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Sudhakar Molleti

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

Ph.D. (Civil Engineering)

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TITRE DE LA THÈSE / TITLE OF THESIS

Hiroshi Tanaka

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

Appupillai Baskaran

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

Heng-Aik Khoo

Beatriz Martin-Perez

Dan Palermo

David Prevatt

Gary W. Slater

LE DOYEN DE LA FACULTÉ DES ÉTUDES SUPÉRIEURES ET POSTDOCTORALES /
DEAN OF THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

Performance Evaluation of Mechanically Attached Roofing Systems

By

Sudhakar Molleti

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fulfillment of the requirements for

Doctor of Philosophy
In Civil Engineering

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To

Sri Sampath Vinayagar Swamy

Sri Satchitananda Samartha Sadguru Sainath Maharaj

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Abstract

Roofing system is an integral part of a building envelope. Keeping the roofs in place against high wind events is a challenging task for architects and roof designers. There are two stages in the design process: first, a comprehensive understanding of the wind induced loads on the roof system and, second, an accurate estimation of the system response to the induced wind loads. The present study contributes to an ongoing research project at the National Research Council Canada in the evaluation of Mechanically Attached Roofing Systems (MAS) for wind uplift design. Accomplishments are grouped in two tasks. Task 1, applied finite element methods to investigate whether an analytical method can be used to predict fastener loads based upon uplift pressures and chamber geometry. Task 2, developed an experimental procedure to quantify the air leakage rate and identified its impact on the wind uplift resistance.

The aspect ratio of the testing chamber plays a critical role in the evaluation of roofing system response. By applying finite element modeling the table size effect was investigated and the numerical results were benchmarked with experimental data. The validated model was further used to identify the required table width. It was found that an increase in the table width beyond required table width did not significantly change the system response. The required table width depends mainly on two system parameters, namely, fastener row spacing and fastener spacing. Based on the parametric investigation generalized correction factor curves were developed such that the roofing designer can apply these factors irrespective of the investigated table width.

In MAS, the fluttering or “billowing” action of the membrane draws air in to system, thereby affecting system’s wind uplift performance. There is no standard specification or test method available to quantify the air leakage rate. By designing an experimental setup, systems with and without barriers were investigated. Data clearly indicate that systems without barrier had a high rate of air leakage, compared to systems with barrier. With the quantification of air leakage, its impact on the wind uplift resistance was also evaluated under a dynamic wind environment. Improvement in wind uplift resistance was evident for systems with barriers.

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Glossary

Symbols:

A	one half of the distance between supports for a strip membrane of the radius of the circular membrane
A	projected area of the inflated membrane
C_p	surface pressure coefficient , function of building location and wind direction
C_d	discharge coefficient for opening, dimensionless, where Kirchoff found in the 19 th century = 0.611
c	flow coefficient
E	modulus of elasticity of the membrane
ELA	Equivalent leakage area (m^2)
h	membrane thickness
K	variable dependent on the intrinsic air permeability of the material, its thickness and the dynamic viscosity of air ($L/s - m^2 - Pa$)
L	table length
F	Fastener force, N
F_r	fastener row spacing, mm
F_s	fastener spacing, mm
m	fastener row spacing over fastener spacing (F_r / F_s)
N	number of simulations
n	table width over fastener spacing (W / F_s)
P	test pressure, psf
Pa	static pressure in undisturbed flow
PCF	Pressure correction factor = $P_{lab\ pressure} / P_{std}$
P_e	pressure outside the inflated membrane = $P_{eo} + P_{et} \sin \omega t$;
P_{eo}	static component of wind pressure
P_{et}	amplitude of the cycle exterior pressure component
P_b	pressure inside the inflated membrane
P_{std}	101.3 Kpa
ρ	air density, kg/m^3
p_i	interior pressure at height of location

p_o	static pressure at reference height in undisturbed flow
p_w	wind pressure at location
p_v	surface pressure relative to static pressure in undisturbed flow, Pa
p	pressure, kPa
Q	volumetric flow rate of air
Q_s	air leakage through the test specimen (m^3/s)
Q_{std}	Standard air flow rate (L/s)
Q	reference velocity pressure, kPa
n	the flow exponent, ranges from 0.5 (turbulent flow) to 1.0 (laminar flow)
T_{std}	20° C (293 ° K)
TCF	Temperature correction factor
V	wind speed, m/s
v_b	volume under the inflated membrane
v_{bo}	volume of trapped air between the membrane and the roof deck
W	table width, m
W_{th}	theoretical fastener load
ΔP	static air pressure differential across the material
Δp	pressure difference between outdoors and indoors at location
α, β, γ	dimensionless coefficients dependent on the shape of the membrane
χ	intrinsic air permeability of the material
η	dynamic viscosity of air

Abbreviations

APP	Atactic Polypropylene
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CPE	Chlorinated Polyethylene
CR	Chloroprene Rubber
CSPE	Chlorosulfonated Polyethylene
DRF	Dynamic Roofing Facility
EPDM	Ethylene-Propylene-Diene-Monomer
EVA	Ethylene Vinyl Acetate
EXP	Experimental
FM	Factory Mutual
NBCC	National Building Code of Canada
NBI	Norwegian Building Research Institute
NM	Numerical Model
NRC	National Research Council of Canada
PIB	Polyisobutylene
PVC	Polyvinyl Chloride
RTW	Required Table Width
SBS	Styrene Butadiene Styrene
SIGDERS	Special Interest Group for the Dynamic Evaluation of Roofing Systems
TP	Thermoplastic
TPO	Thermoplastic Olefin
TS	Thermoset
UEAtc	European Union of Agreement
UL	Underwriters Laboratory
UV	Ultraviolet

Definitions

Flexible membrane roof: A roof assembly in which the waterproofing component is flexible sheets. These sheets are fabricated from compounded synthetic thermoplastic, thermoset or modified bituminous materials.

Roof designer: The person or group of people with prime responsibility for the design of the roof assembly. The roof designer may be an architect, engineer, roof consultant or roofing contractor.

Roof assembly: The structural deck, vapour or air retarder (if present), thermal insulation (if present), cover board (if present) and the waterproof membrane that together constitute the roof.

Roof system: The vapour or air retarder (if present), roof insulation (if present), cover board (if present) and the waterproof membrane that constitute the weather-resistant portion of the roof assembly.

Mechanically attached system: A roof assembly where the wind uplift resistance of the roof membrane is mainly provided by the membrane's mechanical attachments.

Air retarder: An element in the roof assembly intended to limit airflow in a roof system.

Vapour retarder: A layer (or layers) of material used to appreciably reduce the diffusion of water vapour into a roof system.

Chapter 1

Introduction

1.1 General Review

A roof is an integral part of a building envelope. Building envelope consists of other assemblies such as walls, windows and subsurface. The building envelope function is to separate the controlled indoor environment from the outdoor environment to control interior climate (light, temp, humidity). In the outdoor environment several natural phenomenon occur such as wind, rain/snow, temperature changes, solar radiation etc. that can affect the interior climate. These phenomena can impact a roof assembly either independently or collectively. The intensity of these environmental factors depends on the geographical location and the prevailing seasonal conditions. A designer has to select and design the roofing system to withstand these driving forces.

Damage of a roofing system caused by natural wind has a higher impact than the other natural phenomena. According to previous investigations, the most wind damage to houses was restricted to the envelope of buildings, in particular to the roof sheathing (Uematsu and Isyumov, 1999). Therefore, it is quite important to keep the roof unaffected in the face of high wind events.

Wind flow around buildings creates both negative and positive fluctuations over a roofing system. Negative pressure on exterior surface is created by the flow separation on the outside of the roof. Positive pressure, known as building internal pressure, is dependent on the location of dominant openings in the building. It is generated by the wind flow into the building and the temperature difference across the envelope. These pressures are dynamic and can be separated into static and fluctuating components. The static component is simply the mean pressure. The transient component occurs as a random process and its dominant frequencies depend on the frequency of the upstream wind and the geometry of the building. Thus the wind effect on roofing and its response is dynamic. Wind pressure distribution varies spatially over a roof and it can have high suction at the corner and perimeter, due to vortex flow and separations. Figure 1.1 illustrates the pressure variation on a building roof.

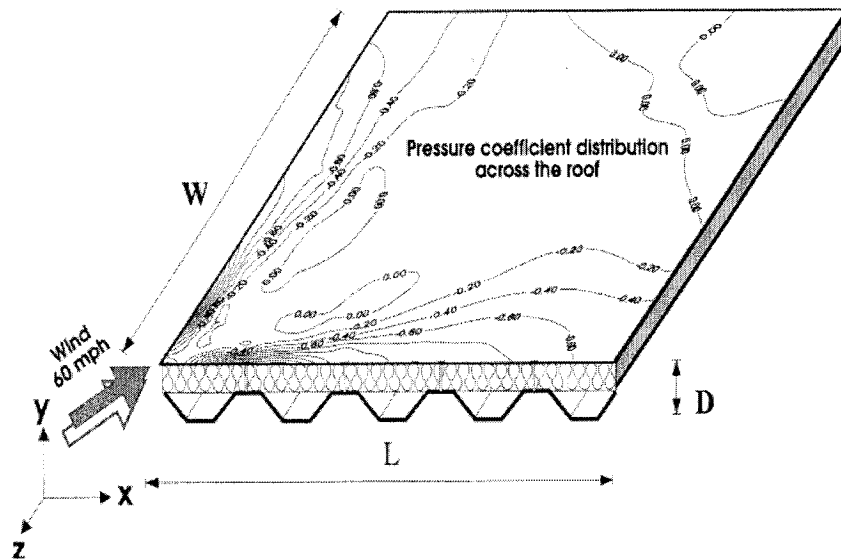


Figure 1.1: Mean pressure variation on a building roof

A roof can be classified as either a low-slope or steep slope system. Roof slopes less than 14° is called low-sloped roof (Borujerdi 2004), which is commonly found on commercial and industrial buildings such as warehouses and factories. On the other hand, steep sloped roof is one that has a roof slope greater than 14° and is commonly prevalent in residential houses. In North America, two main types of low slope roofs are in practice depending on the placement of the roofing membrane in the systems:

Conventional roofing assembly: The membrane is at the top of the insulation and is directly exposed to environmental elements. The conventional roofs may be either the Single-ply roofing system (SPR) or a Built up roofing system (BUR) Figure 1.2 illustrates a typical cross-section of a conventional roof assembly

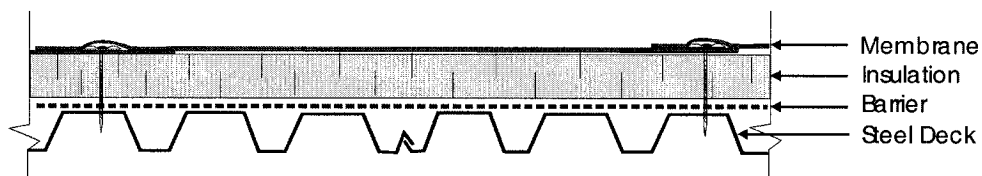


Figure 1.2: Cross-section of a typical conventional roofing assembly

Inverted roofing assembly: It is also known as Inverted roofing system. The membrane is placed below the insulation and, thus is protected from

environmental elements such as wind, rain, UV and temperature. Figure 1.3 shows a typical cross-section of an inverted roofing assembly

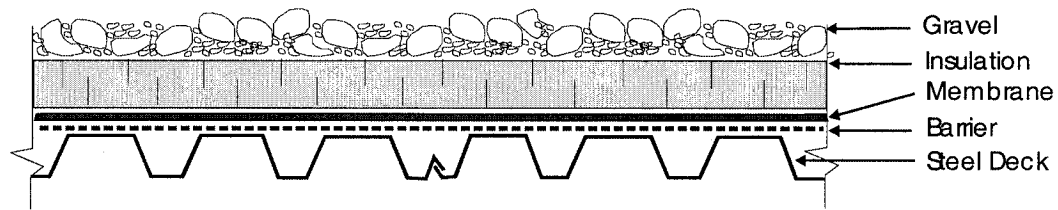


Figure 1.3: Cross-section of a typical inverted roofing assembly

Table 1.1 compares features and limitations of these two types of roofing assemblies. The performance of a conventional single ply roofing system against the wind pressure is the focus of this research study

Table1.1 Roofing Assemblies – Features and Cautions

Conventional Roofing Assembly	
Features	Cautions
➤ Membrane protects insulation from environmental effects ➤ Ballast Optional ➤ Overall load reduced	➤ Membranes exposed to temperature extremes (-40° C to +80° C in Canada) ➤ Moisture can be trapped between vapour barrier and roof membrane
Inverted Roofing Assembly	
➤ Protects membranes against mechanical damage ➤ Minimizes temperature change on membrane ➤ Protects membrane from UV ➤ Provides stable base for the membrane (i.e., deck) ➤ Reduce the risk of trapping condensation in the insulation ➤ Converts roof into a lounge area or a roof garden	➤ Thermal insulation exposed to water from rain and snow ➤ Ballast must be used that adds load to structure ➤ Cannot be used on all buildings ➤ Ballast may be blown away, possibly exposing insulation to UV ➤ Difficult to inspect the membrane after construction to locate leaks ➤ More expensive than conventional system

Considering the history of the conventional roofing systems, the built up roofing systems (BUR) have been applied in the field for over a century. Built-up roofing (BUR) systems typically consist of layers of reinforcing felts that are mopped onto the roof substrate with hot bitumen. When the bitumen cools, a hardened, well-bonded roofing layer is created. These systems derive their wind-uplift resistance from the strength of the adhesive bond between the various layers of the membrane and the cohesive strength between the roofing membrane and insulation. The BUR systems were both labour-intensive to install and cost effective as it involves lot of petroleum products. With the advancement in the roofing technology, the BUR systems are being replaced by the singly ply mechanically attached roofing systems.

Mechanically attached single ply roof membranes are installed as sheets, which are laid over insulation and attached to the steel deck using mechanical fasteners. The membranes are overlapped at the attachment locations and hot air welded to each other to form seams. Wind induced suction lifts the membrane between the attachments and causes membrane elongation and billowing. The magnitude of the wind induced suction and the membranes elastic property determines the billowing shape. Figure 1.4 illustrates the wind uplift mechanism of the mechanically attached single ply roofing assembly and lists the components that comprise a typical roofing assembly.

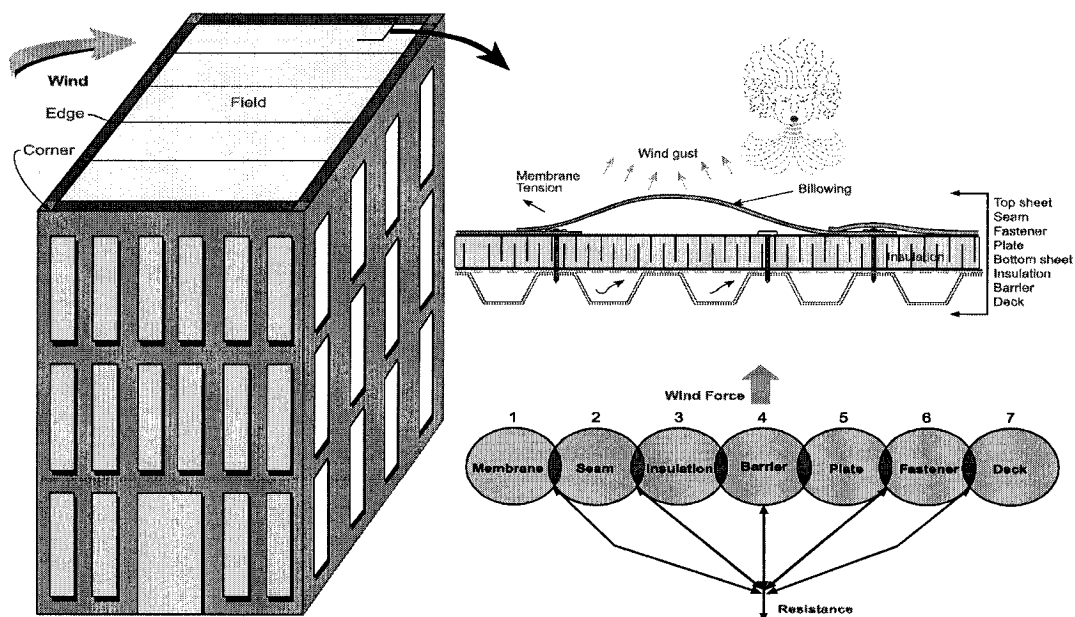


Figure 1.4: Wind effects on single ply mechanically attached roof assemblies
(Baskaran et.al, 2003)

Each component of the roofing assembly offers a certain resistance to the wind uplift force, illustrated through a force-resistance link diagram. All resistance links should remain connected for the roofing assembly to be durable and to keep the roof properly in place. Failure occurs when the wind uplift force is greater than the resistance of any one or more of these links. For example, the roof assembly is considered failed when a fastener (Link 6) pulls out from the deck although the membrane and its seams may be in good condition. Similarly, a roofing assembly is considered failed when a seam (Link 2) opens under gusting wind although the other components remain intact. Therefore, to predict the wind resistance of these roofing assemblies, it is necessary to fully understand the fundamental behaviour of the materials and the nature of wind load structure interaction.

1.2 Problem Definition

In order to evaluate these force resistance links, wind uplift evaluation of MAS was based on standardized test methods, FM (Factory Mutual 1986), and UL Standard (Underwrites Laboratories 1991). These traditional test methods use testing chambers of specified dimensions into which the roofing assembly is installed and subjected to defined wind load cycles, that either follow static, monotonically increasing (or decreasing) or dynamic loading traces. These test methods have been employed for at least the last thirty to forty years and are based on the same premise of increasing the pressure until failure occurs. When a roofing manufacturer presents the roofing assembly for the wind uplift evaluation, the roofing assembly is installed as per the field installation procedure and tested as per the design wind protocol. If the roofing assembly passes the test criteria, the manufacturer would then be presented a rating or approval by the test organization. Basically, to establish the wind design values of a roofing assembly, roofing manufacturers use the data from these tests. Therefore, it is critical that these standardized tests should provide a meaningful measure of the field performance of the roofing systems and not simple relative measurements between various roofing systems. Though the test specimen layout and components are similar to a field roof (e.g. the fastener row spacing, insulation), the chamber dimensions (i.e., length and width) are smaller than those in the field roof. Due to this dimensional variation measured response of the test specimen might be different from that occurring in the field because the chamber frame edges can offer some resistance to the wind uplift force, thereby altering the system responses such as fastener forces and membrane deflection.

This is critical in the evaluation of a roofing system performance. Therefore, testing the roof system on appropriate table dimensions is necessary to obtain realistic wind uplift resistance of that particular roof configuration. Despite the significance of the chamber size on the roofing system performance evaluation, no criteria or standard exists which would recommend a required testing chamber size for specific system configuration.

Wind induced suctions on the exterior roofing surface causes the membrane to lift and flutter thereby creating negative pressure below the lifted membrane. In the absence of an air barrier, the air can infiltrate into the assembly to the side of the lifted membrane due to pumping action. This air movement can affect the membrane response to external wind fluctuations as well as cause condensation below the membrane, if the moving air contains moisture. Main factors that influence air leakages through the MAS are: 1) air permeability of the involved components; 2) joints/junctions/penetrations in the system and 3) change in membrane shape during wind uplift. The mechanically attached systems are being increasingly used in the roofing market but unfortunately currently no standard specifications or test methods exist to quantify the air leakage through these roofing assemblies.

1.3 Research Objectives

Task 1 was numerical evaluation of the wind uplift resistance of the mechanically attached system (MAS) and investigations of the table size effect on the roofing system performance. To achieve this purpose, extensive numerical experiments using the finite element method have been conducted and benchmarked with results obtained from the experimental work. The present contribution is a continuation of previous research (Baskaran, A. and Borujerdi, J. (2001) and can be divided into two parts:

- (1) Undertake additional numerical simulations for wider membranes that were not addressed in the previous works. Due to the advancement in membrane technology, wider membranes are now available in the market and are used in commercial roofing practice as it reduces installation cost. Specific parameters influencing the performance of MAS such as, the effects of specimen size, type of membrane, fastener row spacing and fastener spacing were investigated.
- (2) Develop correction factors for the test chamber size used to test the wider membranes and formulate a methodology to combine and generalize over 400 numerical tests and experiments on various roofing configurations and develop

generalized correction factors such that it can be of practical use to determine the wind uplift resistance of roofs.

Task 2 was the investigation of air leakage through MAS. To accomplish this task, the study was undertaken in two parts:

- (1) Air leakage quantification of MAS. A small-scale experimental setup for quantifying the air leakage rate was developed. The air infiltration rate through the roofing assembly was determined by experimental studies comparing between roofing systems with and without barriers.
- (2) With the quantification of air leakage, its impact on the wind uplift resistance was evaluated on a full-scale experimental setup, following the SIGDERS wind uplift protocol.

1.4 Dissertation Summary

A brief overview of the historical background of the single-ply roof systems and the existing wind uplift testing protocols are systematically reviewed in Chapter 2. Apart from these, a literature review is presented on the research work done on the application of numerical modeling in the evaluation of roofing systems. In that process, one of the major drawbacks namely, the effect of testing table size on the roofing system response has been identified.

Chapter 3 documents the numerical techniques and experimental procedures that are used in the present study. Various mechanically attached single-ply roofing systems were numerically modeled, based on the finite element method with the capability of non-linear analysis. A brief overview of the validated numerical model is discussed. Further in Chapter 4 it is shown how this finite element model was used to investigate the system response of the wider membranes and to identify the appropriate table widths for the testing of these membranes. Also for practical application, correction factor curves were developed which are also shown in this chapter.

Chapter 5 discusses the generalization approach for the development of characteristic correction factor curves, which will be used for determining the Required Table Width for any roofing system configuration. In addition this chapter discusses two scenarios for the application of correction factor curves.

The air leakage quantification through MAS is discussed in Chapter 6. Chapter 6 describes the air leakage characteristics of roofing assemblies. A literature review is also presented on the research work done related to the air movement in roofing assemblies and the existing standards for air leakage quantification.

This is followed by Chapter 7, which describes the developed experimental procedure for air leakage quantification through MAS and discusses the results obtained from this experimental study. With the quantification of air leakage through MAS, its impact on the wind uplift resistance is investigated in Chapter 8. The test setup, materials and equipment that were used to conduct this investigation are described in this chapter. It also discusses the experimental results obtained from this investigation.

Finally, conclusions and recommendations are presented in Chapter 9.

Chapter 2

Literature Review

This chapter presents a general background of the single-ply roofing system, which is one of the new classes of flexible cladding systems. It begins with an introduction to the history of roofing systems and chronological changes in roofing systems. This is followed by a brief overview of the membrane types and attachment mechanisms that are used in single ply roof system. This chapter also examines the different test protocols that are in use to certify the wind uplift performance of flexible membrane systems. The chapter ends with a literature review on the application of numerical models to predict the behaviour of roofing systems.

2.1 Historical Background of Roofing System

Through the first half of the century, roof application methods changed greatly because of the introduction of mechanized equipment, but the design and materials in low slope roofing changed marginally. The majority of low-sloped roofs constructed in the 1950's used either: wood or concrete deck.

- Wood deck
 - 2 plies of nailed felt
 - 3 ply felt and pitch built up roof membrane
 - pitch and gravel surface;
- Concrete deck
 - 25 to 50 mm thick wood fiberboard
 - 4 ply felt and pitch built up roof membrane
 - pitch and gravel surface

These two systems accounted for approximately 40% and 20%, respectively, of the low-sloped roofs in eastern Canada. Wood decks would likely have been even more prevalent in western Canada. The average commercial roof size in eastern Canada in 1958 was approximately 730 m² (Baskaran, Paroli and Booth (1997)). Steel deck had just been introduced into the market: roofs over steel deck were twice that of the average size. Major changes occurred in the second half of the century. Table 2.1 gives the brief overview of the history of roofing industry.

Table 2.1 Changes in the roofing industry

Trends	Changes in Roofing
1950's	Profiled steel roof deck was introduced and very quickly began to replace wood and concrete decks. Being lightweight and strong then previous materials, steel roof decks could span wider distance and was therefore a more economical choice. In the next 20 years, typical roof sizes tripled and steel decks accounted for about 70% of new non-residential low-sloped roof decks. Roof warranty bonds by product manufacturers were terminated in Canada. Because regular maintenance was required to check roof warranty bonds, roof maintenance was not considered optional until the demise of roof bonding.
1960's	New, single ply membranes were introduced into Canada. With very few exceptions, these did not perform well and were therefore removed from the Canadian market. Glass felt built-up roofing was introduced into Canada. Major splitting problems in cold weather occurred because of the inadequate strength of the early glass felts.
1970's	With the OPEC oil crisis of 1972, lightweight plastic insulation foams became more popular to meet an increased consumer demand for thermal efficiency. This resulted in less robust and more blister prone roofs because lightweight foams are typically 3% solid and 97% gas so they have low strength. All lightweight foams have little air permeability, which makes it easier to entrap moisture and other gases during roof application.
1980's	By 1980, a second wave of new membranes had begun to establish itself in the Canadian marketplace such as modified bitumen, EPDM, PVC and TPO. Some of these membranes brought about radically different methods of attachment-such as loosely laid roofing systems that were divorced from the structural deck.

In addition to the above changes, year-round construction, loss of skilled labor and a “never mind the quality, look at the price” attitude has negatively impacted the quality of roofing systems. The pace and style of buildings in North America have led to a higher percentage of large area lightweight roofs. In other words, the lightweight single ply roofing systems, have brought a revolution in the North American roofing market, replacing the decades long built up roofing systems (BUR). Builders, contractors, engineers etc. have had many years of experience using BUR but relatively few with the new single-ply roofing materials. As a result, the knowledge acquired in the past from BUR systems was of little use for explaining the performance of new generation of roofing systems.

2.2 Single- Ply Roofing System

2.2.1 Membranes used in Single-ply Roofing System

Traditionally, the BUR systems were used on low-slope roofs in Canada. The Single-ply roofing system (SPR) was launched in the early sixties as an alternative to BUR. In recent years, SPRs have become a viable alternative because of the rising cost of labor and petroleum-based bituminous materials, and due to environmental implications. In addition, improvements in polymeric materials and the need for easily adaptable membranes for unusual roof configurations make SPR as an alternative option. Figure 2.1 displays a typical example of a single ply conventional roofing system.

Figure 2.2 shows flexible roofing membranes that are in use for the single-ply roofing systems. Asphalt-based membranes are used mainly on Modified Bitumen roofing systems. The Modified Bitumen roofing membranes are composed of one or more pre-manufactured sheets consisting of asphalt, reinforcing layers and in some cases surfacing. During the manufacture of Modified Bitumen roofing membranes, plastic or rubber is added to the bitumen while heating, which gives a higher softening point and greater elasticity (NRCA 1999).

Thermoplastics (TP), referred to as polymers, which are obtained from the polymerization of long chain molecules. This type of material softens when heated and can take new shapes by the application of heat and pressure, but it does not cure or set. The changes seen in this type of membrane are purely physical and with the application of heat are wholly reversible. Therefore, a thermoplastic material can be reprocessed

many times and does not undergo any appreciable chemical change. Examples of thermoplastic membranes are given in Figure 2.2

Thermoset (TS) materials, as the name indicates, is a material that cures or hardens into a given shape generally through the application of heat. Curing is an irreversible chemical process in which permanent connections (cross-links) are made between the molecular chains. These cross-links give the cured polymer a three-dimensional structure, as well as a higher degree of rigidity than it possessed prior to curing. A cured thermoset material will not flow or remelt or otherwise regain the processability it had before curing. Thermoset polymers outperform other materials in a number of properties including mechanical properties, chemical resistance, thermal stability and overall durability. Examples of thermoset membranes are given in Figure 2.2

Thermoplastic and thermoset materials are of great commercial importance in the building industry. However, they cannot always be used as engineering materials without improved properties such as strength. Polymer properties can be enhanced by adding reinforcing fillers that are solid, chemically inert substances added to a resin to modify its properties and most of all, reduce cost. Most fillers are minerals and reduce overall cost, increase speed of cure, add strength, and provide special electrical, mechanical and chemical properties. A wide range of crystalline and amorphous materials can be used as fibers. Carbon black and glass fiber are commonly used in the fabrication of construction materials e.g., roofing. The combination of the polymer (thermoplastic, thermoset, elastomer) and reinforcing-fiber materials such as glass or carbon results in a composite material. Table 2.2 summarizes the some of the features and cautions of roofs with different coverings.

The advancements in roofing systems offers overwhelming choices but they also cause some levels of problems as seen above in the table. Overall there is no perfect system that can satisfy all requirements. Therefore the features and cautions of each system should be taken into account when selecting a system. The present study focuses on the behavior of two main kinds of single-ply roofing systems, Ethylene-Propylene-Diene-Monomer (EPDM) and Thermoplastic Olefin (TPO). Table 2.3 lists the membrane mechanical and physical properties (ASTM 1996, 2003).

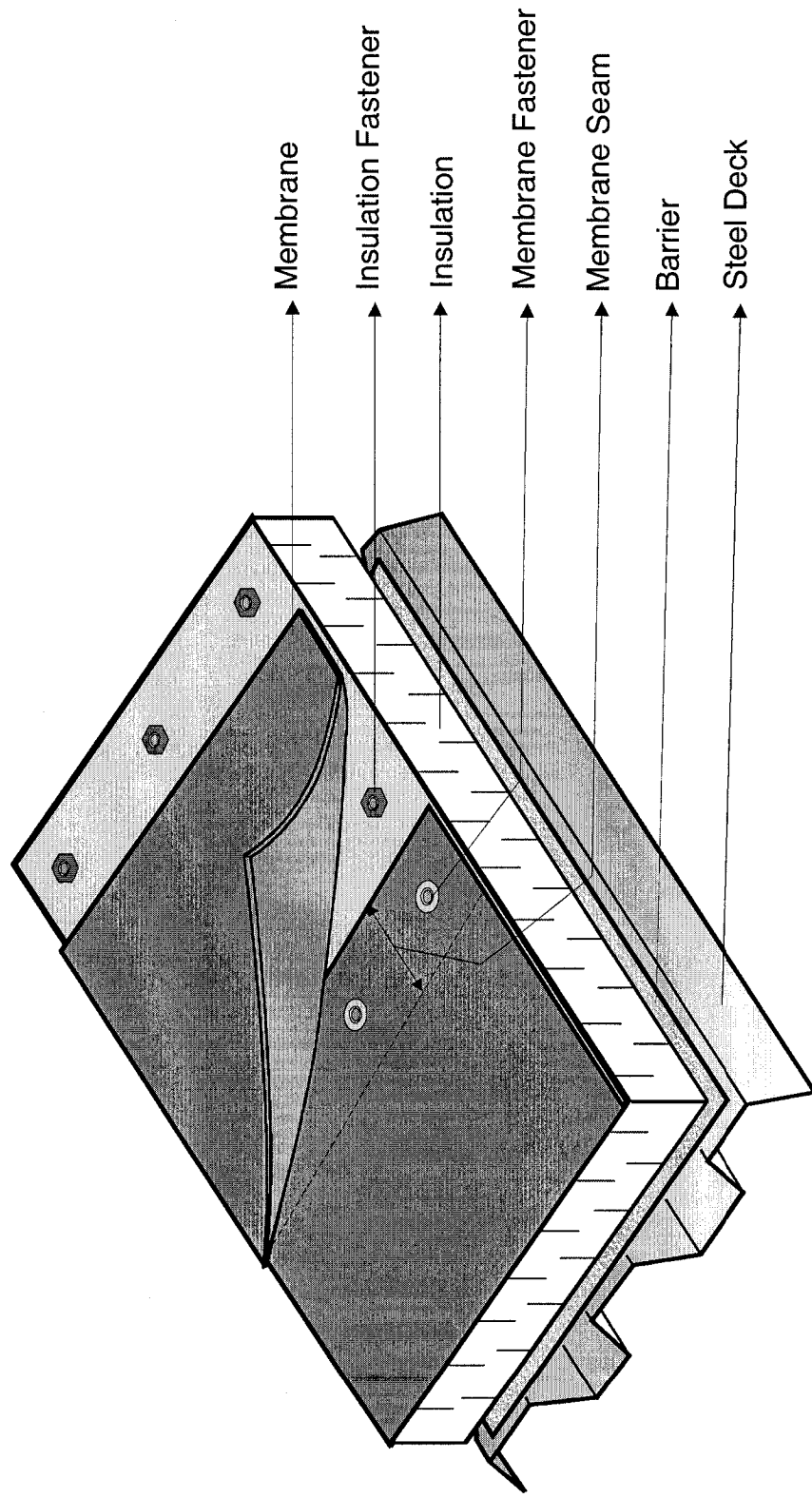


Figure 2.1 A typical layout of a single ply roofing assembly

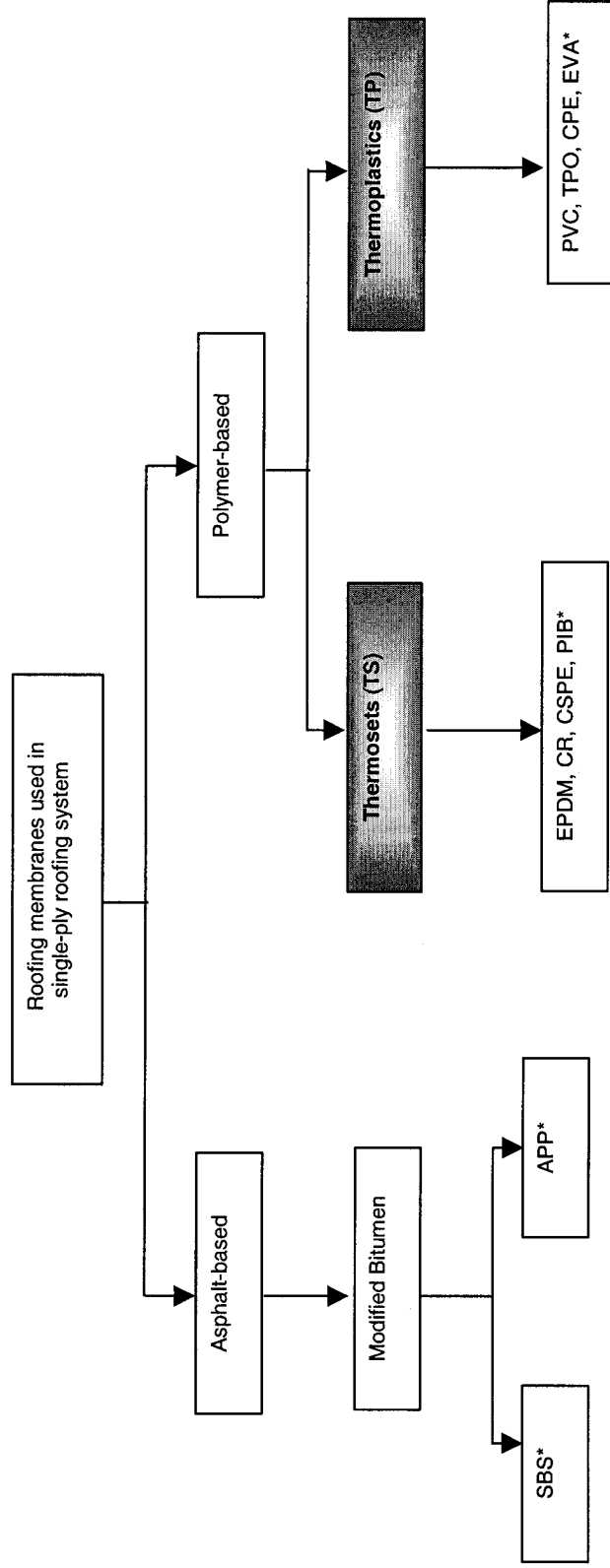


Figure 2.2 Membranes used in single-ply roofing system

* Note: All the abbreviations are given in page xvi

Table 2.2 Features and cautions for roofing systems with different membranes

Features	Cautions
Systems with Modified Bituminous (APP and SBS) membrane	
▪ Similar to a manufactured BUR but it is a two ply system ▪ Asphalt based base and cap sheet ▪ Hot mopping not required, as it is a torched system ▪ Needs less training of workers then with BUR installation	▪ Blistering ▪ Slippage (if low softening point asphalt) ▪ Open flame ▪ Splitting (if weak reinforcement) ▪ UV sensitive (Use granules)
Systems with EPDM membrane	
▪ Highly Elastic ▪ Resistant to Ozone ▪ Resistant to UV ▪ Durable	▪ Requires careful seaming ▪ Sensitive to oils, grease and solvent ▪ Flammable ▪ Shrinkage
Systems with PVC and TPO membrane	
▪ Resin is resistant to biological system ▪ Resistant to most acids and oils ▪ Fire resistant ▪ Easy to apply ▪ Good on-site seaming ▪ Choice of colors	▪ Migration of plasticizers ▪ Shrinkage of embrittlement ▪ Heat sensitive ▪ UV sensitive

Table 2.3 Typical TP and TS membrane material characteristics

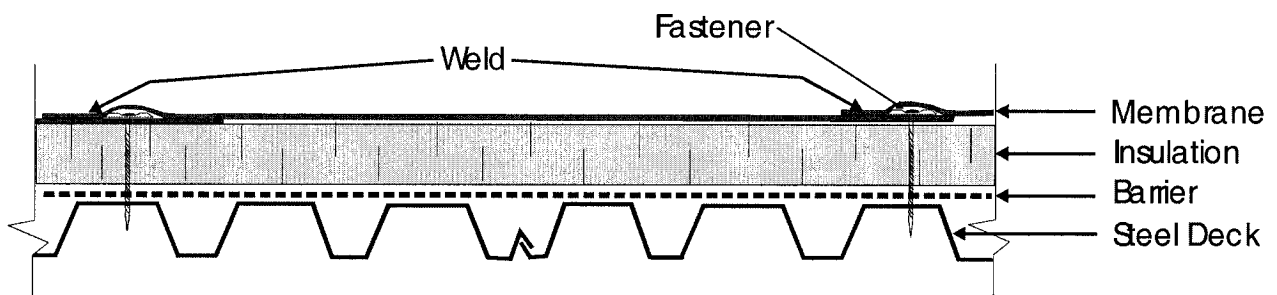
Material	Thickness mm (in)	Elongation Ultimate (%)	Breaking Strength N (lbf)	Tear Strength N (lbf)
Thermoplastic	1.0 (0.04)	250	400 (90)	45 (10)
Thermoset*	1.0 (0.04)	450	976 (220)	245 (55)

* Reinforced

2.2.2 Attachment Methods for Single ply Roofing System

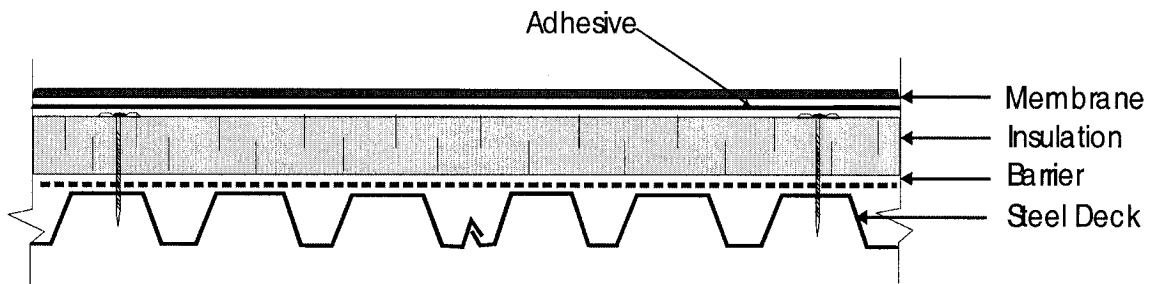
There are generally three attachment methods used to secure the membranes to substrates in single-ply roofing systems, mechanically fastened, fully-adhered, and loose laid system. Figure 2.3 (a) through (c) shows the typical cross sections of roof with these three types of attachments. These figures depict the configurations along with the basic arrangement of roof components. The roof components include: membrane, insulation, deck, barriers and attachment systems.

Mechanically attached SPR: The membrane is attached to the structural substrate either along strips or at numerous points using fasteners. The attachments consist of the mechanical fasteners and plates or metal or polymer batten. Figure 2.3 (a)



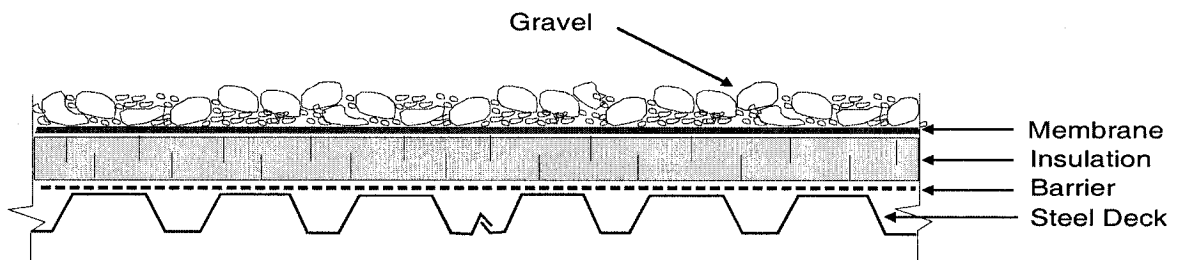
2.3 (a) Mechanically attached SPR

Adhered SPR: The membrane in adhered single-ply roofing system is fully bonded to the substrate by solvent or water-based adhesive or hot bitumen and the substrate is attached to the structural deck. Figure 2.3 (b)



2.3 (b) Adhered SPR

Loose Laid SPR (ballasted configuration): The completed membrane is loose laid and held down by the weight of stones or concrete pavers. However, at the building perimeters, the membrane is attached with the roof/wall junctions. Figure 2.3 (c)



2.3 (c) Loose laid SPR

Figure 2.3 Attachment methods for single-ply roofing system

2.3 Literature Review: Test Methods for Wind Uplift Evaluation of Roofing System

Wind uplift evaluation of roofing systems is critical to understand the response and performance of the system. The design and evaluation of roofing systems are based on the standard test methods that involve placing the roof components in an apparatus and applying simulated wind loads to the roofing system. For the past two decades there has been considerable debate regarding which wind uplift test protocol should be used to certify the wind uplift performance of flexible roofing and building cladding systems. A 1989 workshop on roof wind uplift (OakRidge National Laboratory, 1990), helped to focus the debate on issues related to the adequacy of various wind uplift tests. The debate, which was brought about by the variable performances of these roofing systems in previous windstorms, has occupied the attention of many sections of the construction industry.

