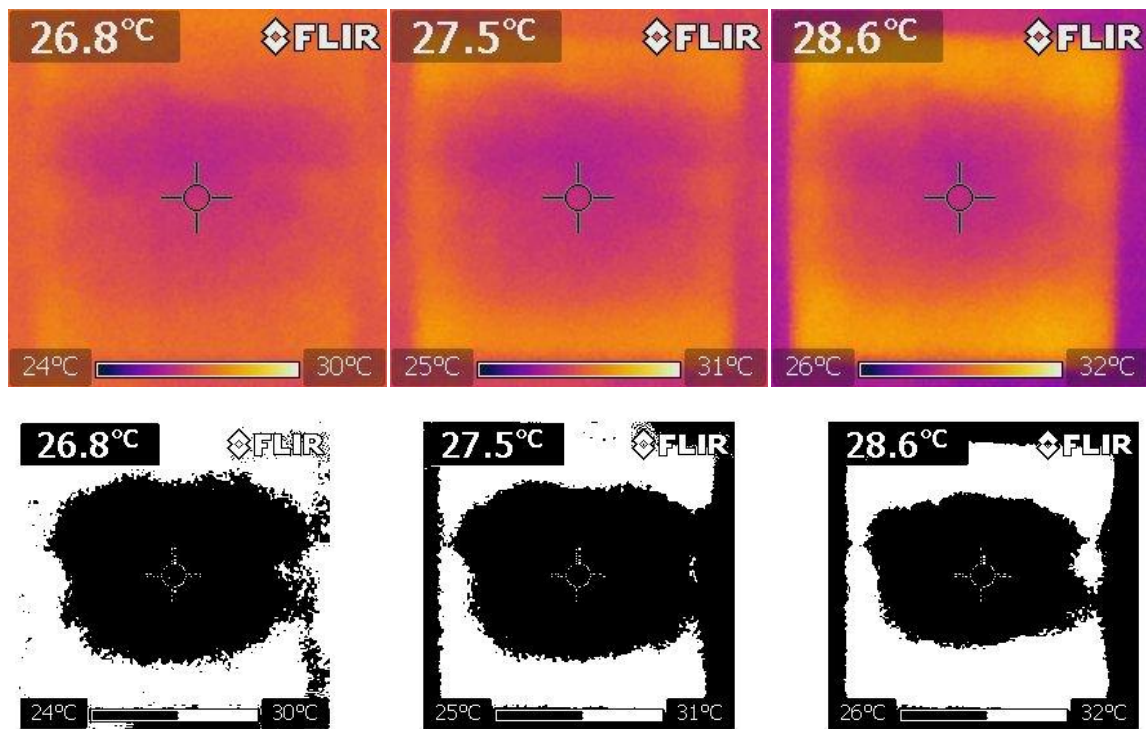


B2/45/R-45/S1/5s

B2/45/ R-45/S1/10s

B2/45/ R-45/S1/15s

Figure H-49: IR and corresponding binary images obtained for B2/45/ R-45/S1 sample.

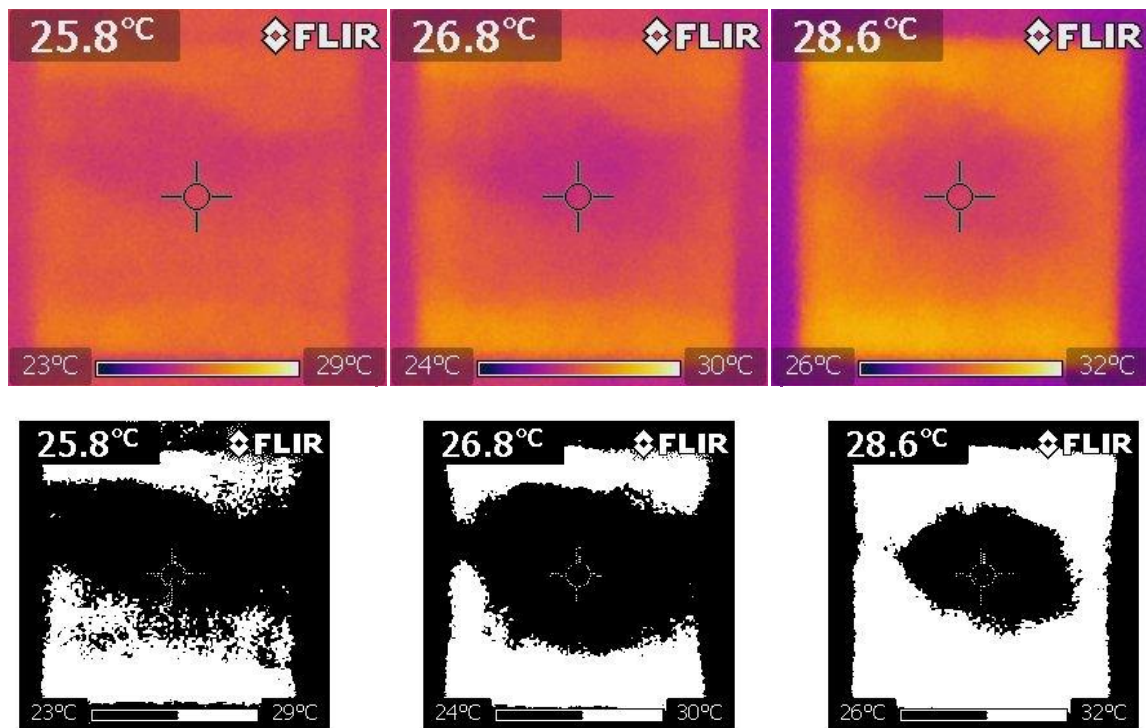


B2/45/R-45/S2/5s

B2/45/R-45/S2/10s

B2/45/R-45/S2/15s

Figure H-50: IR and corresponding binary images obtained for B2/45/R-45/S2 sample.

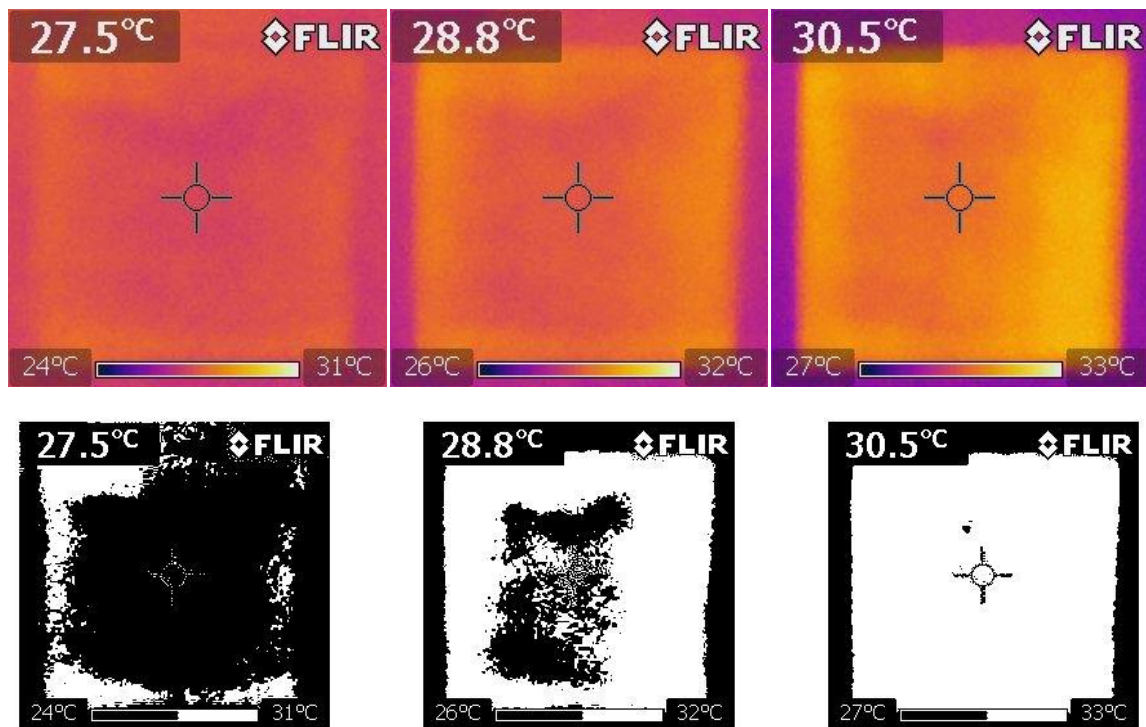


B2/45/R-45/S3/5s

B2/45/R-45/S3/10s

B2/45/R-45/S3/15s

Figure H-51: IR and corresponding binary images obtained for B2/45/R-45/S3 sample.

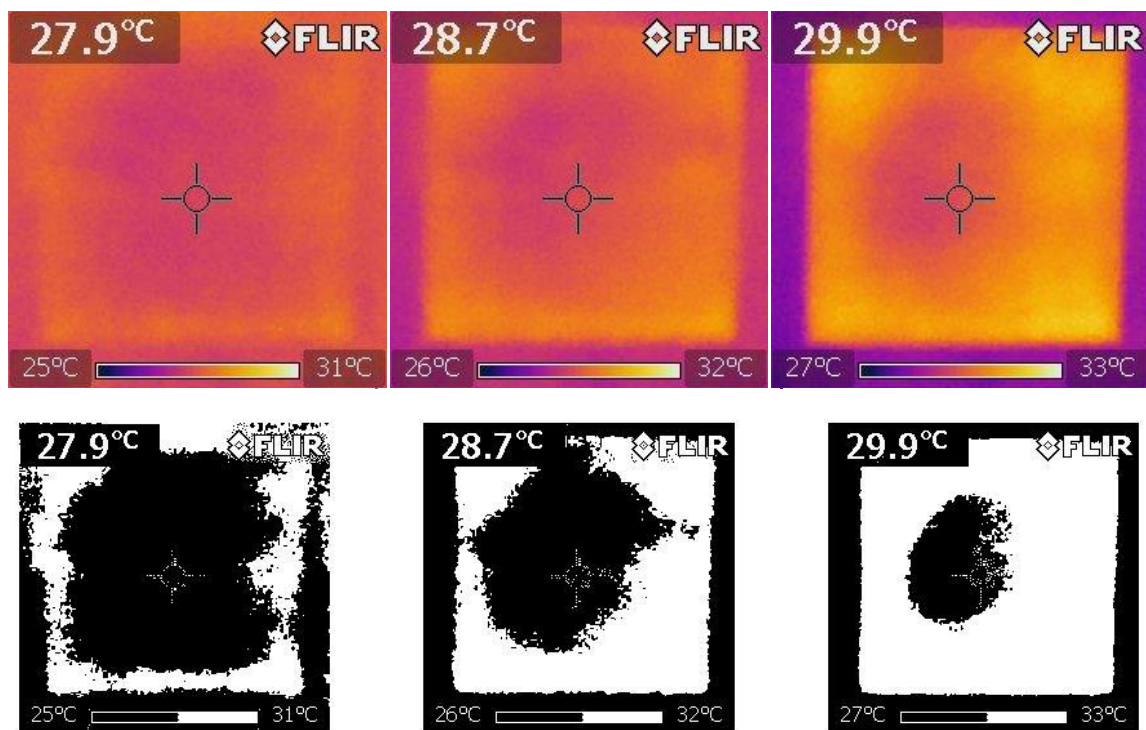


B2/45/R+45/S1/5s

B2/45/R+45/S1/10s

B2/45/R+45/S1/15s

Figure H-52: IR and corresponding binary images obtained for B2/45/R+45/S1 sample.

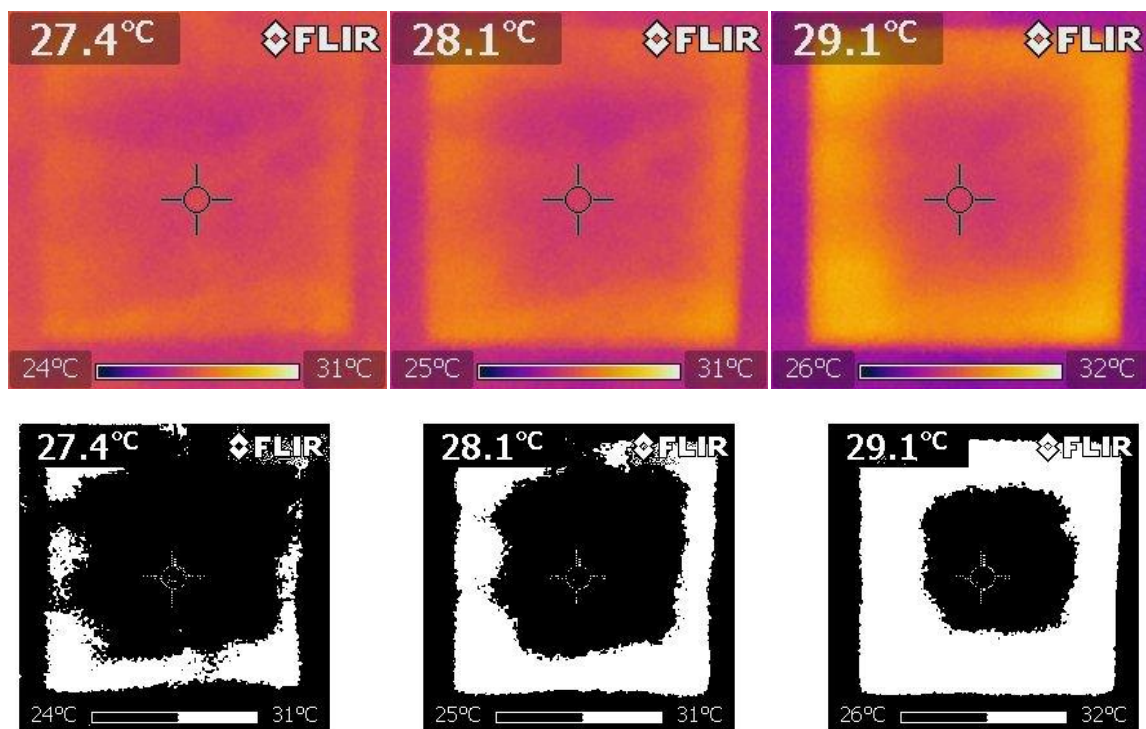


B2/45/R+45/S2/5s

B2/45/R+45/S2/10s

B2/45/R+45/S2/15s

Figure H-53: IR and corresponding binary images obtained for B2/45/R+45/S2 sample.

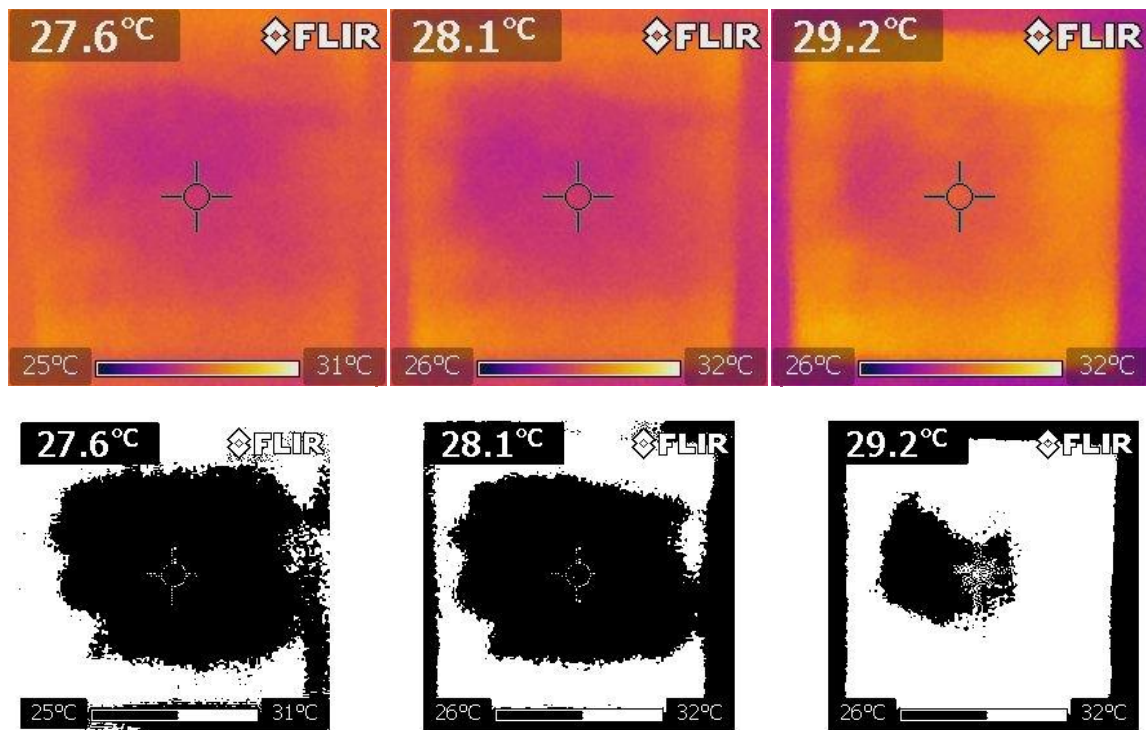


B2/45/R+45/S3/5s

B2/45/R+45/S3/10s

B2/45/R+45/S3/15s

Figure H-54: IR and corresponding binary images obtained for B2/45/R+45/S3 sample.