It has been established that the flexible roofing systems behave differently from the more traditional building cladding materials such as built-up roofs, reinforced concrete slabs and precast panels and should therefore be treated differently. With flexible roofing systems the pattern of load distribution from the membrane to the structural deck varies with the displaced shape of the membrane under increasing load. Wind-induced pressure on a roof varies with time, as well as spatially over the roof. Wind loads are either transferred to a roof structure through a pneumatic load path or a structural load path. If the external wind fluctuations are quicker than the membrane response, the load is shared among the roof components by pressure difference across the components (Cook 1992). This is known as a pneumatic load path. If, the fluctuation of the wind pressure is slower than the membrane response time the load is transmitted through membrane tension to the fasteners through a structural load path.

Early references to wind-resistance testing of roof membranes can be found in the ASTM Symposia of the late 1960's and literature of the Factory Mutual and Underwriters Laboratories in the same period. To elaborate more in this issue, a brief review of existing loading sequences for the evaluation of roofing system are summarized below. More details of the test procedures can be found in a review report by Baskaran and Dutt (1995).

2.3.1 Factory Mutual 4470 Standard

The FM uplift pressure apparatus is a 7300 mm (288") long by 3700 mm (144") wide steel frame. In the FM protocol (FM Research 1992), the pressure is supplied through the positive air pressure to the bottom of the apparatus using an air compressor as shown in Figure 2.4. The initial test pressure of 1.44 kPa (30 psf) is applied and maintained for one minute. Then, the pressure is increased by 0.72 kPa (15 psf) in each successive minute until the occurrence of failure of the test panel. Figure 2.5 illustrates the graphical plot of the loading sequence. The intention of this test procedure is the establishment of a windstorm classification for the roof assembly.

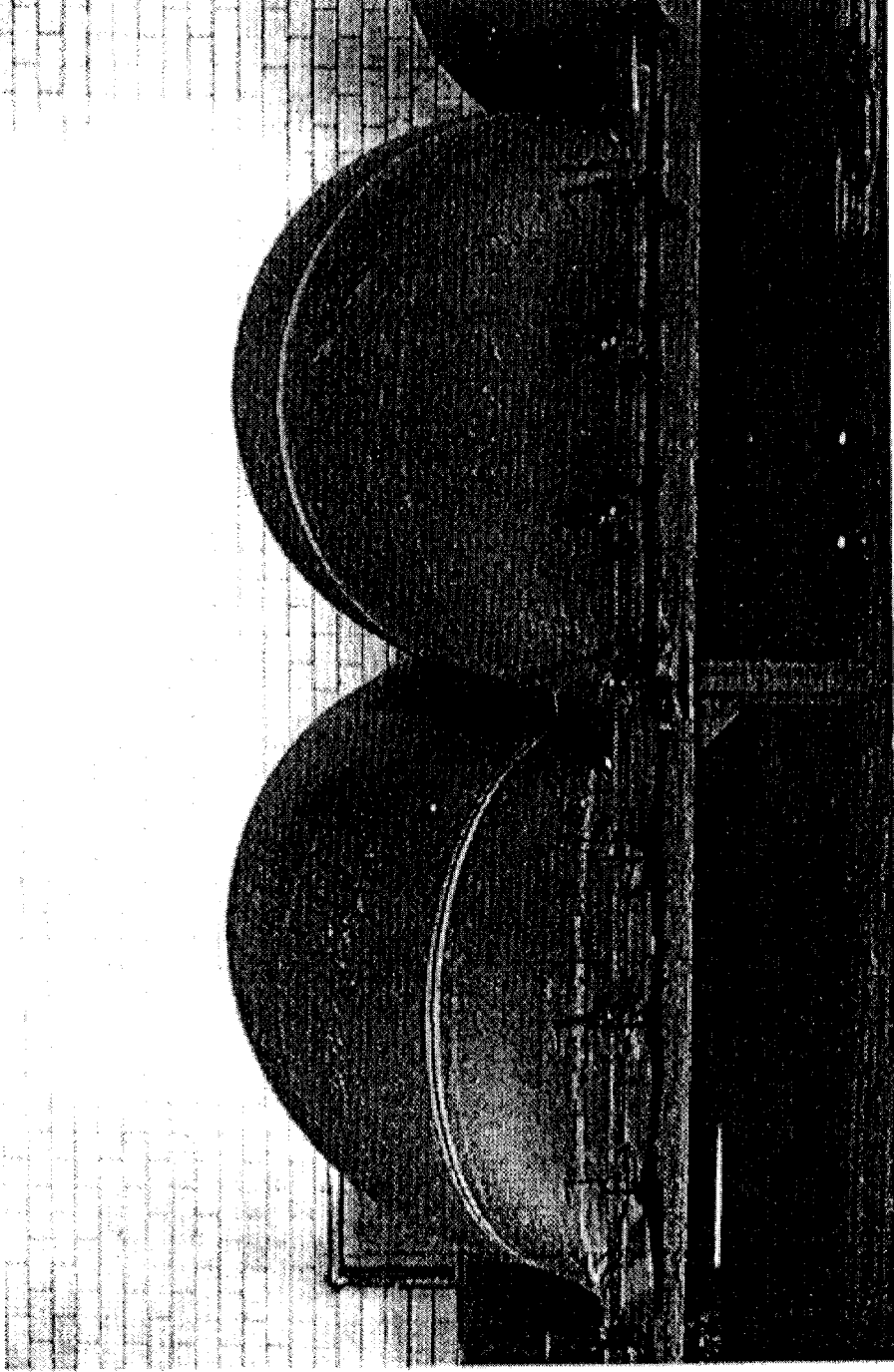


Figure 2.4 FM 4470 test apparatus (FM Research, 1992)

The test assembly should withstand certain pressure levels for 1 minute to obtain approval for a Factory Mutual I roof cover. For example, to get an 1-90 windstorm classification, the test assembly should sustain the 4.3 kPa (90 psf) pressure sequence for one minute. It should be noted FM is not a dynamic test

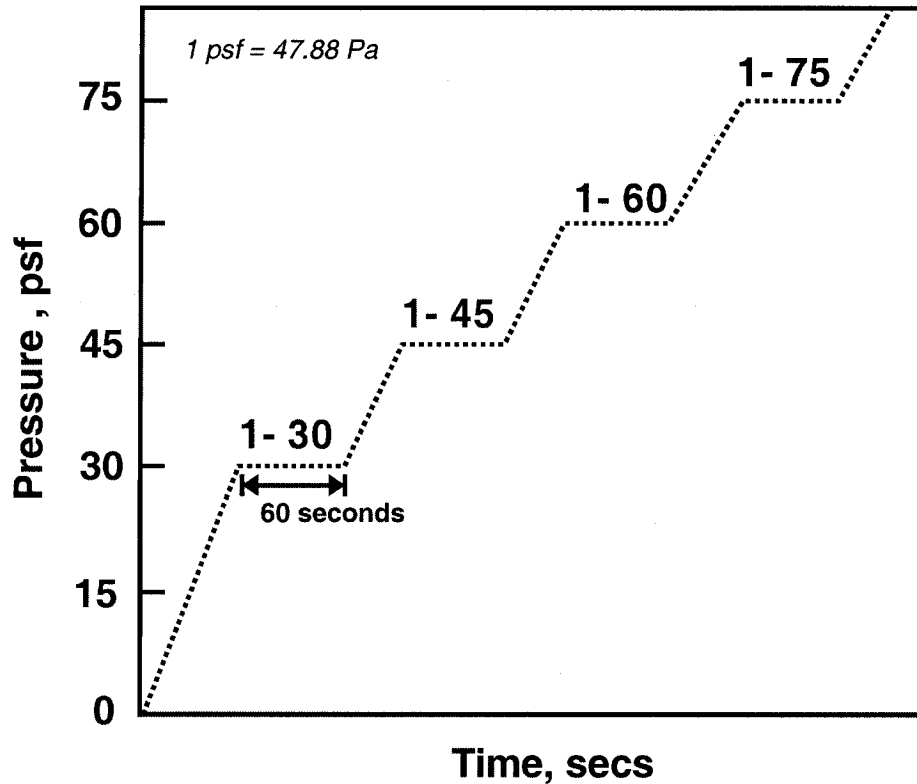


Figure 2.5 Factory Mutual load cycle

2.3.2 Underwriters Laboratories 580 Standard

The UL 580 testing apparatus, illustrated in Figure 2.6, has dimensions of 3050 (120") x 3050 (120"). The UL 580 procedure applies loads on the chamber not only from the bottom as a steady positive pressure, but also from the top as steady and oscillating negative pressure. Table 2.4 shows the negative and positive pressures applied on different test phases at set times. The classification ratings for this protocol are: UL-15, UL-30, UL-60 and UL-90. For instance, to obtain approval for the UL-60 the following load sequences are applied to the roof assembly:

- In the first phase, a 1.55 kPa (32.3 psf) negative pressure is applied for 5 minutes.
- During the second phase, a 1.33 kPa (27.7 psf) positive pressure is added from the bottom of test assembly for an additional 5 minutes.
- Then, a negative oscillating pressure of 0.79 to 2.66 kPa (16.2 to 55.4 psf) is applied at a frequency of 10 second per cycles for 60 minutes.
- In the fourth phase, only a 1.94 kPa (40.4 psf) negative pressure is applied for 5 minutes.
- In the last phase, while the negative pressure is in effect, an additional 1.66 kPa (34.6 psf) positive pressure is applied for 5 minutes.

Similar procedures apply to other classifications, considering that specimens must first pass the upper classes before starting the next class. The UL-90 classification takes around 5 hours to complete.

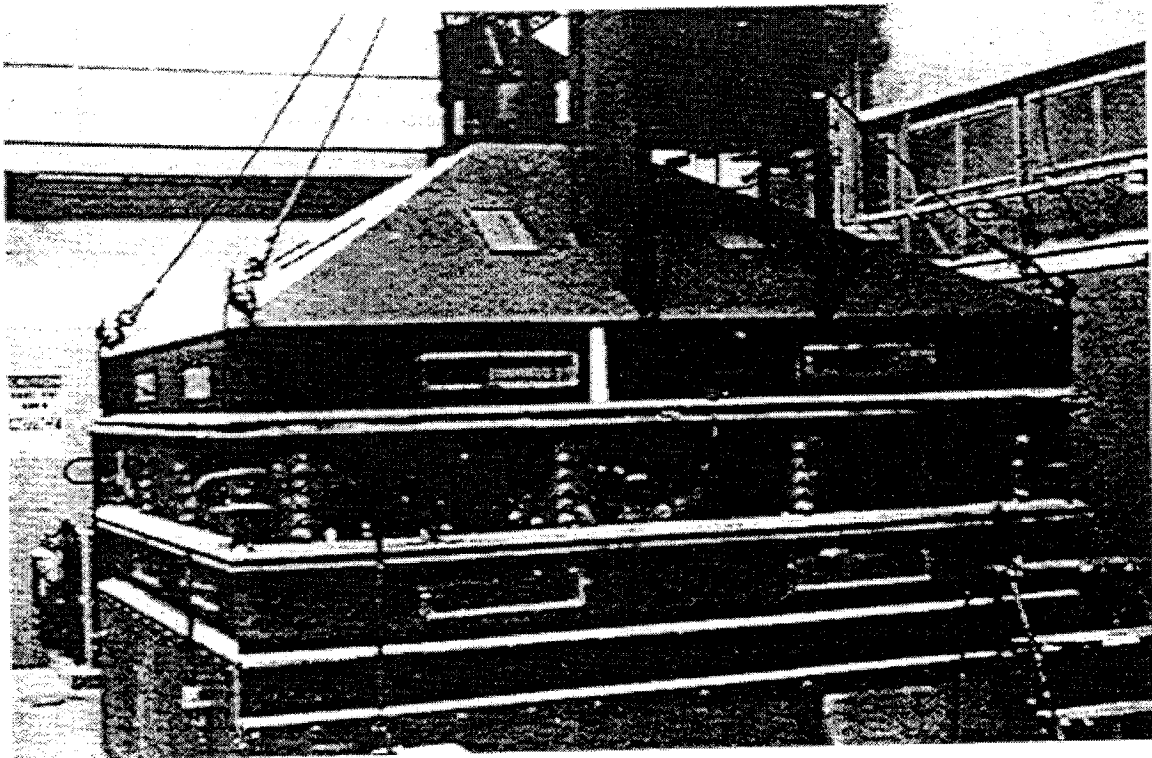


Figure 2.6 UL test apparatus (UL 580, 1991)

Table 2.4 Underwriter laboratories standard load sequence

Rating	Test phase	Time (min)	Negative pressure kPa (psf)	Positive pressure kPa (psf)
UL 15	1	5	0.45 (9.4)	0.0 (0.0)
	2	5	0.45 (9.4)	0.25 (5.2)
	3	60	0.27-0.78 (5.7-16.2)	0.25 (5.2)
	4	5	0.7 (14.6)	0.0 (0.0)
	5	5	0.7 (14.6)	0.4 (8.3)
UL 30	1	5	0.79 (16.2)	0.0 (0.0)
	2	5	0.79 (16.2)	0.66 (13.8)
	3	60	0.39-1.33 (8.1-27.7)	0.66 (13.8)
	4	5	1.16 (24.2)	0.0 (0.0)
	5	5	1.16 (24.2)	1.00 (20.8)
UL 60	1	5	1.55 (32.3)	0.0 (0.0)
	2	5	1.55 (32.3)	1.33 (27.7)
	3	60	0.79-2.66 (16.2-55.4)	1.33 (27.7)
	4	5	1.94 (40.4)	0.0 (0.0)
	5	5	1.94 (40.4)	1.66 (34.6)
UL 90	1	5	2.33 (48.5)	0.0 (0.0)
	2	5	2.33 (48.5)	1.99 (41.5)
	3	60	1.16-2.33 (24.2-48.5)	1.99 (41.5)
	4	5	2.71 (56.5)	0.0 (0.0)
	5	5	2.71 (56.5)	2.33 (48.5)

2.3.3 European Union of Agreement (UEAtc)

The test apparatus has dimensions 1500 mm (60") x 6100 mm (240"). It consists of a suction chamber positioned on a rigid frame to surround the test specimen. The following steps of the UEAtc standard wind load cycle were prepared according to a procedure developed by Gerhardt and Kramer (1986). Figure 2.7 shows the load cycle for a five-year return period

- Four cycles of 1415 gusts with a maximum load of 300 N (68 lbf) per fastener are applied.
- If the back-out behavior of the fastener is unknown, then the roofing system must be subjected to 200,000 fluctuations with a loading of 100 N (22.5 lbf) per fastener and a frequency not exceeding 10 Hz. This is known as the conditioning cycle and it is applied between the third and fourth loading.
- 1415 gusts are applied on the condition the maximum load per fastener does not exceed 400 N (90 lbf).
- The maximum load per fastener is increased in increments of 100 N (22.5 lbf) and applying 1415 gusts in each level until failure occurs.

2.3.4 Norwegian Standard (NT BUILD)

NT BUILD 307 1986-11 (Paulsen 1989), "Roof coverings – Wind load resistance" is a standard method being used to test the strength of wind uplift on roof assemblies. This protocol is a standard method. In 1987, the Norwegian Building Research Institute (NBI), along with other participants from Scandinavian countries, initiated a study of dynamic load application on mechanically attached roof systems. "NBI 162-90 Roof coverings – Dynamic wind load resistance" a modified version of the NT BUILD 307 static test procedure, was developed from that study. As shown in Figure 2.8 the dynamic apparatus consists of a lower and upper box (2400 mm (96") x 2400 mm (96")) between which a test specimen is positioned. The lower box applies a static suction of 0.1 Pa (2.1 psf), while the upper box applies pulsating suction initiated at 0.2 kPa (4.2 psf). In each step the gust applies every 15 seconds for one hour. Figure 2.9 depicts the values and increments of gust intensities.

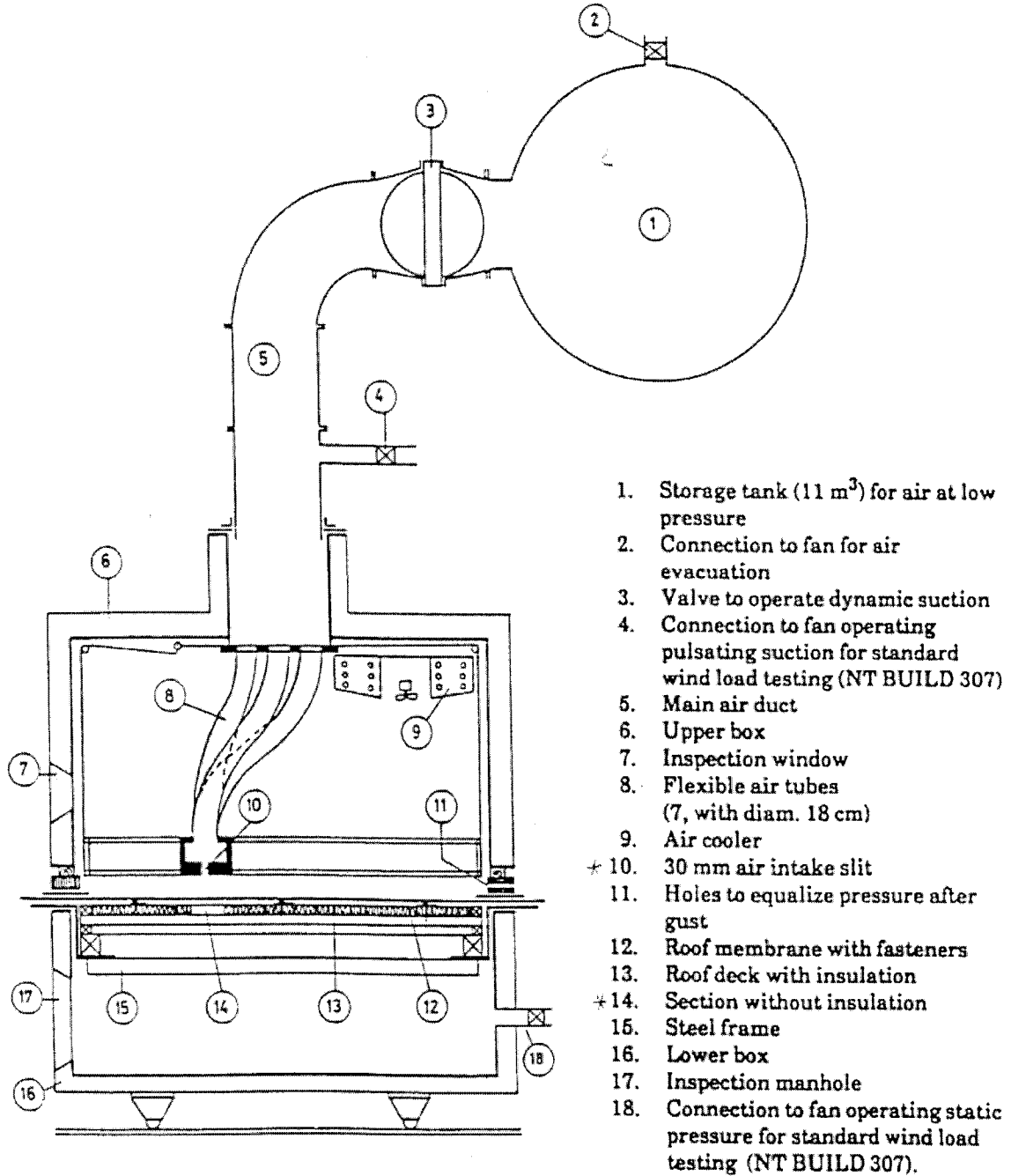


Figure 2.8 NT BUILD 307 test apparatus (Paulsen 1989))

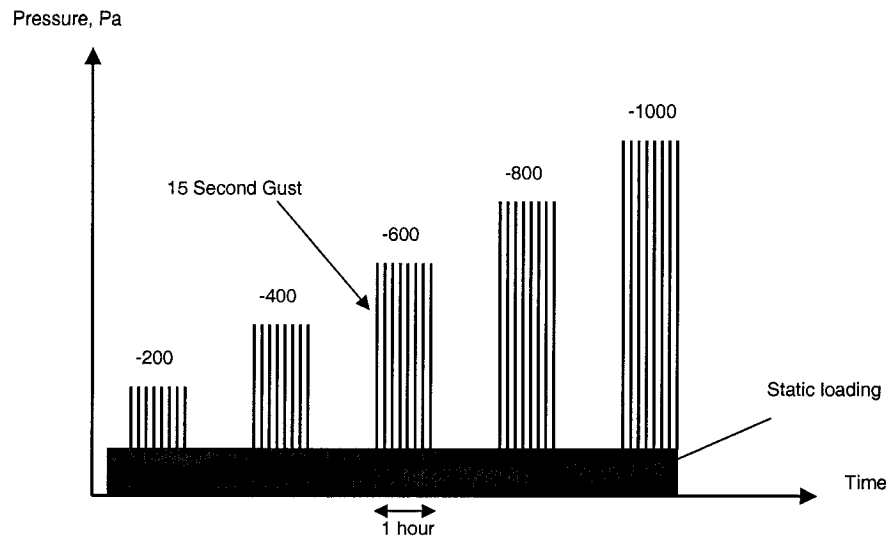


Figure 2.9 Norwegian load cycle (Paulsen 1989)

2.3.5 SIGDERS Dynamic Load Cycle

As shown in Figure 2.10, the SIGDERS experimental apparatus consists of a bottom frame of adjustable height upon which the roof specimen and a removable top chamber are installed. The design allows for the installation and study of roof assemblies of different thicknesses up to 500 mm (18") as well as the evaluation of sloped roofs. The bottom frame and top chamber are 6100 mm (240") long and 2200 mm (86") wide and 800 mm (32") high. The top chamber is equipped with six windows for viewing, and with a gust simulator, which consists of a flap valve connected to a stepping motor through a timing belt arrangement. Pressure suction as high as 10 kPa (209 psf) over the roof assembly is produced by a 37 KW (50HP) fan with a flow rate of 2500 L/sec (5300 cfm). A computer, using feedback signals, controls the operation of the DRF. The computer regulates the fan speed in order to maintain the required pressure level in the chamber. Operation of the flap valve simulates the gusts in the form of uniform cyclic pressure loading over the surface of the roofing system. Closing the flap valve allows pressure to build in the chamber, while opening the valve bleeds the pressure. Also, the test facility has instrumentation for measuring the dynamic response for the specimen. More information of the DRF features is given in Baskaran and Lei (1997).

The SIGDERS load cycle (Baskaran et al 1998) was developed based on the wind-tunnel studies of full-scale roof systems. Studies were made of 3048 × 3048 mm (120" ×

120") roof systems using the National Research Council's (NRC's) 9000 × 9000 mm (360" × 360") wind tunnel. Two series of investigations were carried out using two distinct roofing membranes. The first series dealt with a reinforced Poly Vinyl Chloride (PVC) membrane and the other with a non-reinforced Ethylene Propylene Diene Monomere (EPDM) membrane. Different configurations were tested for variation in building heights, wind speed and wind direction. For PVC, there are 30 different test configurations, whereas for EPDM, 48 configurations were tested.

The model roof systems were instrumented with taps on different locations to record pressure time histories. For each configuration, 60-second pressure time histories were recorded, which represents 51 minutes duration in a full-scale windstorm event. The obtained unsteady histories of wind pressures were used for the load cycle development. The details of the developed load cycle can be found in a report by Baskaran and Chen (1998).

Figure 2.11 shows the load cycle developed for the SIGDERS wind test procedure in five rating levels (A to E). The test pressure corresponds to the design pressure, in accordance with local building codes or wind standards. The pressures for each load sequence are calculated as percentages of the test pressure.

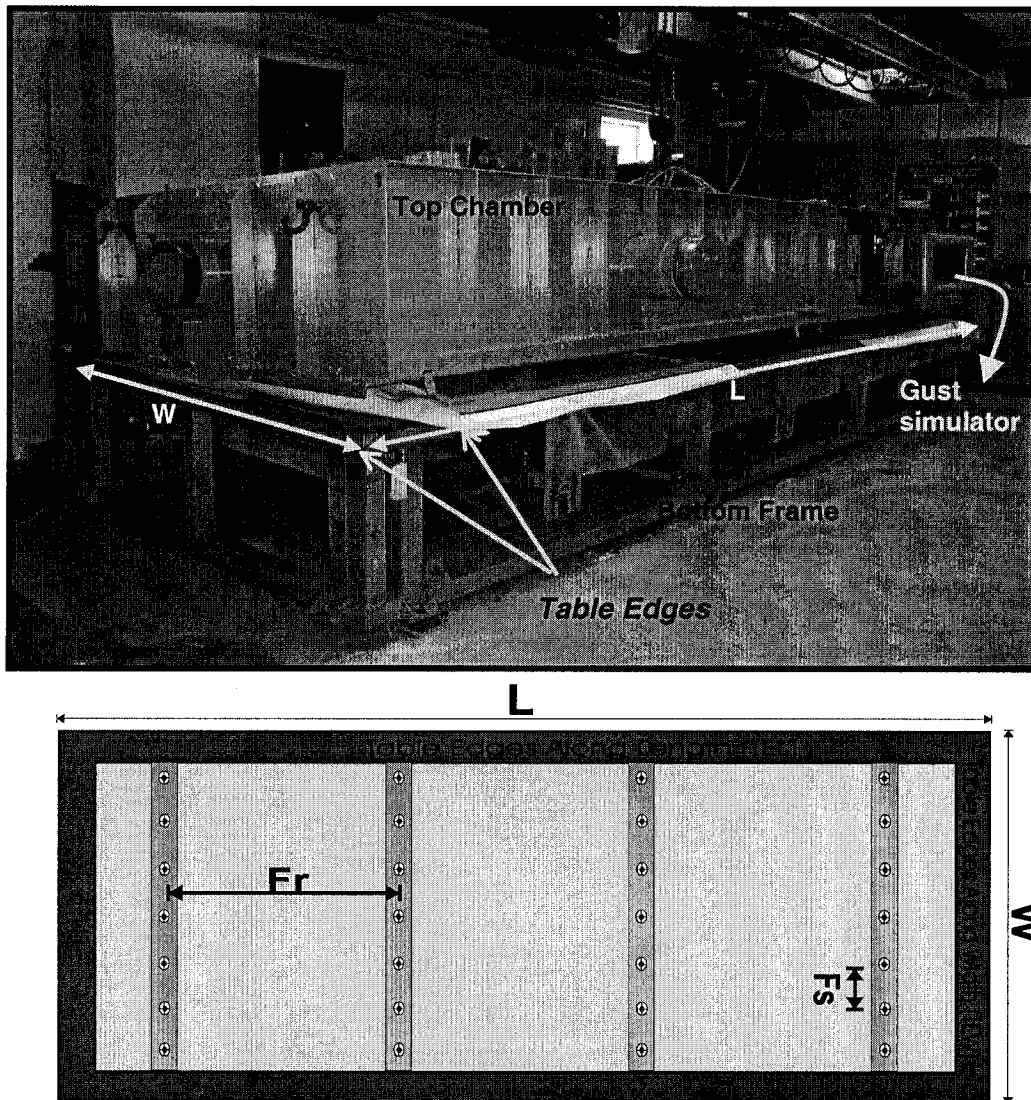
The load sequence is divided in two groups: Group 1 has a zero minimum value and for Group 2 the cycles are applied over a constant static component. Both groups are divided into four load sequences. The pressure level for Group 1, can be viewed as wind-induced suction over the roof assembly and applied as follows:

- 400 gust cycles are applied at 25% of the test pressure
- 700 gust cycles are applied at 50% of the test pressure
- 200 gust cycles are applied at 75% of the test pressure
- 50 gust cycles are applied at the test pressure

In Group 2, the simulation represents the effects of exterior wind fluctuations combined with a constant interior pressure. A constant suction of 25% of the test pressure is applied. Then, four sequences of various gust pressures are applied as follows:

- 400 gust cycles are applied from 25% to 50% of the test pressure
- 400 gust cycles are applied from 25% to 75% of the test pressure
- 25 gust cycles are applied from 25% to 100% of the test pressure
- 25 gust cycles are applied from 50% to 100% of the test pressure

If the tested specimen passes all eight sequences of Group 1 and Group 2 at level “A”, it can be tested with the design pressure increased incrementally by 0.25. These levels provide the manufacturer’s systems with safety factors. The building codes or wind standards however prescribe only a minimum design value. Therefore, the load cycle can evaluate the design pressure or safety factor of two, where the specimen has passed level “E”.



L	= Table Length	TEL	= Table edges along the length	Fr	= Fastener row spacing
W	= Table width	TEW	= Table edges along the width	Fs	= Fastener spacing

Figure 2.10 SIGDERS testing apparatus and nomenclature

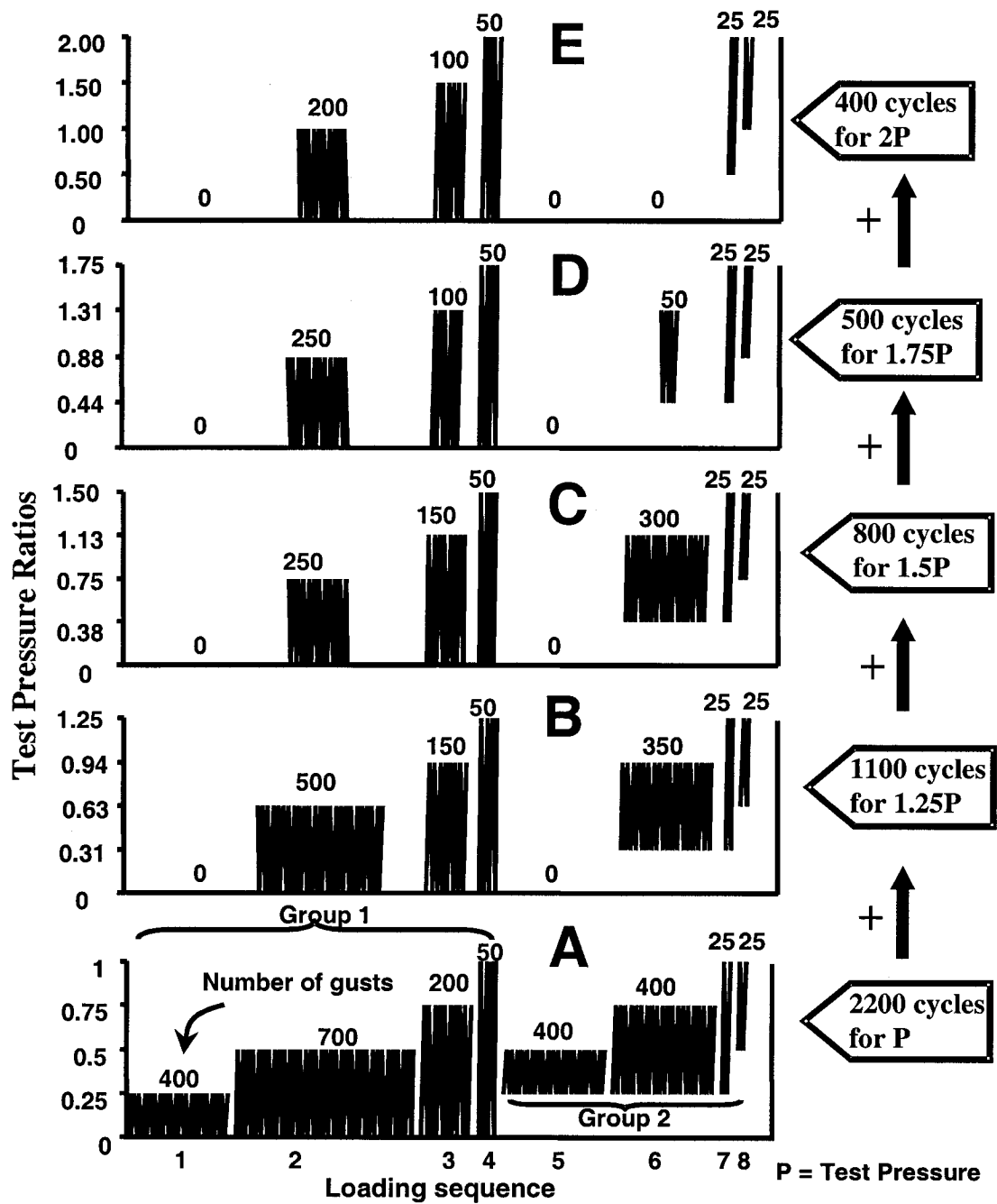


Figure 2.11 SIGDERS Dynamic load cycle (Baskaran et.al , 1998)

2.3.6 Other Test Procedures

BRE Real time wind uniform load follower was designed by the Building Research Establishment, UK (Cook, Keevil, and Stobart, 1988). Technically BRERWULF is not a standardized test procedure. It is a testing equipment that can be used to simulate various dynamic wind pressure sequence on a roofing system. It is portable and can be incorporated into any test chamber to which the test specimen is attached. BRERWULF is designed to reproduce a long-term history of wind pressures for evaluating the structural performance of the building and primarily roofs. Pressure on the test specimen is developed by a centrifugal fan that circulates air through a control valve so that the pressure can be varied using either a static or dynamic controller. With the static controller the pressure can be varied using either a static or dynamic controller. With the static controller the pressure can be increased and the rate adjusted. With the dynamic controller the pressure may be derived from a file containing data such as field-monitored wind pressure data, data collected from wind tunnel or data forming a sinusoidal wave. The target trace is sampled and normalized with the peak value corresponding to the design value in the range of ± 8.5 kPa.

Smith (1992) developed a procedure to test mechanically attached single-ply membranes for fatigue. The number of loading cycles was associated with wind speed increments by using the Weibull probability distribution. Letchford and Norville (1993) proposed a load sequence based on wind pressure records from the Texas Tech University's Wind Engineering Research Field Laboratory. They used level-crossing and mean-crossing and mean-range count analysis as the cycle-counting methods. This load sequence was also applied in the development of a test standard for determining impact resistance from windborne debris, SBCCI (1994). In Australia, Byrne (1976), Morgan and Beck (1977) and Mahendran (1990, 1994) used an experimental setup to apply dynamic loading on sheet-metal roofing. Their findings from this investigation were used to update the Australian Standard (TR – 1978). Clemson University in the United States acquired the Building Research Establishment Real-time Wind Uniform Load Follower (BRERWULF - 1988) facility for wind testing of building envelopes.

The above review of the existing test standards and procedures reveals the following:

- FM 4470 and UL 580 testing procedures do not account for the wind induced fatigue effects on the mechanically attached roofing systems.

- Fatigue is an important factor in the two test procedures of UEAtc and NT BUILD 307. It illustrates that the European dynamic testing procedure is more advanced than the North American.
- The UEAtc procedure provides the fastener design load, whereas FM and UL certify a roof system for a design pressure.
- The UEAtc test is a time consuming procedure and may take more than 1 day for a typical test.

2.4 Literature Review: Numerical Modeling of Roofing Systems

Numerical techniques can be useful for examining roof configurations that would be too expensive, or difficult to set up experimentally. In addition, the analytical models are generally faster than experimental approaches for solving problems where there is a need to investigate the impact of various factors. The effect of driving forces can also be easily modified more efficiently in the numerical models. Recently, application of numerical models to study the performance of roofing systems has increased considerably. The present section reviews the various numerical studies related to:

1. Fully adhered and ballasted single ply roofing systems
2. Mechanically attached single ply roofing systems

2.4.1 Fully Adhered and Ballasted Single-ply Roofing Systems

Koike et al (1978) investigated membrane failure as a result of fatigue rupture of substrates. Substrates such as rigid plastic foams and concrete planks were reported to be susceptible to relatively large joint movement, which led to membrane fatigue. The membrane ability to withstand these large movements were investigated. Strains induced in multi-ply membranes, asphalt felts and reinforcing components were modeled using differential equations. These equations are based on the theory of elasticity. First, the strains in fully bonded membranes were analyzed. Secondly, modifying the boundary conditions, the strain increase in the remaining unbroken felts were investigated up to the rupture of the entire bond. The effects of loosely laying membranes over joints in substrates were also analyzed. This was performed by solving two simultaneously differential equations for the bonded and loosened parts so as to satisfy the boundary conditions.

Limitations

- Study considered only one component of the roof assembly, namely, the membrane.
- Analysis was carried out for the substrate movement-induced strains and no provisions were made for other types of load-induced strains.
- Non-linear membrane response was obtained through incremental linear analysis

In a pioneering study, **Lewis (1980)**, using FEM calculated the thermal induced stresses for a bituminous built up membrane. The membrane was placed on a glass insulation boards that lies over a metal deck. The fiberglass system was double layered, each 47.6 mm (1.9") thick. The primary objective of the study was to evaluate the thermal-induced stresses in the membrane placed on gaps between adjacent roof insulation panels by defining two types of joints namely, overlapped and non-overlapped, as shown in Figure 2.12. To simulate the proper moment of inertia, the steel deck was represented by an equivalent thickness rectangular layer. Thus the corrugated deck was simulated by a 9.93 mm (0.4") thick layer. Parameters studied included: insulation board modules, insulation thickness, gap width between insulation boards, deck thickness, distance between roof deck and structural supports, insulation gap location with respect to roof deck structural supports and finite element grid refinement.

Findings

- Preliminary analysis indicated that membrane stresses are adversely affected by not overlapping insulation panels and by increasing either insulation thickness or stiffness.
- The study showed that stress levels in the membrane at locations above a continuous gap through the two insulation board layers were higher (63% increase) as compared to configuration having no gaps

Limitations

- No experimental verification of the model was carried out
- Analysis involved only isotropic behavior of the materials
- Design geometry and load histories were not included in the analysis
- Study did not consider the time and temperature dependence of material Properties

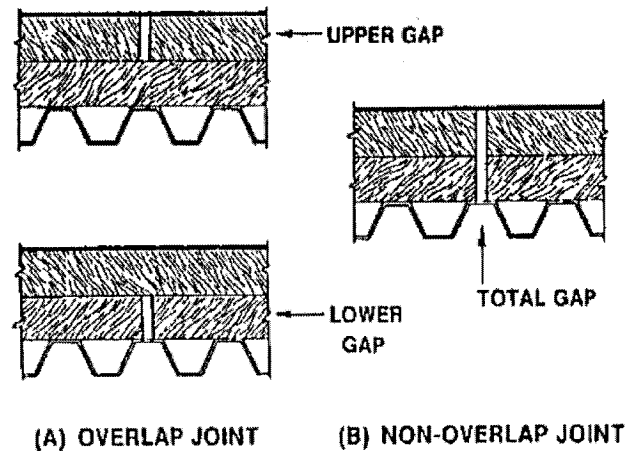


Figure 2.12 Different types of joints between insulation panels (Lewis 1980)

A linear finite element method of analysis was used by **Rossiter and Batts (1985)** to calculate stresses induced in a single-ply roofing membrane due to thermal gradients. The study utilized the MacNeal-Schwendler Corporation (MSC/NASTRAN, 1972) FEM code. An eight node isoparametric quadrilateral element was used in the analysis. The element can simulate membrane or plate bending applications. Two roofing systems were modeled and analyzed to calculate the stresses induced by linear thermal gradients across the roof systems. As shown in Figure 2.13 (a), the first roofing system consisted of a 1.5 mm (0.06") totally adhered EPDM, two layers of fibrous glass insulation board each 48 mm (1.9") thick and a 22 gauge steel deck. In the second system the EPDM was loose-laid and subjected to a uniform surface load of 122 kg/m² (24 lb/ft²) to represent the ballast weight. As shown in Figure 2.13(b) both roofing systems were subjected to temperature differential of 55°C (100° F), having membrane surface temperature at 24°C and the bottom surface (metal deck) at 79°C. During the analysis, the following assumptions were made:

- Only a 2D (plain strain model) roofing system was considered in the analysis
- Membrane was stress-free at 24°C
- Material properties were assumed isotropic and invariable with temperature and therefore the model was linear and elastic
- Membrane had no seams, flaws, or other stress concentrations
- Totally adhered membrane numerical model did not include an adhesive layer: instead the membrane was constrained at all points

- Loose laid membrane was only constrained at the edges and it could subsequently slide horizontally with respect to the insulation

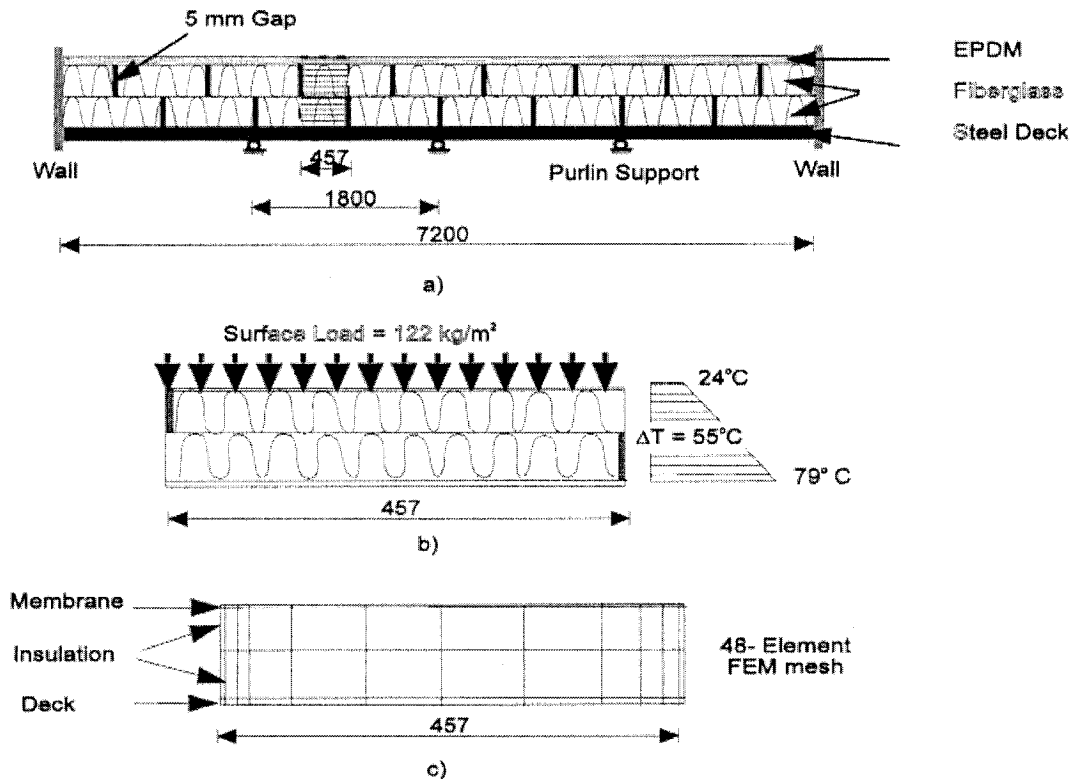


Figure 2.13 (a) Modeled roofing system (b) Typical loading of the roofing system (c) Finite element mesh used in the analysis (Rossiter and Batts , 1985)

Material properties used in the finite analysis are shown in Table 2.5. Both the totally adhered and loose laid membrane systems were modeled with a ballast surface load of 122 kg/m^2 (24 lb/ft^2) to represent the ballast weight. This surface load was reduced for a totally adhered system for comparison purposes. The finite element mesh used for the investigated systems is shown in Figure 2.13 (c). The mesh comprised 48 elements for a length of 457 mm (18") and was repeated 16 times (768 elements) to represent the total roof length.

Findings

- For the adhered system, the results indicated that the temperature-induced membrane stresses were approximately 0.20 MPa (at membrane locations corresponding to the gaps between the insulation boards. This peak stress is about 20% of the ultimate tensile strength of the membrane. The ultimate

strength was measured as 12 MPa in the lab at -18°C for a relatively high loading (50 cm/min)

- For the loose laid system, the corresponding peak stress was about 0.12 MPa.

Table 2.5 Material properties of roofing system components (Rossiter, 1985)

Material	Thickness (mm)	Modulus of Elasticity (MPa)	Coefficient of linear thermal expansion, $\text{mm}/^{\circ}\text{C}$	Poisson's ratio
EPDM	1.5	2	660×10^{-6}	0.45
Fibrous Glass Insulation	48	1.4×10^2	13×10^{-6}	0.30
Steel Deck	9.9	2×10^5	12×10^{-6}	0.30

- The low level stresses (0.12 to 0.20 MPa) for both systems are due to the low elastic moduli of membrane material.

Limitations

- Only 2D geometry was modeled for the roofing assembly and a constant exterior load condition was applied. Also it had been explained that many synthetic materials embrittle and showed increase in modulus and reduction in ultimate strength upon aging.
- Study did not consider the time and temperature dependence of material properties.
- Analysis involved only isotropic behavior of the materials.

Broadland et al. (1993) studied the effect of fully adhered membrane response to differential movements between adjacent substrates. These differential deformations were produced by seasonal temperature changes and aging. The theoretical formulation was based on large strain analysis. A PC based finite element software called REMA (Reinforced Membrane Analysis) was used to perform the analysis. REMA analyzed a fully adhered roofing membrane. It consisted of a mat-reinforced base sheet bonded to a rigid substrate and cap sheet. The cap sheet contained both a polyester scrim and a glass reinforcement bonded to the top of the base sheet as shown in Figure 2.14. At the

center of the sample there was a joint in the substrate. The half length of the sample was 200 mm (8"). The base sheet was measured as 2 mm (0.08") thick. The glass reinforcement with thickness 0.5 mm (0.02") was placed mid-way through the sheet thickness. The cap was measured as 3.5 mm (0.14") thick and its reinforcements were located at its center. The gap was widened by specifying the displacement of the substrate and the analysis was performed for a temperature of -5°C .

Findings:

- Study computed the sequences of the membrane component failures due to gap widening
- Comparison for the load-deflection curves produced by the FEM and measured data from laboratories tests was also attempted (Figure 2.15).

Limitations:

- Study was carried out for the analysis of only one component of the roof assembly, namely, the membrane.
- Analysis was carried out for the substrates movement-induced strains with no provisions for other types of load-induced strains as wind induced loads.
- Study did not consider the time and temperature dependence of the material properties.

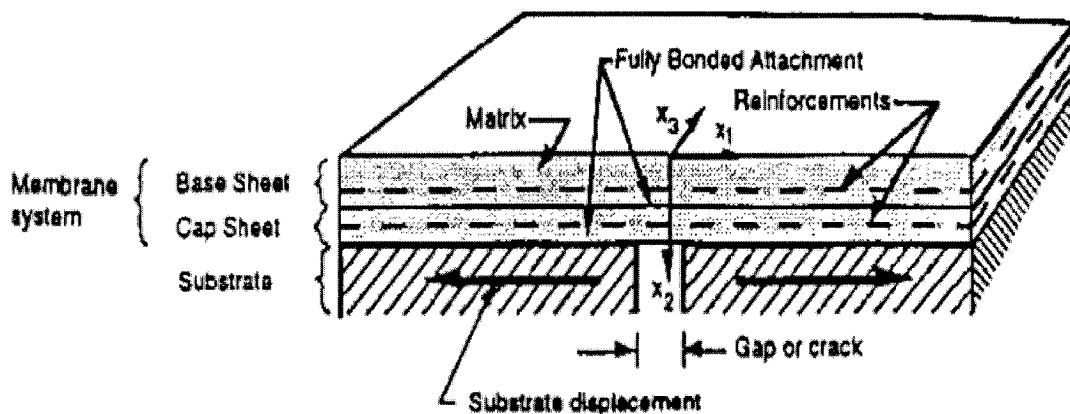


Figure 2.14 In-plane bending of the membrane system (Broadland et al., 1993)

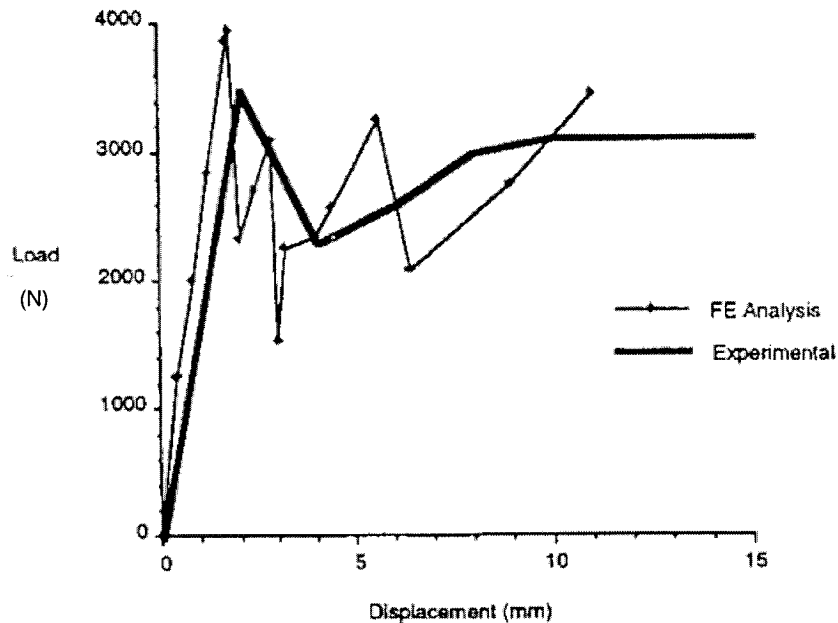


Figure 2.15 Predicted and experimental load-deflection curves
(Broadland et al., 1993)

Bienkiewicz and Sun (1993) developed a numerical model to simulate wind loading in roofing systems with loose-laid *ballast pavers*. The numerical model assumed Darcy's law for modeling the flow beneath and between pavers. The pressure distribution along the paver edges was assumed to be piecewise linear. The mathematical model was obtained for a generic paver system based on the following assumptions.

- pavers had the same dimensions and were uniformly spaced;
- paver thickness was small compared with the other two dimensions;
- flow fields over and between pavers were assumed incompressible and the space is filled with porous media of constant permeability;
- distance between pavers and the roof deck was small compared to pavers thickness;
- pressure distribution between pavers varies linearly; and as shown in Figure 2.16, both external and internal pressures are distributed piecewise linearly along the edged of each pavers.

The numerical model developed by Bienkiewicz and Sun (1993) can be briefly described as follows:

- First, the Laplace equation was obtained based on Darcy's Law and incompressibility assumption.
- By applying the boundary conditions on the developed Laplace equation, a boundary-value problem in a rectangular domain was derived.
- The expression of flow velocity beneath pavers was then determined by employing separation of variables technique.
- After determining the velocity field, expressions of the pressure distribution between the pavers were obtained.
- Computed flow between and beneath pavers was then utilized in mass conservation equations for different control volumes. This resulted in a system of linear algebraic equations which related the unknown underneath pressure to the known external pressure.

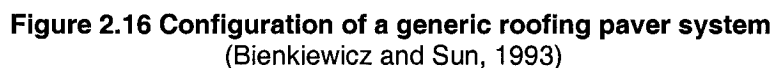
A mathematical model was used in analyzing two types of pavers; pavers A and B. Both were tested in the wind tunnel (Bienkiewicz and Sun, 1993) and the external and underneath pressures were measured. Paver A was a 1:25 scaled model (24 x 18 x 3 mm) (0.9" x 0.7" x 0.12") with a flat underneath surface and located in a windward roof corner of the tested building. The power-law exponent of the mean velocity profile of the flow was 0.14 and the turbulence intensity at building roof height was about 20%. The incidence of the flow to the building was 45°. Paver B, on the other hand, was a prototype concrete paver (419 x 298 x 35 mm) (16" x 12" x 1.4") and had a complex underneath geometry and interlock between them. It was placed on an inclined (10°) platform representing a building roof. The atmospheric boundary layer flow properties for testing paver B was normal flow, power law exponent 0.189 and turbulence intensity at roof height of about 6.5%. The measured external pressure was used as input for the mathematical model to calculate the underneath pressure and was compared with the measured one. Effects of paver size and geometry on the roof wind loading were also studied.

Findings

- The investigation showed that for a given external pressure distribution, the underneath pressure depended only on the ratio of the space between the pavers to the space underneath the pavers. When the ratio approached zero, the underneath pressure distribution was mostly uniform. On the other hand, the

- The study revealed that for a given aspect ratio of the paver, the maximum uplift pressure (the difference between the external and underneath pressure) increased with the decrease of the paver size. Also, for a given paver size, the maximum uplift increased with the increase of the aspect ratio.

- Developed model may not be applicable to other pavers with a different geometry.
- Model excluded the turbulence flow mechanisms that are developed beneath the pavers.
- Model lacks the application of conservation mass law and momentum.



2.4.2 Mechanically Attached Single-ply Roofing System

Mechanically attached SPR systems fall into two basic categories, spot fastener and strap fastener systems, based on the membrane attachment systems. In the spot attachment fastener system (Figure 2.3a) the membrane is fixed at discrete points. In strap fastener systems, parallel battens are used to restrain the movements of the membrane. These systems present a challenge for the designers to safely design them while considering the different aspects related to their behavior. Questions such as the magnitude of the balloon height of the membrane, membrane stresses and fastener stresses must first be answered before a safe design can be achieved. Contrary to the fully adhered and ballasted SPR systems, (Figures 2.3 (b) and (c)), only some research has been carried out to investigate the performance of mechanically attached SPR systems. This section reviews the research work done related to the numerical modeling of mechanically attached SPR systems

Easter (1990) applied the Finite Element Method (FEM) to EPDM membranes to investigate its response to wind uplift forces. The FEM model was built using the PATRAN program, whereas the analysis was done using the SAFEM software. A membrane shell element was used in the numerical simulation. In the analysis, the edge nodes were restrained against movements in all directions. To account for the excessive membrane deformations due to wind suction, large geometry deformation's capability was implemented in the FEM. The force required to restrain the line or batten was found at every node point. The size of the modeled membrane was 1524 x 2743 mm (60" x 108") to compare to the traditional factory mutual, (FM) 1524 x 2743 mm (60" x 108"). An EPDM membrane having Young's modulus of 2.689 MPa and battened in the seam was modeled. Batten strips were 2134 mm (84") apart and were fastened at 305 mm (12") intervals. Battens strips were placed parallel to the short edge 1524mm (60") and they were approximated by fixing a line of nodes with zero width.

Findings

- Results indicated a maximum fastener load of 1.245 kN (282 lbf) and strains of 90% for 5.746 kPa (120 psf) pressures.
- Ballooning phenomenon was predicted by the analysis and its maximum height was calculated as 1829 mm (72").
- Stresses at edges of the table were found to be larger than those at the batten plates because of the edge effect

- A single ply membrane with dimension of 3600 x 7200 mm (142" x 384") was also analyzed for a pressure of 4.309 kPa (90 psf) to compare with FM 3658 x 7316 mm (144" x 288") test. In this case, the ballooning height was calculated as 2438 mm (96").
- The study concluded that FEM modeling could substitute the large-scale wind uplift testing for roofing system subjected to very high loads and only small-scale tests were needed.

Limitations

- Similar to FM test procedure, the dynamic nature of the external pressures was not modeled.
- Only membrane was modeled without considering other roofing components such as insulation and decks.

Zarghamee (1990) studied the effect of the wind pressure on an inflated single-ply roofing membrane and its attachment mechanism. His theory contended that the behaviour of mechanically-attached single ply roof membrane is affected by air infiltration rate below the membrane, in addition to the external pressure changes occurring above it as shown in Figure 2.17. The governing differential equations, expressed in terms of the pressure underneath the inflated membrane, were derived using the flow continuity condition and solved numerically through iterative procedure. Computations were performed for a constant internal pressure, P_i and a sinusoidal varying external pressure, P_e . The frequency range of the exterior sinusoidal pressure was determined based on wind pressure power spectra values measured from wind tunnel for a roof of square plan building model. Zarghamee (1990 b) calculated three values, namely, volume under the inflated membrane, V_b ; vertical reaction per unit length at the boundary of the membrane, R ; and tension per unit width in the membrane, T ; to represent the membrane response. The three values were calculated using the following equations:

$$V_b = V_{bo} + \gamma A \alpha a \left[\frac{a}{EH} (P_b - P_e) \right]^{1/3} \quad (2.1)$$

$$R = \beta (P_b - P_e) a \quad (2.2)$$

$$T = \left(\frac{\beta}{2\alpha} \right) \left[a^2 E h (P_b - P_e)^2 \right]^{1/3} \quad (2.3)$$

where

- v_b = volume under the inflated membrane
- v_{bo} = volume of trapped air between the membrane and the roof deck
- A = projected area of the inflated membrane
- P_e = pressure outside the inflated membrane = $P_{eo} + P_{et} \sin \omega t$;
- P_{eo} = static component of wind pressure
- P_{et} = amplitude of the cycle exterior pressure component
- P_b = pressure inside the inflated membrane
- E = modulus of elasticity of the membrane
- h = membrane thickness
- a = one-half of the distance between supports for a strip membrane of the radius of the circular membrane
- α, β, γ = dimensionless coefficients dependant on the shape of the membrane

A developed mathematical model was then used to study the roofing system response. The effects of several parameters such as membrane stiffness, membrane thickness, membrane strip dimension, values of the external pressure and period of fluctuations of the external pressure were also investigated. The transient response factor (TRF) was used to quantify the results. TRF is defined as the ratio of the fluctuating component of pressure difference across the membrane thickness to the fluctuating component of external wind pressure. The results obtained from equations 2.1 through 2.3 were compared with those obtained using FEM analysis as shown in Table 2.6.

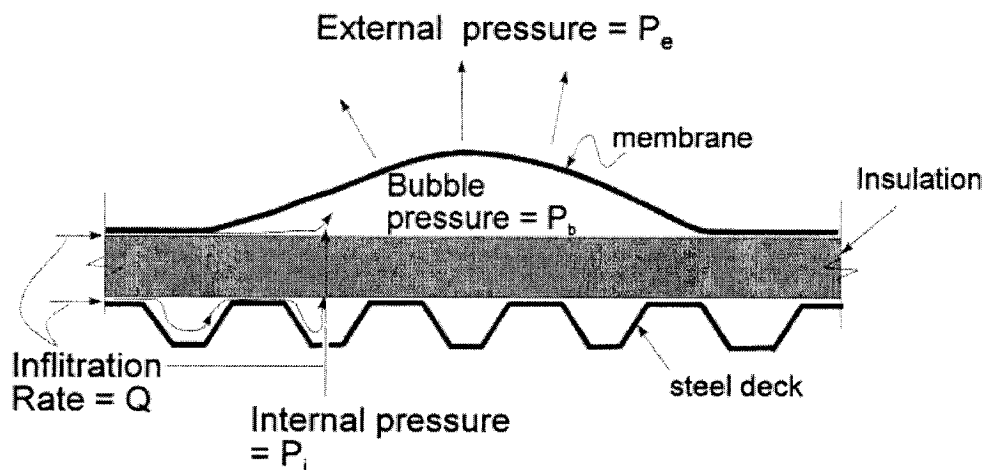


Figure 2.17 Inflated membrane and various pressure regions (Zarghamee, 1990)

Table 2.6 Comparison of the results with FEM analysis (Zarghamee, 1990)

Criteria	FEM	Analytical
Membrane tension(N/mm)		
Center of inflated membrane	5.0	5.3
Maximum at bar attachment	5.9	5.3
Average at mid-width	5.5	5.3
Maximum deflection (mm)	259	267
Maximum vertical reaction	5.5	5.3

Findings:

- It was shown that TRF depended on various factors such as the rate of air flow into the space underneath the membrane, stiffness of the membrane, upstream wind characteristic (period of fluctuating wind, mean hourly wind velocity and value of external pressure) and on the dimensions of the membrane.
- The study also reported that the failure mechanism of single-ply roofing membrane is initiated by air infiltration into the space underneath the membrane followed by ballooning of the membrane with fluctuations in wind pressure.
- If the membrane was laid flat on an air impermeable roof deck with no path for air movements then the membrane would not respond to wind fluctuating forces.

Limitations:

- Analysis did not consider the realistic flow conditions such as spatial variation of pressure with time over the building roof.
- Study applied only the conservation of mass law and exclude the momentum changes of the airflow movement
- Only the membrane was considered in the analysis and the contribution of the whole roof assembly in the response was ignored.
- The study was quasi-static because it ignored the dynamic effects (inertial effects) of the infiltrating air.
- Simplified approach developed by the study produced constant tensile stress across the membrane strip and thus the model was insensitive to the variation of stresses across the membrane.

Gerhardt and Kramer (1992) calculated the membrane stresses and fastener forces under static loads using the theory of a prestressed membrane. These efforts were made for collecting additional data during the development of UEATc test procedure (Gerhardt and Kramer, 1986). At any point with coordinates (x, y) under a constant load w, the membrane stresses, n_x and n_y as well as the vertical deflection, Z, were calculated through iterative procedure from the following equation:

$$n_x \frac{\partial^2 Z}{\partial x^2} + n_y \frac{\partial^2 Z}{\partial y^2} = -W \quad (2.4)$$

At the fastener locations, the membrane deflection, Z, was considered as zero. Using these boundary conditions, the membrane stresses and fastener loads were obtained. Gerhardt and Kramer (1992) investigated the effect of modulus of elasticity of the membrane and membrane thickness on the membrane deformation. In their calculations, the moduli were in the range of $E = 2$ MPa to 160 MPa. Equation 2.4 was applied for two typical fastening cases (Figure 2.18), namely, a field of five-by-five fasteners, and a field of nine-by-nine fasteners. The first case had dimensions: width, $m = 1200$ mm (47"); length, $l = 3800$ mm (150"); fastener row separation, $a = 900$ mm (35"); and fastener spacing (b) = 250 mm (10"). Both cases were analyzed under the effect of a wind suction, p , equalled 1800 Pa (38 psf). The theoretical fastener loads, W_{th} , were calculated by multiplying the wind pressure, p , with the influence areas, A_{inf} , as follows:

$$\begin{aligned} W_{th} &= p * A_{inf} \\ W_{1th} &= 1800 * 0.90 * 0.25 = 405N \\ W_{2th} &= 1800 * 0.50 * 0.25 = 225N \end{aligned} \quad (2.5)$$

Findings

- For a smaller aspect ratio, a/b and larger ratio, m/b , (the second case), the recorded fastener loads were larger with the central fastener carrying the highest load, about 78% of the theoretical fastener load. Also upon the failure of the central fastener, an increase of approximately 1.4 in the load of the next fastener was recorded.
- The modulus of elasticity of the membrane had very little effect on the distribution of fastener loads.

These research findings revealed that the table edge effect was a key-influencing factor affecting the roofing system performance. Based on a parameter study, varying in particular the aspect ratio of the fastener pattern a/b = fastener row separation /fastener spacing, the ratio of test rig width to fastener spacing m/b and the modulus of elasticity, the correction factor C_a = true load related to the theoretical load was developed as shown in Figure 2.19

The permissible load of the roofing system was determined from the experimentally obtained load W_{th} :

$$W_{all} = W_{th} \cdot C_a \cdot C_d \quad (2.6)$$

Where

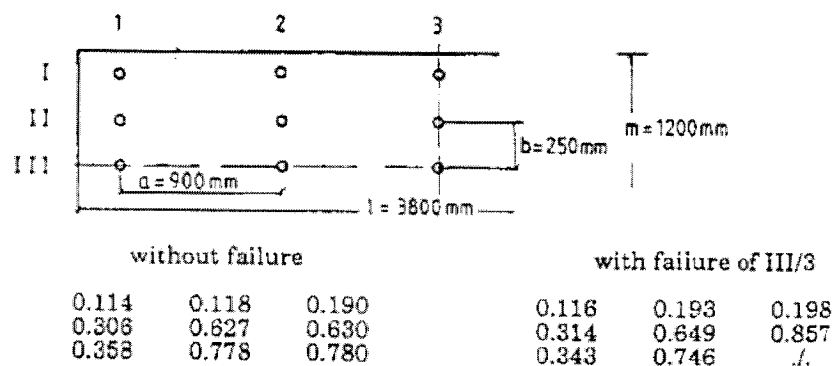
W_{all} = permissible load of a roofing system

C_a = geometrical correction factor

C_d = statistical correction factor to account for different failure probabilities

Limitations:

- Roofing system components such as insulation and decks were not considered in the study.
- Modeling technique was only able to compute fastener vertical forces.
- It was only possible to apply a constant static load.
- Dynamic nature of the external wind pressure was not considered.
- Modeling techniques of the applied FEM software are not well documented.
- The design fastener force is calculated with respect to the tributary area and failure pressure.
- The proposed geometric factor is only applicable to the UEAtc test protocol and is not verified for other table tests.



a) Small test specimen

	without failure			with failure of V/5		
	3	4	5			
III	0.993	0.993	0.993	0.993	1.000	1.033
IV	1	1	1	1.013	1.053	1.375
V	1	1	1	0.980	1.050	./.

b) Extended Roof Area ($a = 500 \text{ mm}$; $b = 250 \text{ mm}$; $l = 4760 \text{ mm}$; $m = 2250 \text{ mm}$)

Figure 2.18 Fastener load before and after failure of the central fastener
(Gerhardt and Kramer, 1992)

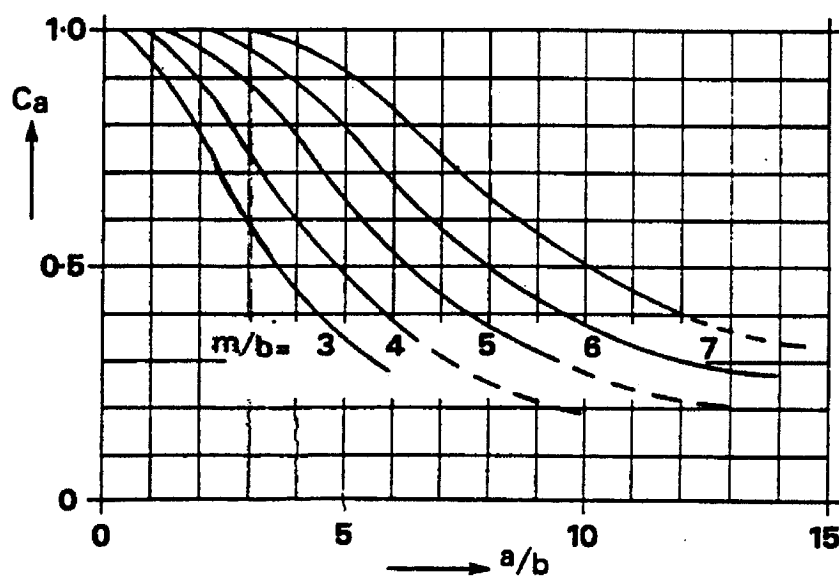


Figure 2.19 Geometric factor to account for test rig size vs aspect ratio
(Gerhardt & Kramer 1992)

Prevatt (1998), investigated the structural behaviour of the mechanically-attached single ply roofing system both experimentally and numerically. On the experimental side, six specimen sizes were run using EPDM, namely;

- 1524 mm x 2743 mm (60" x 108"), 2134 mm x 2134 mm (84" x 84"),
- 2438 mm x 2438 mm (96" x 96"), 1524 mm x 6096 mm (60" x 240"),
- 3048 mm x 3048 mm (120" x 120") and 3660 mm x 7315 mm (144" x 288"),

and three specimen sizes using TPO membrane namely

- 1524 mm x 2743 mm (60" x 108"), 3660 mm x 7315 mm (144" x 288"), and
- 2438 mm x 2438 mm (96" x 96").

Comparisons were made between the uplift pressures obtained with different sized specimens. Changes in load distributions along a fastener seam were also investigated. Finite element modelling was used to investigate whether an analytical method can be used to predict fastener failure loads based upon uplift pressures and chamber geometry. Using the commercially available finite element software package ABAQUS 5.6, the model was designed to observe the displacement behaviour of the reinforced single ply membrane subjected to uniform pressure, and the general stress-strain patterns developed in the membrane. Simulating the experimental specimens using finite element modeling showed a good agreement between the analytical and experimental fastener failure loads as shown in Table 2.7. The experimental study compared the tributary load (failure pressure x tributary area) with the measured load and also investigated the effect of pre-tension load and modulus of elasticity on the experimental results.

Table 2.7 Comparison of fastener failure loads from experiments with analytical results
(Prevatt, 1998)

Specimen Size		Failure Pressure		Experimental Load		Analytical Load		% Difference
mm	in	Pa	psf	N	lbf	N	lbf	
3660 x 7315	12 x 24	3304	69	2002	455	2028	461	-1.33
3048 x 3048	10 x 10	3974	83	1910	434	1892	430	0.91
2438 x 2438	8 x 8	5027	105	1782	405	1901	432	-6.31
2134 x 2134	7 x 7	5075	106	1804	410	1461	332	23.6
1524 x 2743	5 x 9	5458	114	1861	423	1804	410	-3.32
1524 x 6096	5 x 20	5075	106	1729	393	1531	348	12.87

Findings

- A 2400 × 2400 mm (96" × 96") table appears to be sufficient for providing reasonable accurate results to allow the calculated fastener load based on the assumed tributary area times the system failure pressure
- The minimum table width should be at least 1.5 times the fastener row spacing (aspect ratio greater than 1.5)
- If a table has an aspect ratio less than 1.5, a correction factor needs to be developed to convert the calculated fastener load to actual fastener load.
- Load redistribution occurs along line of fasteners with fasteners adjacent to boundary loses load, while the fasteners in the middle gain load.
-

Limitations:

- The numerical study focused only on the EPDM systems
- Though the idea of correction factor is discussed, the study does not present any developed correction factors.

2.5 Concluding Remarks

The content of this chapter presented an elaborate literature review of the following:

- fundamental understanding about single ply roofing system
- existing wind uplift standard performance tests for the evaluation of flexible membrane roofing system and the,
- analytical studies for the prediction of the wind uplift performance of single-ply roofing systems

When reviewing the existing test methods, it was evident that tables with different aspect ratios are being used for the wind uplift evaluation of roofing systems. Most test methods were developed for specific roofing systems without any reference to others. Also, there is no consensus on the test table size to be used by testing protocols in spite of the concern the aspect ratio of the testing table play a significant role in evaluating roofing system performance. The review of all the existing numerical studies indicated that limited studies have been conducted to evaluate the performance evaluation of a flexible membrane systems, in particular the mechanically attached systems. In spite of the limitations of these research studies, the results can still be extended to other similar materials with the same attachment methods.

Chapter 3

Numerical Modeling of Mechanically Attached Roofing Systems

3.1 General Review

FEM analysis of roofing systems has not been able to match the development and cost benefits in comparison to the experimental techniques. When used as a research tool, as in this study, FEM analysis techniques afford greater flexibility in exploring scenarios that are difficult to set up experimentally.

As discussed in Chapter 2, minimal data is available on the physical behaviour of single-ply membranes applying finite element analysis methods. The parameter variables such as fastener spacing, membrane size, roofing component material properties and wind pressure load sequence can affect roofing system responses. When reviewing the existing test methods it is evident that tables with different aspect ratios are being used for the wind uplift evaluation of roofing systems. Despite the differences in the testing table aspect ratio and the significance of the edge effects on the roofing system performance, there is no existing criteria or standard to recommend a required table size for a specific MAS configuration.

An investigation of the effect of table size on roofing system performance is an ideal opportunity to explore the modeling capabilities of numerical approaches. The previous work (Baskaran and Borujerdi, 2004) investigated the influence of table edges on the system response for three thermoplastic systems with membrane widths of 1219 mm (48"), 1828 mm (72") and 3048 mm (120") thermoplastic system and for one thermoset system of 1981 mm (78") wide. The table edge effects were also investigated on systems by simulating 1000 mm (39") wide modified bituminous membranes (Zaharai and Baskaran, 1999). Model validation and required table sizes were identified for the different system configurations (Fr/Fs) and correction factors were developed. The present research study addresses some of the key aspects of the performance of MAS relative to the existing roofing market, which have not been covered in the previous work. Due to the advancement in membrane technology, wider membranes are now available in the market and are used in commercial roofing practice as it reduces the installation cost. None of the existing test protocols (Section 2.4) has the appropriate

table sizes for the evaluation and certification of these wider membranes. To address the performance evaluation of these wider membranes, a numerical modeling approach has been selected by the present study.

This numerical study has been divided into three chapters. The present chapter describes the selection of the numerical model and the validation of the developed model. Using the validated model, Chapter 4 focuses on the numerical modeling of mechanically attached systems with wider membranes. The concept of Required Table Width and correction factors will be introduced in that chapter. Specific parameters influencing the performance of MAS such as, the effects of specimen size, membrane type, fastener row spacing (F_r) and fastener spacing (F_s) will also be investigated. Chapter 5 discusses a generalized approach for developing correction factors for MAS and various chamber sizes such that it can be of practical use to determine the wind uplift resistance of roofs.

3.2 Finite Element Model

Finite element based software programs for the design and analysis of structures have become more common in Civil Engineering practice. A simple graphical user interface with extensive variety of structural modeling makes the simulation and analysis easy. The convenience comes from the numerical techniques used in the software. ABAQUS version 6.3, a commercially available Finite element program having potential to solve problems ranging from simple linear analysis to the more challenging nonlinear simulations, has been selected to carry out all the numerical analysis for the present study. ABAQUS contains a library of elements that can model various material geometries and simulate the behaviour of an extensive list of materials including rubber, metal and polymers. ABAQUS has the flexibility of defining a complex system geometry and varying applied loads. For example, ABAQUS eliminates all unnecessary nodes before performing the analysis. This feature is useful since it allows points to be defined as nodes for node generation purpose. The present numerical model can predict the response of linear or nonlinear analysis systems. In a nonlinear analysis the solution cannot be calculated by solving a single system of linear equations, as would be done in a linear problem. The Riiks Algorithm was used to solve the simultaneous equations generated. The algorithm is a result-seeking routine that is suited to solving non-linear problems. The solution arrives at discrete increments at which all forces on the structure

must be in equilibrium and the program continues further. The new coordinates of the displaced shapes are then used as input for the next increment, and so on until the solution converges.

3.3 Numerical Modeling of Single-ply Roofing Systems

Using the FEM, the mechanically attached thermoplastic and thermoset systems are simulated. An input data file, which replicates the roofing system configuration, has been prepared i.e the model and history data. The model data defines the geometric system configuration such as nodes, elements and material properties while the history data addresses the sequence of loading for which the model response is sought. The history data is also defined as a sequence of steps. Each step is a response period for a particular type of loading. The result of finite element analysis is created in the output text file. The output file format depends on which nodes and element are selected for analysis and it also could be shown in graphical format. Appendix 1 and 2 illustrates a typical input data files.

3.3.1 Finite Element Mesh

Figure 3.1 shows a typical numerical model representation for the experimental single-ply roofing system. Only membrane properties were considered in the numerical modeling, owing to the greater flexibility of membrane compared to other components in the roofing systems. As this study is focused more on the behavior of the membrane with respect to the table width, only membrane deflections were considered in the numerical modeling. The deflections of the steel deck and insulation were assumed small in comparison to the membrane deflection.

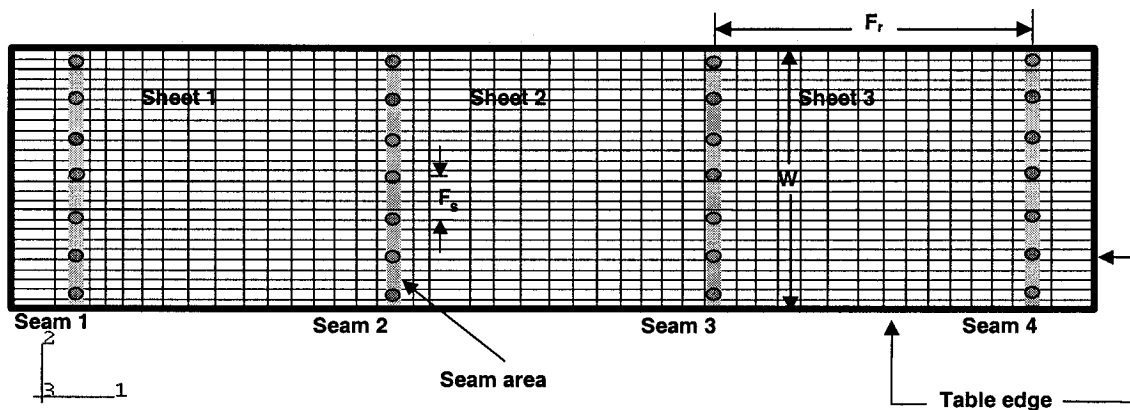


Figure 3.1 FEM representation of typical MAS

The model data defines the geometry layout and material characteristics of the roofing components. To simulate the membrane, a rectangular grid of 4-node and shell elements was used to discretize the elements. Element type S4 accounts for finite membrane strains and will allow for change in thickness. Therefore, S4 is suitable for large-strain analysis involving materials with a nonzero effective Poisson's ratio. This element fully integrates the finite-membrane-strain shell element. The membrane's response is treated with an assumed strain formulation that gives accurate solutions to in-plane bending problems and which is not sensitive to element distortion.

Figure 3.2 shows a typical simulated seam, plates and fastener of the roofing system. Seams details were modeled by doubling the thickness of shell element areas to simulate the overlap region of the membrane. The other material characteristics of the seams remain the same as membranes. SPRING elements were used to simulate fastener attachments with the steel deck. Fasteners were assumed as spring supports with axial stiffness (vertical degree of freedom). Changing the material properties on the corresponding shell elements simulated the fastener plates.

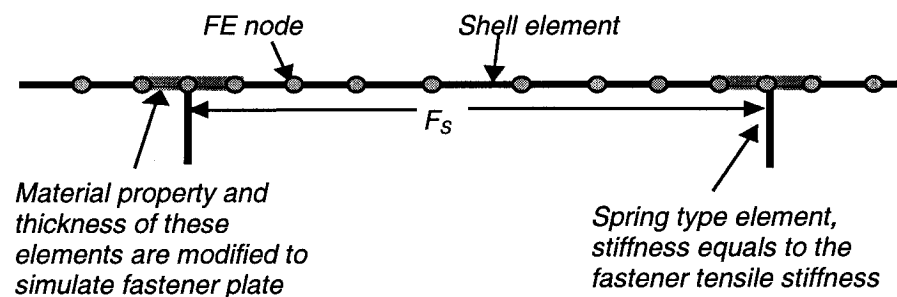


Figure 3.2 Typical seam, fastener and fastener plate details for numerical modeling

3.3.2 History Data

The history data is added to the input file for simulation of the applied forces on the model. A history data is defined by:

- Dividing the problem history into steps;
- Specifying an analysis procedure for each step; and
- Prescribing loads, boundary conditions, and output requests for each step.

Dividing the problem history into steps: A basic concept in the present numerical approach is the division of the problem history into steps. In other words, a step is any convenient phase of the history or each step is a period of response of a particular type

of loading. A general analysis step, whose response can be either linear or nonlinear, was chosen. The starting condition for each general step is the ending condition of the last general step, with the state of the model evolving throughout the history of general analysis steps as it responds to the loading history. The NLGEOM option was selected to include large-displacement effects. Nonlinearities can arise from geometric nonlinearity (change of shape of the structure), material nonlinearity (change of material properties), and/or boundary nonlinearities such as contact and friction. When this option is chosen, most elements are formulated in the current configuration using current nodal position. Therefore elements can distort from their original shapes as the deformation increases. In other words, the membrane, which is flat at the beginning, is allowed to balloon during the loading.

Specifying an analysis procedure for each step: The model has several types of analysis procedures to assign for each step. The static stress analysis was chosen for the numerical modeling since a) inertia effects can be neglected; b) the analysis can be linear or nonlinear and c) it ignores time-dependent material effects; however, it takes rate-dependent plasticity into account.

Prescribing loads, boundary conditions, and output requests for each step: During this step the initial time increment, the time period of the step, minimum and maximum time increment values are assigned. If the user does not provide a suggested initial increment size, the program will attempt to apply all of the loads defined in the step in a single increment. For highly nonlinear problems one can reduce the increment size repeatedly to obtain a solution, resulting in wasted CPU time. It is advantageous to provide a reasonable initial increment size, because the loads in a step can be applied in a single increment only if the problem is quasi-nonlinear.

The boundary conditions are also defined in the history data. In the experimental layout, the membrane edges were held by clamps to restrict any movement. In the model, the perimeter edge nodes were simulated so as to have only rotational degree of freedom. The roofing system was subjected to a uniform static uplift pressure up to 4.31 kPa (90 psf). In the last step, the format of the output file was defined. This option allows the user to select the stresses and displacements for specific nodes and elements. The user can also request output results at the end of each step for multi-step analysis.

3.3.3 Analysis Procedure and Output

In the nonlinear analysis the solution cannot be calculated by solving a single system of linear equations, as would be done in a linear problem. Instead, the solution is found by specifying the loading as a function of time and incrementing time to obtain the nonlinear response. Therefore, the present study breaks the simulation into a number of time increments and finds the approximate equilibrium configuration at the end of each time increment. Then, the final solution from the previous load step is used as the initial solution for the next load step.

Newton's method has been used to solve the nonlinear equilibrium equations. Consider the system of n nonlinear equations of the form $f_i(x) = 0$, ($i = 1, \dots, n$), where x denote the solution variables. With an initial estimate of the solution $\{x_i\} = \{a_i\}$, the function can be expanded about $\mathbf{a}$ in n -space using Taylor's series:

$$f_i(\mathbf{a}) + J(\mathbf{a}) \delta = 0 \quad (3.1)$$

where J is the Jacobian of derivatives evaluated at $\mathbf{a}$.

$$J(x) = \begin{bmatrix} \partial f_1 / \partial x_1 & \partial f_1 / \partial x_2 & \dots & \partial f_1 / \partial x_n \\ \partial f_2 / \partial x_1 & \partial f_2 / \partial x_2 & \dots & \partial f_2 / \partial x_n \\ \vdots & \vdots & \ddots & \vdots \\ \partial f_n / \partial x_1 & \partial f_n / \partial x_2 & \dots & \partial f_n / \partial x_n \end{bmatrix}$$

The solutions to the linear system are the set of deviations $\{\delta_i\}$, which are used to calculate the new approximations to the solution variables of the nonlinear system from the initial solutions a_i , using Equation (3.2)

$$x_i = a_i + \delta_i \quad i = 1, \dots, n \quad (3.2)$$

In nonlinear problems, the challenge is always to obtain a convergent solution in the least possible computational time. Convergence of the Newton's method is highly dependent on the nonlinearity of the functions and the choice of the initial solution. Thus for small loads, which produce small displacements, convergence is likely. For larger loads the convergence probability may be improved by splitting up the applied loads into incremental load steps, and applying them sequentially. Therefore, the solution is usually obtained as a series of increments, with iterations to obtain equilibrium within each increment. Increments must sometimes be kept small (in the sense that rotation and strain increments must be small) to ensure correct modeling of history-dependent

effects. Most commonly, the choice of increment size is a matter of computational efficiency: if the increments are too large, more iterations will be required. Furthermore, Newton's method has a finite radius of convergence; too large an increment can prevent any solution from being obtained because the initial state is too far away from the equilibrium state that is being sought (it is outside the radius of convergence). Thus, there is an algorithmic restriction on the increment size. The selected model automatically adjusts the size of the time increments to solve nonlinear problems efficiently. The number of iterations needed to find a converged solution for a time increment can vary depending on the degree of nonlinearity in the system.