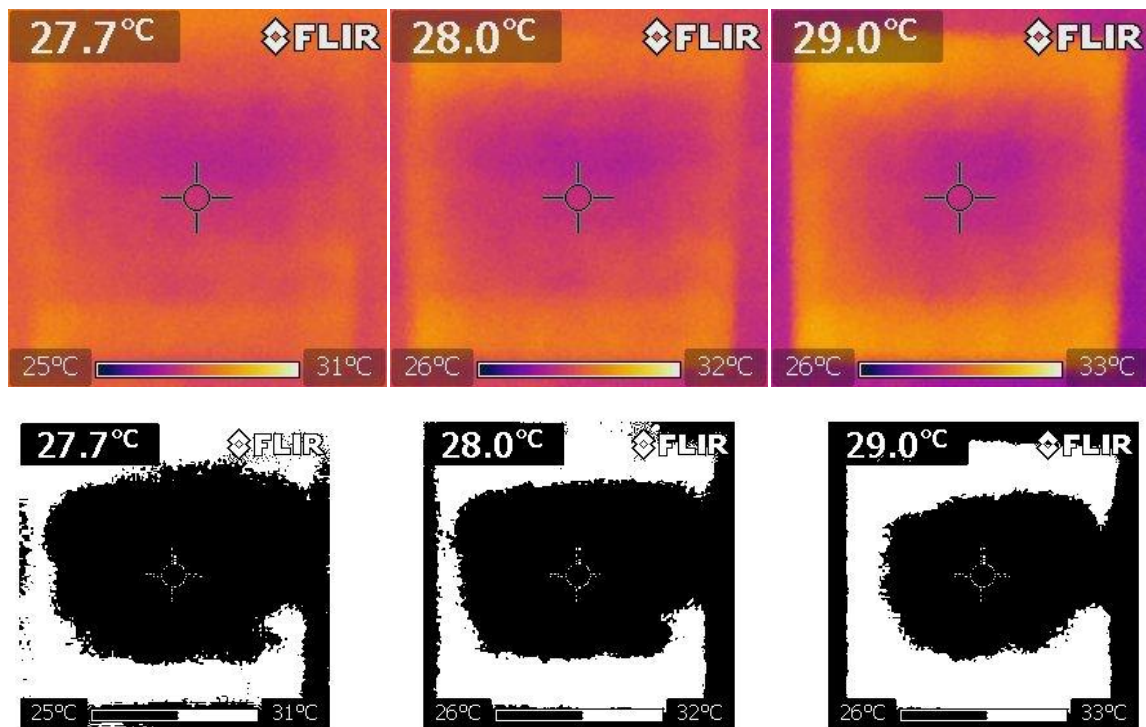


B2/60/R-45/S1/5s

B2/60/R-45/S1/10s

B2/60/R-45/S1/15s

Figure H-55: IR and corresponding binary images obtained for B2/60/R-45/S1 sample.

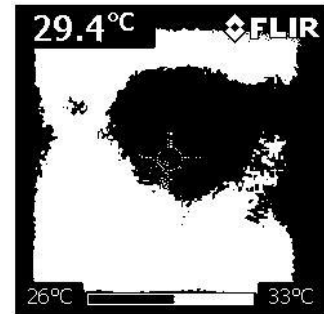
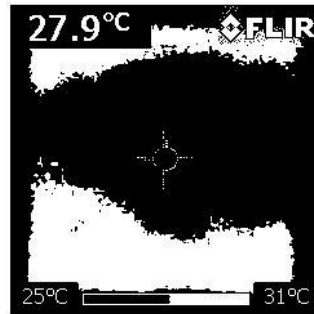
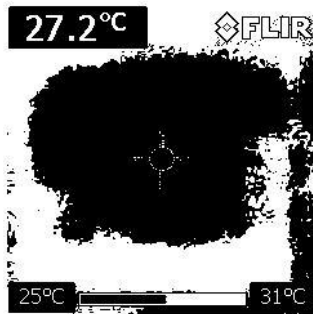
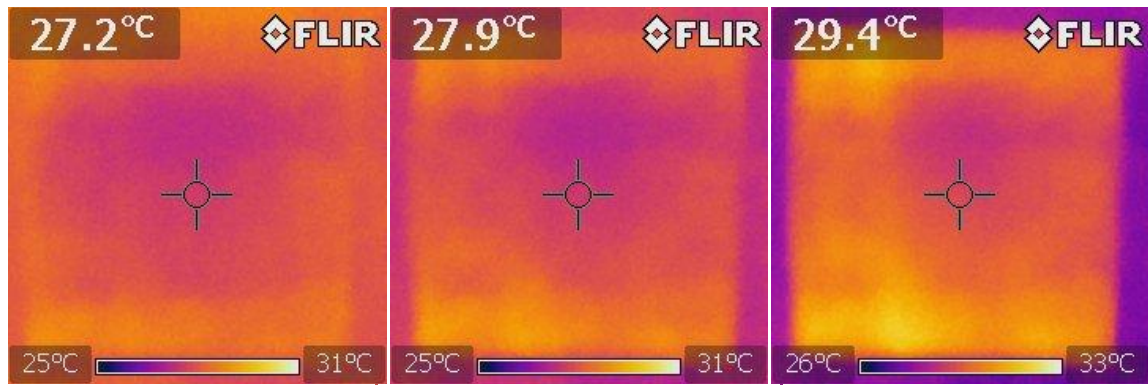


B2/60/R-45/S2/5s

B2/60/R-45/S2/10s

B2/60/R-45/S2/15s

Figure H-56: IR and corresponding binary images obtained for B2/60/R-45/S2 sample.

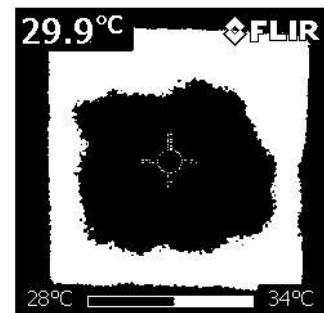
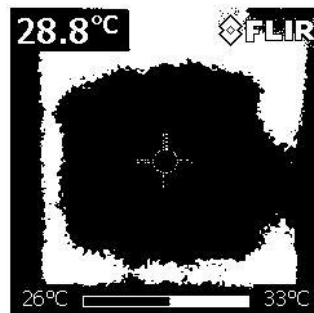
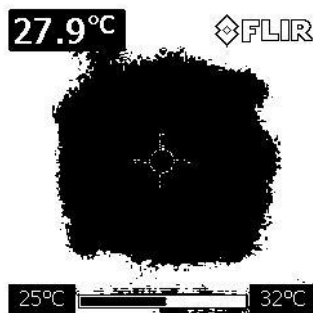
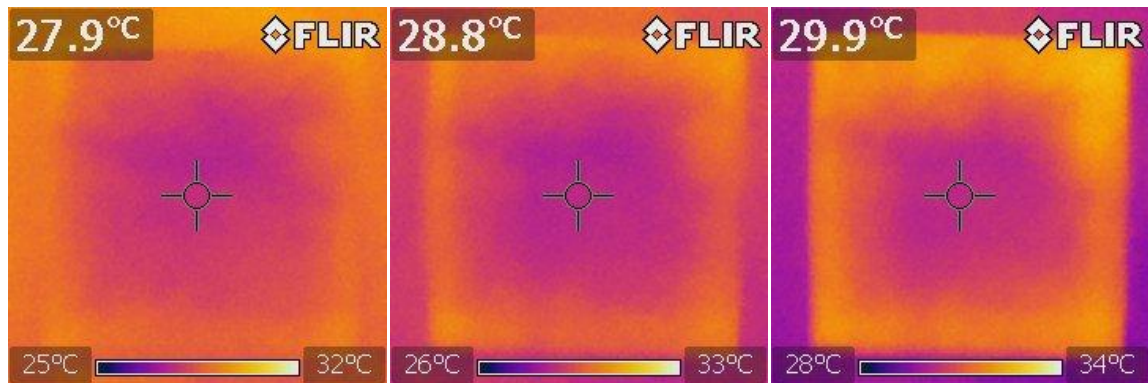


B2/60/R-45/S3/5s

B2/60/R-45/S3/10s

B2/60/R-45/S3/15s

IR and corresponding binary images obtained for B2/60/R-45/S3 sample.

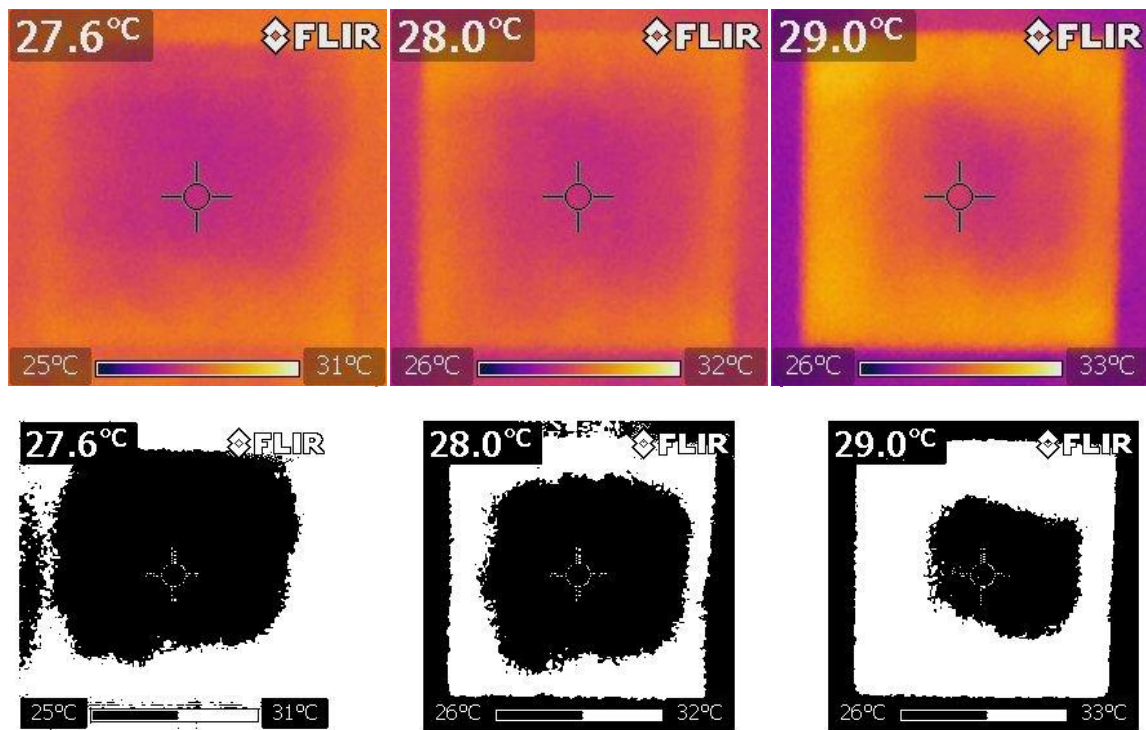


B2/60/R+45/S1/5s

B2/60/R+45/S1/10s

B2/60/R+45/S1/15s

Figure H-58: IR and corresponding binary images obtained for B2/60/R+45/S1 sample.

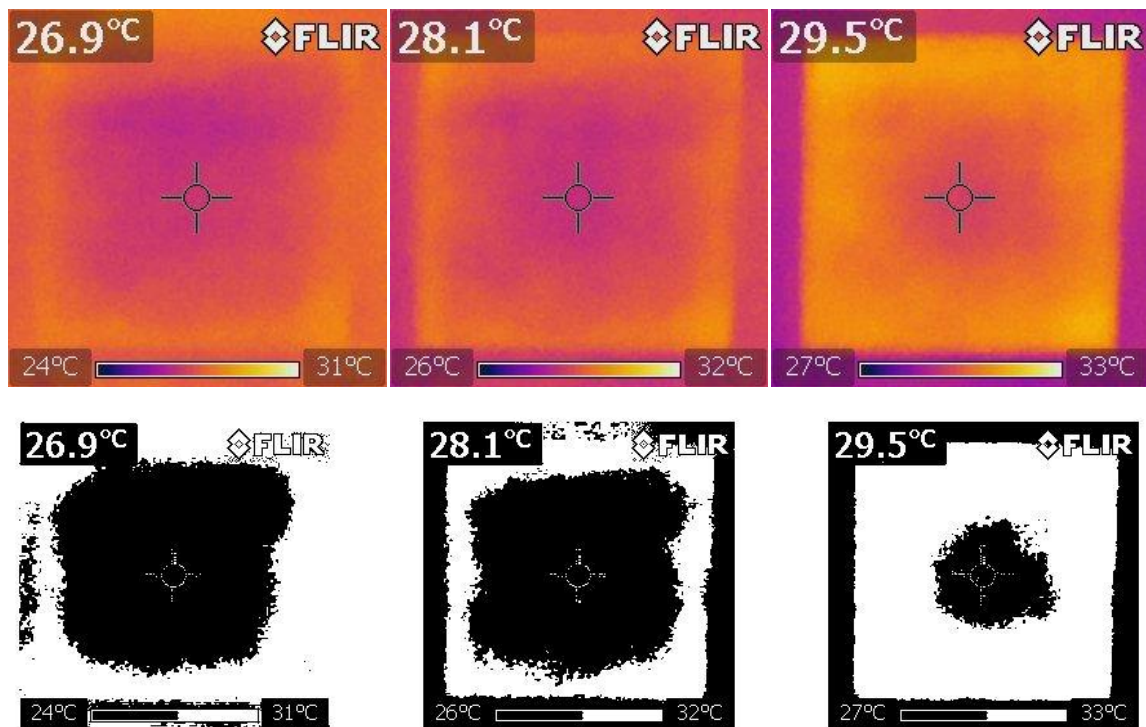


B2/60/R+45/S2/5s

B2/60/R+45/S2/10s

B2/60/R+45/S2/15s

Figure H-59: IR and corresponding binary images obtained for B1/60/R+45/S2 sample.

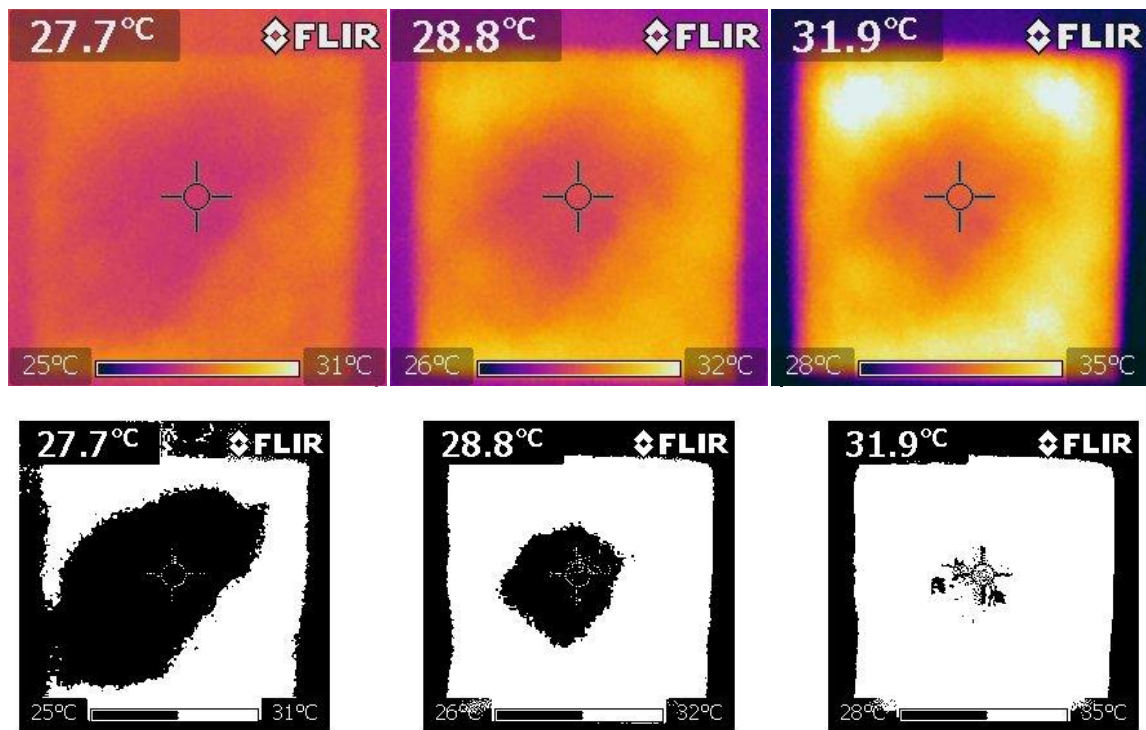


B2/60/R+45/S3/5s

B2/60/R+45/S3/10s

B2/60/R+45/S3/15s

Figure H-60: IR and corresponding binary images obtained for B2/60/R+45/S3 sample.

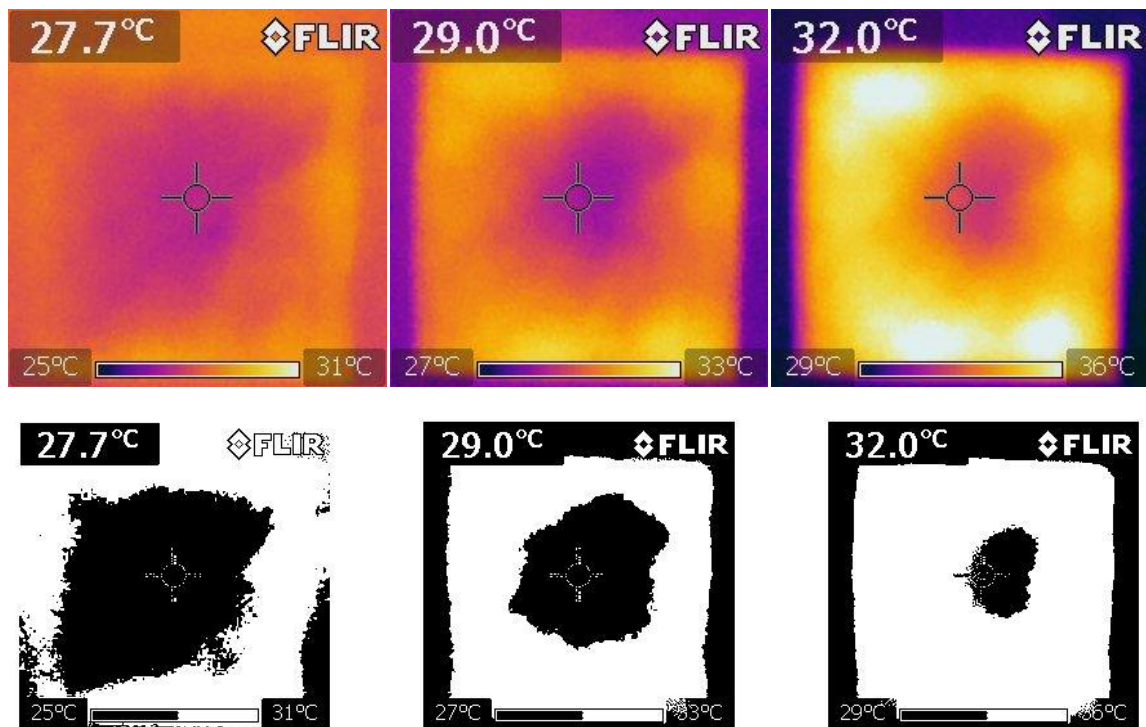


B3/45/R0/S1/5s

B3/45/R0/S1/10s

B3/45/R0/S1/15s

Figure H-61: IR and corresponding binary images obtained for B3/45/R0/S1 sample.