3.4 Validation of the Numerical Model

Experimental data obtained from the DRF (Figure 2.11) was used to benchmark the developed model. Figure 3.3 shows a typical layout of 67/12 mechanically attached thermoplastic system used in the experimental investigation. Further on, set arrangements of this nature will be referred to as configuration 67/12. The first number in the pair represents the fastener row spacing and the second number accounts for the fastener spacing and both are expressed as inch unit. Similarly, Figure 3.4 shows a 78/12 mechanically attached thermoset system used in the experimental investigation. For benchmarking the numerical model, two more additional thermoplastic system configurations (48/18 and 72/18) and one additional thermoset system (78/6) were selected. The roofing system configurations were evaluated using both the FM and SIGDERS dynamic load sequences to measure the maximum fastener force and membrane deflection. Table 3.1 and Table 3.2 tabulate the experimental data derived from the time history response measurements of thermoplastic and thermoset roofing systems. Figure 3.5 shows the typical time histories for the measured pressure, fastener forces and membrane deflections of the tested thermoplastic obtained from the static and dynamic test protocols.

On the numerical investigation, three different input files were created for the simulation of 48/18, 67/12 and 72/18 thermoplastic system configurations and for the thermoset system two configurations of 78/6 and 78/12 were simulated. The models have a uniform static uplift pressure up to 4.31 kPa (90 psf) on the membrane. The load is defined as a function of time in order to obtain the nonlinear system response. Thermoset membrane tensile properties are significantly different from thermoplastic membranes, which

warrant modification in the developed model. Figure 3.6 shows the stress-strain relation for thermoplastic and thermoset membranes based on a tensile testing of the membranes in accordance to the ASTM D 751-98. A typical computer generated depiction of a deflected membrane is shown in Figure 3.7. It shows the membrane ballooning occurring between fastener rows and table edges. A full model of the configuration is also shown to reveal the existence of symmetry. This modeled 67/12 configuration has a maximum deflection of 117 mm (4.6") at the middle of the membrane for the uniform wind uplift pressure of 1.44 kPa (30 psf). Figure 3.8 shows the typical computed fastener force distribution for the 67/12 thermoplastic configuration. The results show that the fastener forces increase along the seam when the fasteners are away from the edges. For the 1.44 kPa (30 psf) pressure the seam two, has the maximum fastener force of 533 N (120 lbf), while the minimum fastener force for the same seam is 80 N (18 lbf)

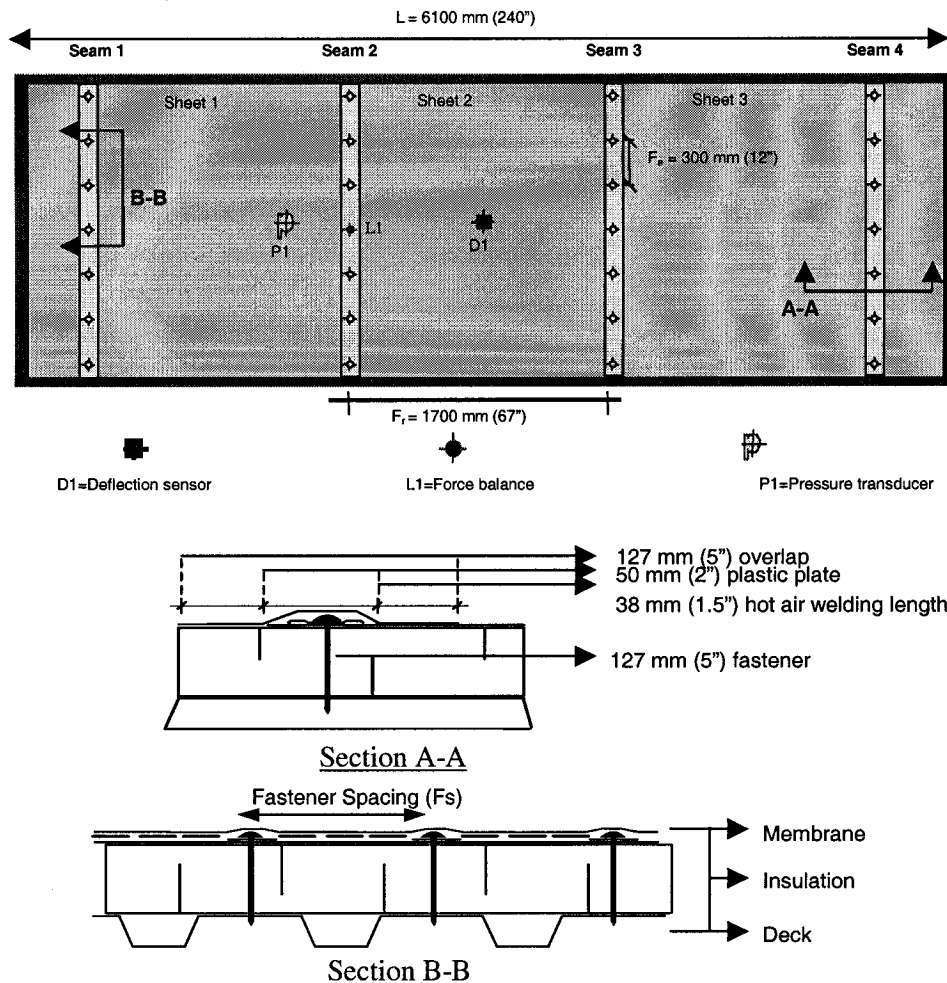


Figure 3.3 67/12 thermoplastic system configuration and seam details

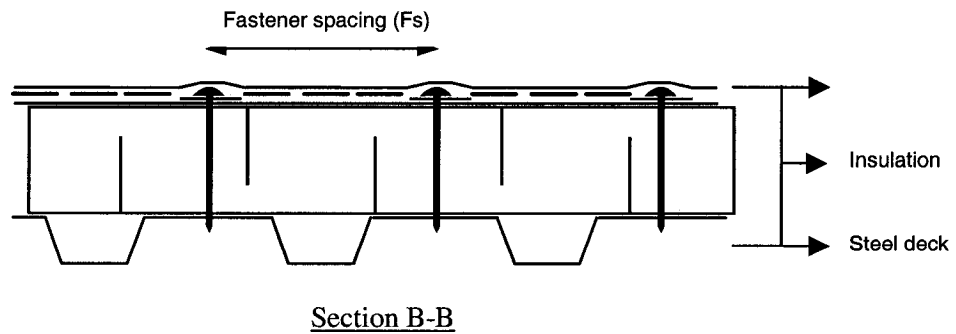
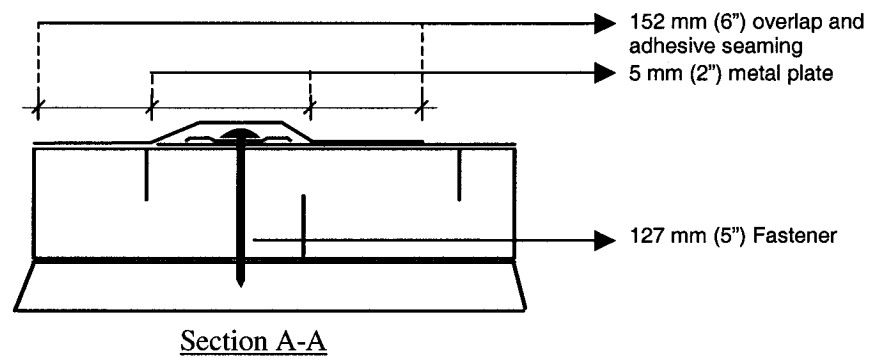
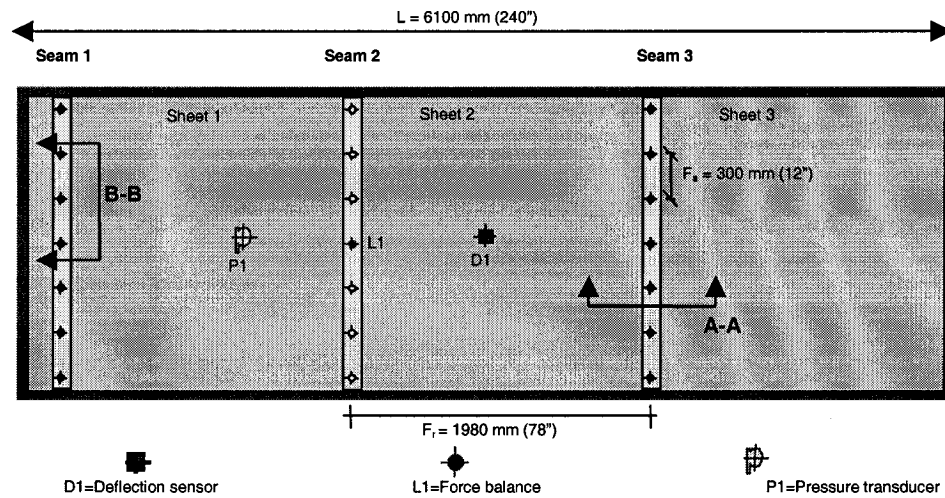


Figure 3.4 78/12 thermoset system configuration and seam details

Table 3.1 Experimentally measured pressure, fastener load, and membrane deflection for thermoplastic systems

Configuration type	Wind Load cycle	Pressure kPa (psf)	Fastener force N (lbf)	Membrane Deflection mm (in)
48/18	FM	1.44 (30)	769 (173)	110 (4.3)
		2.15 (45)	1071 (241)	135 (5.3)
		2.87 (60)	1382 (311)	155 (6.1)
		3.59 (75)	1667 (375)	200 (7.9)
	SIGDERS	0.91 (19)	444 (100)	95 (3.7)
		1.82 (38)	844 (190)	125 (4.9)
		2.73 (57)	1133 (255)	155 (6.1)
67/12	FM	1.44 (30)	516 (116)	136 (5.4)
		2.15 (45)	764 (172)	170 (6.7)
		2.87 (60)	1004 (226)	198 (7.8)
		3.59 (75)	1187 (267)	217 (8.5)
		4.31 (90)	1347 (303)	228 (9.0)
	SIGDERS	0.86 (18)	369 (83)	120 (4.7)
		1.72 (36)	707 (159)	160 (6.3)
		2.59 (54)	951 (214)	190 (7.5)
72/18	FM	1.44 (30)	591 (133)	140 (5.5)
		2.15 (45)	867 (195)	170 (6.7)
		2.87 (60)	1178 (265)	195 (7.7)
		3.59 (75)	1378 (310)	233 (9.2)
	SIGDERS	0.72 (15)	333 (75)	55 (2.2)
		1.44 (30)	644 (145)	130 (5.1)
		2.15 (45)	844 (190)	155 (6.1)
		2.87 (60)	1000 (225)	175 (6.9)

Table 3.2 Experimentally measured pressure, fastener load, and membrane deflection for thermoset systems

System Configuration	Wind Load Cycle	Pressure kPa (psf)	Fastener Force N (lbf)	Membrane Deflection mm (in)
78/6	FM	1.44 (30)	423 (95)	140 (5.5)
		2.15 (45)	667 (150)	165 (6.5)
		2.87 (60)	823 (185)	191 (7.5)
		4.31 (90)	1001 (225)	244 (9.6)
		5.03 (105)	1246 (280)	267 (10.5)
78/12	FM	1.44 (30)	845 (190)	152 (6)
		2.15 (45)	979 (220)	180 (7.1)
		2.87 (60)	1268 (285)	206 (8.1)
		3.59 (75)	1624 (365)	234 (9.2)
		4.31 (90)	1890 (425)	259 (10.2)
	SIGDERS	0.91 (19)	480 (108)	127 (5)
		1.77 (37)	907 (204)	160 (6.3)
		2.59 (54)	1085 (244)	188 (7.4)
78/12*	FM	1.44(30)	885 (199)	178 (7)
		2.15 (45)	1112 (250)	211 (8.3)
		2.87 (60)	1467 (330)	236 (9.3)
		3.59 (75)	1757 (395)	264 (10.4)

** Repeated test*

FM protocol

SIGDERS protocol

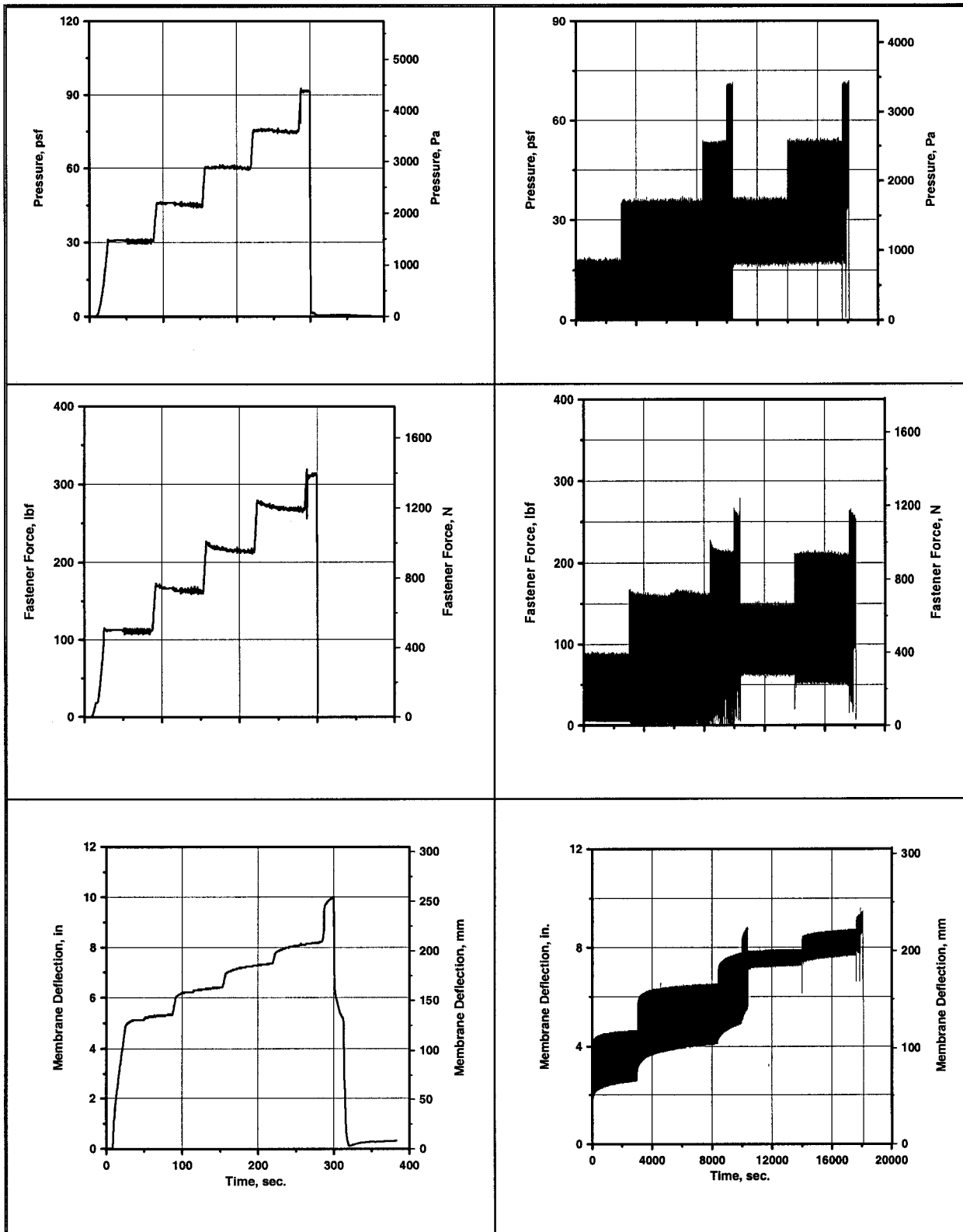


Figure 3.5 Typical system response of 67/12 thermoplastic system configuration

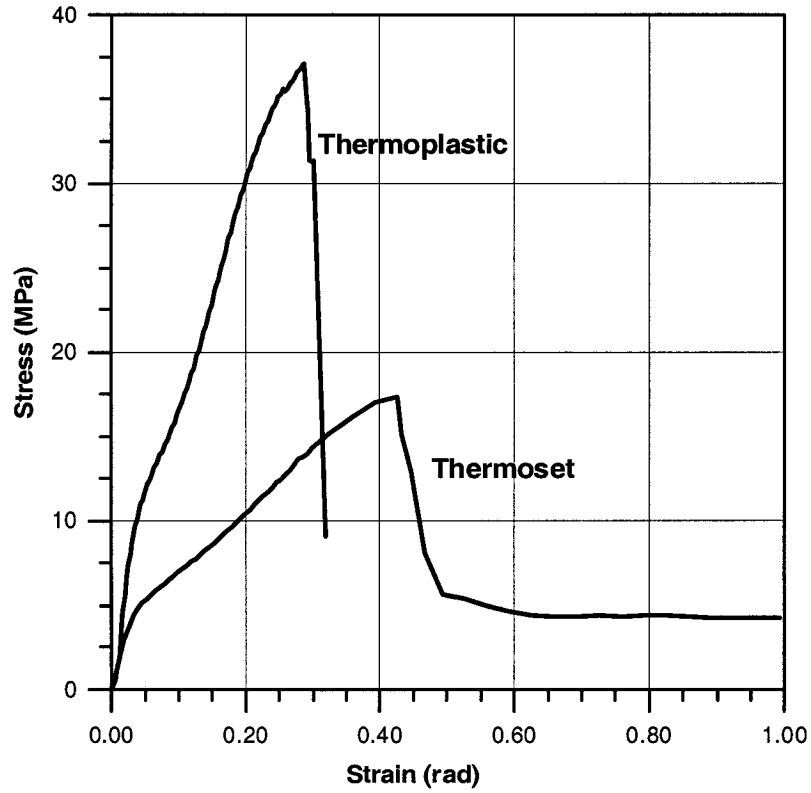


Figure 3.6 Comparison of the tensile strength for thermoplastic and thermoset membranes

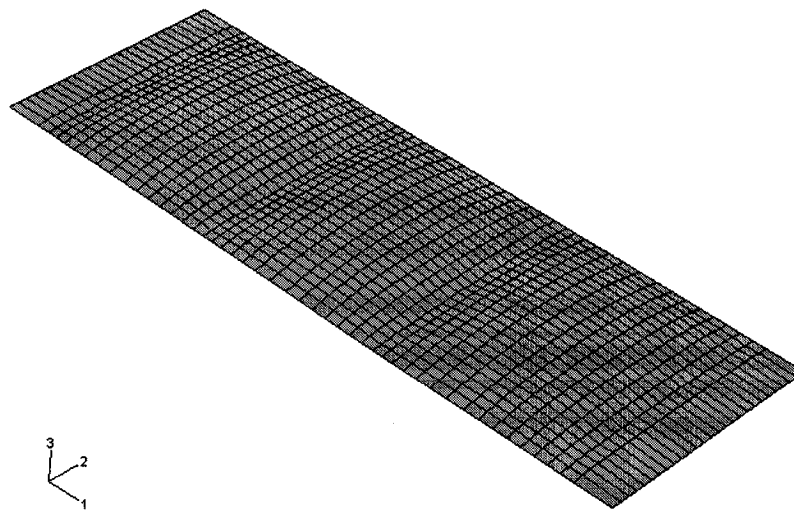


Figure 3.7 Deflected shape of the thermoplastic membrane for the 67/12 configuration at 30 psf (1436 Pa)

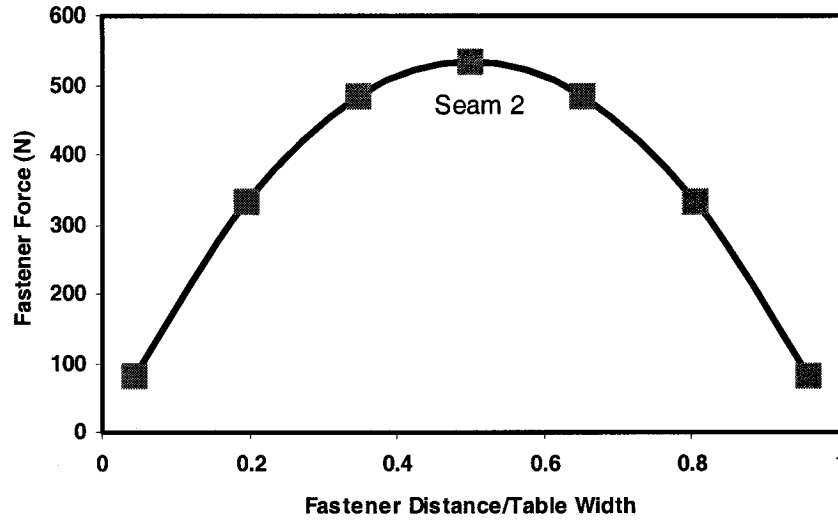


Figure 3.8 Variation of computed fastener forces for 67/12 thermoplastic configuration at 30 psf (1436 Pa)

The developed numerical model was benchmarked with the experimental data obtained from the Dynamic Roof Facility (DRF) for the thermoplastic and thermoset systems. It has to be noted that the numerical model has been developed to predict the performance rather to simulate the failure mode or ultimate strength of the experimental roofing systems. Average values of two characteristic parameters, i.e., fastener loads and membrane deflections measured from the DRF experiments were compared with the output of the FEA (Finite Element Analyses). Comparisons of fastener forces between the experimental and FEA modeling are shown in Figure 3.9, in which the horizontal axis represents the applied suctions on the roofing assembly and the vertical axis represents the fastener forces of the roofing systems response for the applied pressure.

The following expression was used to establish deviations between the two data sets (Experiments versus Numerical Model):

$$\Delta F = \frac{1}{N} \sum_{i=1}^N \frac{F_{NM} - F_{EXP}}{F_{EXP}} \times 100 \quad (3.3)$$

where : F_{NM} = fastener force obtained from the numerical model

F_{EXP} = fastener force obtained from the experimental evaluation

N = number of cases (pressure levels) considered for each configuration

ΔF = fastener force deviation between F_{NM} and F_{EXP} . ΔF with a negative sign (-) means that the model underestimates the roofing system response compared to the experimental approach and vice versa

For the case of $F_r/F_s = 67/12$, an under-estimation of 7% by the FEA model was found. Similar comparisons for the 48/18 and 72/18 configurations respectively revealed 2% and 10% deviations (over-estimations) of the analytical model from the measured fastener loads. Using deflection instead of force in equation 3.3, comparison was made for membrane deflections and Figure 3.10 presents the model validation for the prediction of the membrane deflection for the thermoset system. Table 3.3 illustrates a typical example of the calculation of average deviation for the 67/12 thermoplastic system

Table 3.3 Calculation of average deviations for the fastener force and membrane deflection for the 67/12 thermoplastic roofing system configuration

Experimental			FEM			% Deviation	
Pressure, Pa	Deflection, mm	Fastener Force, N	Pressure, Pa	Deflection, mm	Fastener Force, N	% Deviation (Force)	% Deviation (Deflection)
862	120	369	967	100	376	1.95	-16.42
1436	136	516	1290	112	470	-8.91	-17.50
1724	160	707	1612	123	588	-16.74	-23.44
2155	170	764	2096	136	735	-3.76	-20.00
2586	190	951	2579	148	874	-8.13	-22.21
3399	211	1133	3305	163	1069	-5.68	-22.65
Average Deviation						-6.88	-20.37

Irrespective of the roofing system configurations, the numerical model always underestimates the membrane deflections. One of the reasons for the difference between these results is caused by the difference in the edge conditions of the model. In the numerical model, all four edges are restrained from any movements whereas in the experimental set up membrane slippage from the edges of the test frame may happen during the testing of the roofing system.

Considering the material properties of the thermoplastic ($E = 300$ MPa, $\nu = 0.4$) and thermoset ($E = 150$ Mpa, $\nu = 0.4$) membrane, the thermoset membrane has a tendency to stretch more when compared to the thermoplastic membrane. The edge treatment of the thermoset system is different from the thermoplastic system as shown in Figure 3.11 and 3.12. In the thermoplastic system, the slippage rod is applied all along the frame edges as shown in Figure 3.11. During wind uplift testing the stiffness of the membrane

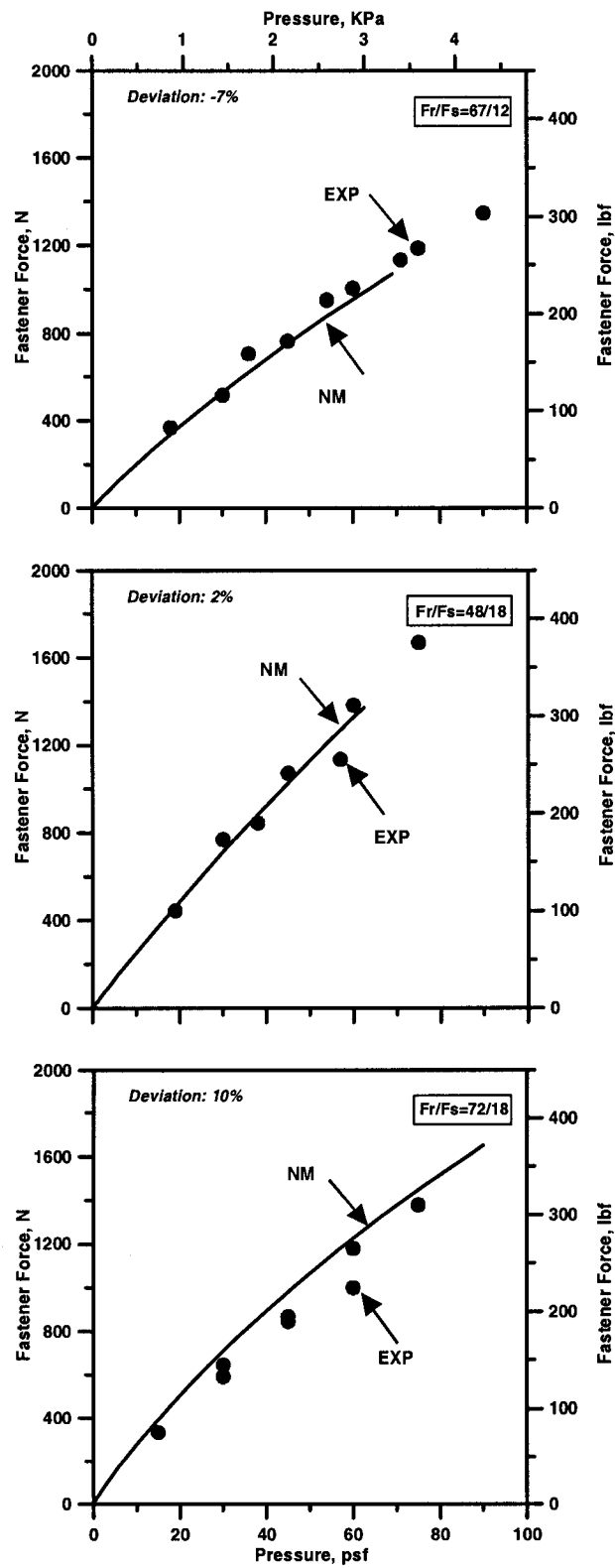


Figure 3.9 Model validation for thermoplastic system - fastener force (Baskaran and Borujerdi, 2001)

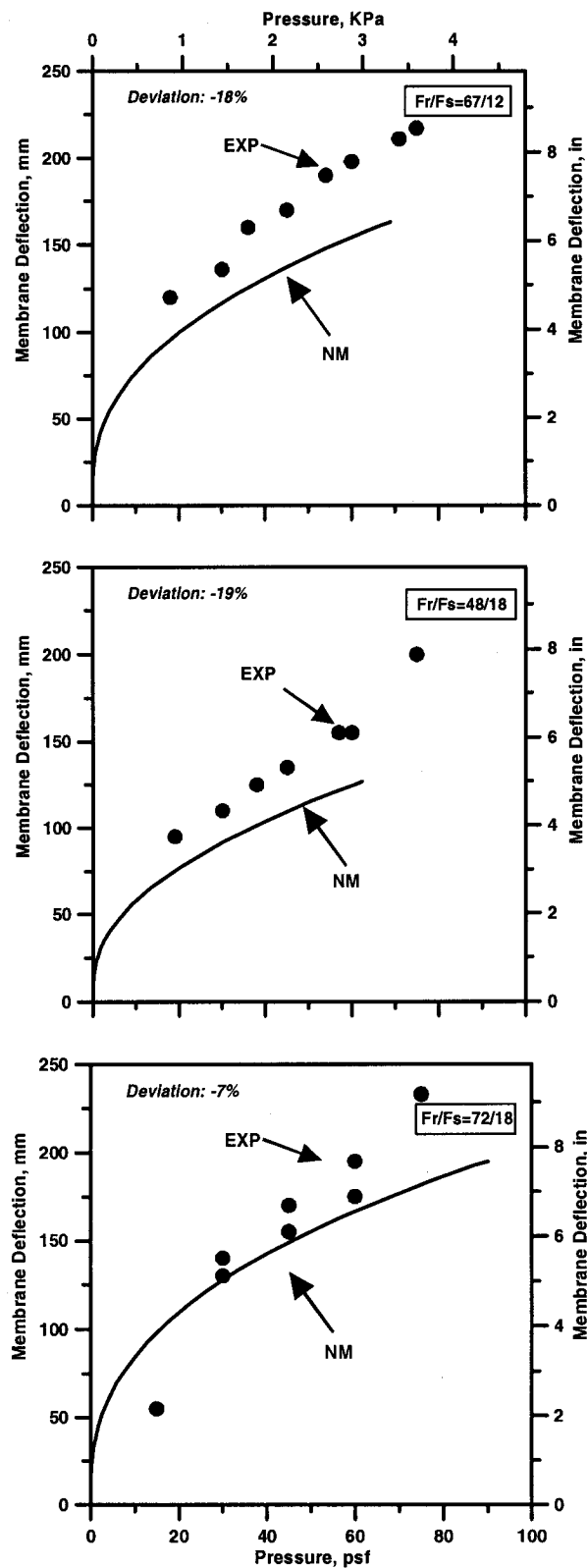


Figure 3.10 Model validation for thermoplastic system – deflection
(Baskaran and Borujerdi, 2001)

tends to pull the membrane along the table edges. Due to this membrane slippage, the measured deflection of the thermoset membrane in the lab is the summation of the true membrane uplift and membrane slippage whereas the model computes only membrane uplift. In the case of thermoset system the overhang membrane is wrapped over the bottom frame and bolted as shown in Figure 3.12. When the system is subjected to wind load, due to the tightness of the edge treatment there is no membrane slippage and the elastic property of the thermoset membrane tends to stretch the membrane. Therefore, the measured deflection of the thermoset membrane in the lab is the true membrane uplift., which deviates very less from the model.

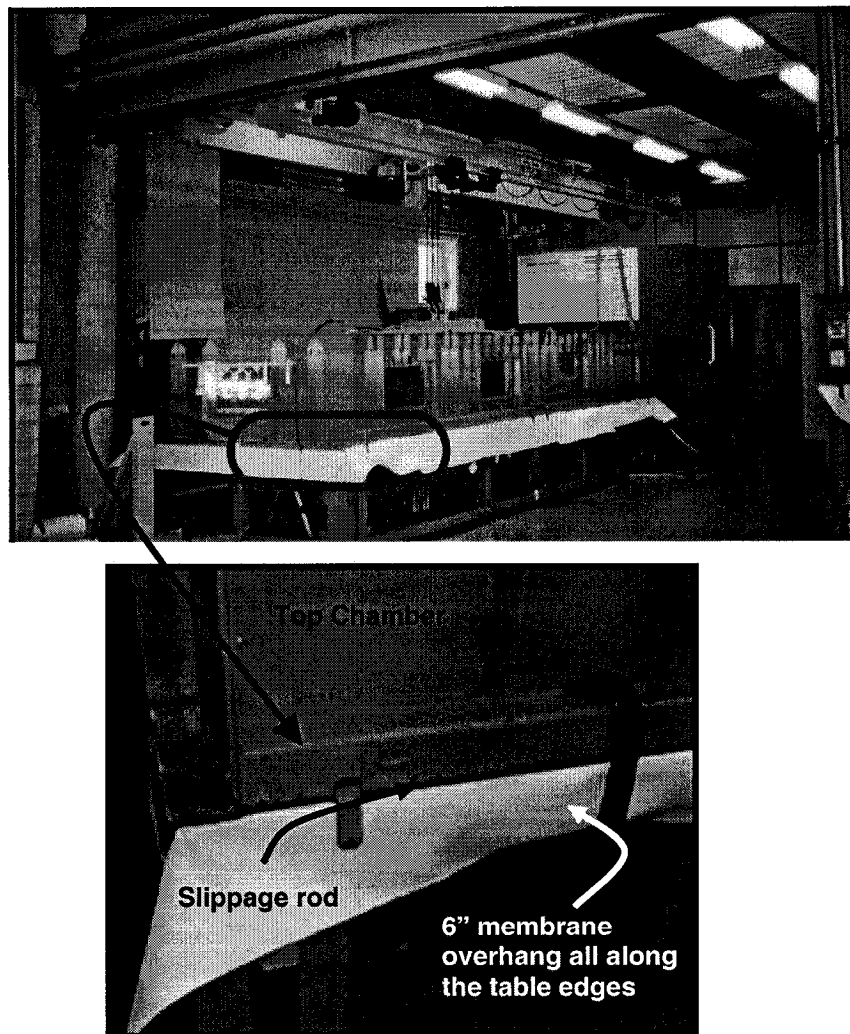


Figure 3.11 Edge treatment of the thermoplastic membrane system

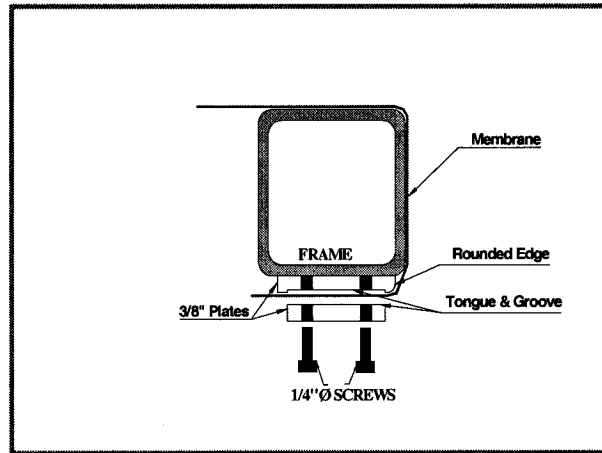


Figure 3.12 Edge treatment of the thermoset membrane system

Similar comparison of fastener forces and membrane deflection between the experimental and numerical modeling for the case of $F_r/F_s = 78/6$ thermoset systems, showed an under-estimated value of 5% by the numerical model, while the 78/12 configurations showed 3.5% deviations (under-estimations) and the variations in the deflection for 78/6 and 78/12 configurations were 2.5% and -4.5% respectively.

Table 3.4 shows the average deviations for the fastener force and membrane deflection for both the thermoplastic and thermoset systems. The average results reveals the finite element model is a viable tool that can be used to predict the fastener forces and membrane deflections of thermoset test specimens at any pressure level.

Table 3.4 Model validation

Thermoplastic	67/12	48/18	72/18	Average
Force Deviation	-7%	2%	10%	1.7%
Deflection	-18%	-19%	-7%	-14.7

Thermoset	78/6	78/12	Average
Force Deviation	-5%	-3.5%	-4.3%
Deflection Deviation	2.5%	-4.5%	-1.0%

Note: Average with a negative sign (-) means that the model underestimates the roofing system response compared to the experimental approach and vice versa

3.5 Concluding Remarks

FEM analysis techniques afford greater flexibility in exploring scenarios that are not economical to set up experimentally. The effect of table size on roofing system performance is an ideal opportunity to explore the modeling capabilities of numerical approaches. This chapter described the selection of the Finite Element Method software and the validation of the developed model. Using FEM, the mechanically attached thermoplastic and thermoset systems were simulated. The numerical model has been developed to predict the performance rather than to simulate the failure mode or ultimate strength of the experimental roofing systems. The model was validated with the average values of two characteristic parameters, i.e., fastener loads and membrane deflections measured from the DRF experiments. Numerical results for various system configurations compared well with those obtained from the experimental studies.

Chapter 4

Application of the Numerical Model - Wind Uplift Resistance of Mechanically Attached Systems with Wider Membranes

4.1 General Review

Currently single-ply membranes are available in the market with membrane widths of up to 3660 mm (144"). The wider membranes provide savings on installation costs by reducing the number of overlaps to be seamed in the field, reducing fasteners and plates for attachment, fewer rolls for the roofing applicator to handle on the roof, and less membrane being utilized in the seam overlaps.

Field performance of systems with wider membranes remains questionable; as they are relatively new in the roofing community. With wider membranes wind uplift resistance design of roofs is more challenging than the narrower membranes. A wider membrane or a longer fastener row spacing increases the fastener influence area thereby inducing higher fastener loads. Therefore, testing these wider membranes on the existing narrow test tables may not simulate the field uplift performance of the roofing assembly. One approach is to apply appropriate correction factors for the roofing system response that is tested on a narrow table.

This chapter presents the modeling aspect of the wider membranes using the validated numerical model. This will be undertaken as follows:

- A brief review of the table size effect and the existing tables used in the roofing industry
- Investigate the effect of table size on roofing systems with wider membranes
- Investigate the effect of table length on the roofing system response

4.2 Effect of Table Size

Though the test specimen layout is similar to the field roof [e.g. the fastener row spacing (F_r), fastener spacing (F_s)] the aspect ratio of the test frame is normally smaller than that of the field roof. Under lab conditions, the aspect ratio is defined as the length of the testing frame over width, whereas in a field roof it can be constructed as the aspect ratio of the building. Due to this variation in the aspect ratio, the measured response of

the roofing system might be different from that of the field performance. When pressure is applied to the test specimen (Figure 2.10), the table edges offer some resistance, thereby reducing the system responses such as fastener force and membrane deflection. This is a critical issue in the certification process of the roofing system.

For example, the use of narrow tables for roofing systems having wider membranes would increase the edge effects on the system response. This is because, the fastener row spacing exceeds the table width, the dominant load transfer direction is along the table edges, thereby reducing the loads transferred to the fasteners. On the other hand, use of wide tables may not be economical for routine testing procedures. If the testing table sizes are sufficient, then the roofing system response remains constant or minimum changes may occur. Table 4.1 shows that the existing test methods use different table sizes for the certification of roofing systems. None of these test procedures uses correction factors.

UEAtc (1986) is the only test protocol that specified a correction factor for evaluation of roofing systems under wind pressure. The proposed correction factor is only applicable to the UEAtc test protocol and should be verified for other table tests that make use of it. Further discussion regarding the UEAtc correction factor will be presented in Appendix G.

Smith (1989) compared the failure pressures obtained from FM (2700 × 1500 mm) (108" × 60") with data obtained from the FM table size of 7300 × 3800 mm (288" × 150"). The results showed that the failure pressure with the 7300 × 3800 (288" × 150") mm was consistently 2.16 kPa (45 psf) lower than that with the 2700 × 1500 mm (106" × 59") table. The fact that a simple change in the table size can alter the failure pressures by 2.16 kPa (45 psf), indicates that the failure pressure alone cannot be used as the yardstick for determining roof uplift capacity. Prevatt (1998) verified this fact and established that the table size indeed plays a major role in evaluating the wind uplift performance of mechanically attached system.

It is still unclear on what basis it is stated that the FM 4470 test protocol provides a realistic method of evaluating roofing performance, rather than providing comparative test results as stated in the similar UL 1897 test protocol. All three dimensions (length,

width and depth) define the table size. The roofing components such as the insulation and membrane used in the lab experiments are similar to those used in the field. Therefore the depth of the roofing system does not affect the system response as table length or width does.

Table 4.1 Table sizes used for the certification of roofing systems

Testing Protocol	Table Size mm (in)		Country	Reference
	Width	Length		
FM 4470 Standard	1500 (60)	2700 (108)	U.S.A.	FM Research 1986
Revised FM 4470	3700 (144)	7300 (288)	U.S.A.	FM Research 1992
UL 580 Standard	3050 (120)	3050 (120)	U.S.A.	UL Inc. 1991
UEAtc Standard	1500 (60)	6100 (240)	Europe	Gerhard et al 1986
NT Build 307 Standard	2400 (96)	2400 (96)	Norway	Paulsen 1989
SIGDERS	2200 (86)	6100 (240)	North America	Baskaran and Lei 1997
SIGDERS (Revised)	4877 (192)	9753 (384)	North America	2004 -Proposed

4.3 Numerical Modeling of Mechanically Attached Systems with Wider membranes

Manufacturers, by taking advantage of the advancements in membrane technology, are introducing wider membranes into the roofing market. The introduction of wider membranes in both thermoplastic and thermoset groups and their extensive application in the field are the basis for the present investigation. Currently thermoplastic (thermoplastic olefin) membranes 3658 mm (144") wide and reinforced thermoset (ethylene propylene diene monomer) membranes 3048 mm (120") wide are available in the market. The wind uplift evaluation of wider membranes is more challenging. Care should be taken to ensure that the deck attachment can accommodate the increased wind uplift load within the existing span. Therefore, in order to evaluate the wind uplift performance of these roofing systems, the size of the testing table plays a critical role.

For the thermoplastic systems, simulations were performed for two configurations 3658 mm/305 mm (144"/12") and 3658 mm/610 mm (144"/24") and for thermoset system with EPDM membrane, the simulations were performed for three configurations, namely, 120/12, 120/18 and 120/24.

The thermoplastic membrane was simulated using 4-node rectangular grid and shell elements to discretize the membrane (Figure 4.1). The element type was S4, which accounts for finite membrane strains and will allow for change in thickness. Shell elements of the membrane had a thickness of 1.04 mm (0.04"), and an equivalent modulus of elasticity of 300 MPa (43.5 ksi) and a Poisson ratio of 0.4. The modulus of elasticity and thickness of the membrane were obtained through mechanical tests in accordance to the ASTM standard (ASTM D 751-00 and ASTM D 6878-03).