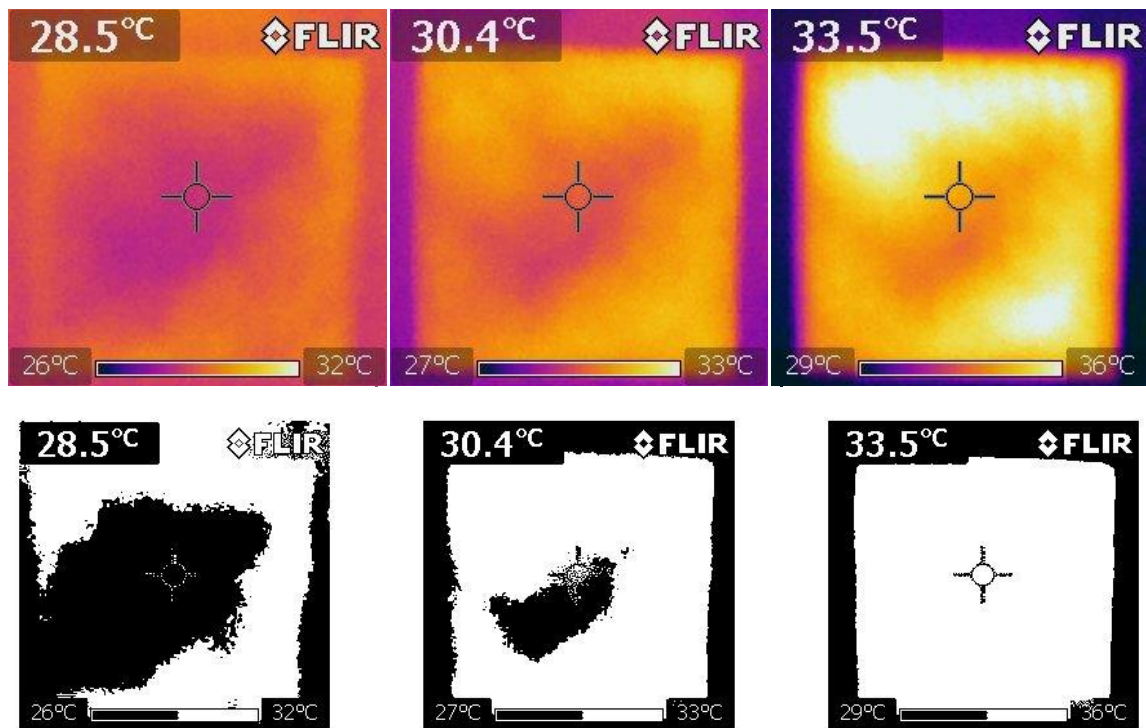


B3/45/R0/S2/5s

B3/45/R0/S2/10s

B3/45/R0/S2/15s

Figure H-62: IR and corresponding binary images obtained for B3/45/R0/S2 sample.

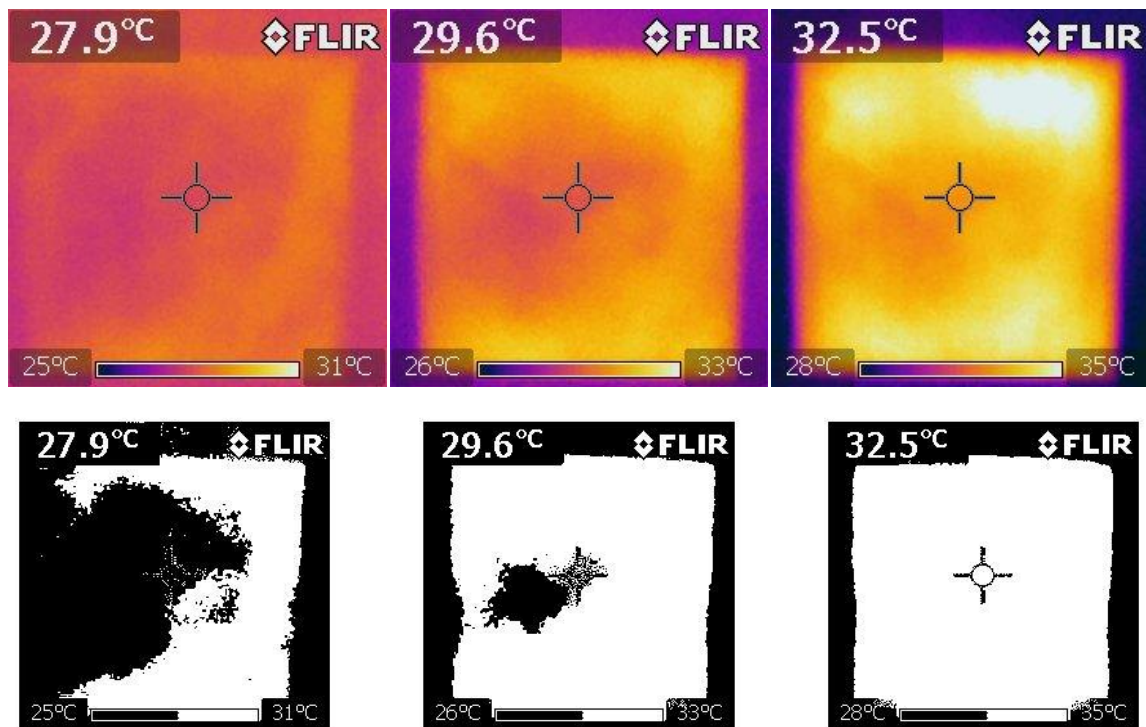


B3/45/R0/S3/5s

B3/45/R0/S3/10s

B3/45/R0/S3/15s

Figure H-63: IR and corresponding binary images obtained for B3/45/R0/S3 sample.

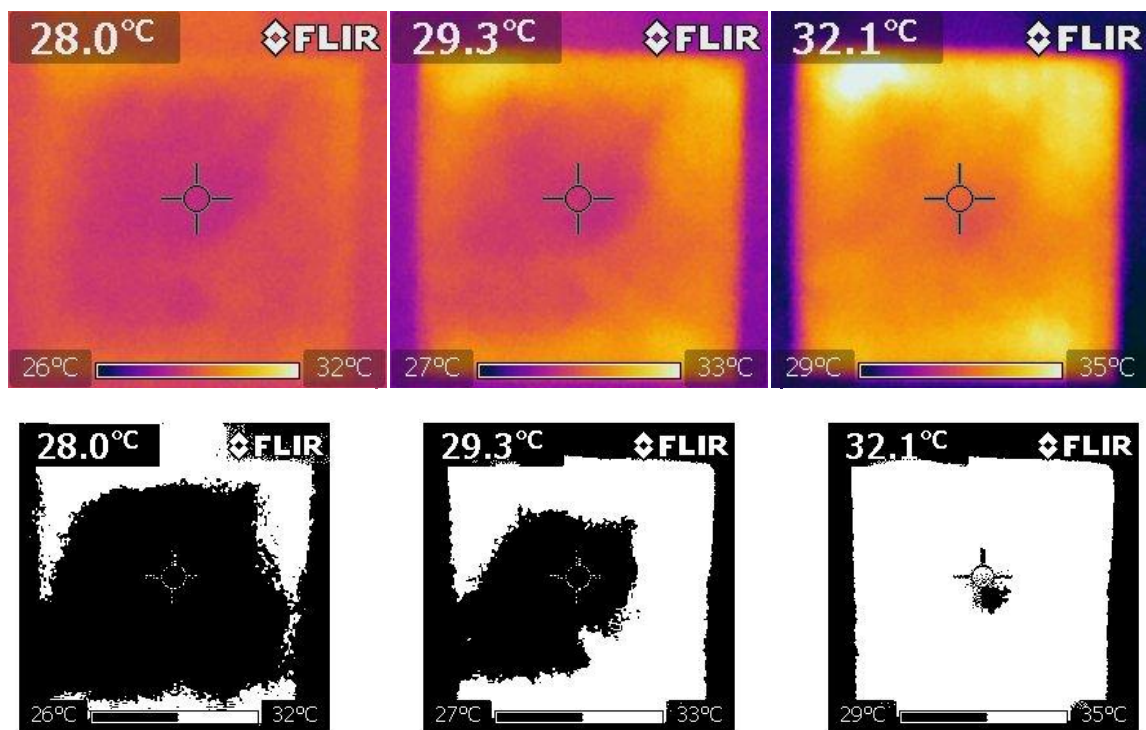


B3/45/R90/S1/5s

B3/45/R90/S1/10s

B3/45/R90/S1/15s

Figure H-64: IR and corresponding binary images obtained for B3/45/R90/S1 sample.

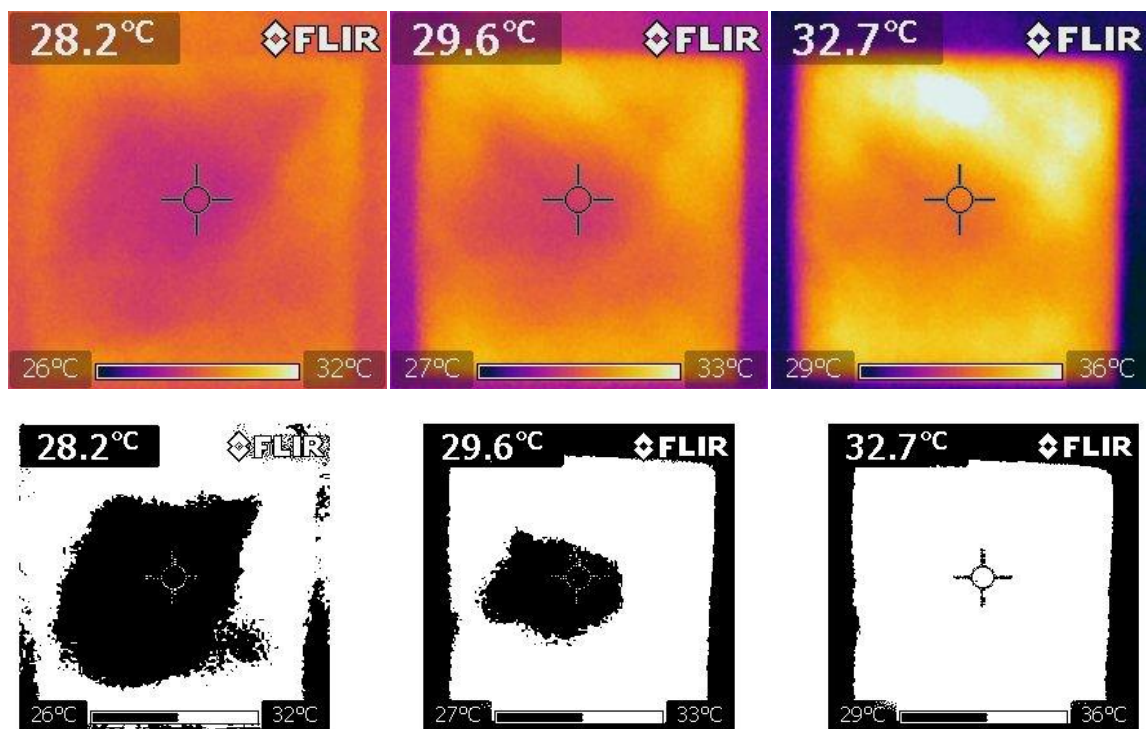


B3/45/R90/S2/5s

B3/45/R90/S2/10s

B3/45/R90/S2/15s

Figure H-65: IR and corresponding binary images obtained for B3/45/R90/S2 sample.

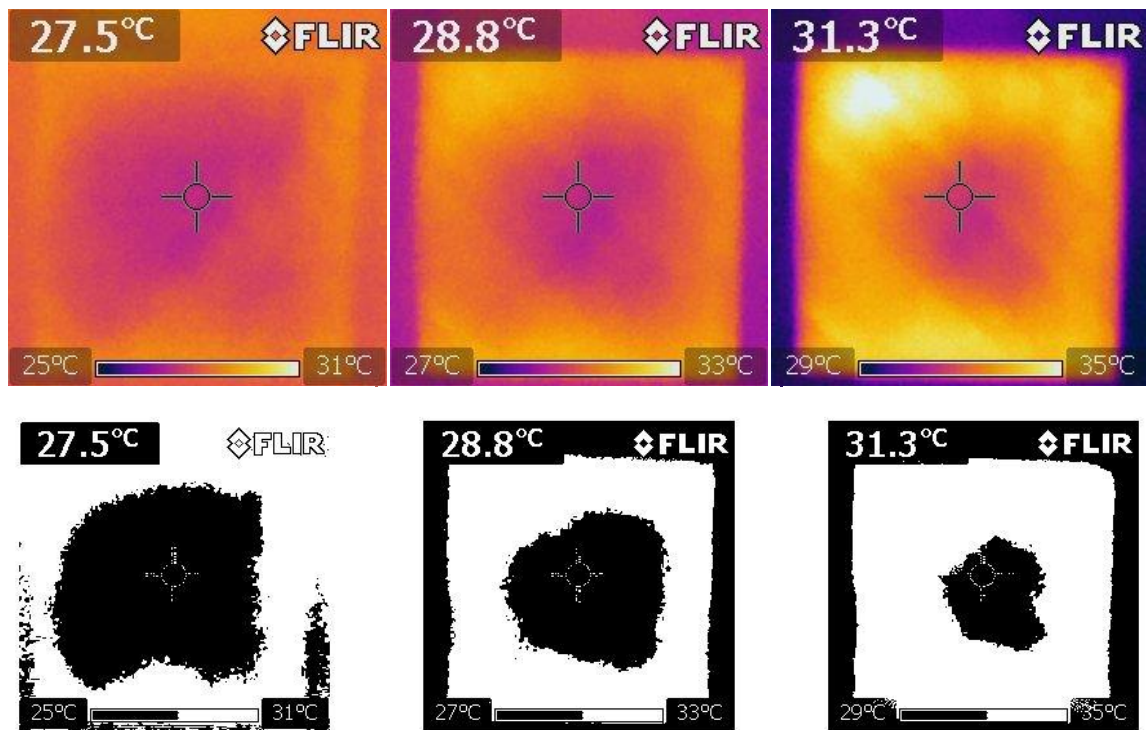


B3/45/R90/S3/5s

B3/45/R90/S3/10s

B3/45/R90/S3/15s

Figure H-66: IR and corresponding binary images obtained for B3/45/R90/S3 sample.

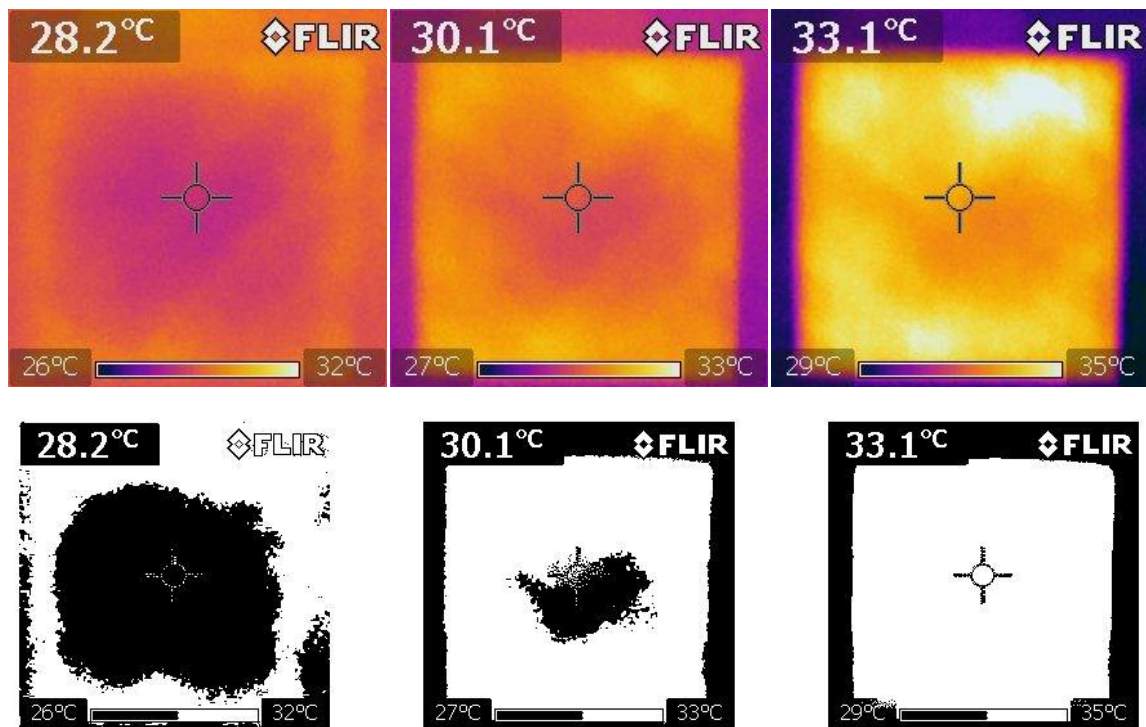


B3/60/R0/S1/5s

B3/60/R0/S1/10s

B3/60/R0/S1/15s

Figure H-67: IR and corresponding binary images obtained for B3/60/R0/S1 sample.

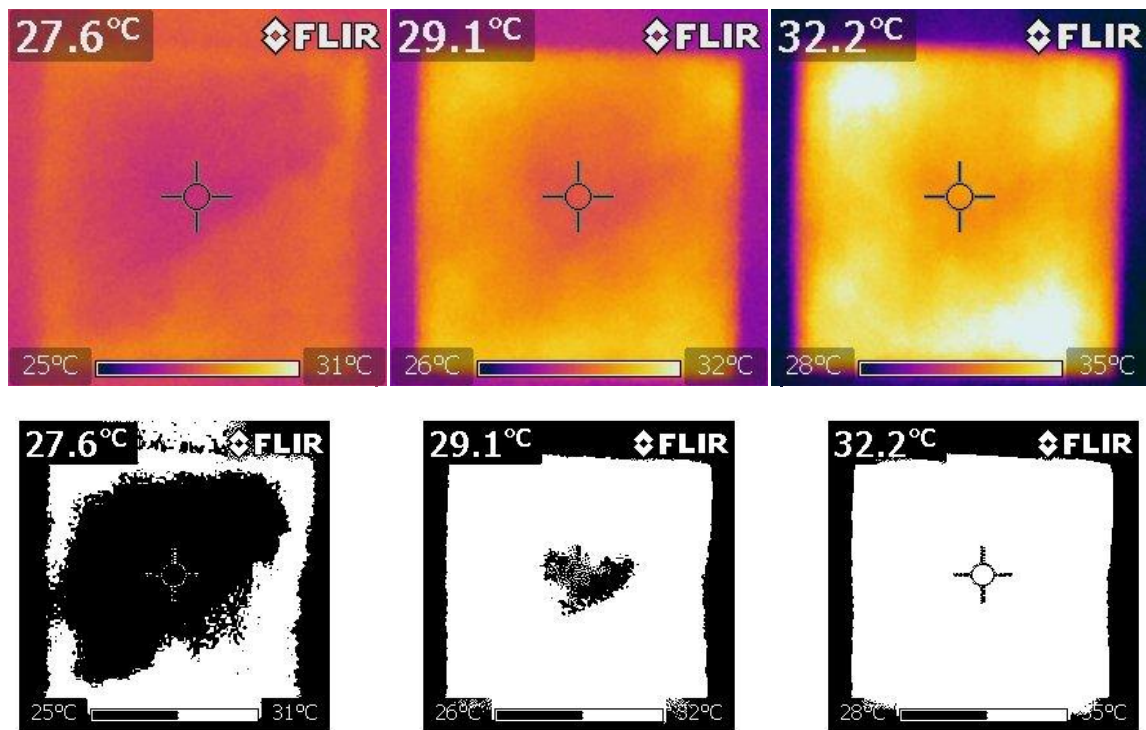


B3/60/R0/S2/5s

B3/60/R0/S2/10s

B3/60/R0/S2/15s

Figure H-68: IR and corresponding binary images obtained for B3/60/R0/S2 sample.

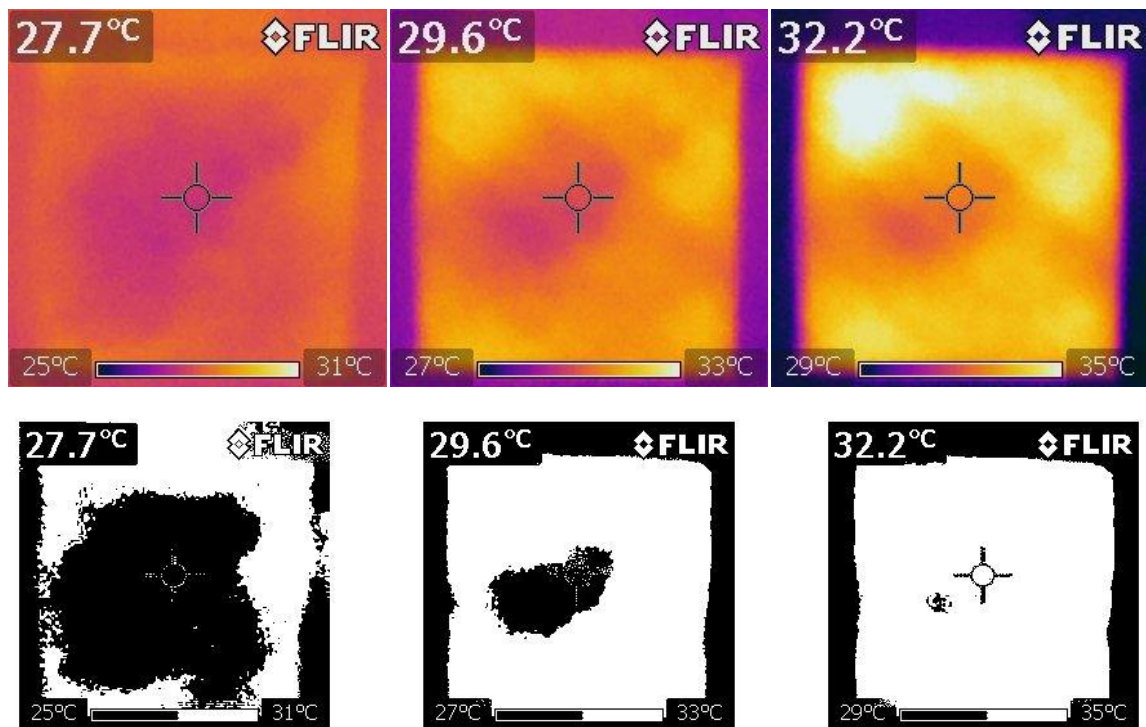


B3/60/R0/S3/5s

B3/60/R0/S3/10s

B3/60/R0/S3/15s

Figure H-69: IR and corresponding binary images obtained for B3/60/R0/S3 sample.

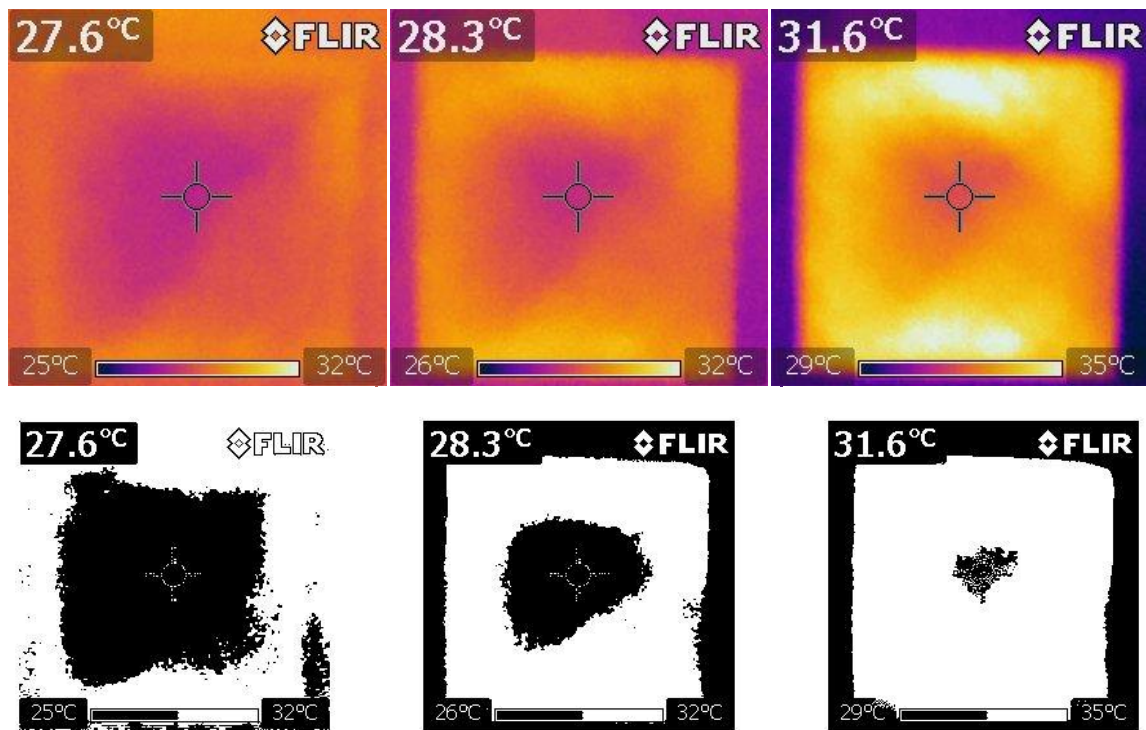


B3/60/R90/S1/5s

B3/60/R90/S1/10s

B3/60/R90/S1/15s

Figure H-70: IR and corresponding binary images obtained for B3/60/R90/S1 sample.

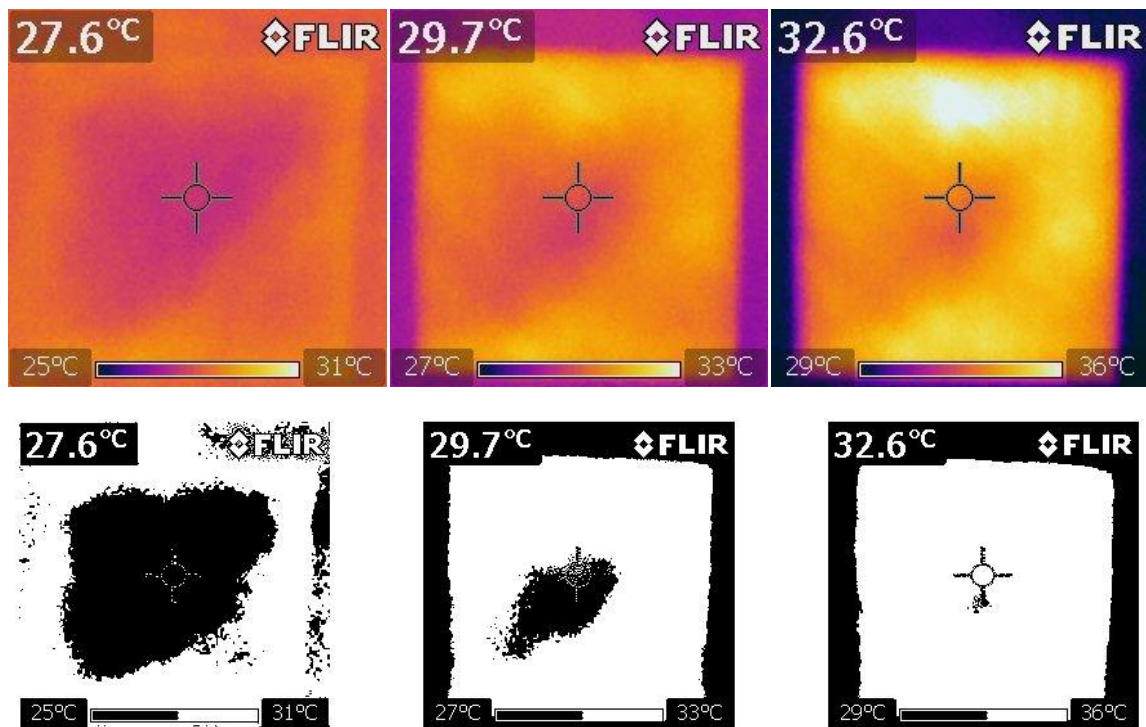


B3/60/R90/S2/5s

B3/60/R90/S2/10s

B3/60/R90/S2/15s

Figure H-71: IR and corresponding binary images obtained for B3/60/R90/S2 sample.



B3/60/R90/S3/5s

B3/60/R90/S3/10s

B3/60/R90/S3/15s

Figure H-72: IR and corresponding binary images obtained for B3/60/R90/S3 sample.

Appendix I

IR image data: Bending samples

I.1 UO-APT Samples

The average (AVG) and temperature difference (ΔT) values of the temperatures obtained from the infrared images for all samples tested in bending which were made from uo-APT preforms are presented here.

Table I-1: Average (AVG) and temperature difference (ΔT) obtained for sub-group A1/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A1	A1/45	R0	5	S1	26.0	28.1	32.0	29.0	6.0
					S2	27.0	28.5	33.0	30.0	6.0
					S3	26.0	28.7	32.0	29.0	6.0
				10	S1	28.0	31.5	36.0	32.0	8.0
					S2	28.0	32.7	38.0	33.0	10.0
					S3	28.0	32.1	34.0	31.0	6.0
				15	S1	29.0	36.2	42.0	35.5	13.0
					S2	29.0	38.0	44.0	36.5	15.0
					S3	29.0	37.1	39.0	34.0	10.0
			R90	5	S1	26.0	28.3	32.0	29.0	6.0
					S2	26.0	28.1	32.0	29.0	6.0
					S3	26.0	28.1	32.0	29.0	6.0
				10	S1	29.0	32.2	35.0	32.0	6.0
					S2	28.0	31.8	35.0	31.5	7.0
					S3	28.0	31.0	34.0	31.0	6.0
				15	S1	29.0	37.4	41.0	35.0	12.0
					S2	29.0	36.6	40.0	34.5	11.0
					S3	29.0	35.4	39.0	34.0	10.0

Table I-2: Average (AVG) and temperature difference (ΔT) obtained for sub-group A1/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature ($^{\circ}C$)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A1	A1/60	R0	5	S1	25.0	27.9	31.0	28.0	6.0
					S2	25.0	28.3	32.0	28.5	7.0
					S3	26.0	28.3	32.0	29.0	6.0
				10	S1	27.0	32.2	34.0	30.5	7.0
					S2	28.0	32.4	34.0	31.0	6.0
					S3	28.0	32.2	34.0	31.0	6.0
				15	S1	28.0	37.3	39.0	33.5	11.0
					S2	29.0	38.5	39.0	34.0	10.0
					S3	29.0	37.4	39.0	34.0	10.0
			R90	5	S1	26.0	28.2	32.0	29.0	6.0
					S2	26.0	29.0	32.0	29.0	6.0
					S3	26.0	28.4	32.0	29.0	6.0
				10	S1	28.0	31.8	34.0	31.0	6.0
					S2	29.0	33.0	35.0	32.0	6.0
					S3	28.0	31.9	34.0	31.0	6.0
				15	S1	29.0	36.4	39.0	34.0	10.0
					S2	29.0	37.9	40.0	34.5	11.0
					S3	29.0	36.5	38.0	33.5	9.0

Table I-3: Average (AVG) and temperature difference (ΔT) obtained for sub-group A2/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A2	A2/45	R0	5	S1	23.0	26.0	29.0	26.0	6.0
					S2	24.0	26.7	30.0	27.0	6.0
					S3	25.0	27.6	31.0	28.0	6.0
				10	S1	25.0	28.1	31.0	28.0	6.0
					S2	26.0	28.5	32.0	29.0	6.0
					S3	26.0	28.9	32.0	29.0	6.0
				15	S1	27.0	30.5	33.0	30.0	6.0
					S2	27.0	30.9	33.0	30.0	6.0
					S3	27.0	30.6	33.0	30.0	6.0
			R90	5	S1	25.0	27.5	31.0	28.0	6.0
					S2	25.0	27.8	31.0	28.0	6.0
					S3	25.0	27.3	31.0	28.0	6.0
				10	S1	26.0	28.7	32.0	29.0	6.0
					S2	26.0	29.4	32.0	29.0	6.0
					S3	26.0	28.7	32.0	29.0	6.0
				15	S1	27.0	30.8	33.0	30.0	6.0
					S2	27.0	31.7	33.0	30.0	6.0
					S3	27.0	31.1	34.0	30.5	7.0

Table I-4: Average (AVG) and temperature difference (ΔT) obtained for sub-group A2/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A2	A2/60	R0	5	S1	24.0	27.0	30.0	27.0	6.0
					S2	25.0	28.0	32.0	28.5	7.0
					S3	25.0	27.9	32.0	28.5	7.0
				10	S1	25.0	28.7	31.0	28.0	6.0
					S2	26.0	29.5	32.0	29.0	6.0
					S3	27.0	29.5	33.0	30.0	6.0
				15	S1	28.0	32.2	34.0	31.0	6.0
					S2	28.0	32.4	34.0	31.0	6.0
					S3	28.0	32.2	34.0	31.0	6.0
			R90	5	S1	26.0	27.7	32.0	29.0	6.0
					S2	26.0	28.1	32.0	29.0	6.0
					S3	25.0	27.6	32.0	28.5	7.0
				10	S1	26.0	29.1	33.0	29.5	7.0
					S2	26.0	29.0	33.0	29.5	7.0
					S3	26.0	29.3	33.0	29.5	7.0
				15	S1	28.0	31.3	34.0	31.0	6.0
					S2	28.0	30.8	34.0	31.0	6.0
					S3	27.0	31.5	34.0	30.5	7.0

Table I-5: Average (AVG) and temperature difference (ΔT) obtained for sub-group A3/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A3	A3/45	R0	5	S1	26.0	28.4	32.0	29.0	6.0
					S2	26.0	28.3	32.0	29.0	6.0
					S3	26.0	28.5	32.0	29.0	6.0
				10	S1	28.0	31.7	34.0	31.0	6.0
					S2	28.0	32.2	34.0	31.0	6.0
					S3	28.0	31.7	34.0	31.0	6.0
				15	S1	29.0	36.9	38.0	33.5	9.0
					S2	29.0	36.7	38.0	33.5	9.0
					S3	29.0	37.0	38.0	33.5	9.0
			R90	5	S1	25.0	28.0	32.0	28.5	7.0
					S2	26.0	28.0	32.0	29.0	6.0
					S3	26.0	28.1	32.0	29.0	6.0
				10	S1	27.0	29.6	33.0	30.0	6.0
					S2	28.0	31.2	35.0	31.5	7.0
					S3	29.0	31.9	35.0	32.0	6.0
				15	S1	29.0	35.5	39.0	34.0	10.0
					S2	29.0	35.1	38.0	33.5	9.0
					S3	29.0	36.5	39.0	34.0	10.0

Table I-6: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group A3/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	<i>AVG</i>	ΔT
uO-APT	A3	A3/60	R0	5	S1	26.0	29.1	33.0	29.5	7.0
					S2	27.0	29.1	33.0	30.0	6.0
					S3	27.0	29.1	33.0	30.0	6.0
				10	S1	29.0	33.3	35.0	32.0	6.0
					S2	29.0	32.8	35.0	32.0	6.0
					S3	29.0	33.9	35.0	32.0	6.0
				15	S1	29.0	38.5	40.0	34.5	11.0
					S2	30.0	37.5	40.0	35.0	10.0
					S3	30.0	38.7	40.0	35.0	10.0
			R90	5	S1	27.0	29.1	33.0	30.0	6.0
					S2	26.0	29.0	33.0	29.5	7.0
					S3	27.0	29.2	33.0	30.0	6.0
				10	S1	29.0	33.7	35.0	32.0	6.0
					S2	29.0	33.9	36.0	32.5	7.0
					S3	29.0	33.5	35.0	32.0	6.0
				15	S1	29.0	38.9	41.0	35.0	12.0
					S2	30.0	39.1	40.0	35.0	10.0
					S3	30.0	39.0	40.0	35.0	10.0

I.2 Saertex Samples

The average (AVG) and temperature difference (ΔT) values of the temperature obtained from the infrared images for all samples tested in bending which were made from Saertex industrial preforms are presented here.