Seam details were modeled by doubling the thickness of the shell element at the seam areas, 2.08 mm (0.08") to simulate the spliced region of the membrane as schematically illustrated in Figure 3.2. Fasteners were modeled as spring supports with axial stiffness (vertical degree of freedom) of 20 N/mm (114 psi). The stiffness was extracted from the experimental results of force and displacement measurements of fasteners. The fastener plates were simulated as plastic discs by changing the material properties on the corresponding shell elements. These plastic plates were 3 mm (0.1") thick with a diameter of 50 mm (2") and a modulus of elasticity of 500 MPa (72.5 ksi).

As the seam area is subjected to high concentrated stresses, the aspect ratio of one was attained for the elements near the seam. In the model, the membrane edges, i.e. the nodes along the perimeter of the membrane, as shown by the dotted lines in Figure 4.1, were restricted from any translation movement by fixing its three degrees (x , y , z) of freedom. The edge nodes have only rotational degrees of freedom (Φ_x , Φ_y , Φ_z). To include the large-displacement effects, the NLGEOM option was selected.

Therefore, most elements are formulated in the current configuration using current nodal position. Static stress analysis was applied. This is found to be appropriate because mass or inertia effects can be neglected. The analysis can be linear or non-linear and time-dependent effects of the membrane can be neglected; however, the rate-dependent plasticity is taken into account.

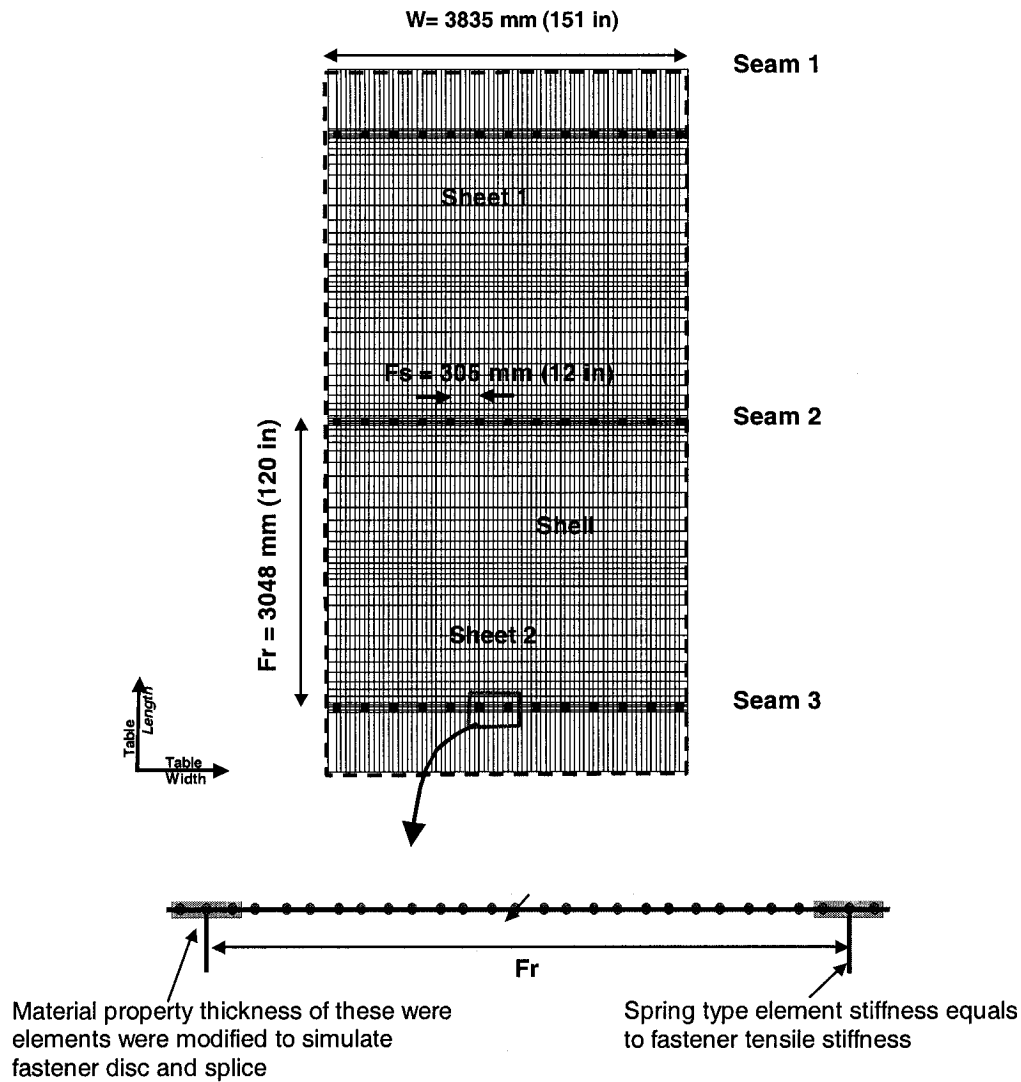


Figure 4.1 FEM representation of 144/12 thermoplastic system and seam details

The loading conditions are defined in the model by assuming a uniform static uplift pressure of 1.44 KPa (30 psf) on the membrane. Table 4.2 shows a typical example of the mesh sensitivity analysis for the 144/12 thermoplastic. Five models were simulated and the mesh sensitivity was analyzed by increasing the number of elements by a factor of two and running the analysis until the answers between successive analyses did not vary by more than 5 %. Figure 4.2 illustrates a typical layout of simulated models with different number of elements.

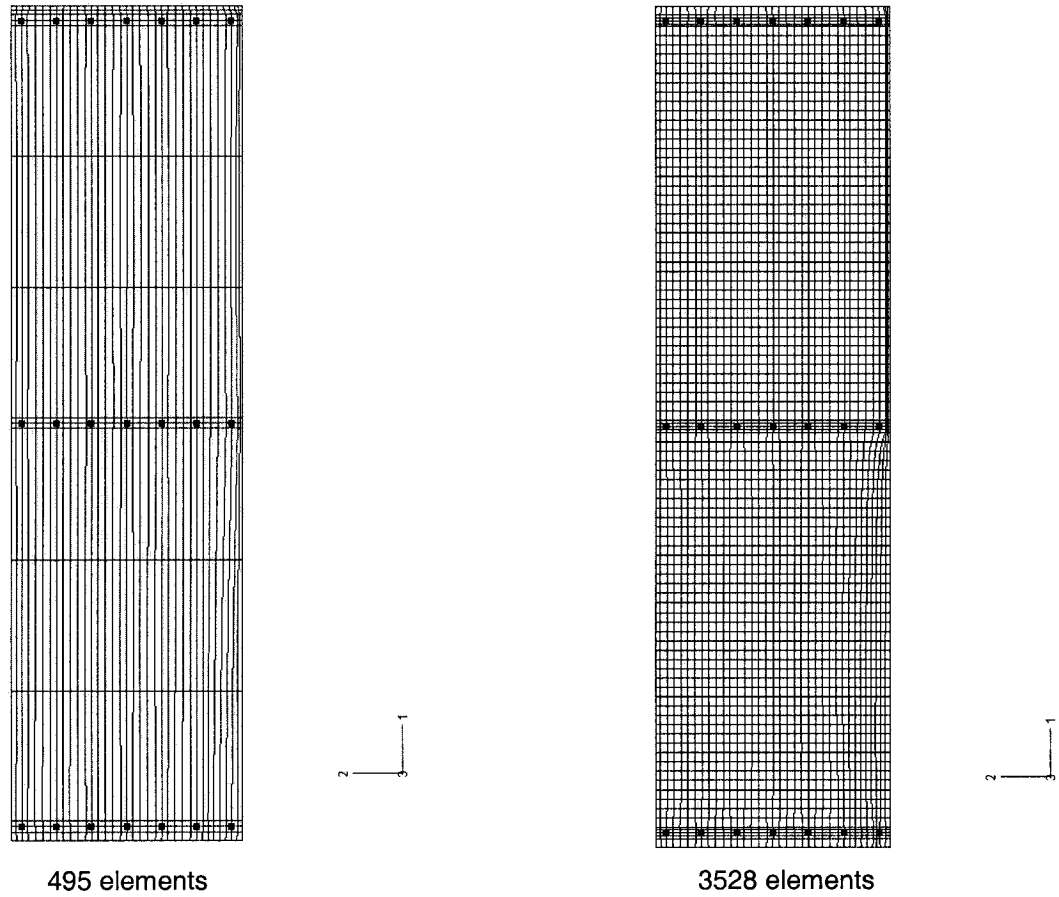


Figure 4.2 Mesh sensitivity analyses for 144/12 roofing system configuration

Table 4.2 Mesh sensitivity analyses

No. of Elements	Fastener Force N (lbf)	Deflection mm (in)
495	508 (116)	163 (6.4")
980	517 (118)	152 (5.9")
2016	527 (120)	145 (5.7")
2664*	535 (121)	143 (5.6")
3528	535 (121)	143 (5.6")

** selected model for this study*

A similar approach was used for systems with thermoset membranes. However, shell elements had a thickness of 1.1 mm (0.043") and an equivalent modulus of elasticity of 150 MPa (22 ksi) and a Poisson's ratio of 0.22. Seam details were modeled by doubling the thickness of the shell element at the seam areas, 2.2 mm (0.086"). Fasteners were modeled as spring supports with axial stiffness (vertical degree of freedom) of 60 N/mm (345 psi). The fastener plates were simulated as metal plates with a thickness of 2 mm (0.08").

To investigate the table width effect, simulations were performed for a 3658 mm /305 mm (144"/12") thermoplastic system. The simulations were started from a 2006 mm (79") wide table and incremented by 305 mm (12") up to a table width of 4445 (175"). Figure 4.3 gives an example of two simulated table widths. Both simulated tables had three rows of fasteners with 7 fasteners in each row in the case of the 2006 mm (79") wide table and 15 fasteners for that of the 4445 mm (175") wide. Appendix C and D illustrate all the simulated configurations in the present study.

A static pressure of 1.44 kPa (30 psf) was applied to a roof system. Figure 4.4 (a) to (e) illustrates the contour plots of the membrane deflection for all the simulated table widths, for the 144/12 thermoplastic system configurations, which clearly shows the influence of the table edges on the membrane behaviour. The deflection of the membrane is a combination of the lateral deflection (i.e. between the table edges along the length (TEL)) and longitudinal deflection (i.e. between the fastener rows). For table widths less than the fastener row spacing (Fr) or membrane width, the deflection of the membrane is laterally restricted by the table edges. The orientation of the membrane deflection is between the fastener rows thereby indirectly affecting the fastener forces along the seam with the middle fastener having the maximum fastener force. When the table width is greater than the Fr, the orientation of the membrane deflection changes along the length (TEL) and due to the greater membrane width and less influence of the table edges, the deflection of the membrane increases. The elongated shape of the middle contour along the table width indicates that the middle fastener and its adjacent fasteners may have similar fastener force.

To demonstrate this observation, the resulting fastener forces (along the middle seam or seam 2) for the 2006 mm (79") and 4445 mm (175") are plotted in Figure 4.5 with respect to the normalized table width. Computed results indicated that on a 4445 mm (175") table, three fasteners along the seam have similar fastener force with a variation of 2%, compared to the 2006 mm (79") table where the middle fastener force varies by 10% from the adjacent ones. This reveals the existence of edge influence on the fastener force on the 2006 mm (79") table, while it is very minimal on the 4445 mm (175") table. An ideal condition is one where edge effects are minimal and most of the fasteners have equal forces since they are subjected to the same magnitude of wind uplift pressure. However, during the laboratory experiments, the edge will always offer some resistance.

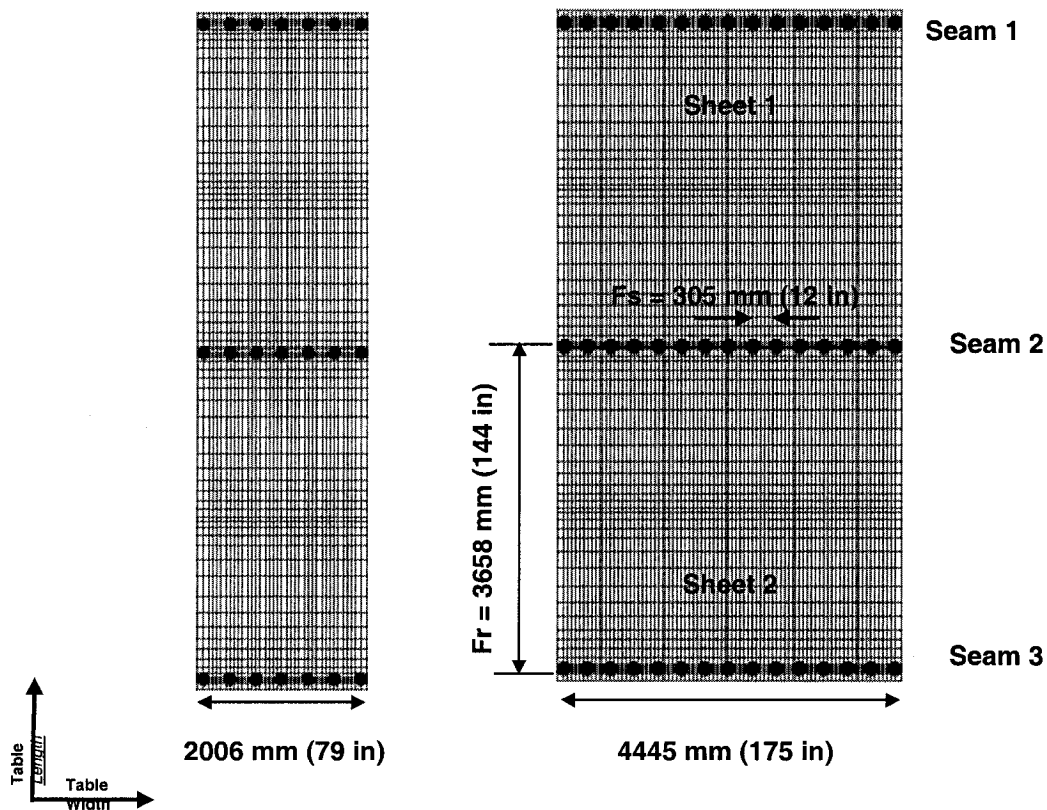
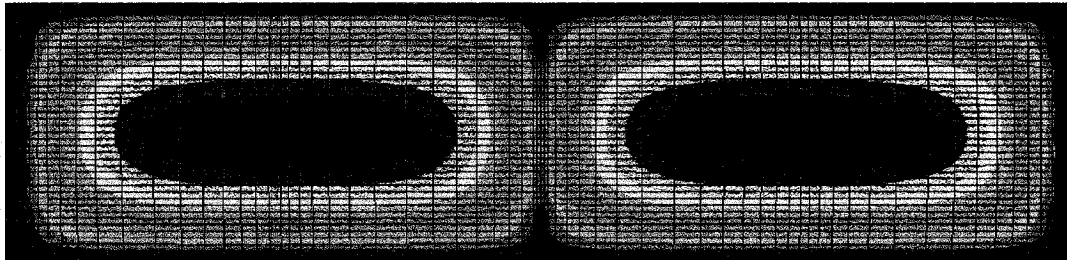
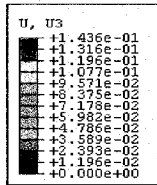
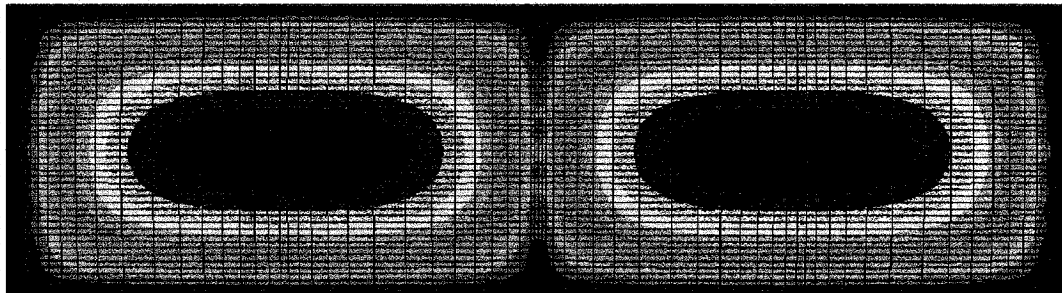
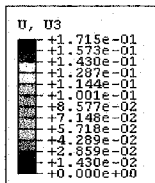


Figure 4.3 FEM representation of 144/12 thermoplastic system on two different table widths

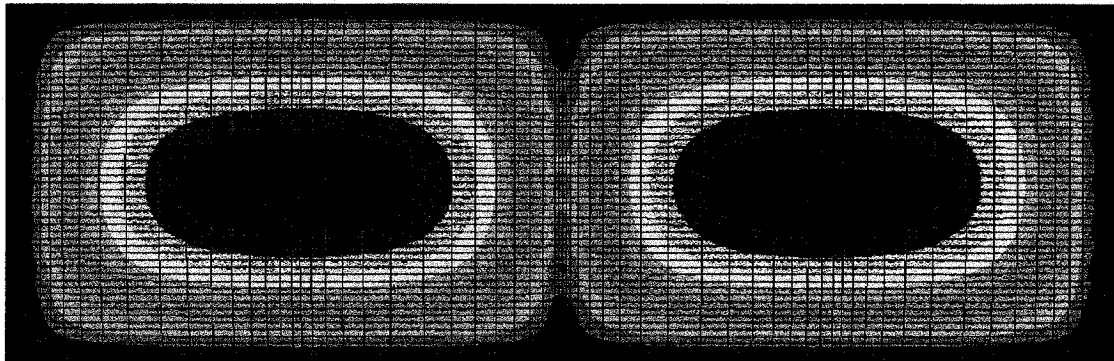
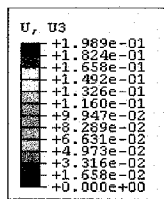


W: 2006 mm (79")

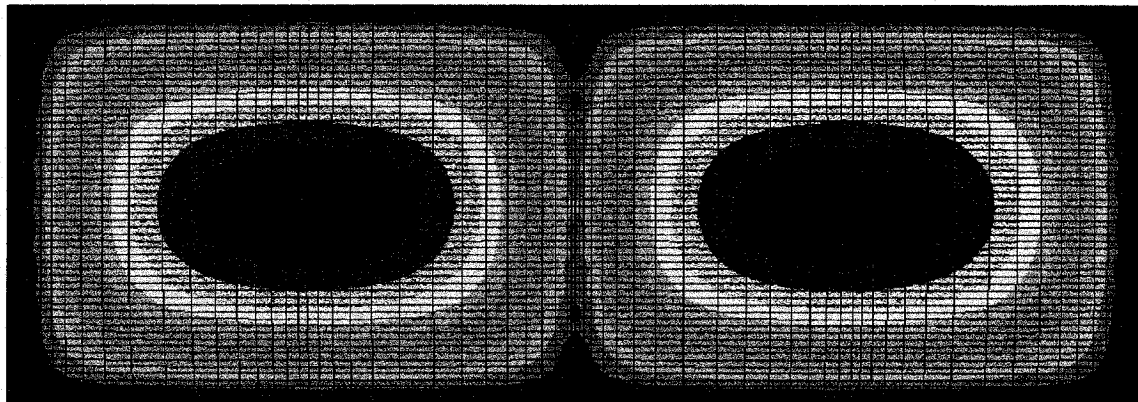
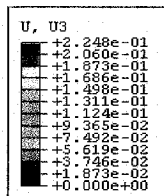


W: 2311 mm (91")

Figure 4.4 (a) Contour plot of the membrane deflection for 144/12 thermoplastic system on table widths 2006 mm (79") and 2311 mm (91")

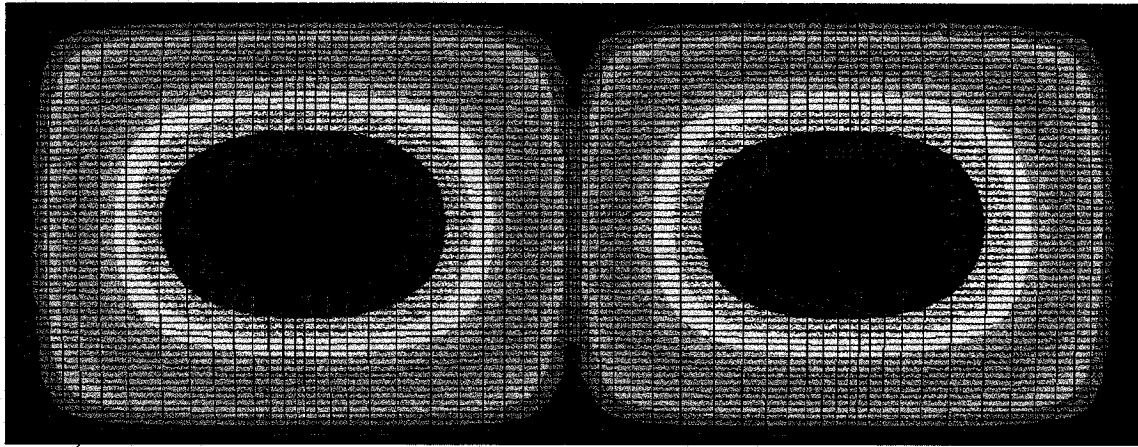
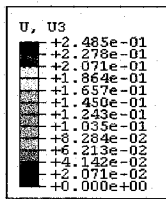


W: 2616 mm (103")

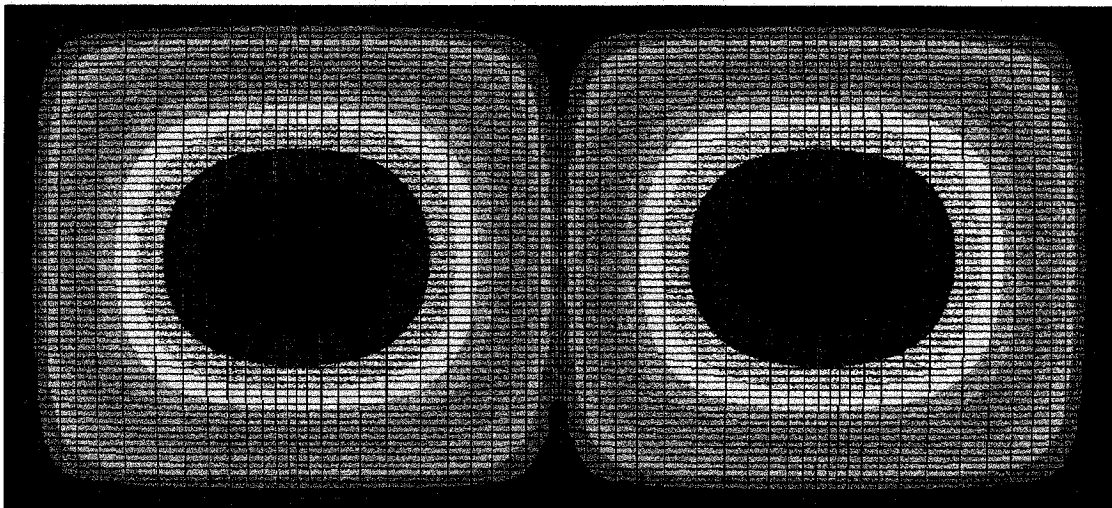
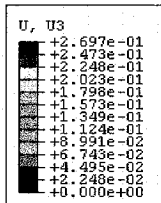


W: 2921 mm (115")

Figure 4.4 (b) Contour plot of the membrane deflection for 144/12 thermoplastic system on table widths 2616 mm (103") and 2921 mm (115")

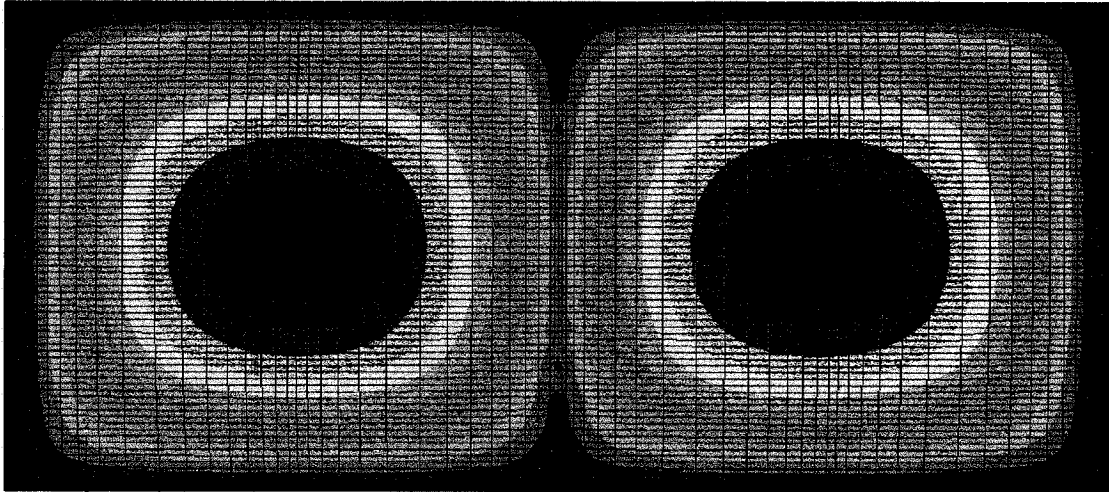
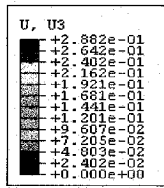


W: 3225 mm (127")

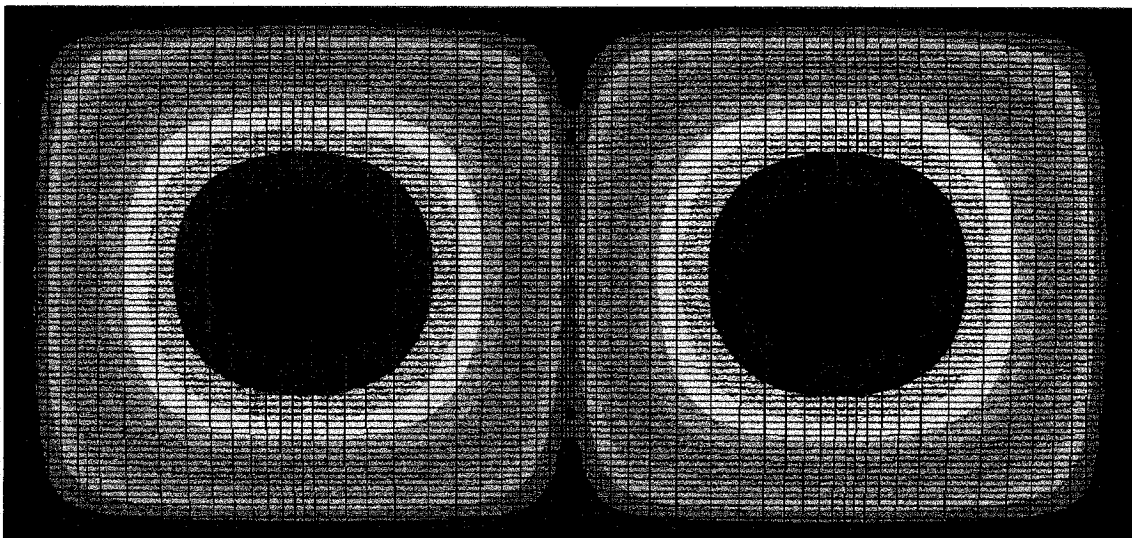
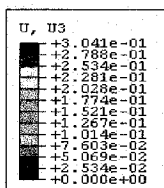


W: 3530 mm (139")

Figure 4.4 (c) Contour plot of the membrane deflection for 144/12 thermoplastic system on table widths 3225 mm (127") and 3530 mm (139")



W: 3835 mm (151")



W: 4140 mm (163")

Figure 4.4 (d) Contour plot of the membrane deflection for 144/12 thermoplastic system on table widths 3835 mm (151") and 4140 mm (163")

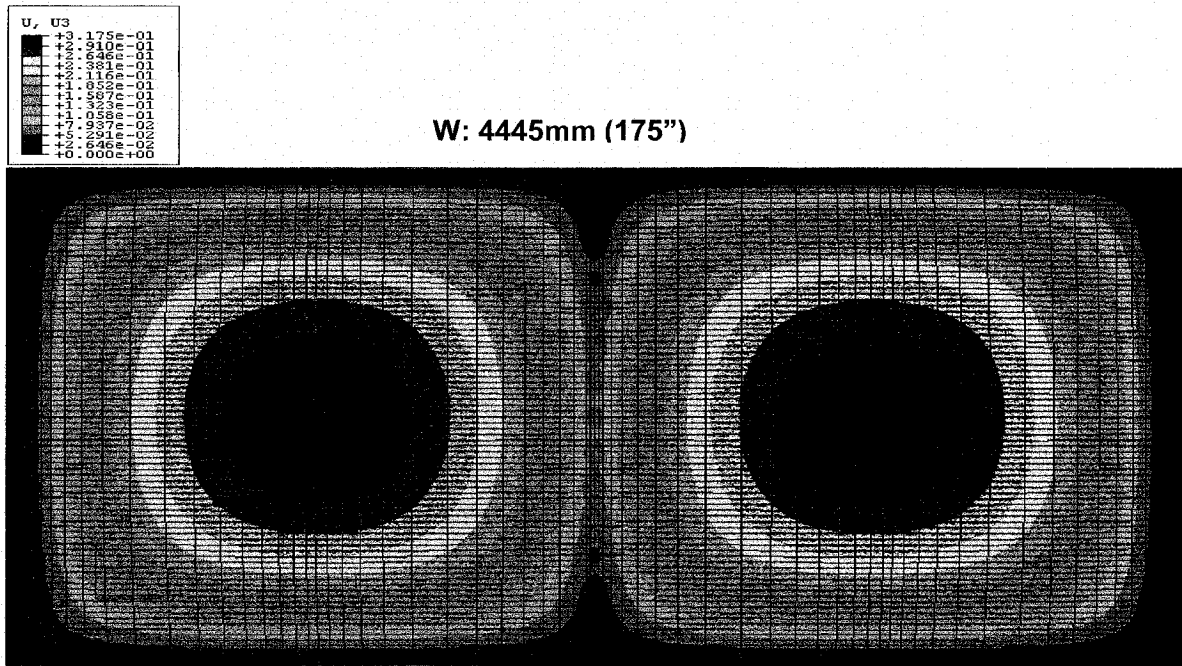


Figure 4.4 (e) Contour plot of the membrane deflection for 144/12 thermoplastic system on 4445 mm (175") table width

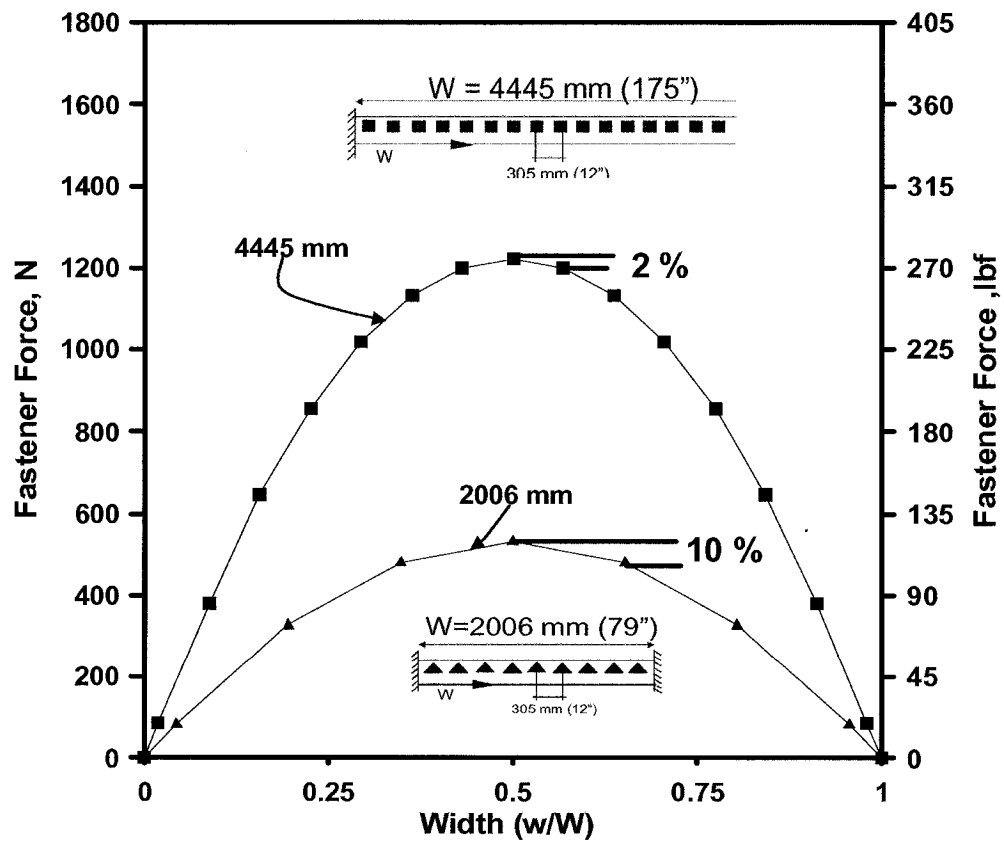


Figure 4.5: Fastener force variation along the seam for 144/12 thermoplastic system on 2006 mm (79") and (4445 mm) 175" tables

4.3.1 Required Table Width (RTW)

For every specific roofing system configuration, there exists an ideal table and with all other parameters maintained constant, the Required Table Width (RTW) is one that has a minimum table edge effect on the roofing system performance. Moreover, the development of RTW requires several levels of generalization of the true wind-induced effect over a roofing assembly. Often, these generalizations warrant compromise from the technically sound approach to the practically acceptable procedure. This research work had the advantage of receiving input from all parties concerned with roofing, including researchers, manufacturers, roofing associations representing the contractors, and building owners. Based on the numerical investigation and the practical inputs the following criteria were established to identify the RTW:

“The table with RTW should provide no change in the maximum fastener forces or change in the maximum fastener force should be within 5% compared to those obtained while decreasing the table width by 305 mm (12”)”.

To identify the RTW for the different mechanically attached roofing systems, simulations were performed for various table widths. The range of table widths covered the different tables that are used for the current roofing system evaluation (Table 4.1). For illustrating the above criteria and involved calculations, a typical example is shown in Table 4.3. Table 4.3 presents the computed maximum fastener forces for the configuration of 144/12. A computed fastener force of 1343 N (302 lbf) was calculated for a table width of 5054 mm (199”). By decreasing the table width to 4445 mm (175”), the fastener force was decreased to 1232 N (277 lbf). Further reduction of the table width reduces the fastener force. For a table width of 2006 mm (79”), the computed fastener force was only 538 N (121 lbf). This reduction from 1343 N (302 lbf) to 538 N (121 lbf) is due to the greater influence of the table edges on the 2006 mm (79”) table width when compared to the 5054 mm (199”) table width. By applying the established criteria of the RTW, a table width of 4445 mm (175”) can be selected as the RTW.

For the thermoplastic systems, simulations were performed for one F_r configurations 3657 mm (144”) with two F_s configurations 305 and 610 mm (12” and 24”). Similarly for the thermoset systems, simulations were performed for one F_r configuration 3048 mm (120”) with three F_s configurations 305, 460 and 610 mm (12”, 18” and 24”). By applying

the established criteria of the RTW, similar calculations were done for the configuration of 144/24 thermoplastic system and a 5054 mm (199") table width was determined as the RTW. For the thermoset systems, the RTW for the investigated configurations is as follows:

- ❖ Configuration: 120/12; RTW = 3835 mm (151")
- ❖ Configuration: 120/18; RTW = 3835 mm (151")
- ❖ Configuration: 120/24; RTW = 4140 mm (163")

Table 4.3 Determining the RTW for 144/12 thermoplastic system

Table Width		Force		% Change
mm	in	N	lbf	
5054	199	1343	302	
4749	187	1290	290	3.97
4445	175	1232	277	4.48(RTW)
4140	163	1156	260	6.14
3835	151	1085	244	6.15
3530	139	992	223	8.60
3225	127	912	205	8.07
2921	115	809	182	11.22
2616	103	725	163	10.44
2311	91	618	139	14.72
2006	79	538	121	12.94

A number of factors can influence the RTW. Three critical parameters, namely, variations in the membrane properties, fastener spacing (F_s) and fastener row spacing (F_r) were investigated and discussed below.

Variation in the thermoplastic membrane: There are two main types of thermoplastic membranes used for industrial roofing, namely, TPO and PVC. A roofing system, with PVC membrane instead of TPO, was modelled to investigate the effect on the RTW for membrane variations in the thermoplastic group. The same finite element model was used with the exception of different input parameters. A typical 67/12 configuration was selected with appropriate modulus of elasticity and poisson's ratio ($E_{TPO} = 300$ MPa, $\nu_{TPO} = 0.4$, $E_{PVC} = 175$ MPa, $\nu_{PVC} = 0.4$) details of which are documented in Zahrai and Baskaran (1999). Computed fastener forces for different table widths ranging from 781 to 5048 mm (31" to 199") are shown in Figure 4.6. A comparison of data shows minimum variations in fastener forces between the PVC and TPO roofing systems. Therefore, it was decided to use one set of RTW for the evaluation of roofing assemblies with thermoplastic membrane.

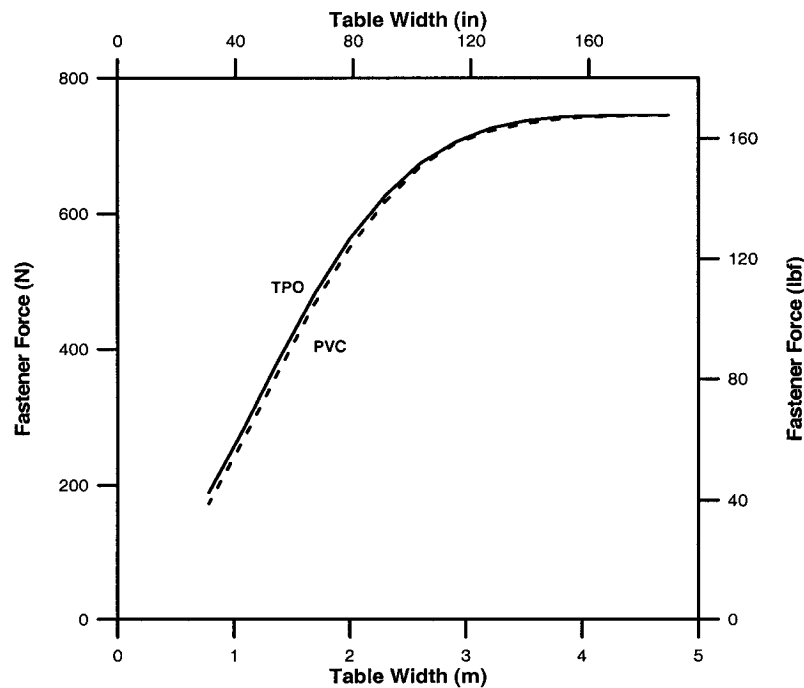


Figure 4.6 Effect of membrane on the computed fastener force

Fastener row spacing (F_r): To quantify the impact of F_r on the RTW, two thermoplastic configurations were selected. The layouts were 48/12 and 144/12 and all other parameters such as fastener spacing and applied pressure were maintained constant. The selected fastener row spacing of 1220 and 3657 mm (48" and 144") can cover systems with minimum and maximum fastener row spacing available in the roofing industry. Computed fastener loads for both configurations and for different table widths are presented in Figure 4.7. Fastener forces were calculated for a 1436 Pa (30 psf) uplift pressure. For the system with a 3657mm (144") fastener row spacing, the RTW is 4130 mm (175"), whereas for a system with an F_r of 1220 mm (48") the RTW is 2610 mm (103"). This reveals that the F_r has a direct influence on the RTW and that its dependency is not linear.

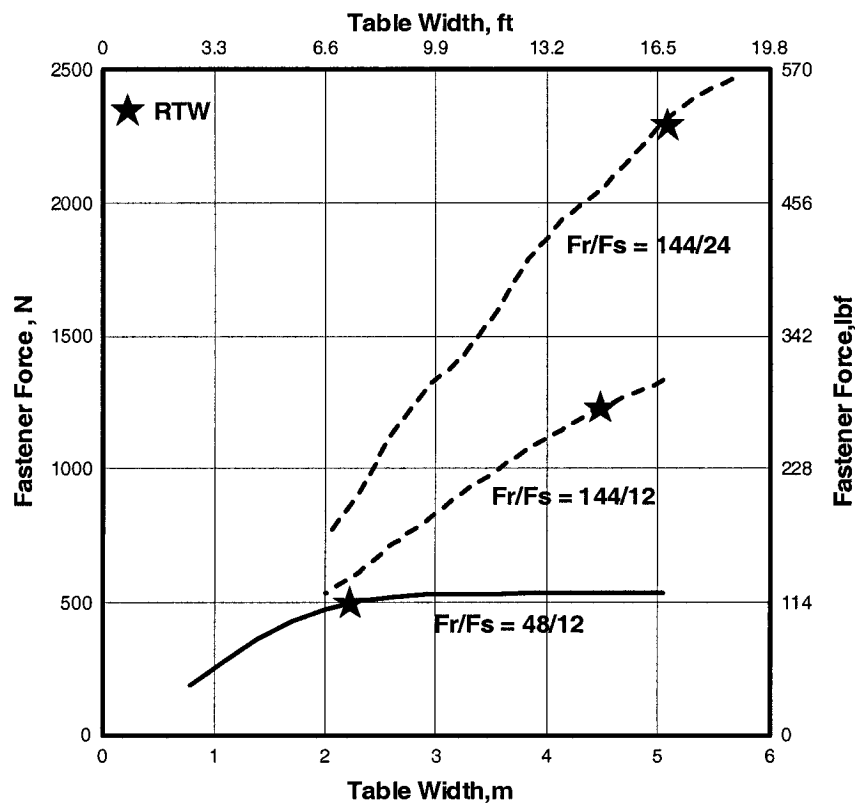


Figure 4.7 Influence of fastener row spacing on RTW

Fastener spacing (F_s): In order to investigate the influence of fastener spacing on the RTW, computed fastener forces for 144/24 layout are added in to the Figure 4.7. It is evident that increasing fastener spacing from 305 to 610 mm (12" to 24") causes an increase in the computed fastener force. This has been found for all simulated table

widths. Overall, the Figure 4.7 data confirms that one should consider the effect of fastener row spacing (F_r) and fastener spacing (F_s) in determining the RTW. One can assign higher importance factor for F_r than F_s when generalizing the RTW. This will be further explained in the following section in which RTW is used to develop correction factors.

4.3.2 Correction Factors

For every roofing system configuration there exists an ideal table size not affected by the table edge effect. Testing that particular system configuration on a narrow table would affect the wind uplift performance and reducing the system responses such as the fastener force and membrane deflection. One objective of the present study was to develop correction factors (C_f) for the tables having width smaller than the established RTW. This section explains the development of C_f for the 144/12,144/24 thermoplastic system and 120/12,120/18,120/24 thermoset systems.

The correction factors can be calculated by dividing the fastener force obtained from the RTW table with that of the narrow ones. Tables having larger widths than RTW have correction factors equal to one. For instance, in Table 4.4 for the 144 / 24 thermoplastic system, the width of 5054 mm (199") was identified as the RTW with 2309 N (519 lbf) as the fastener force. Using a 2006 mm (79") table would reduce the fastener force to 743 N (167 lbf). To correct this, the fastener force obtained from the table that has a width of 2000 mm (79") needs to be multiplied by the correction factor of 3.1 (2309/743). Similarly for the 120/24 thermoset system, the table width of 4140 mm (163") was identified as the RTW and use of a table width of 79" required the application of correction factor 2.3, to obtain the actual fastener force.

$$C_F = \frac{\text{Computed Fastener Force (RTW)}}{\text{Computed Fastener Force (NarrowTable)}} \quad (4.1)$$

More than 50 simulations were performed for the variations of the two influencing factors discussed in the previous section, namely, fastener row spacing (F_r) and fastener spacing (F_s) for both the thermoplastic systems and thermoset systems. For each system configuration, correction factors were developed and the curves of correction factors for different fastener row spacing and fastener spacing are presented in Figure 4.8. These data clearly revealed that wider membranes require wider tables.

Table 4.4 Examples to illustrate the development of correction factors

144/24 Thermoplastic System						
Simulation number	Table width		Force		% Change	C_F
	mm	in	N	lbf		
1	5664	223	2468	555		
2	5359	211	2406	541	2.54	
3	5054*	199	2309	519	4.07	1.0
4	4750	187	2162	486	6.35	1.1
5	4445	175	2037	458	5.76	1.1
6	4140	163	1939	436	4.80	1.2
7	3835	151	1788	402	7.79	1.3
8	3531	139	1583	356	11.39	1.5
9	3226	127	1419	319	10.39	1.6
10	2921	115	1308	294	7.83	1.8
11	2616	103	1143	257	12.58	2.0
12	2311	91	912	205	20.23	2.5
13	2006	79	743	167	18.53	3.1
120/24 Thermoset System						
Simulation number	Table width		Force		% Change	C_F
	mm	in	N	lbf		
1	4445	175	2464	554		
2	4140*	163	2415	543	2.00	1.0
3	3835	151	2295	516	5.01	1.1
4	3531	139	2086	469	9.10	1.2
5	3226	127	1903	428	8.74	1.3
6	2921	115	1801	405	5.37	1.3
7	2616	103	1592	358	11.60	1.5
8	2311	91	1289	290	18.99	1.9
9	2006	79	1058	238	17.95	2.3

Note: * indicates RTW

For the proper evaluation of the wind uplift resistance of these wider membranes, testing has to be done on the appropriate table width such that their wind uplift performance is least affected by table edges, thereby simulating the correct wind uplift loads. It has to be emphasized that none of the existing testing organizations, as grouped in Table 4.1, is appropriate to investigate such wide membranes without the application of the correction factors. The fastener force results are given in tabular format in the Appendix C and D and the developed correction factors in Appendix E and F.

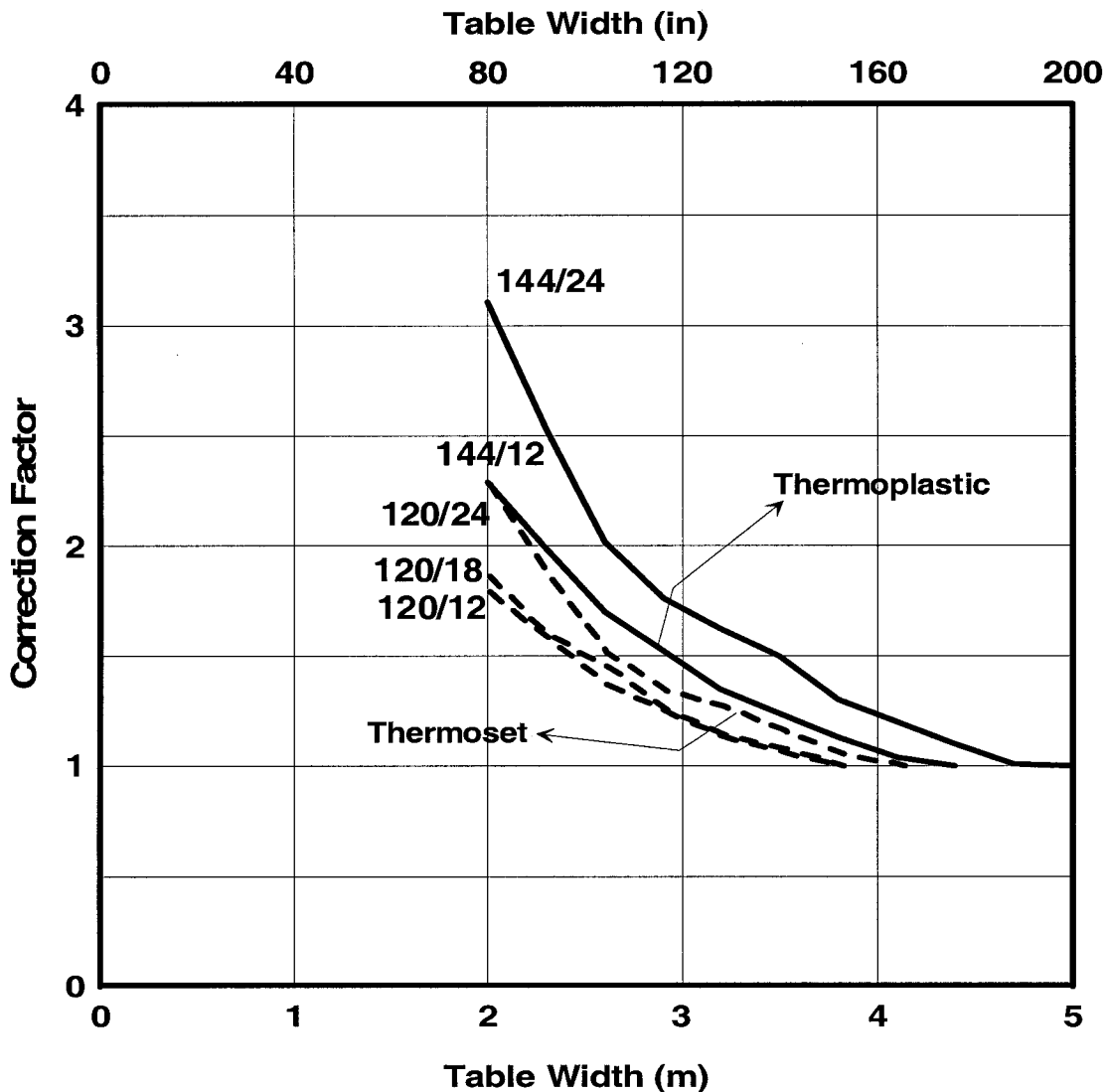


Figure 4.8 Developed correction factors for the systems with wider membranes

4.4 Effect of Table Length

The table length effect was also investigated using the validated finite element numerical models. The selected configuration for this study was a 24/6 thermoplastic system. Four different table lengths were simulated starting from 2006 x 1219 mm (79" x 48") and the the table length was increased by increments of 600 mm (24") while all other parameters were kept constant. The simulated systems were subjected to a static pressure of 1.44 kPa (30 psf). The results of the fastener forces obtained from the middle seam middle fastener were normalized and plotted with respect to the normalized table length (L/F_r) as shown in Figure 4.9. As shown, the difference of fastener forces in each configuration up to 2006 x 2438 mm (79"x 96") is equal to 1.0. This confirms that as long as the table length has a minimum of three seams, the table length does not significantly influence the system response. The length of the table is directly proportional to the number of seams and this is mainly because during the system installation, membrane width forms parallel to the table width.

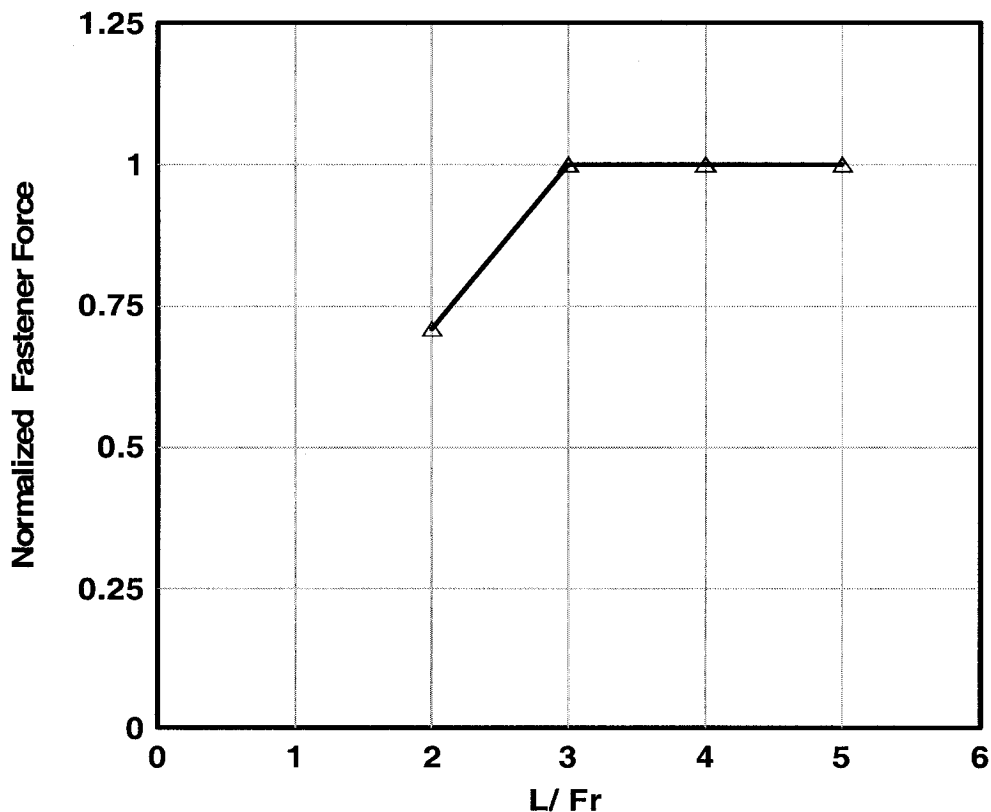


Figure 4.9: Effect of table length on fastener force

4.5 Concluding Remarks

Summarising the present chapter, it addressed one of the key issues in the current roofing industry i.e. the appropriate table widths for testing wider membrane. As the roofing system response is dependent both on fastener spacing and fastener row spacing, more than 50 simulations were performed for the variations of the two influencing factors for both the thermoplastic systems and thermoset system. Within the thermoplastic systems the influence of the membrane material was very small when compared to the thermoset systems. The Poisson's effect was significant in the thermoset material. The data clearly revealed that wider membranes require wider tables. It has to be emphasized that none of the existing testing tables are appropriate for testing such wide membranes without the application of the correction factors. In order to obtain the correction factors, the ideal table size was identified for all the system configurations and correction factors were developed. The measured fastener force attained by the experimental results can be multiplied by the correction factor to adjust for the influence of edge effect. The length of a testing table is a function of the number of seams. Using the validated model the table length effect was investigated and it was confirmed that as long as the table length has a minimum of three seams, the table length does not significantly influence the system response.

Chapter 5

Generalization of Correction Factors for Roofing Design

5.1 General Review

The intent of this present study is to achieve characteristic correction factor curves such that guidelines can be developed for the general roofing system design. It would be ideal for roof designers to have a single correction factor graph for the MAS. This chapter describes the developed generalization approach to obtain the correction factors from a single graph, such that it can be of practical use to determine the wind uplift resistance of roofs. To achieve this objective, the following approach was adopted:

- For the modified bituminous system, data from Zaharai and Baskaran, 1999 (Figure 5.1) were used.
- For the thermoplastic system, data from Baskaran and Borujerdi, 2001 (Figure 5.2) and wider membrane data from the present study (Figure 4.7) were combined.
- For the thermoset system, data from Baskaran and Borujerdi, 2001 (Figure 5.3) and wider membrane data from the present study (Figure 4.7) were combined.

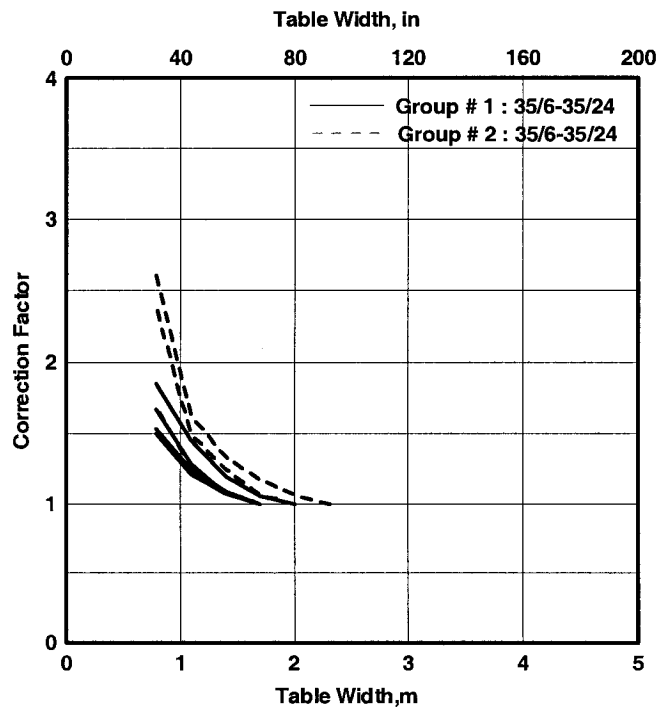


Figure 5.1: Developed correction factors for Mod-Bit systems
(Zaharai and Baskaran, 1999)

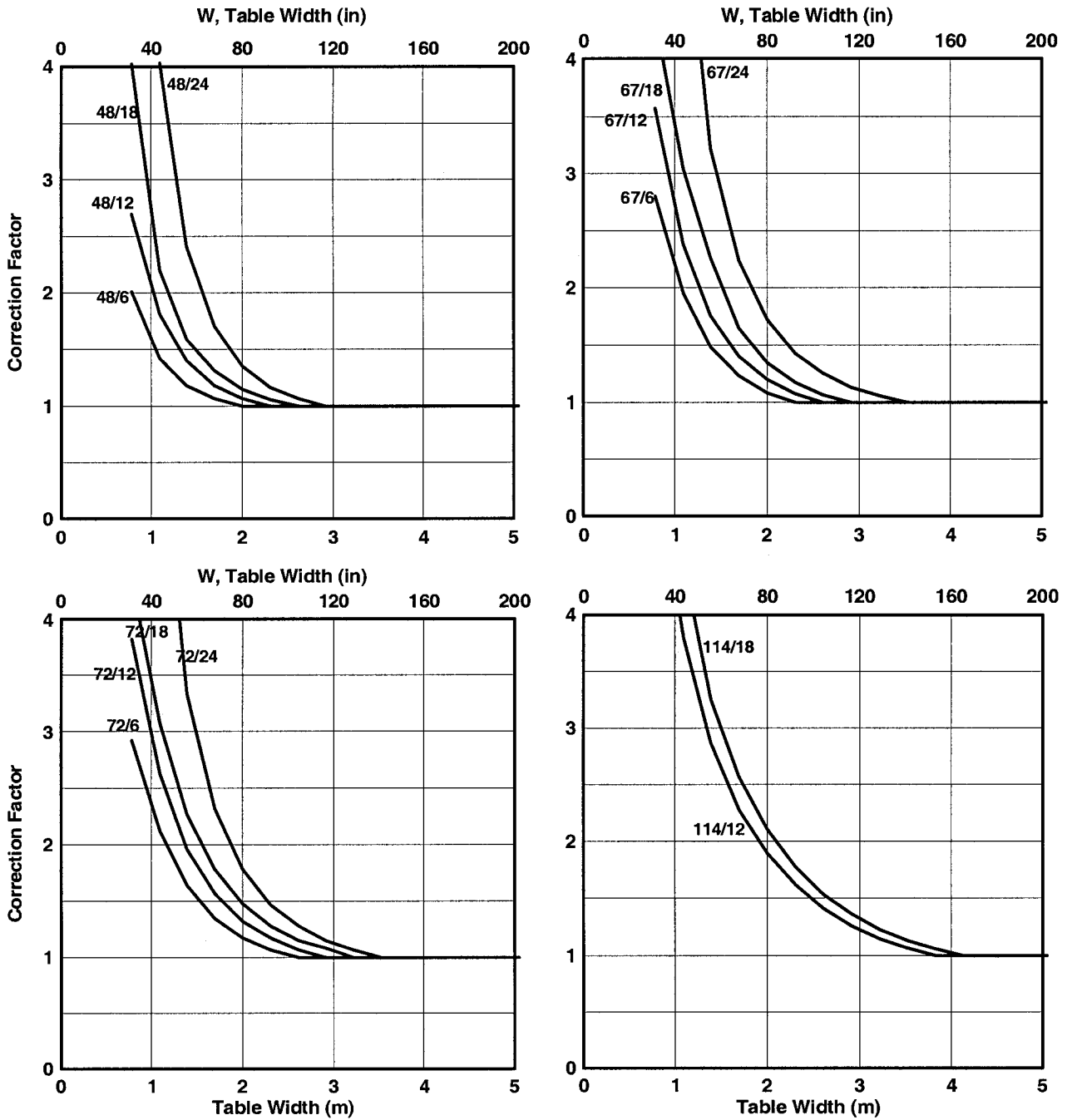


Figure 5.2: Developed correction factors for thermoplastic systems
(Baskaran and Borujerdi, 2001)

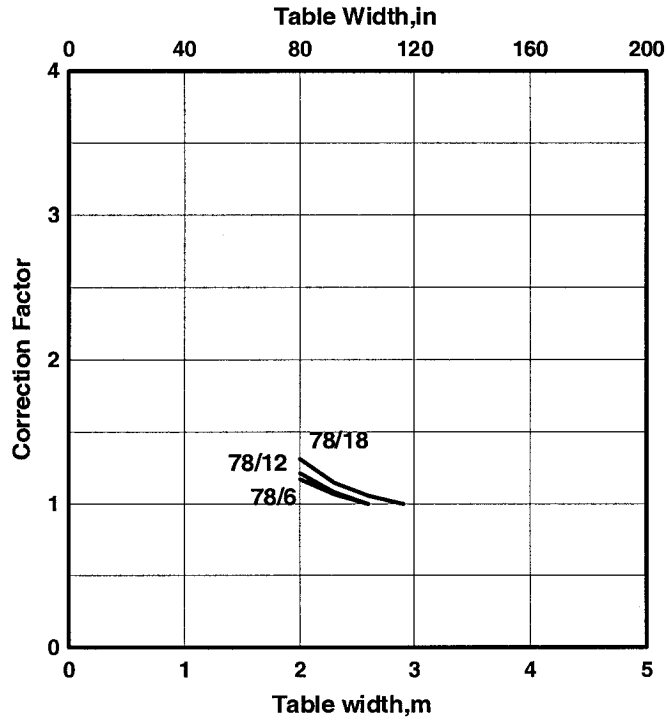


Figure 5.3: Developed correction factors for thermoset systems
(Baskaran and Borujerdi, 2001)

5.2 Generalization Approach

Table 5.1 summarizes all the simulations performed for the different system configurations to form a database. In total, 372 numerical tests were combined with 20 benchmark experiments to provide a wide range database. The fifth column in Table 5.1 indicates the number of data set for each configuration. For example, configuration 6 on the thermoplastic system with fastener row spacing of 1701 mm (67") and fastener spacing of 305 mm (12") has 15 numerical data (simulations from 76 to 90) by covering a range of table widths from 787 to 5054 mm (31" to 199"). It also has 6 experimental results (experiments from 3 to 8) for variation in the test protocol and repetitive experiments.

To generalize the developed correction factor, attempts have been made to identify a relationship between the correction factor and the influencing parameters (F_r , F_s and W). Using the data sets from Table 5.1, three parameters were calculated. Those values consist of a ratio of:

- Fastener row spacing to fastener spacing (F_r/F_s) – labeled as ***m***
- Table width to fastener spacing (W/F_s) – labeled as ***n***
- Table width to fastener row spacing (W/F_r) – labeled as ***k***

Table 5.1: Data Base used for the generalization of correction factors

Thermoplastic Systems					
Configuration	Fr* (mm)	Fs* (mm)	Table Width (W) range (mm)*	# of Simulations	# of Experiments
1 (48/6)	1219	152	787 – 5054	1-15	
2 (48/12)	1219	305	787 – 5054	16-30	
3 (48/18)	1219	457	787 – 5054	31-45	1-2
4 (48/24)	1219	610	787 – 5054	46-60	
5 (67/6)	1701	152	787 – 5054	61-75	
6 (67/12)	1701	305	787 – 5054	76-90	3-8
7 (67/18)	1701	457	787 – 5054	91-105	
8 (67/24)	1701	610	787 – 5054	106-120	
9 (72/6)	1829	152	787 – 5054	121-135	
10 (72/12)	1829	305	787 – 5054	136-150	
11 (72/18)	1829	457	787 – 5054	151-165	9-10
12 (72/24)	1829	610	787 – 5054	166-180	
13 (114/12)	2896	305	787 – 5054	181-195	
14 (114/18)	2896	457	787 – 5054	196-210	
15 (144/12)	3658	305	2006 – 5054	211-221	
16 (144/24)	3658	610	2006 – 5664	222-234	
Modified Bituminous Systems: Group # 1					
1 (35/6)	890	152	787 – 4140	1-12	
2 (35/12)	890	305	787 – 4140	13-24	11-14
3 (35/18)	890	457	787 – 4140	25-36	
4 (35/24)	890	610	787 – 4140	37-48	
Modified Bituminous Systems: Group # 2					
5 (35/6)	890	152	787 – 4140	49-60	
6 (35/12)	890	305	787 – 4140	61-72	
7 (35/18)	890	457	787 – 4140	73-84	15-16
8 (35/24)	890	610	787 – 4140	85-96	
Thermoset Systems					
1 (78/6)	1981	152	2006 – 3225	1-5	17-18
2 (78/12)	1981	305	2006 – 3225	6-10	19-20
3 (78/18)	1981	457	2006 – 3225	11-15	
4 (120/12)	3048	305	2006 – 4445	16-24	
5 (120/18)	3048	457	2006 – 4445	25-33	
6 (120/24)	3048	610	2006 – 4445	34-42	
				372	20
Total Numerical Tests and Experiments				392	

When a configuration m is tested on a table width W , n gives the number of fasteners for that table. A relationship between m and n is developed for further analysis of the data. Table 5.2 shows an example of the developed relationship between m , n and C_F for the thermoplastic roofing system in tabular format showing examples for m as 2, 5.6 and 12.

First, the trend of systematically decreasing the correction factor becomes clear for each set of m . Then the table was grouped based on m ratio. It was owing to the fact some configurations such as 72/18 and 48/12 had the same m ratio of four. Then, the data sets in each category were sorted in descending order according to correction factor values. In order to investigate the result of this study in more detail, the computed values are shown in graphic format in Figure 5.4 by introducing a constant value of m , which is the ratio of F_r/F_s . The X-axis shows the relation between the width (W) over the fastener spacing (F_s), and correction factor is presented in the Y-axis. As shown in Figure 5.4, a total of 13 curves were generated and drawn in three sets based on the following relationship.

$$\text{Set 1 : } \frac{F_r}{F_s} \leq 5 \qquad \text{Set 2 : } 5 < \frac{F_r}{F_s} \leq 7 \qquad \text{Set 3 : } \frac{F_r}{F_s} > 7$$

The comparison of these three sets revealed the following:

1. The computed data has the width over fastener spacing ratio (W/F_s) ranging from 1.8 to 17.2, which has the corresponding correction factor of 4.0 and 1.0 respectively.
2. Increasing the width over fastener spacing reduces the correction factor if F_r/F_s is kept constant. It also reveals that, the ratio of W/F_s increases while the table width increases, causing the correction factor reduction when a roofing system is tested on a wider table.
3. For a constant value of W/F_s , the correction factor has a direct relation with F_r/F_s . In other words, the correction factor increases as F_r/F_s increases, when the W/F_s remains constant.
4. Increasing F_r increases the correction factor if the other parameters remain constant. Therefore when W/F_s remains constant, F_r/F_s increases, and as a result the correction factor increases.

Following the similar methodology, correction factors for the thermoset systems and modified bituminous systems were developed, as shown in Figures 5.5 and 5.6. This trend was similar to that observed for a thermoplastic system.

Table 5.2: Parameter normalization for correction factor – thermoplastic system

W mm (in)	F_r mm (in)	F_s mm (in)	C_r	k = $\frac{W}{F_r}$	n = $\frac{W}{F_s}$	m = $\frac{F_r}{F_s}$
1086 (43)	1220 (48)	610 (24)	4.025	0.9	1.8	2
1390 (55)	1220 (48)	610 (24)	2.405	1.1	2.3	2
1695 (67)	1220 (48)	610 (24)	1.706	1.4	2.8	2
2000 (79)	1220 (48)	610 (24)	1.353	1.6	3.3	2
2305 (91)	1220 (48)	610 (24)	1.166	1.9	3.8	2
2610 (103)	1220 (48)	610 (24)	1.062	2.1	4.3	2
2914 (115)	1220 (48)	610 (24)	1	2.4	4.8	2
....						
....						
781 (31)	1700 (67)	305 (12)	3.683	0.5	2.6	5.6
1086 (43)	1700 (67)	305 (12)	2.464	0.6	3.6	5.6
1390 (55)	1700 (67)	305 (12)	1.877	0.8	4.6	5.6
1695 (67)	1700 (67)	305 (12)	1.505	1	5.6	5.6
2000 (79)	1700 (67)	305 (12)	1.285	1.2	6.6	5.6
2305 (91)	1700 (67)	305 (12)	1.144	1.4	7.6	5.6
2610 (103)	1700 (67)	305 (12)	1.057	1.5	8.6	5.6
2914 (115)	1700 (67)	305 (12)	1	1.7	9.6	5.6
....						
....						
781 (31)	1830 (72)	152 (6)	2.921	0.4	5.2	12
1086 (43)	1830 (72)	152 (6)	2.120	0.6	7.2	12
1390 (55)	1830 (72)	152 (6)	1.634	0.8	9.2	12
1695 (67)	1830 (72)	152 (6)	1.344	0.9	11.2	12
2000 (79)	1830 (72)	152 (6)	1.170	1.1	13.2	12
2305 (91)	1830 (72)	152 (6)	1.063	1.3	15.2	12
2610 (103)	1830 (72)	152 (6)	1	1.4	17.2	12

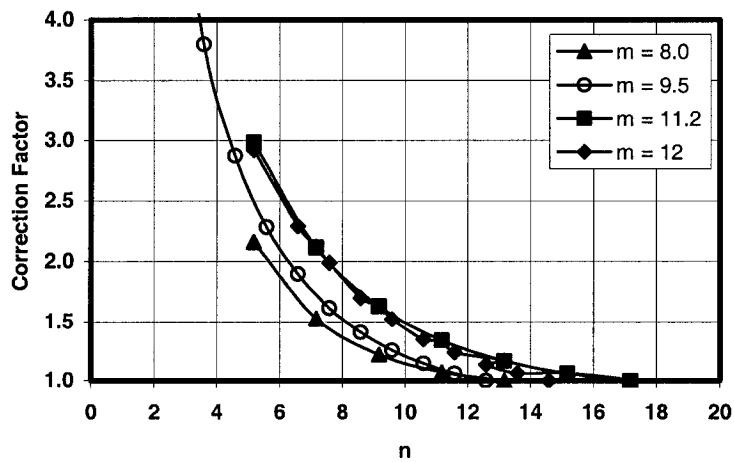
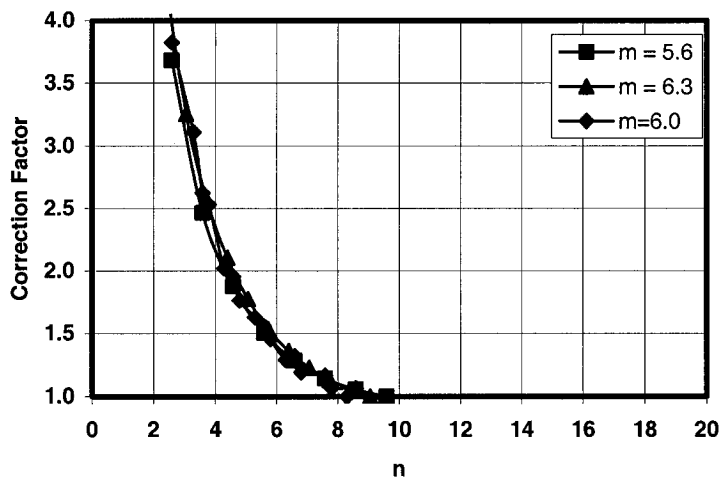
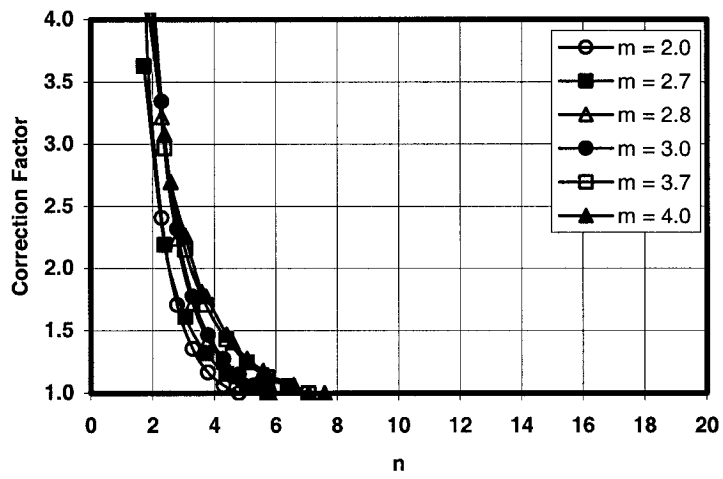


Figure 5.4 Grouping of correction factors for thermoplastic systems

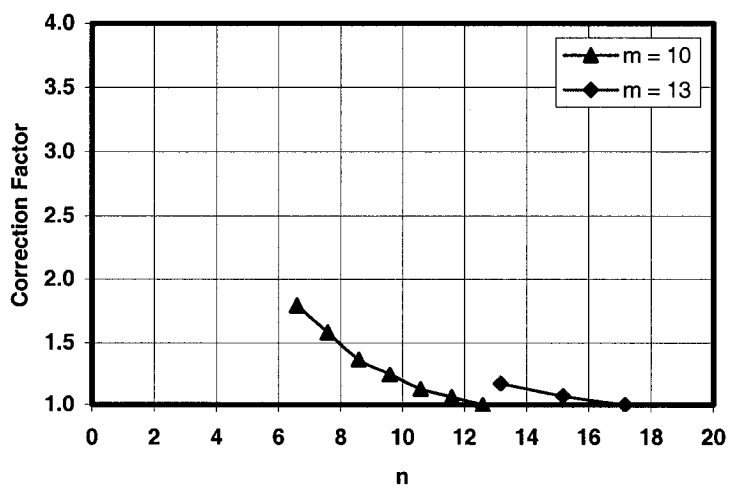
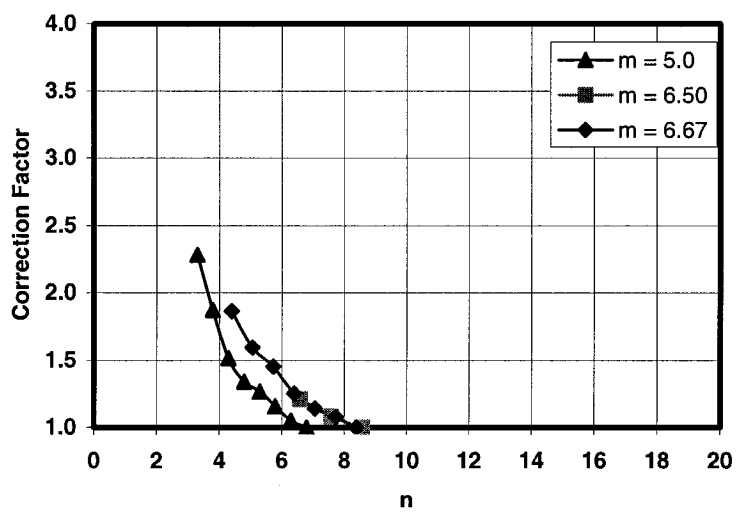
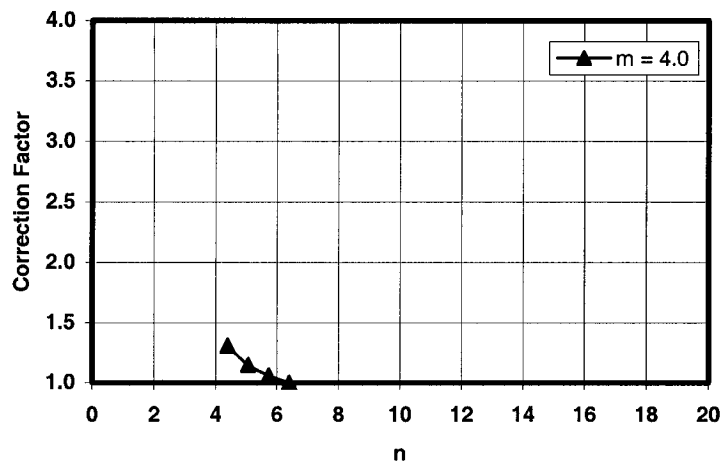


Figure 5.5 Grouping of correction factors for thermoset systems

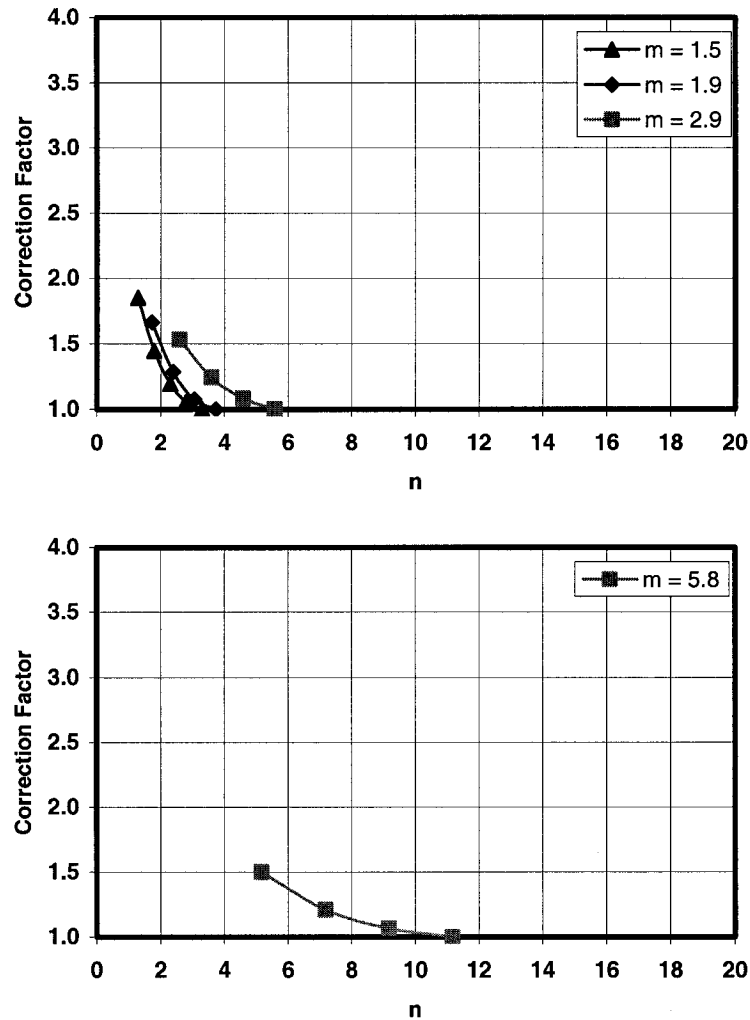


Figure 5.6 Grouping of correction factors for modified bituminous systems

Figures 5.4 to 5.6 indicate the independently developed correction factors for thermoplastic, thermoset and modified bituminous systems, respectively, such that the measured fastener force attained by the experimental results can be multiplied by the correction factor to adjust for the influence of edge effect. In order to obtain a generalized single correction factor graph for all the mechanically attached systems, the calculated correction factors for thermoplastic, thermoset and modified bituminous systems were combined and a normalization procedure was applied. In doing so, the 23 different configurations were reduced to 8, generating a total of 8 characteristic curves. These characteristic curves are shown in Figure 5.7 & 5.8 with an n value on the x-axis and a correction factor on the y-axis. Comparison of these curves revealed the following points:

1. Characteristic curves can be grouped into four sets based on the following relationships:

Set 1: $m < 2.0$

Set 2: $2 = m < 3.5$

Set 3: $3.5 = m < 7$

Set 4: $m > 7$

2. In the computed data n ranges from 1 to 20, which has the corresponding correction factors of 4.0 and 1.0 respectively. This indicates that a table width of 12192 mm (480") can be sufficient to evaluate any system configuration without the application of correction factors. This forecast is based on the maximum value of the x-axis value for Set 4 and calculated as follows:

Maximum x-axis value from Figure 5.8 = 20

$n = 20$

$W/F_s = 20$

$W = 20 F_s$

Taking the maximum fastener spacing $\{F_s = 610 \text{ mm (24")}\}$ used in the industry,

$$W = 20 \times 24 = 480" (12192 \text{ mm}).$$

3. For a given constant value of m , increasing the n reduces the correction factor. It also reveals that the ratio of n increases while the table width increases and causes the correction factor to reduce when systems are tested on a wider table.

For a constant value of n , the correction factor has a direct relation with m . In other words, the correction factor increases while m increases. For instance, for a value of $n =$ eight (Set 4 in Figure 5.8), the values of the correction factor increase linearly from 1.4 to 1.8 while m increases from 8 to 12. This provides the option to interpolate values between m -curves.

Based on the above analysis, it can be concluded that no correction factor is needed or the correction factor is equal 1.0, if:

- $m < 2$ as $n > 5$
- $m < 3$ as $n > 10$
- $m < 7$ as $n > 15$
- $m < 12$ as $n > 20$

This is evident from Figure 5.7 and 5.8 as the value of the x-axis for Set 2, Set 3 and Set 4 can be obtained by multiplying the Set 1 x-axis value using 2, 3 and 4 respectively.