Table I-7: Average (AVG) and temperature difference (ΔT) obtained for sub-group B1/45 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
Saertex industrial reinforcement	B1	B1/45	R-45	5	S1	24.0	27.3	31.0	27.5	7.0
					S2	25.0	27.2	31.0	28.0	6.0
					S3	25.0	27.7	31.0	28.0	6.0
				10	S1	27.0	30.4	33.0	30.0	6.0
					S2	27.0	29.1	33.0	30.0	6.0
					S3	26.0	29.1	33.0	29.5	7.0
				15	S1	29.0	34.3	35.0	32.0	6.0
					S2	29.0	31.9	36.0	32.5	7.0
					S3	28.0	31.9	35.0	31.5	7.0
			R+45	5	S1	25.0	27.8	31.0	28.0	6.0
					S2	25.0	27.9	32.0	28.5	7.0
					S3	25.0	27.8	31.0	28.0	6.0
				10	S1	27.0	29.2	33.0	30.0	6.0
					S2	26.0	28.8	33.0	29.5	7.0
					S3	27.0	29.1	33.0	30.0	6.0
				15	S1	28.0	32.3	34.0	31.0	6.0
					S2	29.0	31.5	35.0	32.0	6.0
					S3	28.0	31.9	35.0	31.5	7.0

Table I-8: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group B1/60 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	<i>Tmin</i>	<i>Tcen</i>	<i>Tmax</i>	<i>AVG</i>	ΔT
Saertex industrial reinforcement	B1	B1/60	R-45	5	S1	24.0	27.1	30.0	27.0	6.0
					S2	25.0	27.6	31.0	28.0	6.0
					S3	25.0	27.5	31.0	28.0	6.0
				10	S1	25.0	28.3	31.0	28.0	6.0
					S2	26.0	28.9	33.0	29.5	7.0
					S3	26.0	28.6	33.0	29.5	7.0
				15	S1	27.0	31.3	34.0	30.5	7.0
					S2	28.0	31.9	35.0	31.5	7.0
					S3	28.0	30.7	34.0	31.0	6.0
			R+45	5	S1	25.0	27.6	31.0	28.0	6.0
					S2	25.0	27.8	31.0	28.0	6.0
					S3	24.0	27.3	30.0	27.0	6.0
				10	S1	26.0	28.5	32.0	29.0	6.0
					S2	27.0	29.3	33.0	30.0	6.0
					S3	26.0	28.7	32.0	29.0	6.0
				15	S1	28.0	31.1	34.0	31.0	6.0
					S2	28.0	32.2	35.0	31.5	7.0
					S3	27.0	30.6	34.0	30.5	7.0

Table I-9: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group B2/45 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	<i>Tmin</i>	<i>Tcen</i>	<i>Tmax</i>	<i>AVG</i>	ΔT
Saertex industrial reinforcement	B2	B2/45	R-45	5	S1	25.0	27.3	31.0	28.0	6.0
					S2	24.0	26.8	30.0	27.0	6.0
					S3	23.0	25.8	29.0	26.0	6.0
				10	S1	25.0	28.0	32.0	28.5	7.0
					S2	25.0	27.5	31.0	28.0	6.0
					S3	24.0	26.8	30.0	27.0	6.0
				15	S1	27.0	29.2	33.0	30.0	6.0
					S2	26.0	28.6	32.0	29.0	6.0
					S3	26.0	28.6	32.0	29.0	6.0
			R+45	5	S1	24.0	27.5	31.0	27.5	7.0
					S2	25.0	27.9	31.0	28.0	6.0
					S3	24.0	27.4	31.0	27.5	7.0
				10	S1	26.0	28.8	32.0	29.0	6.0
					S2	26.0	28.7	32.0	29.0	6.0
					S3	25.0	28.1	31.0	28.0	6.0
				15	S1	27.0	30.5	33.0	30.0	6.0
					S2	27.0	29.9	33.0	30.0	6.0
					S3	26.0	29.1	32.0	29.0	6.0

Table I-10: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group B2/60 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	<i>Tmin</i>	<i>Tcen</i>	<i>Tmax</i>	<i>AVG</i>	ΔT
Saertex industrial reinforcement	B2	B2/60	R-45	5	S1	25.0	27.6	31.0	28.0	6.0
					S2	25.0	27.7	31.0	28.0	6.0
					S3	25.0	27.2	31.0	28.0	6.0
				10	S1	26.0	28.1	32.0	29.0	6.0
					S2	26.0	28.0	32.0	29.0	6.0
					S3	25.0	27.9	31.0	28.0	6.0
				15	S1	26.0	29.2	32.0	29.0	6.0
					S2	26.0	29.0	33.0	29.5	7.0
					S3	26.0	29.4	33.0	29.5	7.0
			R+45	5	S1	25.0	27.9	32.0	28.5	7.0
					S2	25.0	27.6	31.0	28.0	6.0
					S3	24.0	26.9	31.0	27.5	7.0
				10	S1	26.0	28.8	33.0	29.5	7.0
					S2	26.0	28.0	32.0	29.0	6.0
					S3	26.0	28.1	32.0	29.0	6.0
				15	S1	28.0	29.9	34.0	31.0	6.0
					S2	26.0	29.0	33.0	29.5	7.0
					S3	27.0	29.5	33.0	30.0	6.0

Table I-11: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group B3/45 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	<i>Tmin</i>	<i>Tcen</i>	<i>Tmax</i>	<i>AVG</i>	ΔT
Saertex industrial reinforcement	B3	B3/45	R0	5	S1	25.0	27.7	31.0	28.0	6.0
					S2	25.0	27.7	31.0	28.0	6.0
					S3	26.0	28.5	32.0	29.0	6.0
				10	S1	26.0	28.8	32.0	29.0	6.0
					S2	27.0	29.0	33.0	30.0	6.0
					S3	27.0	30.4	33.0	30.0	6.0
				15	S1	28.0	31.9	35.0	31.5	7.0
					S2	29.0	32.0	36.0	32.5	7.0
					S3	29.0	33.5	36.0	32.5	7.0
			R90	5	S1	25.0	27.9	31.0	28.0	6.0
					S2	26.0	28.0	32.0	29.0	6.0
					S3	26.0	28.2	32.0	29.0	6.0
				10	S1	26.0	29.6	33.0	29.5	7.0
					S2	27.0	29.3	33.0	30.0	6.0
					S3	27.0	29.6	33.0	30.0	6.0
				15	S1	28.0	32.5	35.0	31.5	7.0
					S2	29.0	32.1	35.0	32.0	6.0
					S3	29.0	32.7	36.0	32.5	7.0

Table I-12: Average (*AVG*) and temperature difference (ΔT) obtained for sub-group B3/60 samples made from Saertex reinforcements.

Type	Group	Sub-group	Setup			Temperature (°C)				
			Stitch	Pulse (sec)	Sample	<i>Tmin</i>	<i>Tcen</i>	<i>Tmax</i>	<i>AVG</i>	ΔT
Saertex industrial reinforcement	B3	B3/60	R0	5	S1	25.0	27.5	31.0	28.0	6.0
					S2	26.0	28.2	32.0	29.0	6.0
					S3	25.0	27.6	31.0	28.0	6.0
				10	S1	27.0	28.8	33.0	30.0	6.0
					S2	27.0	30.1	33.0	30.0	6.0
					S3	26.0	29.1	32.0	29.0	6.0
				15	S1	29.0	31.3	35.0	32.0	6.0
					S2	29.0	33.1	35.0	32.0	6.0
					S3	28.0	32.2	35.0	31.5	7.0
			R90	5	S1	25.0	27.7	31.0	28.0	6.0
					S2	25.0	27.6	32.0	28.5	7.0
					S3	25.0	27.6	31.0	28.0	6.0
				10	S1	27.0	29.6	33.0	30.0	6.0
					S2	26.0	28.3	32.0	29.0	6.0
					S3	27.0	29.7	33.0	30.0	6.0
				15	S1	29.0	32.2	35.0	32.0	6.0
					S2	29.0	31.6	35.0	32.0	6.0
					S3	29.0	32.6	36.0	32.5	7.0

Appendix J

Binary image data: Bending samples

J.1 UO-APT Samples

White area percentage of the total area obtained from the binary image for all samples tested in bending which were made from uo-APT preforms are presented here.

Table J-1: Percentage of white area in the binary images for sub-group A1/45 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A1	A1/45	R0	5	S1	19.86
					S2	12.99
					S3	45.77
				10	S1	52.05
					S2	41.23
					S3	60.47
				15	S1	58.66
					S2	60.10
					S3	65.23
			R90	5	S1	27.88
					S2	17.40
					S3	25.04
				10	S1	67.81
					S2	67.67
					S3	54.36
				15	S1	62.55
					S2	63.61
					S3	63.69

Table J-2: Percentage of white area in the binary images for sub-group A1/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A1	A1/60	R0	5	S1	51.26
					S2	44.59
					S3	46.57
				10	S1	65.09
					S2	63.35
					S3	61.29
				15	S1	62.35
					S2	62.55
					S3	60.92
			R90	5	S1	43.39
					S2	33.55
					S3	51.19
				10	S1	61.76
					S2	58.80
					S3	66.21
				15	S1	62.66
					S2	63.39
					S3	64.03

Table J-3: Percentage of white area in the binary images for sub-group A2/45 samples
made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A2	A2/45	R0	5	S1	40.12
					S2	40.13
					S3	37.80
				10	S1	22.42
					S2	55.57
					S3	54.62
				15	S1	52.78
					S2	64.41
					S3	65.50
			R90	5	S1	30.83
					S2	35.73
					S3	39.45
				10	S1	52.70
					S2	54.60
					S3	35.87
				15	S1	65.69
					S2	67.73
					S3	64.45

Table J-4: Percentage of white area in the binary images for sub-group A2/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A2	A2/60	R0	5	S1	27.86
					S2	28.06
					S3	39.04
				10	S1	65.16
					S2	50.62
					S3	38.83
				15	S1	64.61
					S2	66.44
					S3	65.08
			R90	5	S1	39.39
					S2	35.81
					S3	38.46
				10	S1	31.96
					S2	31.46
					S3	32.49
				15	S1	68.01
					S2	62.33
					S3	70.75

Table J-5: Percentage of white area in the binary images for sub-group A3/45 samples
made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A3	A3/45	R0	5	S1	31.36
					S2	59.24
					S3	49.35
				10	S1	65.44
					S2	67.48
					S3	63.11
				15	S1	64.79
					S2	64.68
					S3	62.31
			R90	5	S1	60.17
					S2	50.33
					S3	53.33
				10	S1	43.18
					S2	55.61
					S3	61.16
				15	S1	59.58
					S2	63.83
					S3	63.91

Table J-6: Percentage of white area in the binary images for sub-group A3/60 samples made from uO-APT reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
uO-APT	A3	A3/60	R0	5	S1	52.16
					S2	55.52
					S3	60.81
				10	S1	63.59
					S2	64.45
					S3	66.00
				15	S1	61.20
					S2	63.07
					S3	63.00
			R90	5	S1	60.60
					S2	66.46
					S3	64.98
				10	S1	64.16
					S2	65.35
					S3	66.02
				15	S1	61.00
					S2	61.19
					S3	63.56

J.2 Saertex Samples

White area percentage of the total area obtained from the binary image for all samples tested in bending which were made from Saertex industrial preforms are presented here.

Table J-7: Percentage of white area in the binary images for sub-group B1/45 samples made from Saertex industrial reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B1	B1/45	R-45	5	S1	36.96
					S2	39.38
					S3	47.86
				10	S1	70.05
					S2	37.80
					S3	55.75
				15	S1	69.58
					S2	56.27
					S3	72.20
			R+45	5	S1	47.00
					S2	41.02
					S3	47.19
				10	S1	59.14
					S2	62.76
					S3	47.59
				15	S1	73.52
					S2	69.05
					S3	70.05

Table J-8: Percentage of white area in the binary images for sub-group B1/60 samples
made from Saertex industrial reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B1	B1/60	R-45	5	S1	70.12
					S2	41.56
					S3	36.30
				10	S1	65.20
					S2	54.41
					S3	46.41
				15	S1	70.79
					S2	70.98
					S3	56.50
			R+45	5	S1	45.17
					S2	39.01
					S3	65.01
				10	S1	46.10
					S2	63.15
					S3	49.12
				15	S1	68.76
					S2	71.17
					S3	65.96

Table J-9: Percentage of white area in the binary images for sub-group B2/45 samples
made from Saertex industrial reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B2	B2/45	R-45	5	S1	37.20
					S2	43.99
					S3	32.04
				10	S1	37.34
					S2	35.06
					S3	33.51
				15	S1	49.97
					S2	41.55
					S3	52.85
			R+45	5	S1	16.42
					S2	27.40
					S3	19.64
				10	S1	55.47
					S2	40.50
					S3	32.08
				15	S1	70.69
					S2	57.46
					S3	47.25

Table J-10: Percentage of white area in the binary images for sub-group B2/60 samples
made from Saertex industrial reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B2	B2/60	R-45	5	S1	37.33
					S2	33.98
					S3	39.16
				10	S1	34.52
					S2	33.52
					S3	29.98
				15	S1	61.44
					S2	40.13
					S3	47.96
			R+45	5	S1	46.64
					S2	40.56
					S3	42.63
				10	S1	29.41
					S2	35.33
					S3	31.65
				15	S1	39.55
					S2	51.41
					S3	60.29

Table J-11: Percentage of white area in the binary images for sub-group B3/45 samples made from Saertex industrial reinforcements.

Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B3	B3/45	R0	5	S1	39.08
					S2	49.39
					S3	43.13
				10	S1	60.25
					S2	52.04
					S3	62.42
				15	S1	68.06
					S2	64.33
					S3	68.31
			R90	5	S1	36.67
					S2	24.76
					S3	50.80
				10	S1	63.85
					S2	44.93
					S3	58.77
				15	S1	68.71
					S2	67.94
					S3	67.64

Table J-12: Percentage of white area in the binary images for sub-group B3/60 samples
made from Saertex industrial reinforcements.

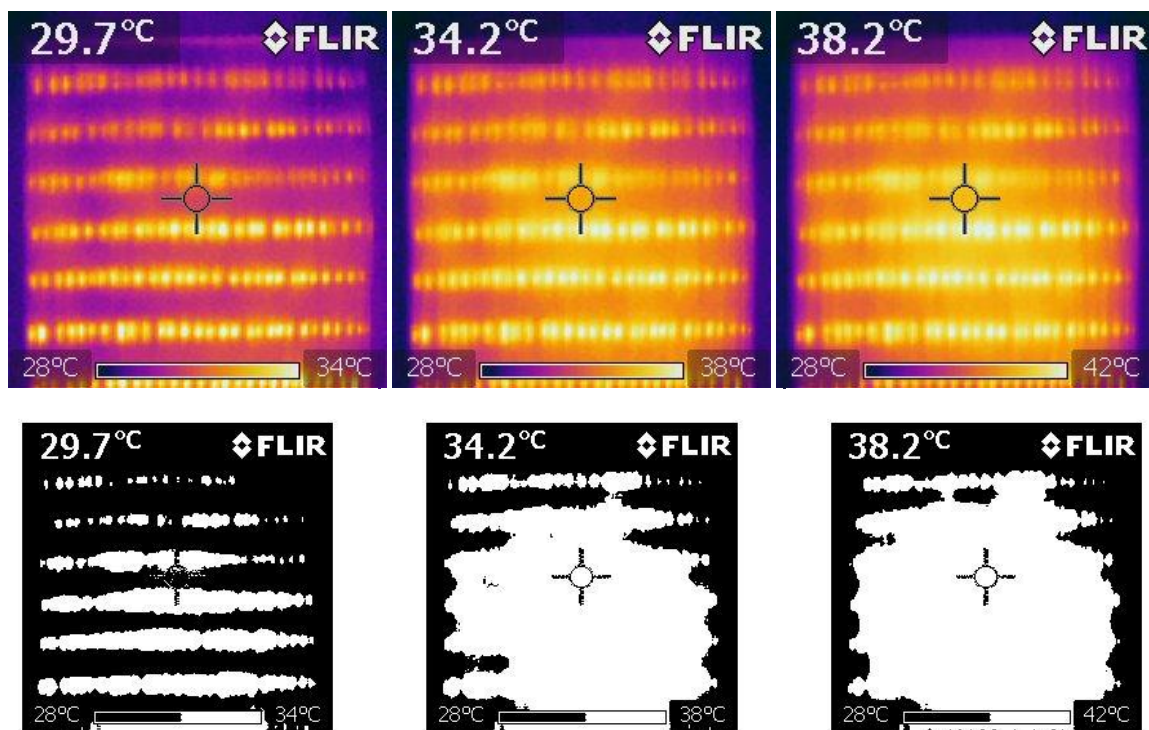
Type	Group	Sub-group	Setup			White area (%)
			Stitch	Pulse (sec)	Sample	
u0-APT	B3	B3/60	R0	5	S1	49.04
					S2	42.11
					S3	35.29
				10	S1	49.70
					S2	63.22
					S3	66.91
				15	S1	60.06
					S2	68.72
					S3	69.60
			R90	5	S1	37.36
					S2	49.13
					S3	53.95
				10	S1	62.68
					S2	54.68
					S3	62.49
				15	S1	67.88
					S2	67.14
					S3	66.60

Appendix K

IR and binary images: Shear samples

K.1 Introduction

All infrared images result from the active IRT tests for all shear samples and corresponding binary images conducted on both types of preforms are presented here. The images represent the temperature distributions after exposure times of 10 seconds, 15 seconds and 20 seconds.

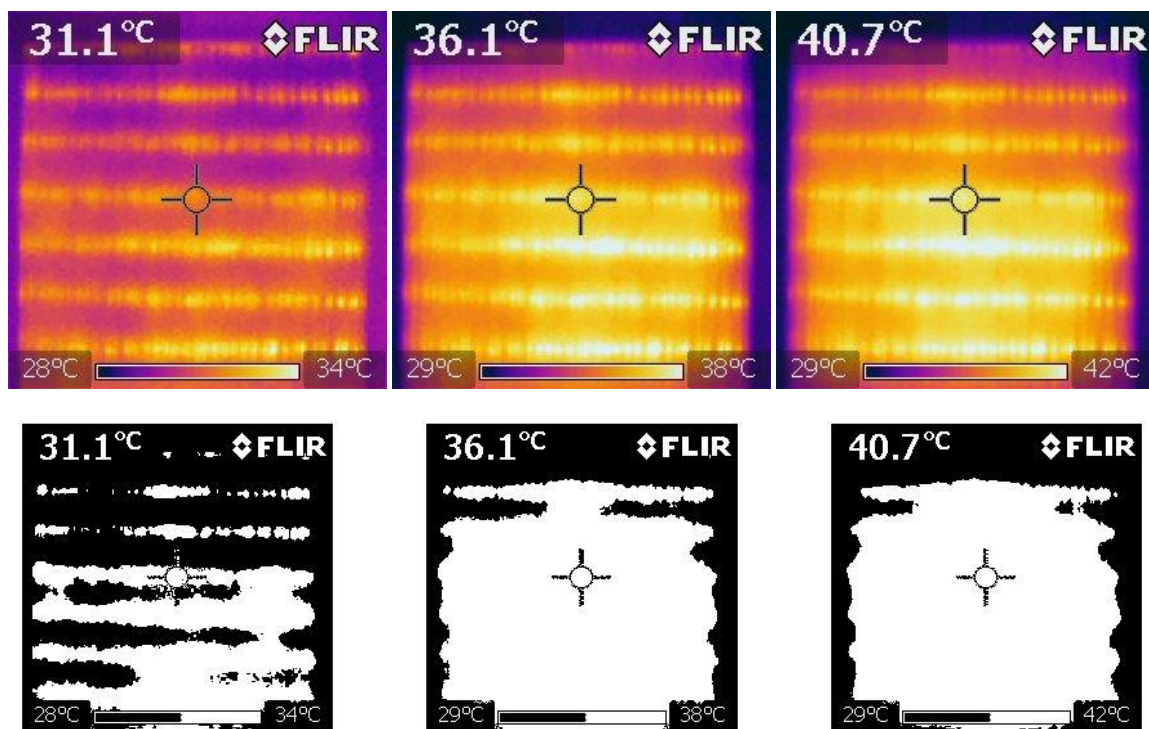


A4/R-45/S1/10s

A4/R-45/S1/15s

A4/R-45/S1/20s

Figure K-1: IR images and corresponding binary images for A4/R-45/S1 sample.

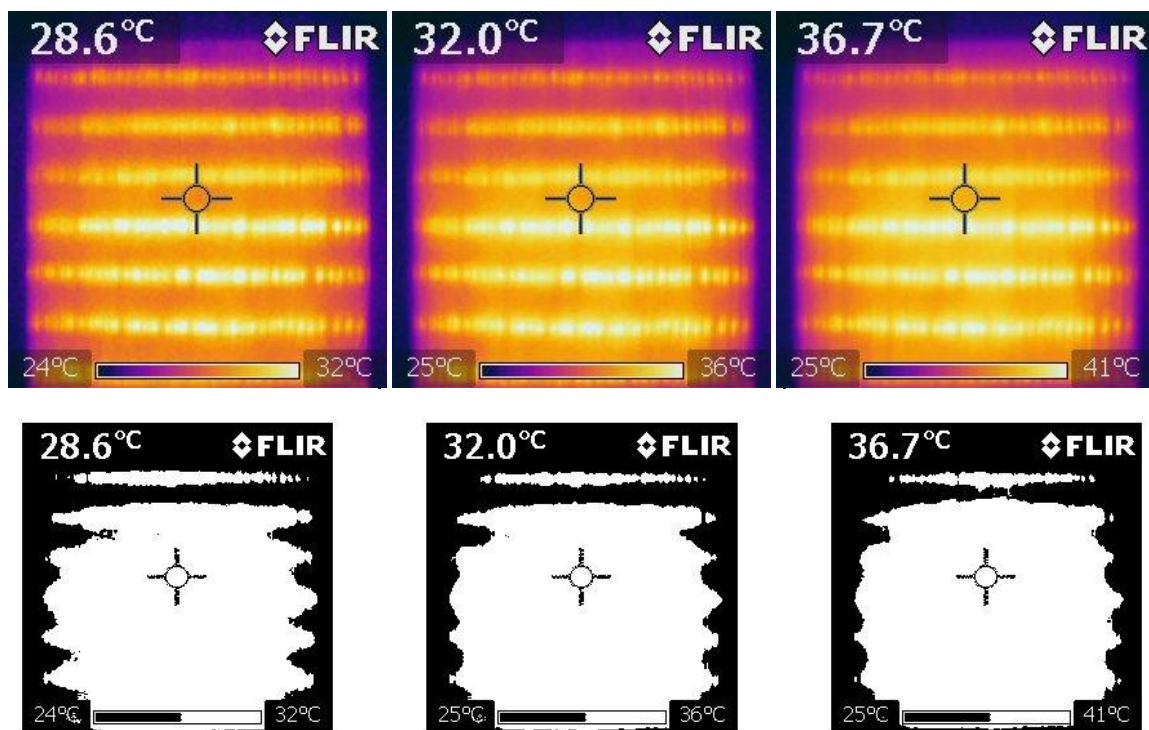


A4/R-45/S2/10s

A4/R-45/S2/15s

A4/R-45/S2/20s

Figure K-2: IR images and corresponding binary images for A4/R-45/S2 sample.

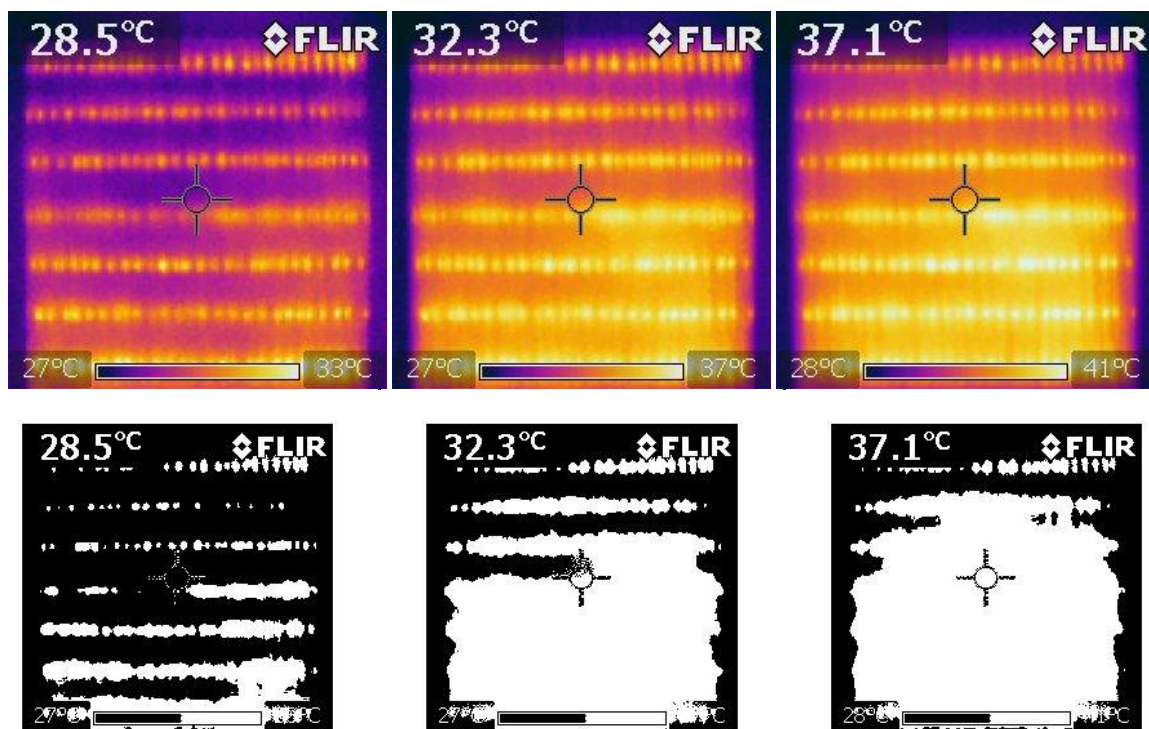


A4/R+45/S1/10s

A4/R+45/S1/15s

A4/R+45/S1/20s

Figure K-3: IR images and corresponding binary images for A4/R+45/S1 sample.

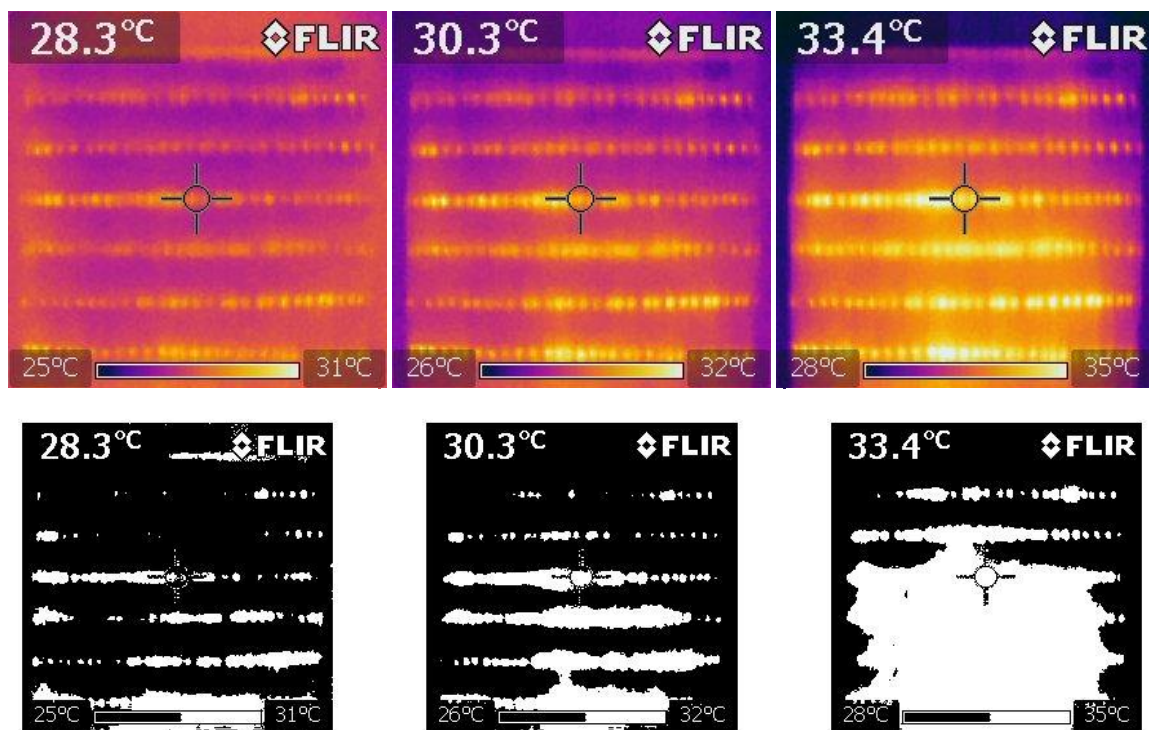


A4/R+45/S2/10s

A4/R+45/S2/15s

A4/R+45/S2/20s

Figure K-4: IR images and corresponding binary images for A4/R+45/S2 sample.

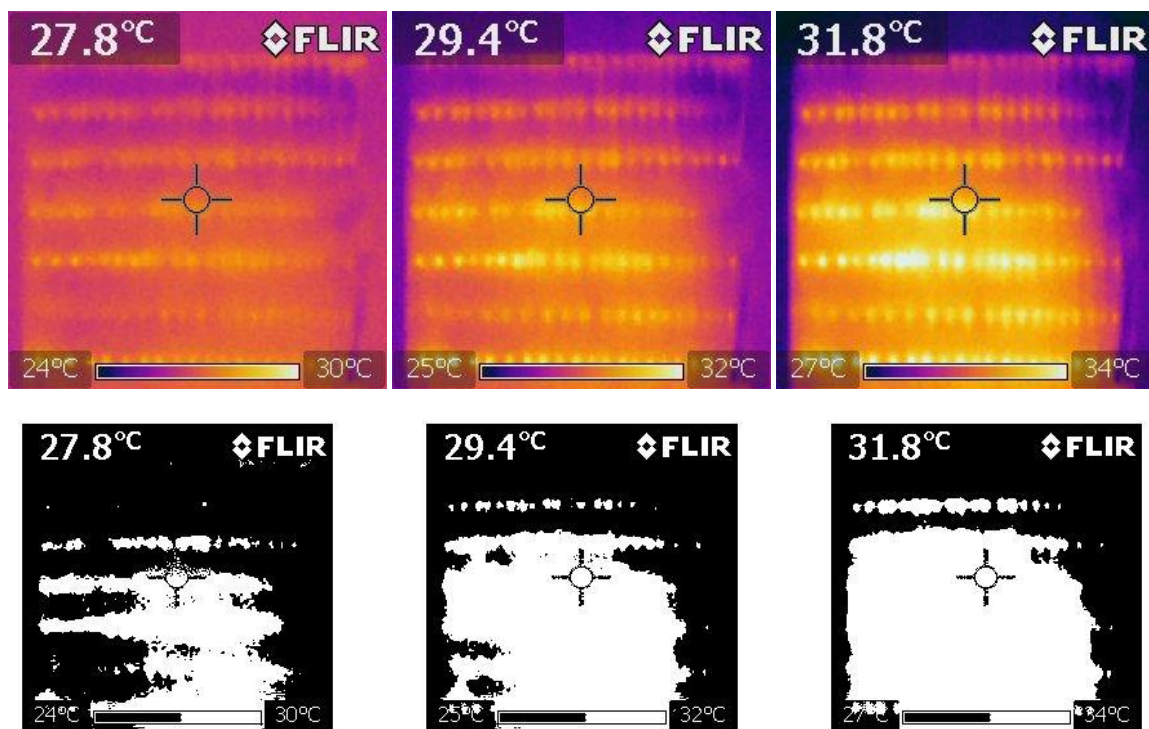


A5/R-45/S1/10s

A5/R-45/S1/15s

A5/R-45/S1/20s

Figure K-5 IR images and corresponding binary images for for A5/R-45/S1 sample.