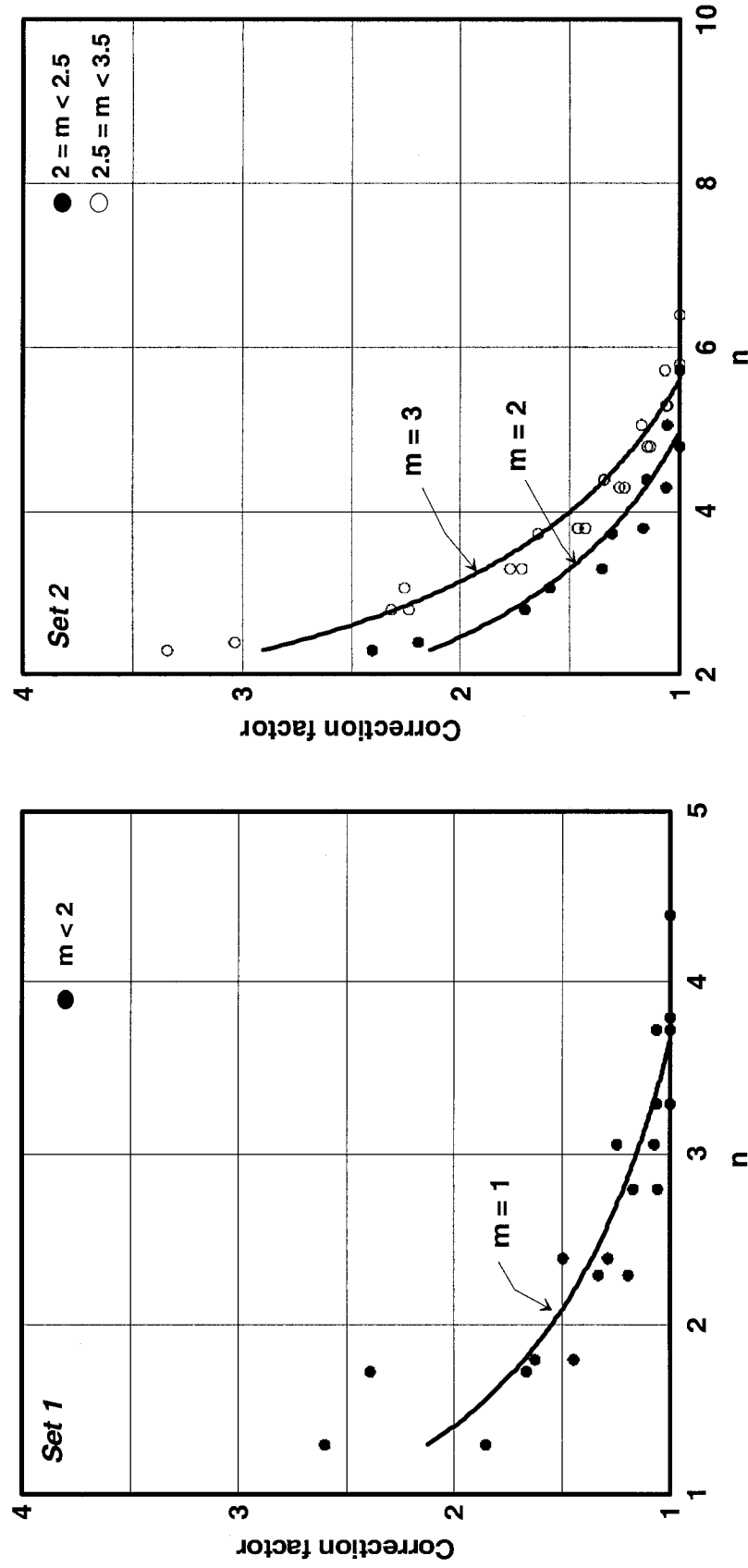


Figure 5.7: Characteristics curves for the correction factor (Set 1 & Set 2)

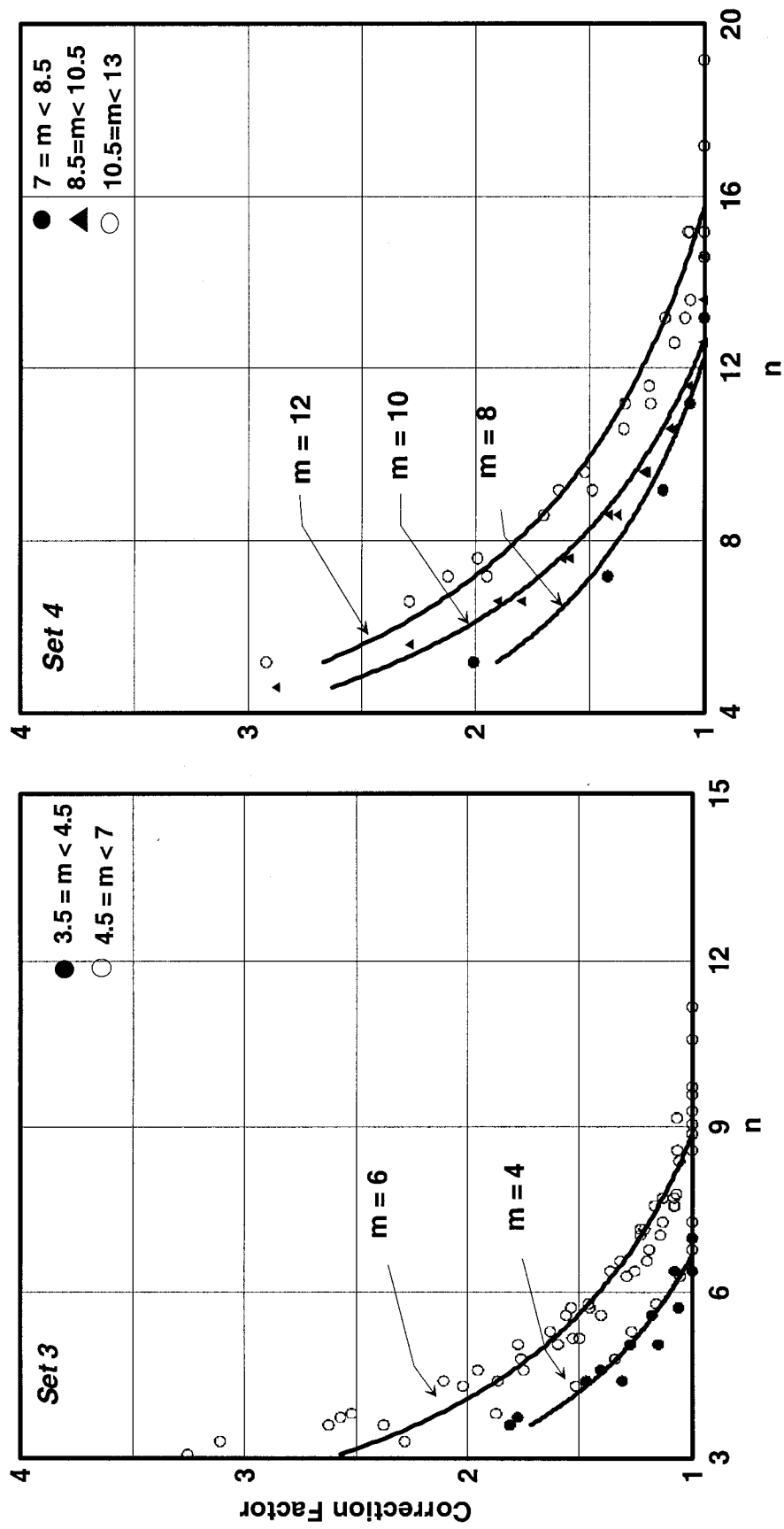


Figure 5.8: Characteristics curves for the correction factor (Set 3 & Set 4)

Although the correction factors (Figure 5.7 & 5.8) cover a wide range of table widths, the factors may not be practical for some cases. Displayed data of Set 1 clearly shows a minimum value of n as 4 on the x-axis. Note that the n shows the number of fasteners along the table. This means that a minimum table width should be greater than 3 times the fastener spacing. For example, when the width of the table decreases to 787 mm (31”), the table cannot be used for the evaluation of a system with a fastener spacing of the 610 mm (24”). For particular application, Set 1 can be excluded. Therefore, it has been decided to set a maximum figure of 1.5 for the correction factor. In other words, the measured fastener force can be corrected only as much as twice to get the design fastener force. Based on this extensive data analysis, Figure 5.9 shows the generalized correction factor for the roofing system design. One can make interpolation to obtain correction factors for m values that are not shown in Figure 5.9 The following section illustrates two practical scenarios for the application of correction factors.

As discussed in chapter 4, UEAtc (1986) is the only test protocol that specified a correction factor for evaluation of roofing systems under wind pressure. In Appendix G, with the limited available data in the literature attempts have been made to compare the present study correction factors with the UEAtc

5.3 Application of the Generalized Correction Factor Curves

For a given system configuration, the m -curve intercept with the x-axis of Figure 5.9 gives the RTW. Systems tested with RTW or greater table widths are exempted from the application of the correction factor (i.e. the influences of table edges on the measured fastener force are minimum). For systems tested in all other tables that are less than RTW, the y-axis gives the correction factors. Using these correction factors, one can obtain the design fastener force. To illustrate the involved process, a case study is shown as follows:

Scenario 1: A proponent tested a flexible membrane roofing system with fastener row spacing of 1829 mm (72”) and a fastener spacing of 305 mm (12”) using a table width of 2743 mm (108”). The experimentally measured fastener force was 1300 N (295 lbf).

Step 1: Calculate m and n

$$\begin{array}{rcl|lcl} m & = & Fr/Fs & | & n & = & W/Fs \\ & = & 72/12 & | & & = & 108/12 \\ & = & 6 & | & & = & 9 \end{array}$$

Step 2: Identify correction factor

For the values of 6 and 9, Figure 5.8 gives a correction factor of 1.00.

Step 3: Calculate design fastener force

This implies that the measured fastener force is not affected by the table edges. Therefore the design fastener force is the same as the measured fastener force of 1300 N (295 lbf).

Scenario 2: A membrane with fastener row spacing of 2743 mm (108") was tested in the same table with the same fastener spacing. Experimentally measured fastener force was 1700 N (382 lbf).

Step 1: Calculate m and n

$$\begin{array}{rcl|lcl} m & = & F_r/F_s & | & n & = & W/F_s \\ & = & 108/12 & | & & = & 108/12 \\ & = & 9 & | & & = & 9 \end{array}$$

Step 2: Identify correction factor

By Interpolating the curves for the ratio of m = 8 and 10, Figure 5.9 gives a correction factor of 1.32.

Step 3: Calculate design fastener force

$$\begin{aligned} \text{Design fastener force} &= \text{Measured fastener} \times \text{Correction factor} \\ &= 1700 \times 1.32 = 2244 \text{ N (510 lbf)} \end{aligned}$$

5.4 Concluding Remarks

The intent of this present study is to achieve characteristic correction factor curves such that guidelines can be developed for the general roofing system design. This chapter describes the generalization approach to obtain the correction factors from a single graph. By identifying a relationship between the correction factors and the influencing parameters (F_r , F_s and W), a generalized correction factor graph was developed. This graph would interpret the experimentally measured fastener force to the true fastener force if that particular system is tested on a table size smaller than the required table size.

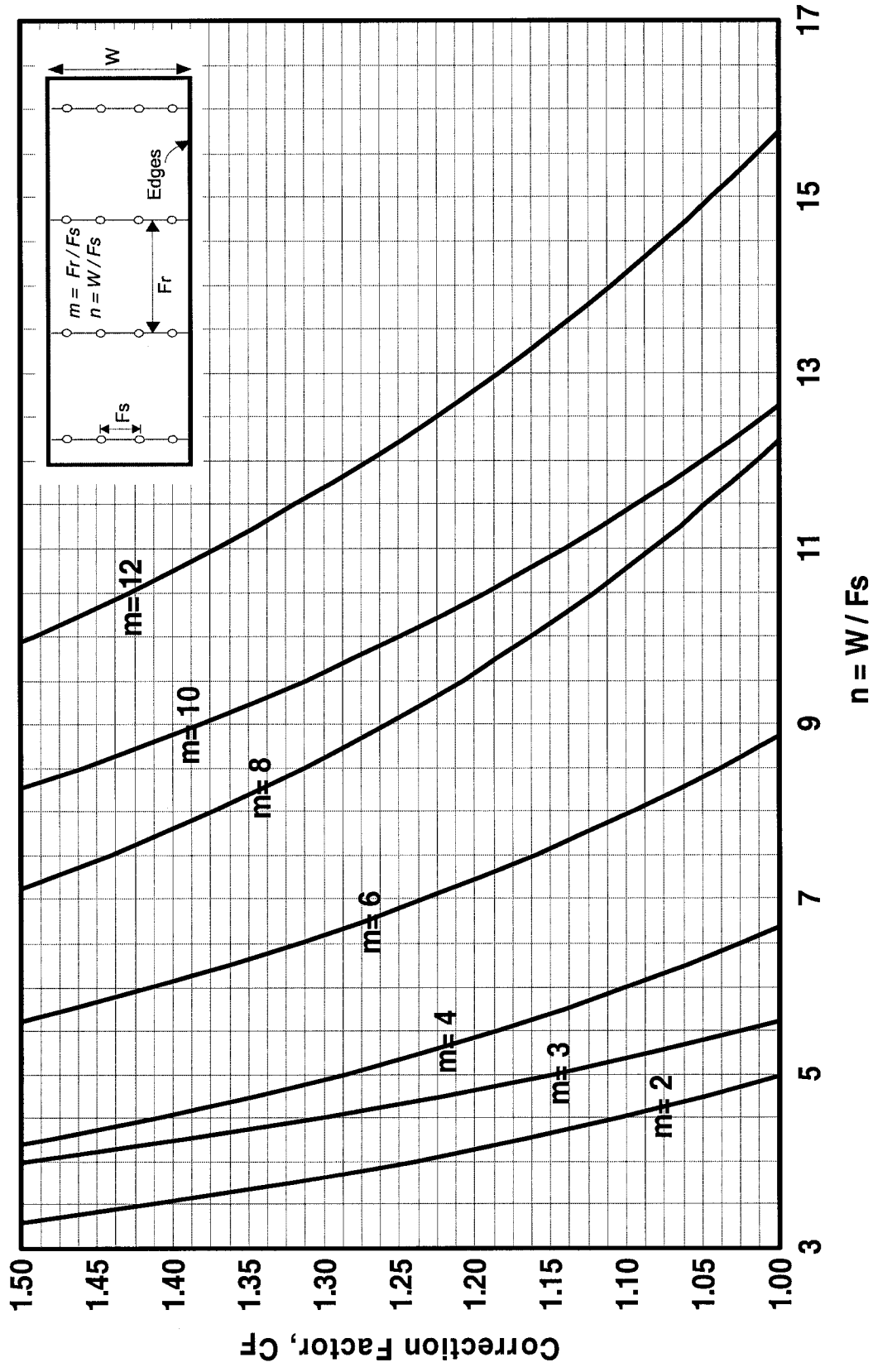


Figure 5.9: Generalized correction factor curves for roofing design

Chapter 6

Air Flows Through Roofing Assemblies

6.1 General Review

In buildings three different modes of air exchange exist:

- Forced ventilation
- Natural ventilation
- Air Leakage through the building envelope

Mechanical fans provide forced ventilation and in most of the commercial buildings it is mandatory to maintain acceptable indoor air quality. Natural ventilation is provided through openings of windows and doors and other design openings to provide adequate ventilation for contaminant dilution and temperature control. Air leakage is the uncontrolled air movement through unintentional openings in the building envelope. Air leakage into a building is infiltration and air leakage out of a building is exfiltration. These air leakage modes differ significantly in the performance of the building envelope. Air leakage characterizes the relationship between the pressure difference across the envelope and the airflow rate. For an air leakage to occur there must be both:

- a pressure or temperature difference between two locations
- a continuous flow path or opening connecting the pressure differential locations

This chapter begins with a brief overview of the two prerequisites necessary for air leakage to occur. It examines the concept of air pressure difference and the different paths for air leakage in the roofing assembly. It also catalogues prior research work related to air movement in the roofing assembly including some of the existing air leakage standards to justify the need of the present research work.

6.2 Air Leakage – Driving Mechanisms Causing Differential Pressure

Three different mechanisms individually or combined can influence the direction and magnitude of air pressures across the building envelope. These are wind pressure, stack (chimney) effect and mechanical ventilation systems. The net pressure difference across a roof or wall system may be due to a single mechanism or combination of all three and

the pressure difference may varies from one location of the building envelope to the other. Pressure differences across the building envelope are governed by the conservation of mass equation i.e the mass inflows equal the mass outflow. In general, density differences between indoors and outdoors can be neglected and the volumetric inflow into the building equals to the volumetric outflow. When wind impinges on a building surface, it creates a pressure distribution that is dependant on the wind direction and the location on the building exterior. This pressure distribution is independent of the pressure inside the building p_i . If no other forces act on building, i.e no temperature difference between the indoor and outdoor, and no mechanical ventilation forces, the pressure difference can be approximated by (ASHRAE 1993):

$$\Delta p = p_o + p_w - p_i \quad (6.1)$$

where :

- Δp = pressure difference between outdoors and indoors
- p_o = static pressure at reference height in undisturbed flow
- p_w = wind pressure
- p_i = interior pressure

If no indoor and outdoor temperature difference exists, the interior static pressure p_i decreases linearly with height at a rate dependent on the interior temperature. This rate of pressure decrease equals $-p_{i,r}$. The interior static pressure equilibrates to a value such that the total airflow into the building equals the total airflow out of the building. The interior static pressure may be determined by calculating the air flow through each opening as a function of the interior pressure, adding all other flow rates together, setting this sum equal to zero, and solving for the interior pressure. To solve the interior pressure in this way, the relationship between airflow rate and pressure difference for each opening are needed. When an indoor-outdoor temperature difference exists, it imposes a temperature gradient in the pressure difference. The pressure difference Δp_s is a function of height and temperature difference and may be added to the pressure difference due to wind into the equation 6.1. The pressure difference can be expressed as:

$$\Delta p = p_o + p_w - p_{i,r} + \Delta p_s \quad (6.2)$$

The parameter $p_{i,r}$ is the interior static pressure at some reference height, and this pressure again assumes that the total inflow equals the total outflow.

Therefore the pressure difference across the building envelope varies considerably depending on the building specific information and the airflow rate/ pressure difference for every opening in the building envelope. These inputs are difficult to obtain for any building, making such a determination unrealistic. A brief review of the three driving forces for air leakage will be highlighted below

6.2.1 Wind Pressure Differential

Winds typically create a positive pressure on the windward face and negative pressure on the leeward side of a building. Pressures on the other sides are negative or positive, depending on the wind angle and building shape. Generally low slopped roofs tend to have mostly negative (uplift) pressures, especially on the leading edge (Figure 6.1). Roofs with slopes above about 25 degrees experience positive pressures on the leading edge, and suction on the leeward.

The wind pressure or velocity head is given by Bernoulli's equation,

$$p_v + \rho v^2 / 2 + \rho gh = 0 \quad (6.3)$$

assuming no height change or pressure loss:

$$p_v = C_p \rho v^2 / 2 \quad (6.4)$$

where

p_v = surface pressure relative to static pressure in undisturbed flow, Pa

ρ = air density, kg/m³

v = wind speed , m/s

C_p = surface pressure coefficient, function of building location and wind direction

Combining equations 6.4, equation 6.1 can be rewritten as:

$$\Delta p = p_o + C_p \rho v^2 / 2 - p_i \quad (6.5)$$

Structural damage from very strong winds is the most obvious effect of wind on roofs, but even moderate winds could promote damage. The movement of air through roofing assembly must also be considered because the same wind induced pressure

distributions that cause structural loading also can cause air leakage in to the roofing assembly, even at moderate wind speeds, from regions of high pressure to low pressure regions if openings exist either intentionally or accidentally.

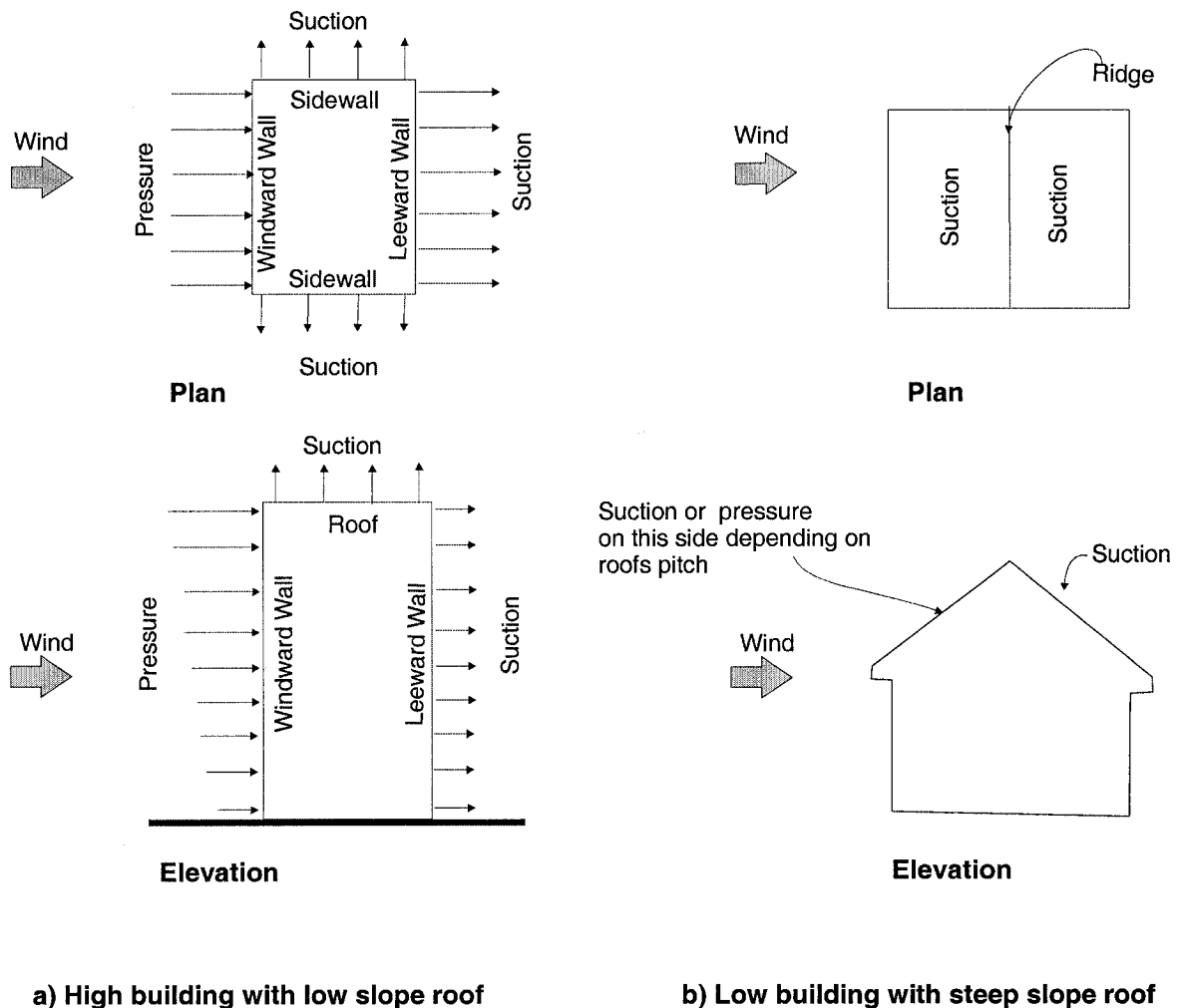


Figure 6.1 Wind pressure differential pattern facilitating air leakage

The importance of internal pressure whether positive or negative, to the resultant uplift forces on the roof is apparent. To take an extreme case, an airport hanger with a large overhead door (dominant opening) open on the windward side receives the positive pressure under the roof. This adds to the external suction to cause uplift. With the wind coming from the opposite direction the effect is reversed. Even though the wind may not blow strong enough to cause serious structural loads, suctions and pressures exist and when these added up with the air leakage, it may affect seriously the operation of a

roofing system as shown in Figure 6.2. Therefore an understanding of what actually happens when air enters the roofing system and how to quantify and minimise this air leakage is very important for a sound roof design.

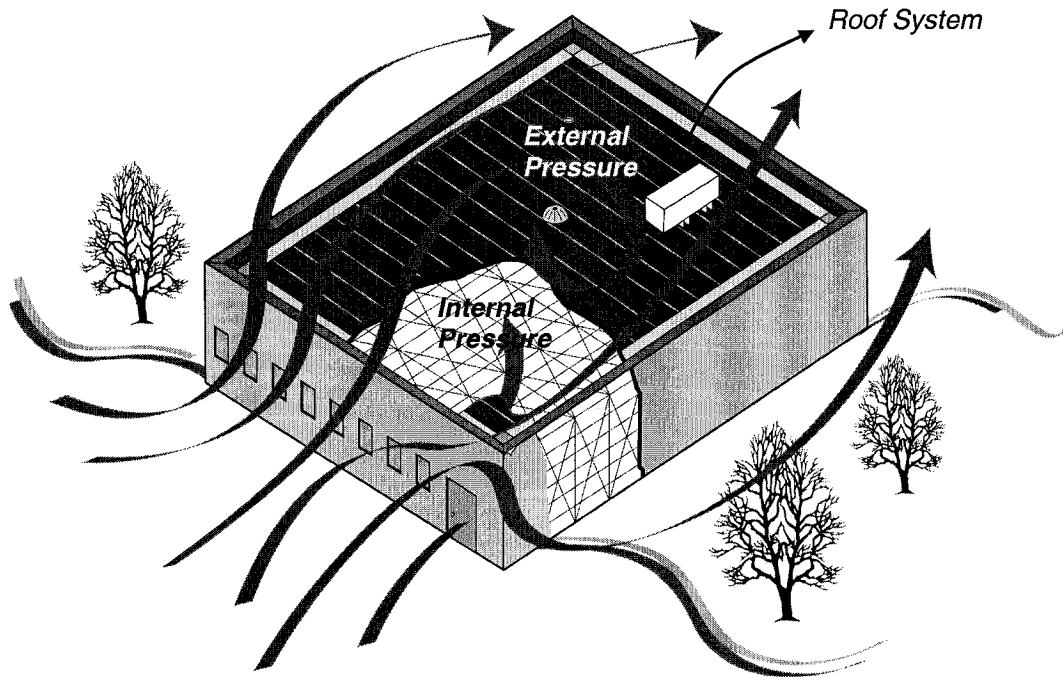


Figure 6.2 Combination of external suction and internal pressure on a roofing assembly

6.2.2 Stack Effect

Stack effect is a condition, which can occur in all buildings in winter and summer. It is a tendency for a mass of air at one temperature (building air volume) to rise or fall in another mass of air at a different temperature (the outdoor air). In winter, the tendency is for building air to rise up and out of building. This air movement results from the difference in density between the indoor and outdoor air masses, which generally causes a slight outward positive pressure at the top of a building, while exerting a slight inward negative pressure at the base. As a result, air will tend to infiltrate at the lower levels of the building while exfiltrating at the upper levels. In summer the opposite effect occurs. The location in the building where the pressure difference diminishes to zero as shown in Figure 6.3, is termed the neutral plane.

An experimental investigation on a 20-storey student residence building at the University of Ottawa (Lee, Tanaka, Shaw, 1982) indicated that the stack effect is linearly proportional to the difference of the reciprocal outside and inside (absolute) temperatures, and varies almost linearly with height. The neutral pressure level occurs at a height of ~ 4000 mm (157"), or 70% of the height of the building. Generally stack effect is the weak force, which generally has a value around 10 Pa (0.2 psf) to 50 Pa (1.04 psf).

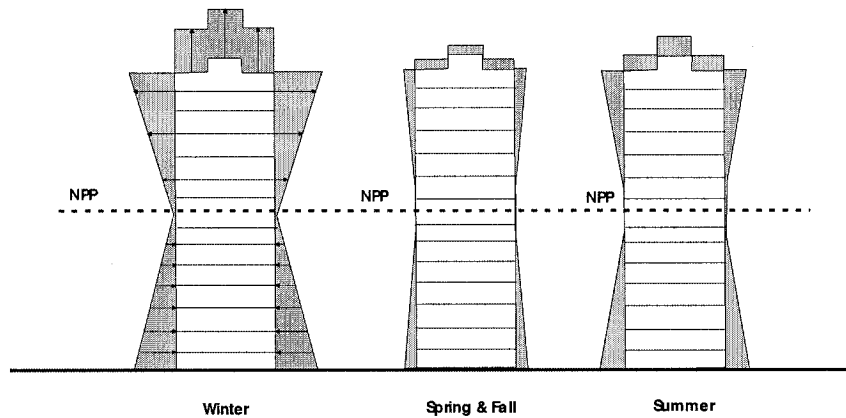


Figure 6.3 Stack effect facilitating air leakage (Quirouette, 1985)

6.2.3 Mechanical Ventilation

Fans provide ventilation air into a building as shown in Figure 6.4. They are usually called upon to

- control humidity
- minimize air infiltration

The fans may also be configured to create negative pressure to prevent moist indoor air from exfiltrating through a roof or exterior walls. For example this configuration may be used for in a auditorium, indoor swimming pool and other high humidity buildings in a cold climate. In terms of structural loading, the ventilation fans produce a small pressure difference, but this air pressure difference is significant with respect to the operation of the building. This air pressure difference could result in many problems such as difficulty in closing lobby doors, excessive exfiltration at openings, formation of icicles at holes and cracks, moisture in wall or roof cavities and premature corrosion of metal fasteners. A mechanical ventilation system imposes an additional airflow within the building. The pressure difference is still calculated using equation 6.2, but the interior pressure changes so that the balance between inflow and outflow is maintained.

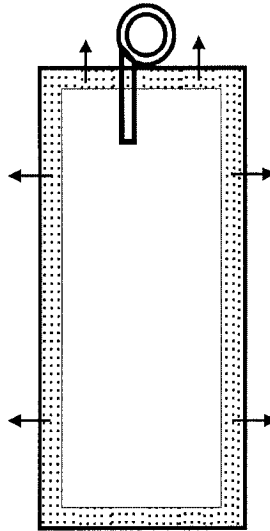


Figure 6.4 Mechanical ventilation facilitating air leakage (Quirouette, 1985)

6.2.4 Net Differential Pressure

The above-discussed three primary differential pressure mechanisms can act individually or in combination to provide the necessary differential pressure for air leakage (Figure 6.5). The relative importance of the wind and stack pressures in buildings depends on the surroundings of the building while the effect of ventilation is more complex and depends on the direction of the ventilation flow. Of the three airflow driving mechanisms wind pressures across the roofing system is of most significant for a roofing assembly but it has greatest uncertainty. Hence the present research study was undertaken to quantify the relationship between air leakage through a roofing assembly and the wind differential pressures across the assembly.

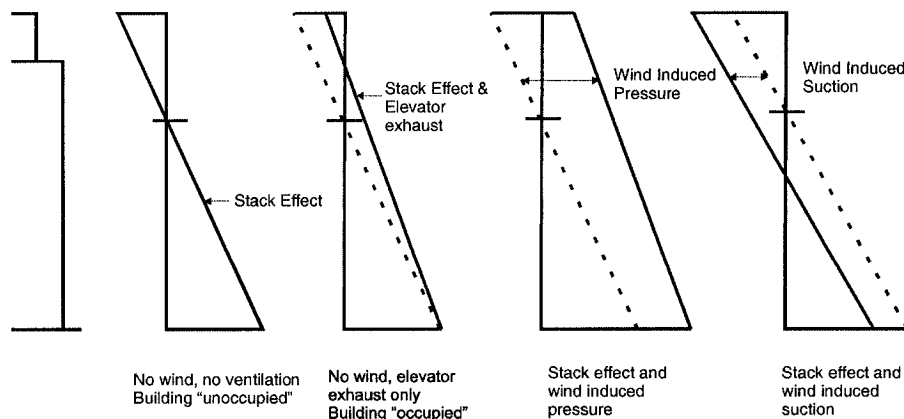


Figure 6.5 Net air pressure difference (Lee, Tanaka, Shaw, 1982)

6.3 Air Leakage – Flow Paths

The nature of holes, openings and flow paths determines the air leakage through the roofing assembly. A roofing assembly comprises many components that are separated at involves various junctions, penetrations and terminations. Though it is difficult estimating the effective cross-sectional area and the flow path lengths of these openings, it is certain that air leakage will occur. Openings or leakage paths in a roofing assembly may be classified as:

- Channel Flow
- Orifice Flow
- Diffuse flow

A detailed description of these three types of flow with typical examples is discussed below.

6.3.1 Channel Flow and Orifice Flow

Channel Flow: This is the most common type of opening or leakage path in the roofing assembly characterized by a tortuous path from an opening on one side of a roofing assembly to an opening on the other. Channel flow paths include air leakage along steel deck flutes, at insulation joints and the base of gypsum board finishes. Figure 6.6 shows channel flow paths in a typical roofing system, the gap between the insulation joints provide the necessary flow paths. Some openings or leakage paths may develop after construction because of thermal expansion and contraction of cladding elements.

Orifice Flow: Orifice flow is characterized by a direct opening such as a hole, crack or joint through which the air entry and exit are in a linear pathway. The flow path is short and direct. Figure 6.7 illustrates a good example of orifice flow between the insulation and the parapet wall. Another typical example of orifice flow in a mechanically attached roofing system is the fastener hole. In a re-roofing process if the fastener holes are not properly sealed they may provide the necessary flow path for air seepage, which may add up to the overall system leakage of the roofing assembly.

The theoretical representation of the channel and orifice flow can be related to the airflow through cracks and gaps. The relationship between the airflow through an opening and pressure difference across it is called the leakage function of the opening.

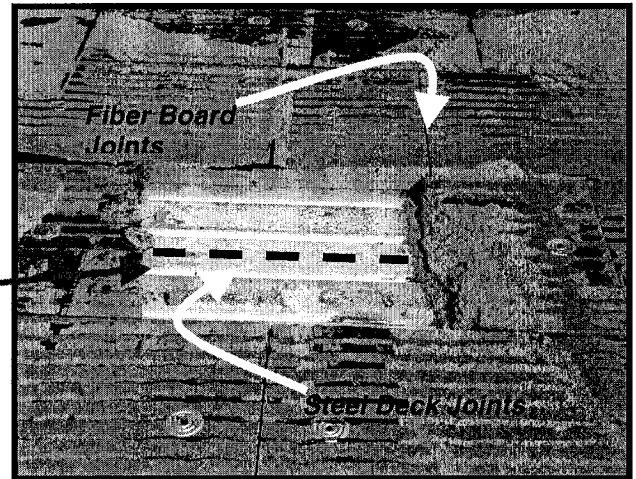
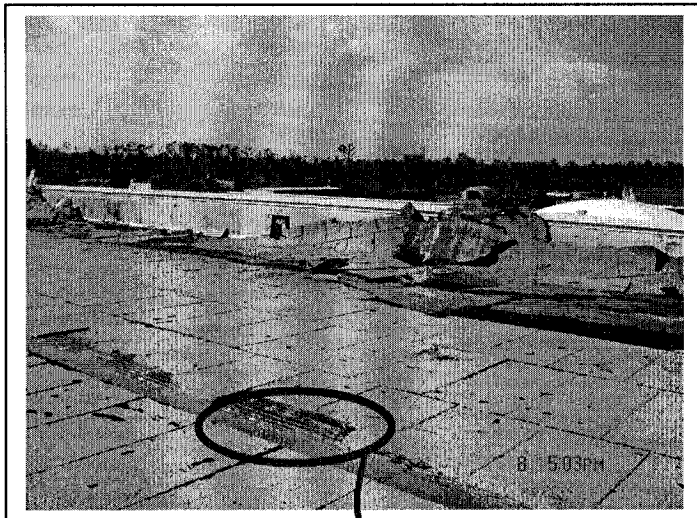


Figure 6.6 Channel flow in a typical roofing assembly

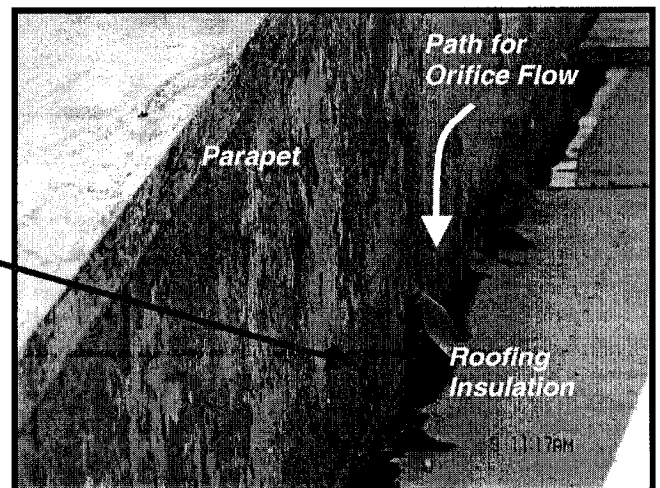
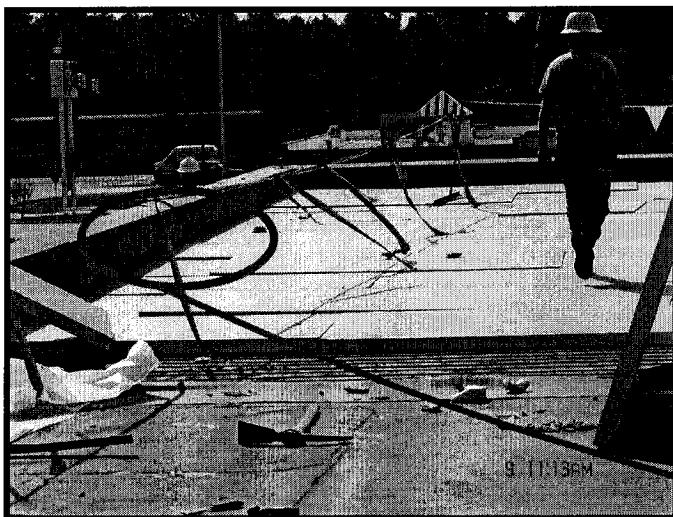


Figure 6.7 Orifice flow at wall/roof junction

The form of the leakage function depends on the geometry of the opening. It is obvious from Bernoulli's law that if a fluid flows through an opening, having the bulk mean velocity, V_m from a vessel with static pressure p_1 to another with static pressure p_2 , then

$$p_1 = p_2 + \frac{\rho V_m^2}{2} \text{ and}$$

$$\Delta p = \frac{\rho V_m^2}{2} \quad \text{or} \quad V_m = \sqrt{\frac{2 \cdot \Delta p}{\rho}} \quad (6.5)$$

In practice, however the flow rate is reduced due to flow contraction so that:

$$V_m = C_d \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

$$Q = C_d A \sqrt{\frac{2 \cdot \Delta p}{\rho}} \quad (6.6)$$

where

Q = airflow rate, m^3/s

C_d = discharge coefficient for opening, dimensionless, Kirchoff gave a value = 0.611 (ASHRAE 1993)

A = cross-sectional area of opening, m^2

ρ = air density kg/m^3

Δp = pressure difference across opening, Pa

If the wall is thin and the edges of the opening are sharp, an energy-loss factor of around 0.97 should be applied. The coefficient of discharge, C_d can be denoted by C_d^* , if energy losses are included and

$$C_d^* = 0.97 \times C_d = 0.593$$

These C_d and C_d^* are valid for both sharp edged holes and slots as in the channel and orifice flow. The discharge coefficient C_d is a dimensionless number that depends on the opening geometry and the Reynolds number of the flow. At a sufficiently low Reynolds numbers (i.e in a laminar flow), C_d depends on the square root of the pressure difference; Therefore, Q is proportional to Δp . At large Reynolds numbers, the flow becomes turbulent. In turbulent flow, the discharge coefficient is constant at a fixed Reynolds number and therefore the flow Q is proportional to $\sqrt{\Delta p}$.

The openings in a roofing assembly are much less uniform in geometry. Generally the flow never becomes fully developed, thereby preventing the applicability of the simple relations between Q and Δp . Each opening in the roofing assembly can still be described by equation 6.6, where A is an equivalent cross sectional area and C_d depends on the opening geometry and the pressure difference across it.

Equation 6.6 can also be represented using the power law equation as follows:

$$Q = c (\Delta p)^n \quad (6.7)$$

where

c = flow coefficient

n = flow exponent

The power law equation only approximates the relationship between Q and Δp . In fact, the values of c and n depend on the range of Δp over which equation 6.6 is applied and do not have a physical interpretation. Honma (1975) measured Q as a function of Δp for several simple openings and the measured data were fitted to equation 6.6. It was found that cracks with larger flow resistances i.e., greater flow lengths or narrower widths, tended to have an exponent n closer to one than did gaps with less resistance.

6.3.2 Diffuse flow

Diffuse flow occurs when materials used in the roofing system are ineffective in controlling air leakage due to porosity, such as fibrous insulation or wood decks. It is a combination of both diffusion and air leakage. Diffusion is simply the movement of water vapour in a material due to vapour pressure difference and, it is relatively a slow process. When there is a airflow driven by air pressure differences the diffuse flow is accelerated moving the water vapour in the direction that the air pressure drives. Diffuse flow is characterized by the screen effect or the permeance of the construction material. Figure 6.8 illustrates the occurrence of diffuse flow in a typical roofing assembly.

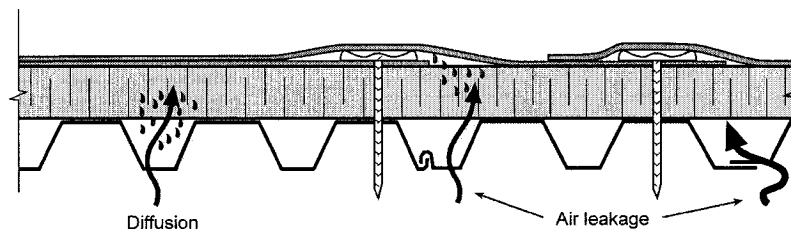


Figure 6.8 Diffuse flow

In diffuse flow, air flows through an air permeable material when a pressure difference acts across the material. In its macro structure, an air-impermeable material must contain airflow paths going all the way through the material sample. In porous materials, such as most building materials, the flow paths often consist of interconnected pores. Airflow is possible only if at least part of the pore space is interconnected. The interconnected part of the pore system is called the effective pore space of the porous medium. The permeability of a material is a property, which measures the degree of easiness for a fluid to pass through the material under the influence of pressure gradient. The permeability is, in other words, the fluid flow conductivity of a permeable material. Based on Darcy's law, a unidirectional steady flow of air through the permeable material of thickness t , from a region of pressure p_1 , to a region of pressure p_2 can be expressed as

$$\frac{Q}{A} = -\frac{\chi}{\eta} \cdot \frac{\Delta P}{t} \quad (6.8)$$

If the air pressure p_1 is not significantly larger than atmospheric pressure p_2 (and hence the difference $p_1 - p_2$ is not large) for all practical purposes

$$\Delta P \approx p_2 - p_1 \quad (6.9)$$

and equation (6.8) becomes

$$Q = K A (\Delta P) \quad (6.10)$$

where

Q = volumetric flow rate of air (L/s)

χ = intrinsic air permeability of the material

η = dynamic viscosity of air (Pa.s)

K = variable dependent on the intrinsic air permeability of the material, its thickness and the dynamic viscosity of air (L/s $\cdot$ m² $\cdot$ Pa)

A = normal cross-sectional area of the material (m²)

$\Delta P = p_1 - p_2$ (static air pressure differential across the material (Pa))

A unidirectional steady flow of air through a permeable material is represented in Figure 6.9. The mode of airflow may be laminar, turbulent or a combination of both. Based on the Reynolds number the criterion is selected for the breakdown into laminar motion and the transition to turbulent motion. For a laminar flow of air through a permeable material,

the rate of airflow is expressed by equation 6.10, while for a turbulent flow the rate of airflow can be expressed by:

$$Q = K A (\Delta p)^{1/2} \quad (6.11)$$

where

Q = volumetric flow rate of air (L/s)

K = variable dependent on the intrinsic air permeability of the material, its thickness and the dynamic viscosity of air (L/s –m² –Pa)

A = normal cross-sectional area of the material ((m²)

Δp = static air pressure differential across the material (Pa)

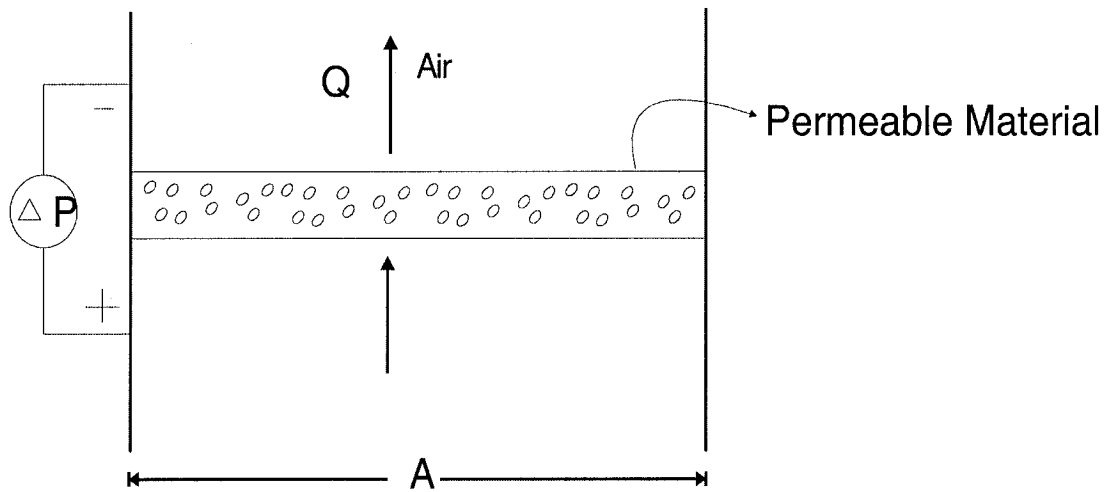


Figure 6.9 Airflow through a permeable material

Roofing materials are heterogeneous by nature. Therefore within the material the transition of flow from laminar to turbulent may exist. Furthermore, due to the entrance and exit effects different modes of flow may exist within the material. Therefore, in order to cover all possibilities, the rate of airflow may be expressed by:

$$Q = K A (\Delta p)^n \quad (6.12)$$

where n is an exponent with value ranging from $0.5 < n < 1.0$. Figure 6.10 illustrates the different modes of airflow through a permeable material.