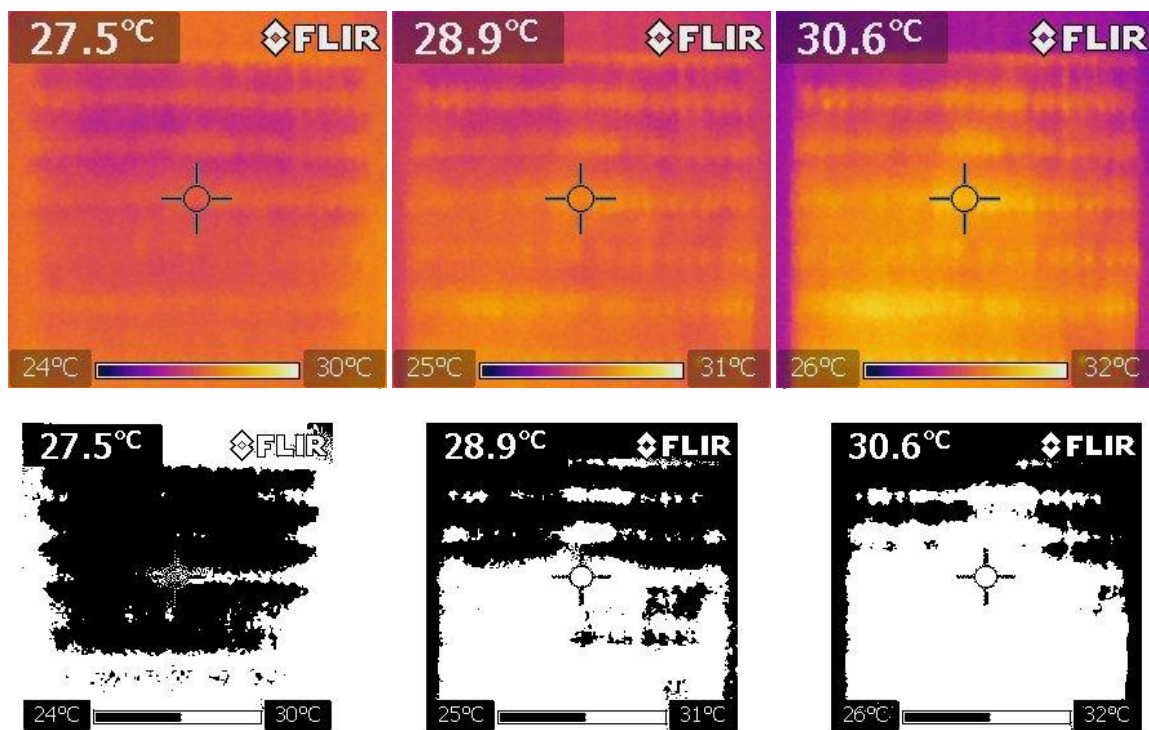


A5/R-45/S2/10s

A5/R-45/S2/15s

A5/R-45/S2/20s

Figure K-6: IR images and corresponding binary images for A5/R-45/S2 sample.

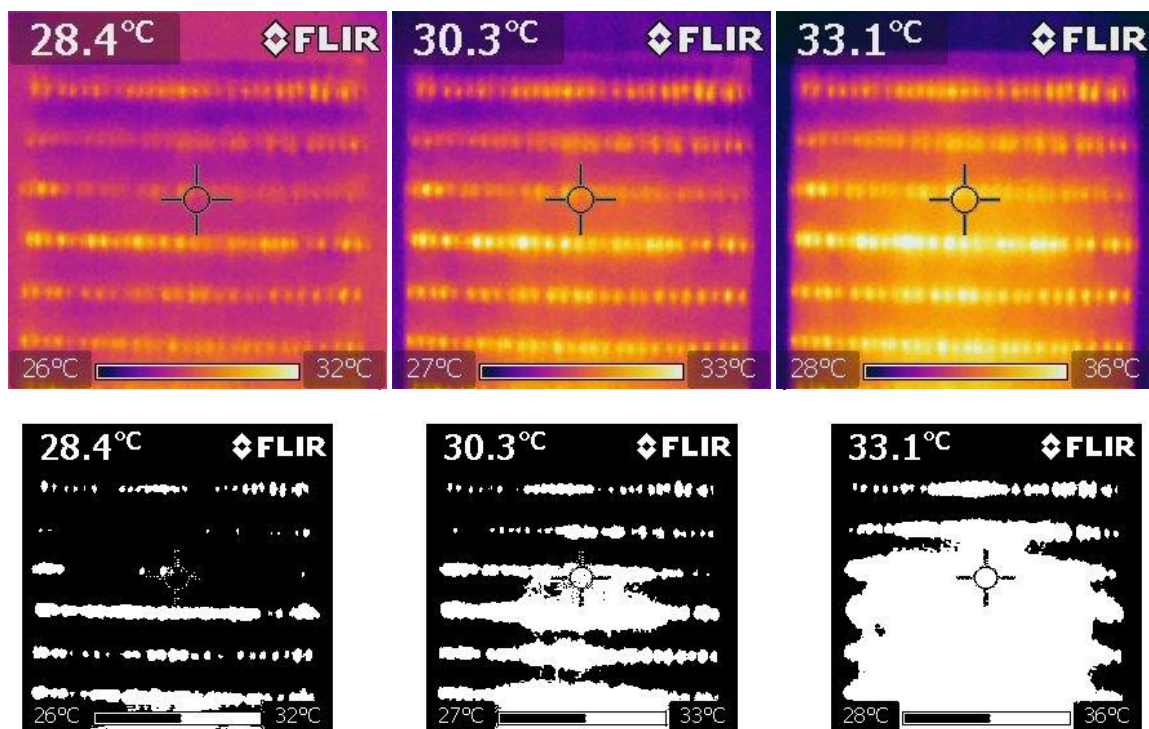


A5/R+45/S1/10s

A5/R+45/S1/15s

A5/R+45/S1/20s

Figure K-7: IR images and corresponding binary images for A5/R-45/S1 sample.

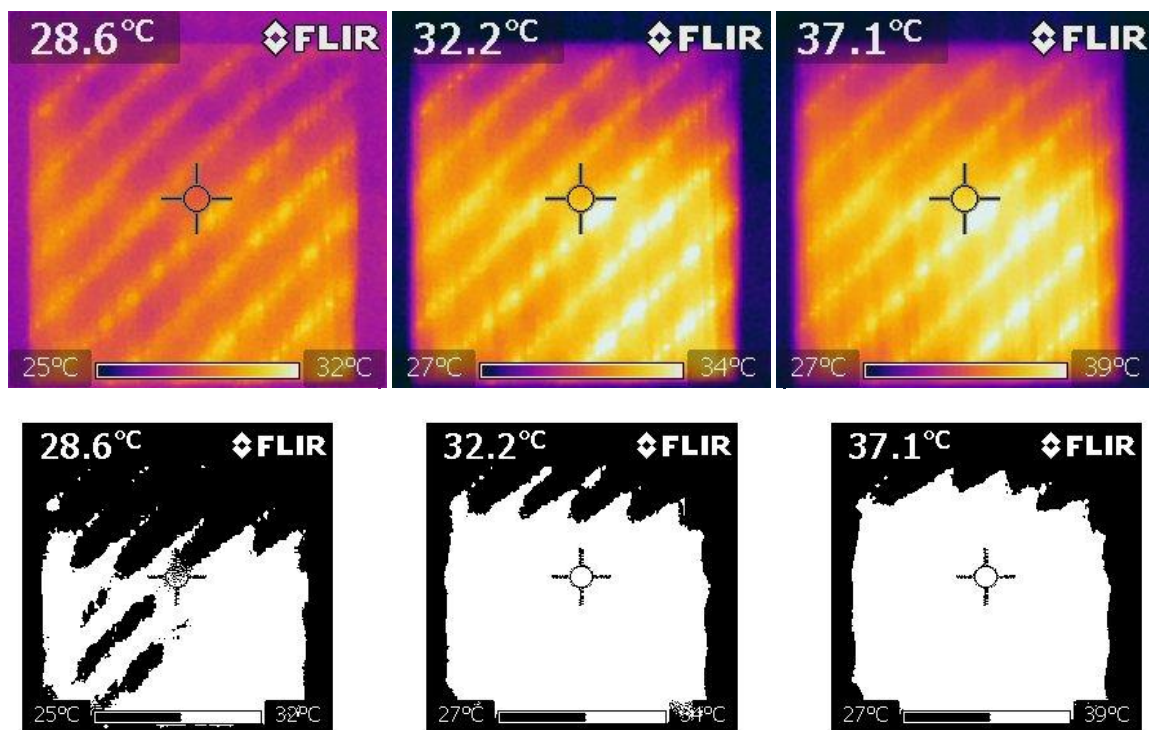


A5/R+45/S2/10s

A5/R+45/S2/15s

A5/R+45/S2/20s

Figure K-8: IR images and corresponding binary images for A5/R+45/S2 sample.

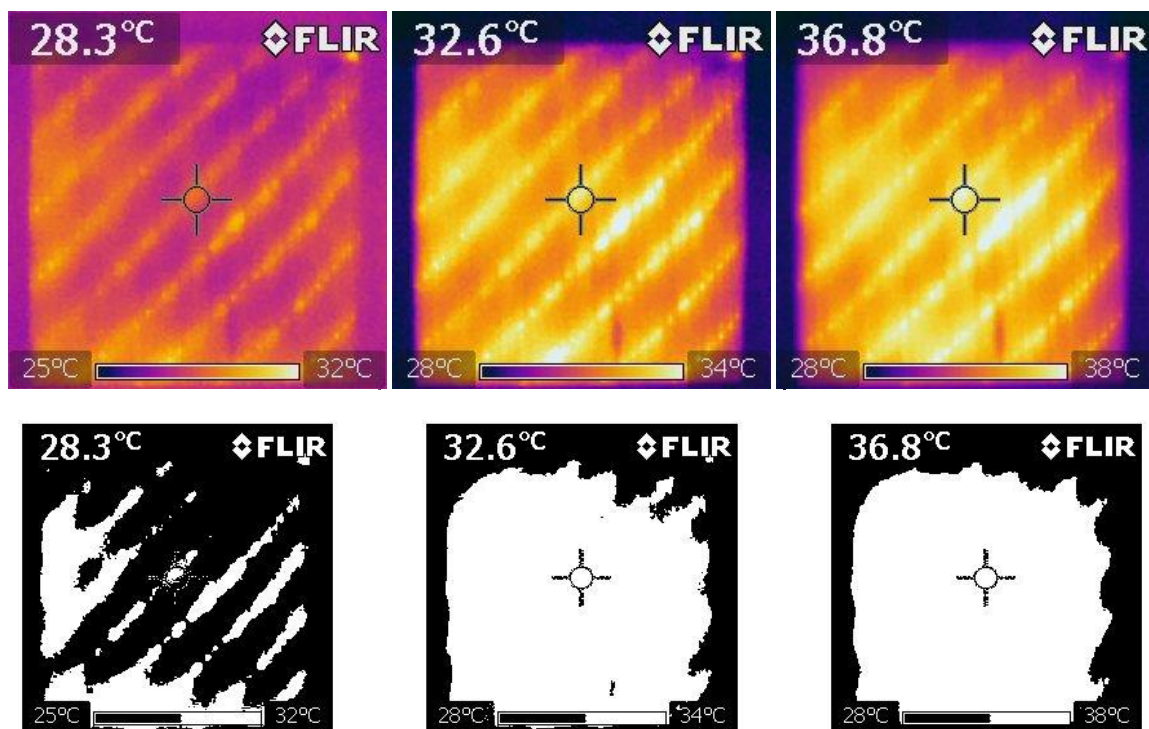


A6/R0/S1/10s

A6/R0/S1/15s

A6/R0/S1/20s

Figure K-9: IR images and corresponding binary images for A6/R0/S1 sample.

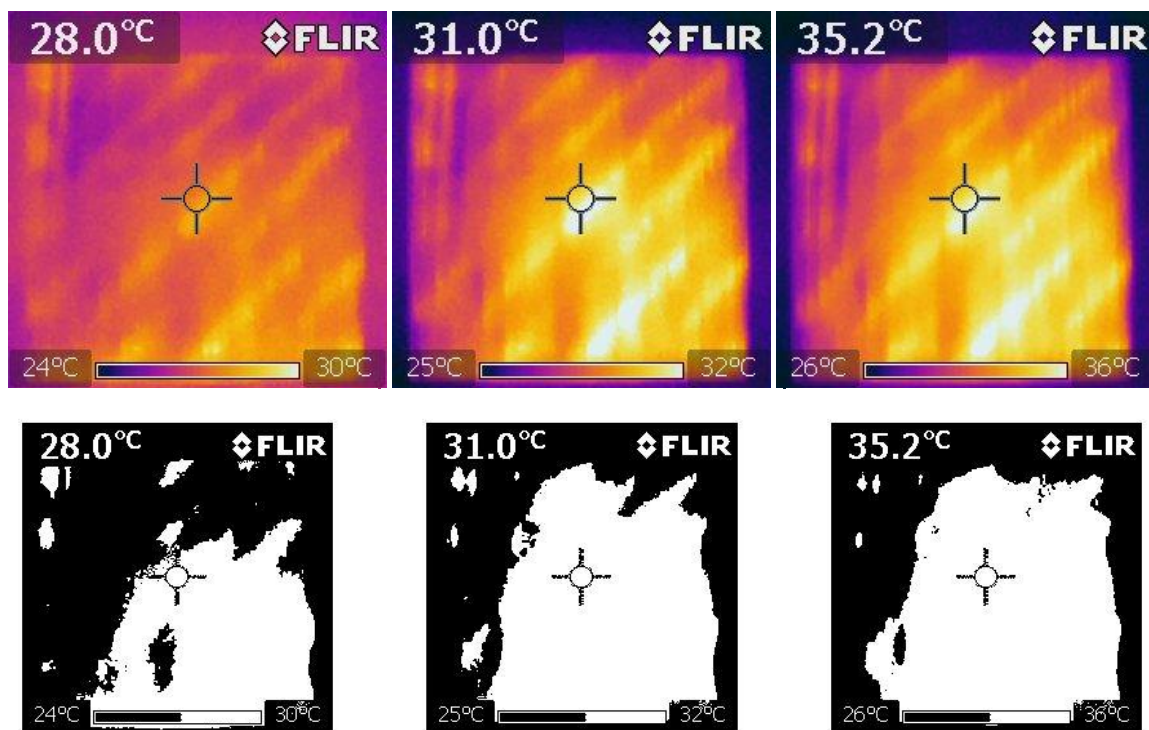


A6/R0/S2/10s

A6/R0/S2/15s

A6/R0/S2/20s

Figure K-10: IR images and corresponding binary images for A6/R0/S2 sample.

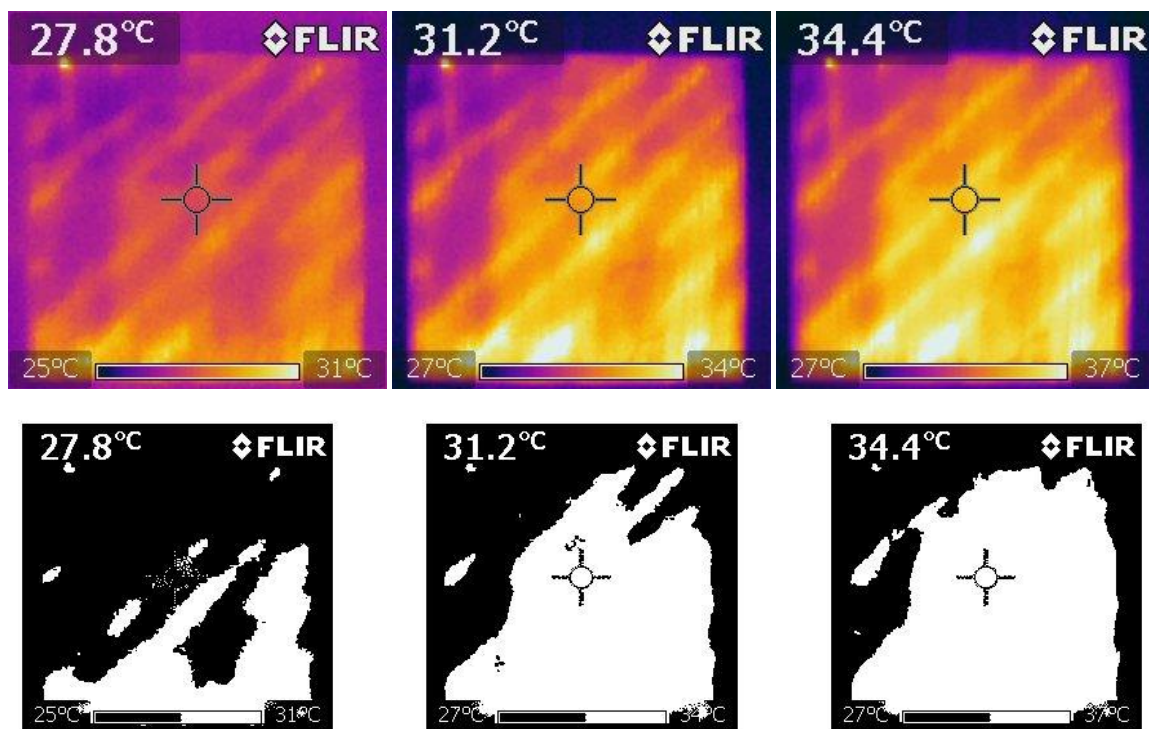


A6/R90/S1/10s

A6/R90/S1/15s

A6/R90/S1/20s

Figure K-11: IR images and corresponding binary images for A6/R90/S1 sample.

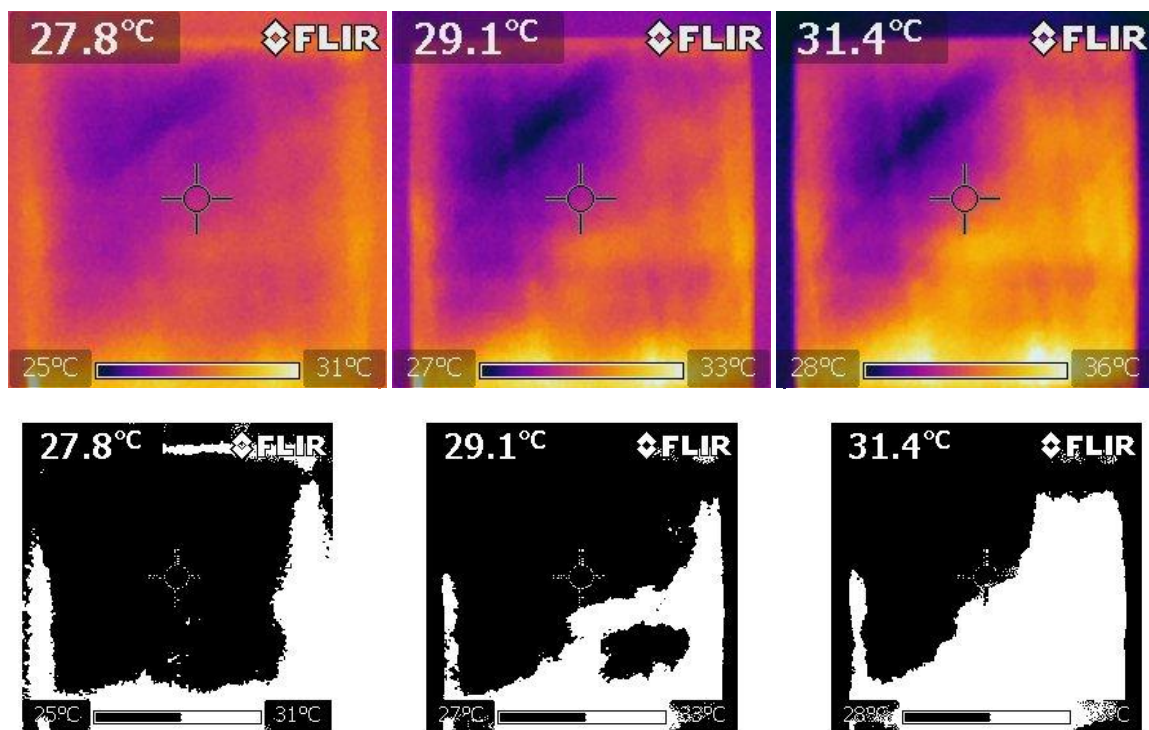


A6/R90/S2/10s

A6/R90/S2/15s

A6/R90/S2/20s

Figure K-12: IR images and corresponding binary images for A6/R90/S2 sample.

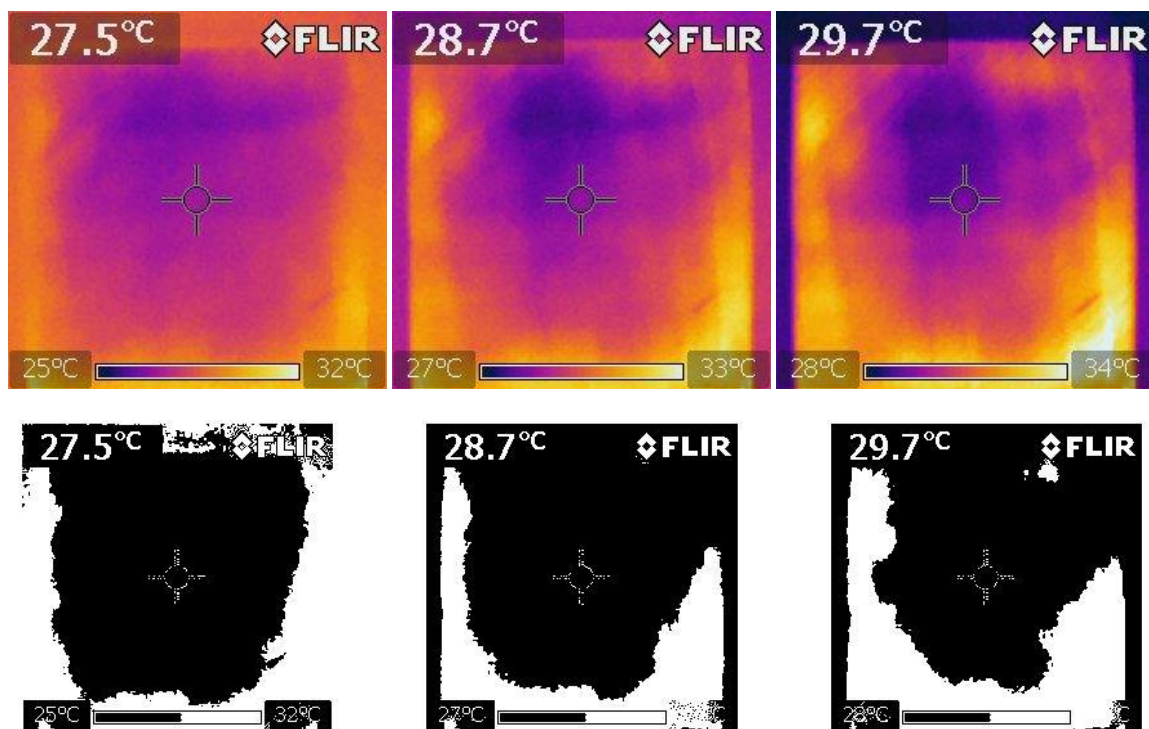


B6/R0/S1/10s

B6/R0/S1/15s

B6/R0/S1/20s

Figure K-13: IR images and corresponding binary images for B6/R0/S1 sample.

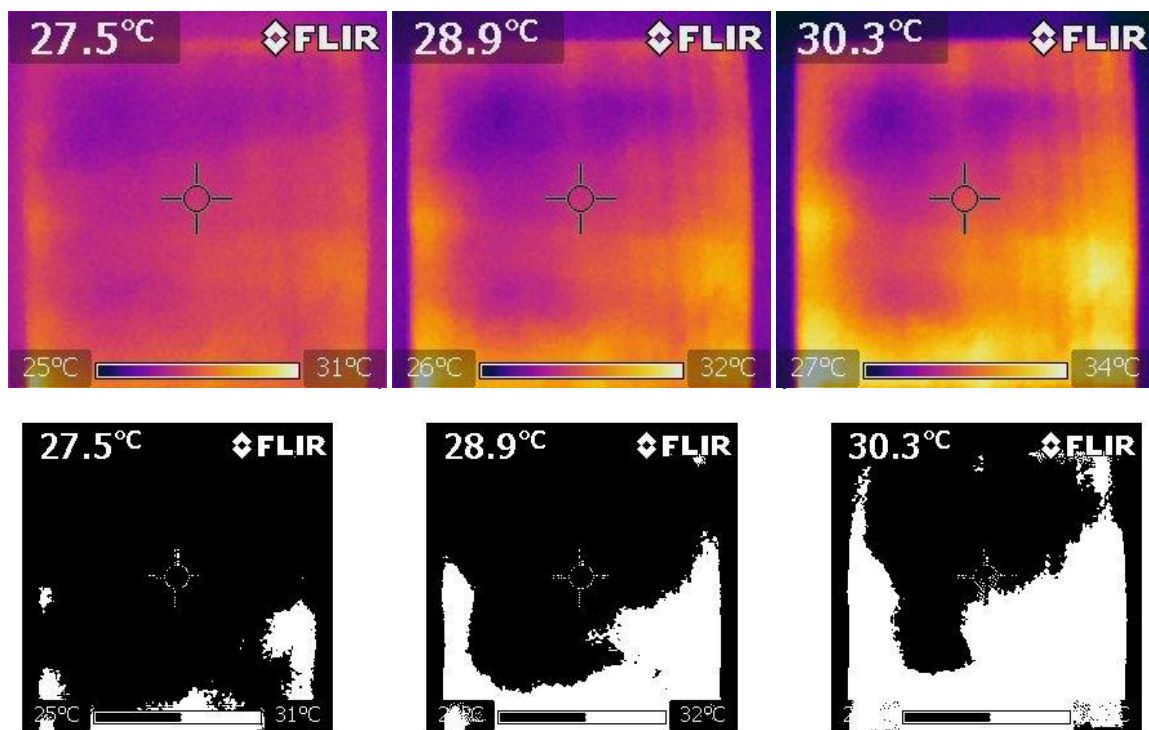


B6/R0/S2/10s

B6/R0/S2/15s

B6/R0/S2/20s

Figure K-14: IR images and corresponding binary images for B6/R0/S2 sample.

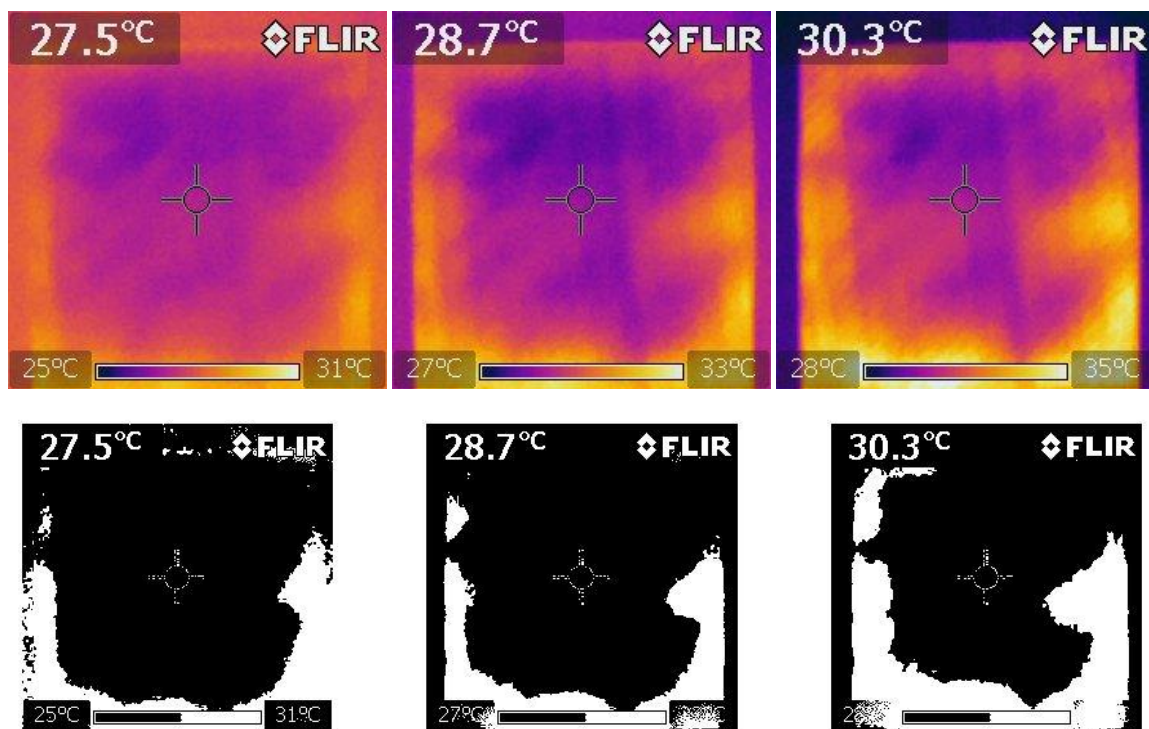


B6/R90/S1/10s

B6/R90/S1/15s

B6/R90/S1/20s

Figure K-15: IR images and corresponding binary images for B6/R90/S1 sample.



B6/R90/S2/10s

B6/R90/S2/15s

B6/R90/S2/20s

Figure K-16: IR images and corresponding binary images for B6/R90/S2 sample.

Appendix L

IR image data: Shear samples

L.1 UO-APT Samples

The average (AVG) and temperature difference (ΔT) values of the temperatures obtained from the infrared images for all samples tested in shear which were made from uo-APT preforms are presented here.

Table L-1: Average (AVG) and temperature difference (ΔT) obtained for group A4 samples made from uO-APT reinforcements.

Type	Group	Setup			Temperature (°C)				
		Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
uO-APT	A4	R-45	10	S1	28.0	29.7	34.0	31.0	6.0
				S2	28.0	31.1	34.0	31.0	6.0
			15	S1	28.0	34.2	38.0	33.0	10.0
				S2	29.0	36.1	38.0	33.5	9.0
			20	S1	28.0	38.2	42.0	35.0	14.0
				S2	29.0	40.7	42.0	35.5	13.0
		R+45	10	S1	24.0	28.6	32.0	28.0	8.0
				S2	27.0	28.5	33.0	30.0	6.0
			15	S1	25.0	32.0	36.0	30.5	11.0
				S2	27.0	32.3	37.0	32.0	10.0
			20	S1	25.0	36.7	41.0	33.0	16.0
				S2	28.0	37.1	41.0	34.5	13.0

Table L-2: Average (*AVG*) and temperature difference (ΔT) obtained for group A5 samples made from uO-APT reinforcements.

Type	Group	Setup			Temperature (°C)				
		Stitch	Pulse (sec)	Sample	<i>T_{min}</i>	<i>T_{cen}</i>	<i>T_{max}</i>	<i>AVG</i>	ΔT
uO-APT	A5	R-45	10	S1	25.0	28.3	31.0	28.0	6.0
				S2	24.0	27.8	30.0	27.0	6.0
			15	S1	26.0	30.3	32.0	29.0	6.0
				S2	25.0	29.4	32.0	28.5	7.0
			20	S1	28.0	33.4	35.0	31.5	7.0
				S2	27.0	31.8	34.0	30.5	7.0
		R+45	10	S1	24.0	27.5	30.0	27.0	6.0
				S2	26.0	28.4	32.0	29.0	6.0
			15	S1	25.0	28.9	31.0	28.0	6.0
				S2	27.0	30.3	33.0	30.0	6.0
			20	S1	26.0	30.6	32.0	29.0	6.0
				S2	28.0	33.1	36.0	32.0	8.0

Table L-3: Average (*AVG*) and temperature difference (ΔT) obtained for group A6 samples made from uO-APT reinforcements.

Type	Group	Setup			Temperature (°C)				
		Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	<i>AVG</i>	ΔT
uO-APT	A6	R0	10	S1	25.0	28.6	32.0	28.5	7.0
				S2	25.0	28.3	32.0	28.5	7.0
			15	S1	27.0	32.2	34.0	30.5	7.0
				S2	28.0	32.6	34.0	31.0	6.0
			20	S1	27.0	37.1	39.0	33.0	12.0
				S2	28.0	36.8	38.0	33.0	10.0
		R90	10	S1	24.0	28.0	30.0	27.0	6.0
				S2	25.0	27.8	31.0	28.0	6.0
			15	S1	25.0	31.0	32.0	28.5	7.0
				S2	27.0	31.2	34.0	30.5	7.0
			20	S1	26.0	35.2	36.0	31.0	10.0
				S2	27.0	34.4	37.0	32.0	10.0

L.2 Saertex Samples

The average (AVG) and temperature difference (ΔT) values of the temperature obtained from the infrared images for all samples tested in shear which were made from Saertex industrial preforms are presented here.

Table L-4: Average (AVG) and temperature difference (ΔT) obtained for sub-group B6 samples made from Saertex reinforcements.

Type	Group	Setup			Temperature (°C)				
		Stitch	Pulse (sec)	Sample	T_{min}	T_{cen}	T_{max}	AVG	ΔT
Saertex industrial reinforcement	B6	R0	10	S1	25.0	27.8	31.0	28.0	6.0
				S2	25.0	27.5	32.0	28.5	7.0
			15	S1	27.0	29.1	33.0	30.0	6.0
				S2	27.0	28.7	33.0	30.0	6.0
			20	S1	28.0	31.4	36.0	32.0	8.0
				S2	28.0	29.7	34.0	31.0	6.0
		R90	10	S1	25.0	27.5	31.0	28.0	6.0
				S2	25.0	27.5	31.0	28.0	6.0
			15	S1	26.0	28.9	32.0	29.0	6.0
				S2	27.0	28.7	33.0	30.0	6.0
			20	S1	27.0	30.3	34.0	30.5	7.0
				S2	28.0	30.3	35.0	31.5	7.0

Appendix M

Binary image data: Shear samples

M.1 UO-APT Samples

White area percentage of the total area obtained from the binary image for all samples tested in shear which were made from uo-APT preforms are presented here.

Table M-1: Percentage of white area in the binary images for group A4 samples made from uO-APT reinforcements.

Type	Group	Setup			White area (%)
		Stitch	Pulse (sec)	Sample	
uO-APT	A4	R-45	10	S1	25.89
				S2	36.58
			15	S1	55.30
				S2	62.45
			20	S1	59.24
				S2	62.38
		R+45	10	S1	57.87
				S2	22.13
			15	S1	57.73
				S2	54.78
			20	S1	57.42
				S2	60.19

Table M-2: Percentage of white area in the binary images for group A5 samples made from uO-APT reinforcements.

Type	Group	Setup			White area (%)
		Stitch	Pulse (sec)	Sample	
uO-APT	A5	R-45	10	S1	15.19
				S2	27.94
			15	S1	20.27
				S2	43.25
			20	S1	46.72
				S2	50.10
		R+45	10	S1	43.38
				S2	15.11
			15	S1	49.39
				S2	30.10
			20	S1	59.37
				S2	52.92

Table M-3: Percentage of white area in the binary images for group A6 samples made from uO-APT reinforcements.

Type	Group	Setup			White area (%)
		Stitch	Pulse (sec)	Sample	
uO-APT	A6	R0	10	S1	42.50
				S2	25.31
			15	S1	56.87
				S2	62.31
			20	S1	58.58
				S2	61.55
		R90	10	S1	36.30
				S2	25.39
			15	S1	50.64
				S2	48.83
			20	S1	53.11
				S2	54.97

M.2 Saertex Samples

White area percentage of the total area obtained from the binary image for all samples tested in shear which were made from Saertex industrial preforms are presented here.

Table M-4: Percentage of white area in the binary images for group B6 samples made from uO-APT reinforcements.

Type	Group	Setup			White area (%)
		Stitch	Pulse (sec)	Sample	
uO-APT	B6	R0	10	S1	26.18
				S2	30.19
			15	S1	27.47
				S2	25.99
			20	S1	41.87
				S2	31.99
		R90	10	S1	10.43
				S2	19.59
			15	S1	26.82
				S2	19.32
			20	S1	43.61
				S2	28.99