The air permeance of a material is defined as the rate of air flow (L/s), per square meter of area (m²) under a unit static pressure differential (Pa). It is represented by P and is expressed by:

$$P = \frac{Q}{A (\Delta P)^n} \quad (6.13)$$

Equations 6.10 to 6.13 are applicable to homogenous materials and membranes. However, for non-homogenous materials it is useful to define the airflow resistance. The resistance to air flow provided by a building material is the reciprocal of the air permeance and is expressed as

$$R = \frac{1}{P} = \frac{(\Delta P)^n \cdot A}{Q} \quad (6.14)$$

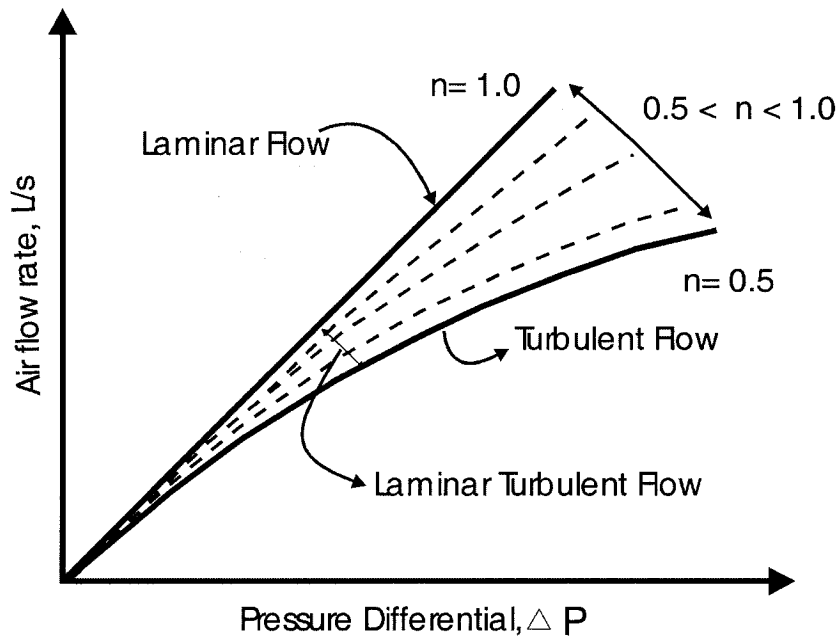


Figure 6.10 Modes of airflow (CMHC 1988)

The air flow resistance determined will be an average property of the material for the metering area and so the material need not be homogeneous or of uniform thickness. As per the CAN-149.10-M85 Standard, "Determination of the air tightness of building envelopes by fan depressurization method", an equivalent leakage area is the area of a single sharp-edged orifice with flow coefficient of 0.6 and the flow exponent of 0.5, which would yield the same rate of air flow as the combined leakage of openings in the permeable material subjected to a static pressure differential of 1 Pa. The equivalent leakage area can be calculated by the following equation (CMHC 1988):

$$ELA = 0.001157 \sqrt{\rho} C_r 10^{n-5} \quad (6.15)$$

where

ELA = Equivalent leakage area (m^2)

ρ = air density at reference conditions. (kg/m^3)

C_r = air flow rate that would occur through the specific permeable material at reference ambient conditions and at $P = 1 \text{ Pa}$ and in units $\text{L/s} - \text{Pa}$

The equivalent orifice diameter is defined as the diameter of a sharp-edged orifice showing the same cross-sectional area as the ELA. The equivalent orifice diameter can be calculated by the following equation:

$$\text{EOD} = \sqrt{\frac{4 \cdot \text{ELA}}{\pi}} \times 10^3 \quad (6.16)$$

where

ELA = Equivalent leakage area (m^2) as defined in 6.15

EOD = Equivalent orifice diameter (mm)

Figure 6.11 shows a graphical representation of ELA for a given permeable material.

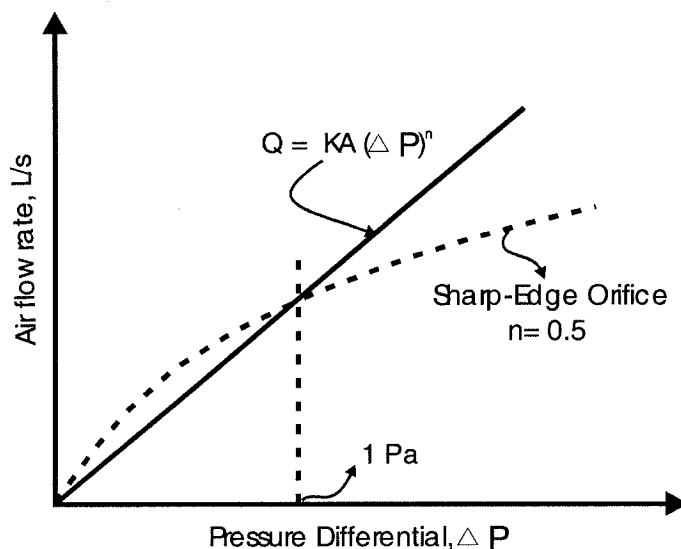


Figure 6.11 Equivalent leakage area (CMHC 1988)

In summary, the above sections described the two prerequisites necessary for generating air leakage in a roofing assembly. Air leakage through a roofing assembly is a physical property of the building and is determined by its design, construction, seasonal effects and deterioration over time. Though, controlling prerequisite one is a complex task but controlling prerequisite two is certainly within the reach by attempting

to seal the openings at one plane in the roofing assembly, Appendix G discusses in further regarding the air leakage control.

6.4 Literature Review: Air Leakage Through Roofing Assemblies

Despite the significance of air leakage on roofing systems performance, currently, no study exists in the literature that addresses the air leakage characteristics of a roofing assembly such as:

- (a) the porosity of a roofing assembly,
- (b) test procedures and acceptance criteria to characterize the air permeance of a roofing assembly, and
- (c) influence of air leakage on the wind performance of the roofing assembly

The present section discusses some of the prior studies done related to air movement in the roofing assembly, which will highlight both the lack of research data and research attention towards the air leakage quantification of roofing assemblies.

Feldman, Stathopoulos, Cosmulescu and Wu, 1998, developed a simple apparatus for the evaluation of air infiltration through the building envelope components. The facility is developed according to ASTM Standard E283-91. The simple apparatus consists of two identical chambers of dimensions 1m x 1m x 0.5 m (39" x 39" x 19") with test specimens installed and sealed between them. The testing process involves the pressurization technique where air is supplied into one chamber while the other chamber is open to the ambient atmospheric pressure. The test chamber is calibrated and tested for the determination of air leakage through the building envelope components such as impregnated brick walls and composite wall sections.

Dregger, 1991, discussed the role of air retarders in helping to resist wind uplift forces on a roofing assembly. The emphasis was laid particularly on the loose laid and mechanically attached single-ply roofing systems. An air retarder can be any sheeting material installed next to the steel deck. However some roof decks, such as cast in place concrete deck and steel deck with concrete toppings can also act as air retarders. When using a polyethylene sheet or other sheet membranes as air retarders they must be held down by an adhesive or mechanically fastened insulation boards. Air retarders, like chains, are only strong as the weakest link. The lack of proper sealing around roof penetrations and terminations are common "weak links" in roof assembly construction.

The role of vapour retarder in providing air leakage resistance and its effect on wind uplift force was also discussed, but no experimental proof has been mentioned or any results presented in this paper. The paper further indicates that influence of air leakage is not only important in flexible roofing systems but also in adhered systems, where it leads to problems of delamination.

Zarghamee (1990 a), studied the effect of the wind pressure on an inflated single-ply roofing membrane and its attachment mechanism. He contended that the behaviour of mechanically attached single ply roofing membrane is affected by air infiltration rate below the membrane in addition to the external pressure changes occurring above the membrane. The relationship between air infiltration and the response of roofing membranes to the fluctuating, or dynamic, component of wind pressure is described. He proposed that the roofing system design take into account a percentage of the dynamic wind pressure component. The percentage used would depend on whether the roofing section is considered to allow low, average or high rates of air infiltration. He concluded by mentioning that further research is needed to quantify the relationship between air infiltration and the distribution of wind uplift forces.

Bumbaru, Patenaude, (CMHC 1988), developed a new test procedure for quantifying the air permeance of building materials. Air infiltration and exfiltration through the building envelope have been blamed for the premature failure of any new wall systems. To achieve air tightness of a building envelope, an air barrier system should be designed to perform the unique function of resisting air infiltration and air exfiltration. To accomplish this, the system must have the following attributes: continuity, strength, air impermeability and durability. Among the above aforementioned attributes, the air permeability of building materials used to build the air barrier system is certainly the first characteristic to evaluate in order to set limitations. A total of 126 specimens from 36 building materials were tested at static pressure differentials varying from 25 to 100 Pa (0.5 to 2 psf). Validation of the test results was conducted on orifice plates and on building materials. When applied to orifice plates, the validation process clearly shows that the test results are within 1 to 7% of each other. Furthermore, best accuracy is reached at pressure differentials of 75 to 100 Pa. The study confirmed that at pressure differentials of 25 and 100 Pa (0.5 to 2 psf), the airflow regime through building materials is mainly laminar.

Quirouette, (1985), defined the functions of vapour barrier and air barrier. The function of the vapour barrier is to prevent water vapour diffusion through an insulated building envelope. Vapour diffusion control is simple to achieve and is primarily a function of the water diffusion resistance of the chosen materials and their position within the envelope assembly. The function of the air barrier is to eliminate the flow of air from inside to outside through the envelope and vice versa. Air leakage control is a more complex objective, which must be considered as a separate and distinct function for any wall, roof, window and especially joint details. The vapour and air barriers may or may not be the same material; if they are the same material, then it must meet all the requirements of air tightness control and of vapour diffusion control.

The above review of the existing studies on air leakage through roofing assemblies reveals the following:

- The studies clearly indicate that no data currently exists related to the air leakage porosity of the roofing assembly.
- The air retarders play a major role to resist wind uplift forces acting on the roof deck and improve the wind uplift performance.
- It was highlighted that a vapor retarder could do the dual functionality of vapor control and air control.
- The studies asserted that the behavior of mechanically attached single ply roofing membrane is affected by air infiltration rate below the membrane in addition to the external pressure changes occurring.
- In the existing studies, attempts were not made to identify the influence of air barrier on the wind uplift resistance.

6.5 Review of Existing Standards For Air Leakage Quantification

Currently the roofing industry has no test procedure and acceptance criteria to estimate the porosity of a roofing assembly. This raises the question about the air tightness of a roofing assembly. The present section gives a brief overview of the existing test protocols to measure air leakage through building materials and systems. In relation to the present research study, emphasis will be laid on the dimensions of the testing chamber/specimen size and testing protocol used in these test methods and based on which limitations of existing standards will be identified.

Standard Test Method for Air Permeance of Building Materials – ASTM E2178-03

Testing chamber:

It consists of an airtight test chamber, which shall be at least 320 mm (12") deep and capable of receiving a 1m x 1m (39" x 39") test specimen, as shown in Figure 6.12.

Test Protocol:

The air permeance of the test specimen shall be determined with a minimum of six measurements, which shall be taken at 25, 50, 75, 100, 150 and 300 Pa (0.5, 1, 1.6, 2.1, 3.1 and 6 psf) differential pressures. The air permeance rate of the material is assigned at a reference pressure difference of (ΔP) of 75 Pa (1.6 psf).

Limitation:

This test method is to determine the air permeance of flexible sheet and rigid panel type building materials.

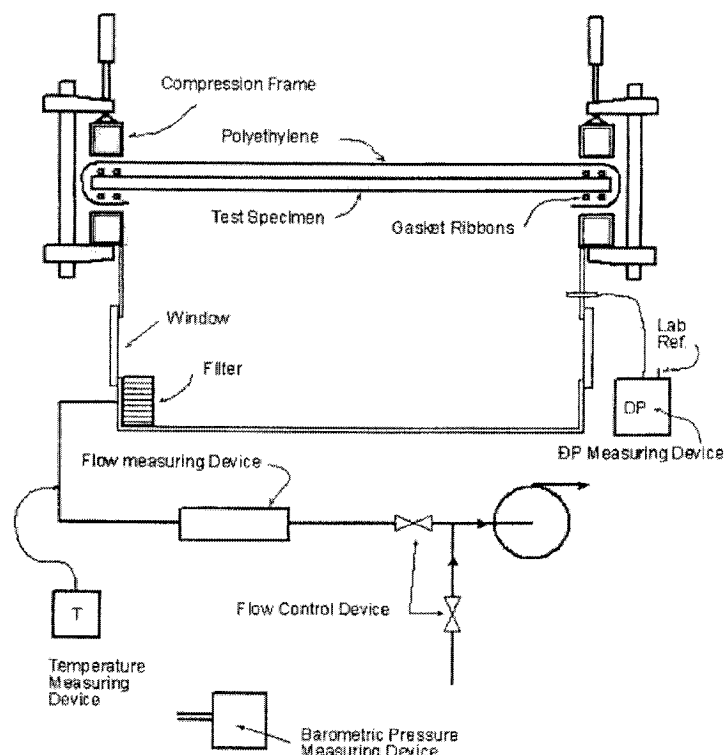


Figure 6.12 Configuration of test apparatus (ASTM E2178 –03)

Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen – ASTM E283 - 91

Testing Chamber:

There is no fixed dimension of the testing chamber, as it is dependent on the test specimen size. The test specimen size depends on the type of component being tested such as the walls, curtain walls, doors, windows and skylights. Figure 6.13 illustrates the schematic of the air leakage apparatus.

Test protocol:

A specific test protocol is not defined. It depends on the testing agency whether they want to do infiltration test or exfiltration. If no value is designated a test pressure difference of 75 Pa (1.5 psf) is recommended.

Limitation:

This test methodology is technically applicable only for testing the vertical components of the building envelope such as windows, curtain walls, and doors. The testing components are mounted vertically in the testing chamber.

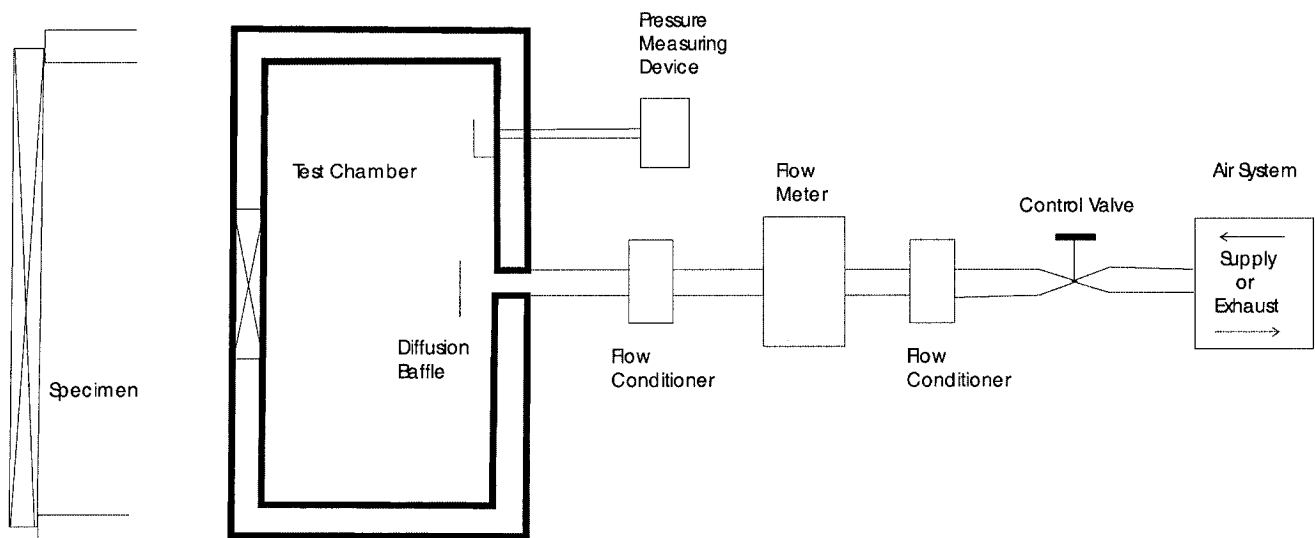


Figure 6.13 General arrangement of air leakage apparatus (ASTM E283 –2000)

Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and temperature differences Across the Specimen –ASTM E 1424 - 91

Testing Chamber:

There is no fixed dimension of the testing chamber, as it is dependent on the test specimen size. The chamber shall be capable of withstanding the differential test pressures and temperatures. Figure 6.14 illustrates the schematic of the air leakage apparatus.

Test Protocol :

When unspecified, the air flow will be air infiltration and the test pressure shall be 27 Pa (0.75 psf), 75 Pa (1.57 psf) , and 300 Pa (6 psf). The test temperature difference will be applies in two modes, the cold temperature mode and warm temperature mode. The cold temperature mode shall be $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$ room side and $-17^{\circ}\text{C} \pm 2^{\circ}\text{C}$ weather side. The warm temperature mode shall be $22^{\circ}\text{C} \pm 2^{\circ}\text{C}$ room side and $43^{\circ}\text{C} \pm 2^{\circ}\text{C}$ weather side.

Limitation:

Similar to ASTM E283, the test protocol is applicable only for testing the vertical components of the building envelope such as windows, curtain walls, and doors.

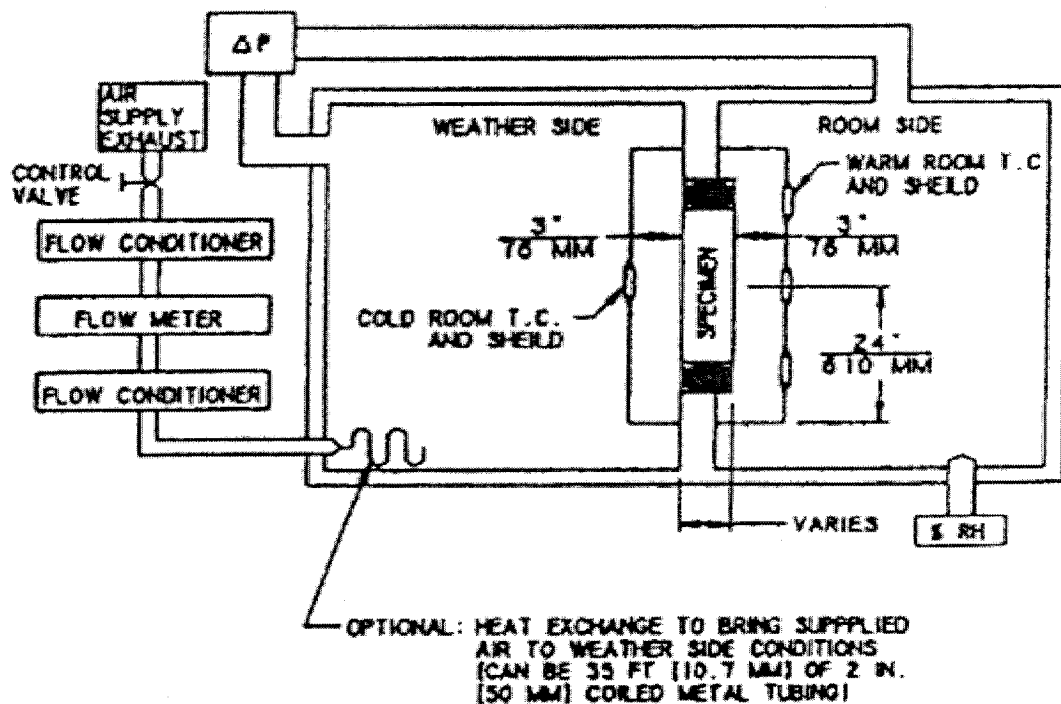


Figure 6.14 Schematic of environmental chamber (ASTM E1424 –91)

Standard Test Method for Rate of Air Leakage Through Exterior Metal Roof Panel Systems—ASTM E 1680 - 95

Testing Chamber:

Similar to the E283 test method, there is no fixed dimension of the testing chamber and it depends on the roof specimen size. The roof specimen shall accommodate three panel widths plus the side rail supporting elements at each edge. The specimen shall contain three assembled side lap seams; this allows partial width units and it shall be of sufficient length to develop a multispan conditions unless the panel is used only in single span applications.

Test Protocol:

If not specified by the testing agency, the test pressure difference at which air leakage is to be determined shall be both + and -75 Pa (1.6 psf). The air leakage through the specimen is obtained by applying air pressure for a minimum of 10 s and then allowing the test specimen to recover for 2 min. A similar procedure is followed for negative static air pressure differential.

Limitation:

This test method is a specialized adaptation of the Test Method E283. This test method is exclusively for quantifying air leakage through metal panels rather than the assembly. This test procedure is intended to measure only the air leakage associated with the field of the roof, including the panel side laps and structural connections; it does not include leakage at the openings or perimeter or any other details. This test procedure does not include the structural deck, barrier and insulation in the specimen. Figure 6.15 illustrates the schematic of the air leakage apparatus.

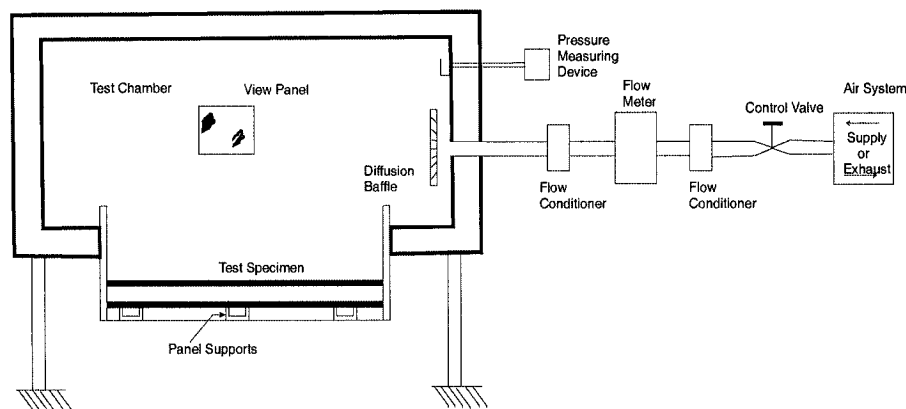


Figure 6.15 General arrangement of air leakage apparatus (ASTM E1680 -95)

6.6 Objective of the Present Study

Based on the above literature review, it is clear that a single test protocol cannot be applied to all types building envelope components due to the involved complexities. Air leakage must be considered as a separate and distinct function for any wall, roof, and window. From the building envelope perspective wall is vertical and a flat roof is horizontal. Though both separate the uncontrolled outdoor environment from the controlled indoor environment, the construction methods are different from each other. This raises the question about the validity among the existing wall assembly test protocols. Though the theory is the same behind all these testing protocols, what is important is the test methodology or approach. For example, the use of the test method ASTM E283 for quantifying air leakage through a roofing assembly may not be an appropriate method. As discussed, ASTM E283 is limited to walls, windows and doors, where the test specimen is mounted vertically in the testing chamber. Low slope roof comprises of different junction, penetrations and terminations, and it is very tedious and cumbersome to mount a flat roof vertically incorporating all the attachment mechanisms. As discussed earlier, a roof is divided into three zones namely field, edge and corner. The air leakage through a roofing assembly is not homogenous and it depends on several factors. For example air leakage in the field zone of a roof might not be same as that of a corner. This is due to the fact that the corner zone has numerous junctions and terminations and also it may be subjected to higher wind pressures compared to the field zone of the roof. Air leakage through the roofing assembly, which is a crucial and intrinsic part of the overall building performance, has not drawn much attention as compared to the research concerning the quantification of air leakage through walls and windows.

A mechanically attached system is highly susceptible to air leakage due to the flexibility of the membrane and the attachment mechanism. During windy periods the roofing membrane undergoes shape changes and air can move laterally at the underside of a membrane where localized suction creates pumping action. The potential for positive internal pressure increases, and if the roof porosity is high, it might influence the roofing assembly performance. This internal pressure along with the external suction pressures on top of the roofing assembly exerts a wind uplift force on the entire roofing assembly. In comparison to the walls where air leakage is a primary concern on the condensation

problems, air leakage in a mechanically attached system influences both the moisture entrapment and wind uplift performance.

The review of the existing studies on air leakage quantification through roofing assemblies clearly indicated the lack of data with reference to the porosity of a roofing assembly. Though the studies highlighted the importance of air infiltration rates in mechanically attached systems, none of the reviewed studies provided experimental data that predicts the relationship between pressure difference and airflow rate through a roofing assembly.

Considering the existing air leakage standards review here, the requirement for acceptable air barrier rating of a tested assembly is 0.15 L/s at 75 Pa differential pressures. In the case of mechanically attached roofing assembly, the differential pressures due to wind gusts are very high much greater than 75 Pa (1.6 psf), therefore the question arises of how well the mechanically attached roofing assemblies can provide resistance to air flow. Mechanically attached roofing assemblies are a growing segment of the low-slope roofing market and there are currently no formal performance criteria, standard specifications or test methods to quantify or evaluate the air leakage through them. Owing to the increasing use of wider roofing membranes (larger volume under the ballooned membrane) and the introduction of newer roofing materials such as air barriers, cover boards, insulation, fasteners etc; there is clearly a need to develop a standard procedure to evaluate the air leakage resistance of the mechanically attached assembly. The main contribution of this research study is to:

- 1) Quantify the air leakage rates of MAS.
- 2) Determine which components best perform the role of air barrier in MAS.
- 3) Demonstrate the effect of an air barrier in the MAS wind uplift resistance

The first two objectives will be addressed in the following chapter, which will present the experimental setup and procedure for quantifying air leakage through MAS. Chapter 8 will address the third objective by carrying out experiments to identify the role of air barrier in wind uplift resistance of MAS.

Chapter 7

Air Leakage Quantification of Mechanically Attached Roofing Systems

7.1 Air Leakage Through Mechanically Attached Systems

As discussed in Table 2.1 on the history of the roofing assemblies, the Built-up roofing assemblies (BUR) have dominated the Canadian roofing industry for over a century. In BUR, different plies of roofing felt are fully adhered to the substrate and the continuous BUR membranes offer significant resistance to air flow. Therefore much of the research efforts have been focussed on the system performance rather than the study of air leakage into the roofing assembly. The knowledge acquired in the past is of little use for explaining the performance of new generation of single-ply roofing systems.

As shown in Figure 1.2, in MAS, the roofing membrane is attached to the structural deck at discrete points using fasteners. The main function of the roofing membrane is to act as a waterproof barrier to the roofing assembly. In single ply systems the thickness of the membrane varies from 1.016 mm (0.04") to 2.032 mm (0.08"). The flexibility of membrane and the attachment mechanism makes the MAS highly susceptible to air leakage.

Figure 7.1 illustrates the airflow mechanism through the MAS. The wind-induced suction lifts the membrane between the attachments and causes membrane elongation and billowing. The magnitude of the wind induced suction and the membrane's elastic property determines the billowing shape of the membrane. This momentarily displacement or billowing of the membrane creates a relative negative pressure below the lifted membrane and this differential pressure draws indoor air into the roof, thereby satisfying the first prerequisite condition of air infiltration. Secondly, due to the absence of air barrier at the deck level, the three different flow paths namely the orifice flow, diffuse flow and channel flow are created by 1) roof terminations/penetrations/junctions in the system and 2) air permeability of the involved components. These flow paths transfer the positive pressure to components above roof deck increasing the danger of uplift damage to the roof. For example if the deck is not air tight due to cracks,

construction joints etc. the positive pressure is transmitted to the part of the assembly above it.

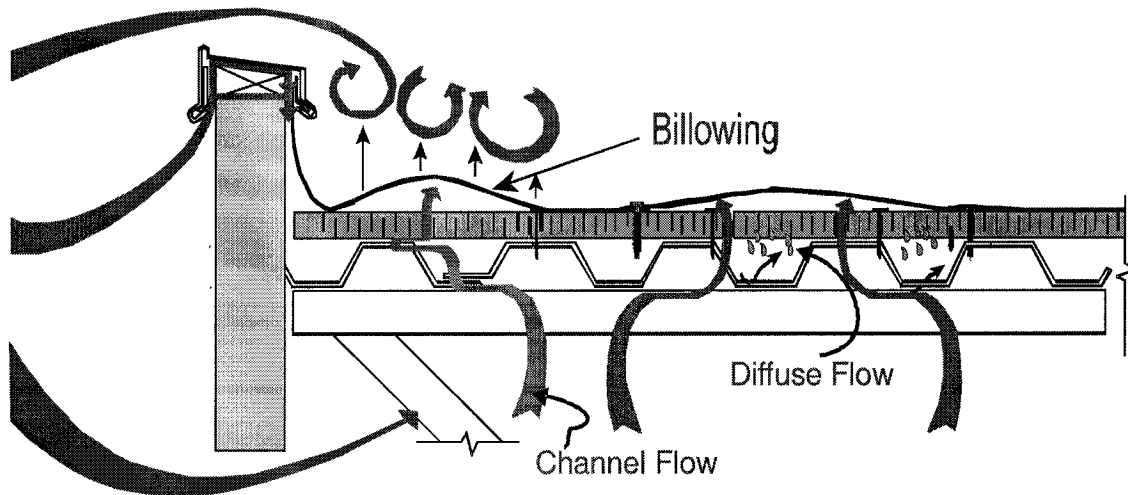


Figure 7.1: Air leakage mechanism of MAS during wind uplift

Positive pressure can also act on the roofing components above the deck if the membrane is not sealed to the deck at the edge and penetrations. Some leakage may occur even though edge is sealed and well constructed decks. This uncontrolled air leakage into the roofing assembly induces asymmetrical loading pattern among the roofing components in which major load is transmitted through membrane tension to the fasteners, thereby leading to premature failure of the roofing system. When the edges of the roof are sealed and the deck is airtight, uplift on the roof covering is minimized as the load is shared among the roofing components. Billowing of the membrane will be minimized. Thus air leakage into MAS does not only lead to condensation problems but also would influence its wind uplift performance. Figure 7.2 indicates the different air leakage sources in mechanically attached systems. As it can be seen, it can be divided into three levels. The first level is the billowed membrane, which provides the necessary pressure differential for air leakage. This differential pressure paves the way for air entry into the roofing system via the flow paths provided by the second and third levels. The present study focuses on the second level of air leakage quantification i.e the flow paths through the roofing assembly components

In general, control of airflow is achieved through an air barrier by providing resistance to the movement of air. The function of the air barrier in a roofing assembly is to minimize air leakage through the roofing system. Apart from the condensation problems from the

transfer of air-borne moisture, the air barrier acts as a load barring element, thereby reducing the membrane flutter and associated fatigue. To be effective the air barrier must be impermeable to air flow and be continuous. Appendix H gives the air permeance values of some of the common construction materials.

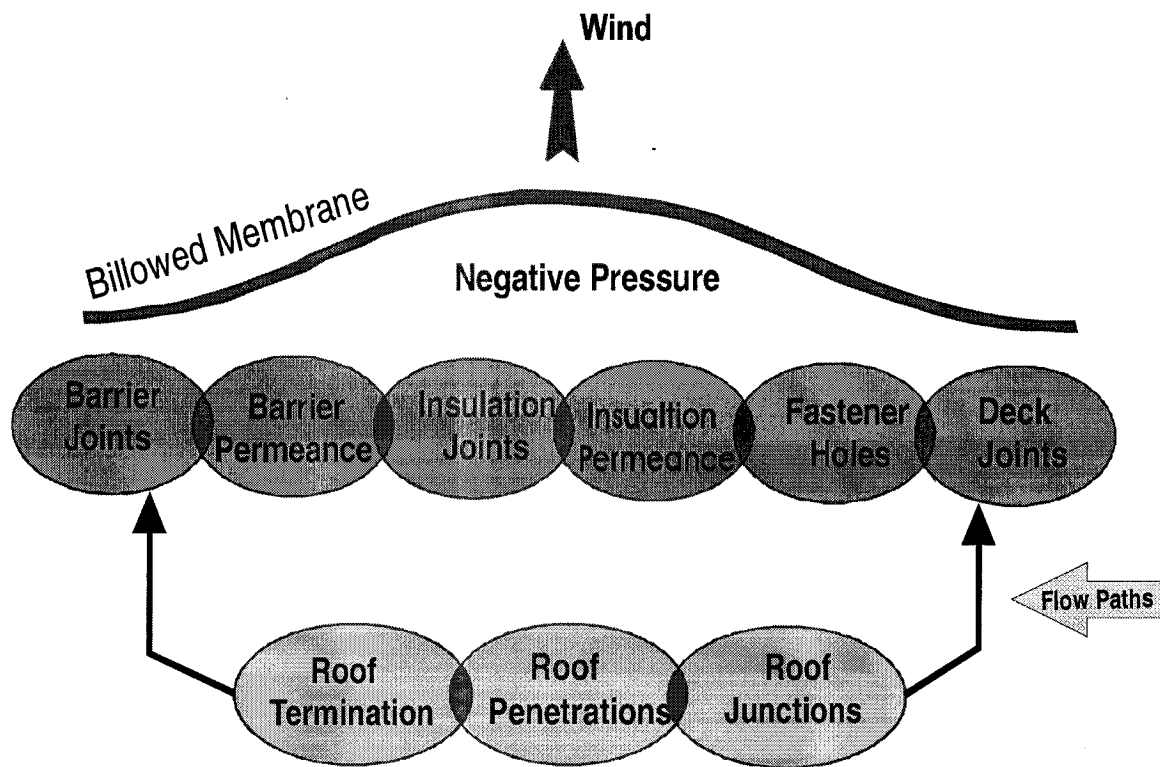


Figure 7.2: Air leakage sources of MAS during wind uplift

Given the possibility of airflow within the assembly due to the pumping action of the cyclical wind loads or convection, it is preferable to locate the barrier where it will remain above the dew point temperature of the inside air i.e. essentially on the warm side of the insulation or above the steel deck. It also acts as an immediate barrier for the air entering from the steel deck joints. If the roof deck were airtight, it could perform the air barrier function. As this is rare, therefore for an effective air barrier system, number of components is required to act as the air barrier. The term air barrier (retarder) and vapour barrier (retarder) are sometimes misunderstood. Sometimes both air barrier and vapour barrier property requirements can be achieved by one material, however the properties and system requirements should be considered separately before deciding one material to do the double function.

Therefore, to address this crucial task of air leakage through MAS, an experimental study was carried out at the Dynamic Roofing Facility located at the National Research Council of Canada (IRC/NRC). This experimental study was intended to measure only the air leakage associated with the field of the roof and it does not include leakage at the openings or perimeter of the roof. The experimental setup assumed that in a roofing assembly the continuous waterproof membrane is airtight and there by it can be excluded from the investigation and thereby all the experimental mock-ups were constructed up to the insulation level

7.2 Air Leakage Quantification of Mechanically Attached Systems

7.2.1 Experimental Apparatus

The small-scale study was aimed at understanding the air leakage resistance of the roofing components installed in a roofing assembly rather the whole system. So the constructed experimental mock-ups were devoid of any kind of joints or junctions but these will be undertaken in the full-scale study.

The small-scale test apparatus comprise the following components:

1. Testing chamber
2. Air flow measuring device
3. Pressure measuring device
4. Vacuum blower

Testing chamber : As shown in Figure 7.3 , the simple apparatus consists of 1 m x 1m x 0.32 m (39" x 39" x 13") top chamber and 1000 mm x 1000 mm x 140 mm (39" x 39" x 5.5") bottom frame. The depth of the bottom chamber can be adjusted based on the test specimen. Both the top chamber and the bottom frame are constructed of 19 mm thick plywood and the test specimen is constructed in the bottom frame and covered by the top chamber. The top chamber is fitted with 50 mm (2") outlet pipe through which the air is evacuated out of the chamber to create the necessary differential pressure. To measure this differential pressure a 6mm (0.25") opening is made on the top chamber, which is connected to a differential pressure transducer using a tygon hosing. There are two windows to allow observation of the specimen behaviour during the testing process. To ensure proper apparatus air tightness,

- all surfaces of the testing chamber are treated inside and outside with several coats of paint,
- the top chamber and the bottom frame are interlocked by a tongue and groove joint,
- closed cell foam gaskets are used as seal between the tongue and groove joint.
- clamping devices are applied to compress the top chamber with the bottom frame.

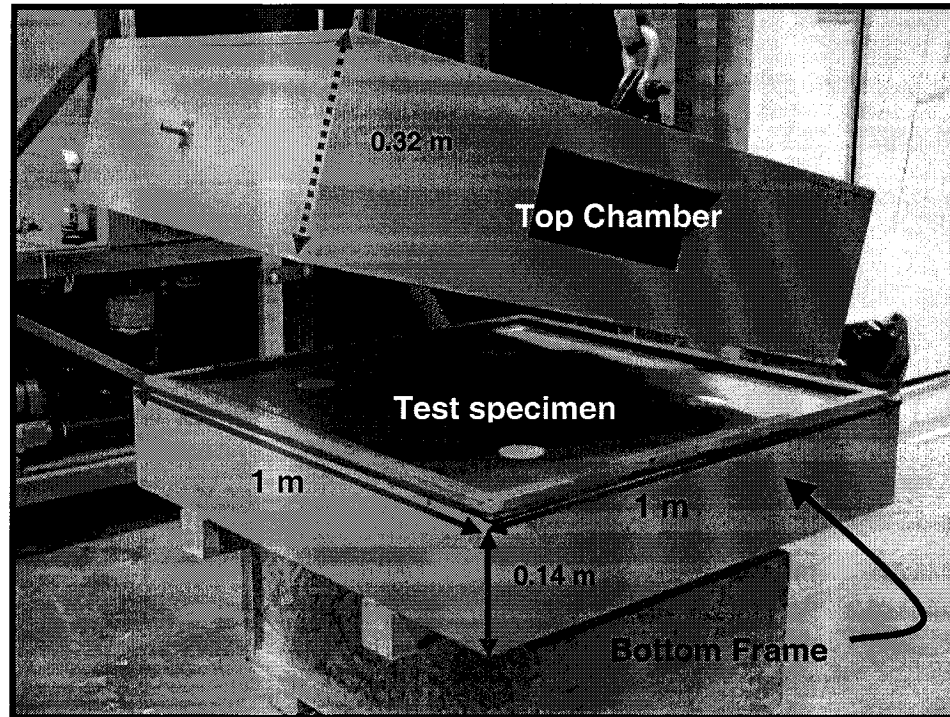


Figure 7.3: Small scale testing chamber for measuring air leakage of MAS

Airflow measuring device: In the current study, a Merriam Laminar Flow Element – (Model 50 MW20) is used to measure the airflow. Merriam laminar flow elements are devices to measure the rate of airflow operating on capillary flow principles. The airflow setup comprises of three laminar flow elements with flow ranges of 8, 23 and 44 CFM respectively. Based on the test specimen any one of the laminar flow elements can be selected. The accuracy of the laminar flow elements is 0.50% of actual reading.

Pressure measuring device: The differential pressure across the test specimen is detected by using MKS Type 220 Baratron differential pressure transducer, which has a measuring range upto 10 Kpa (200 psf). This pressure transducer works on the principle

of variable capacitance technique. It contains a tensioned metal diaphragm; on one side is exposed to the gas whose pressure is to be measured and the other side is the reference side that is open to the atmospheric pressure. The capacitance change generates an AC voltage, which is amplified, demodulated, and converted in to high level DC voltage outout, linear with pressure. The Type 220 has an accuracy of 0.15 % of the reading.

Figure 7.4 illustrates the schematic of the air leakage setup and Figure 7.5 shows the schematic of the testing chamber

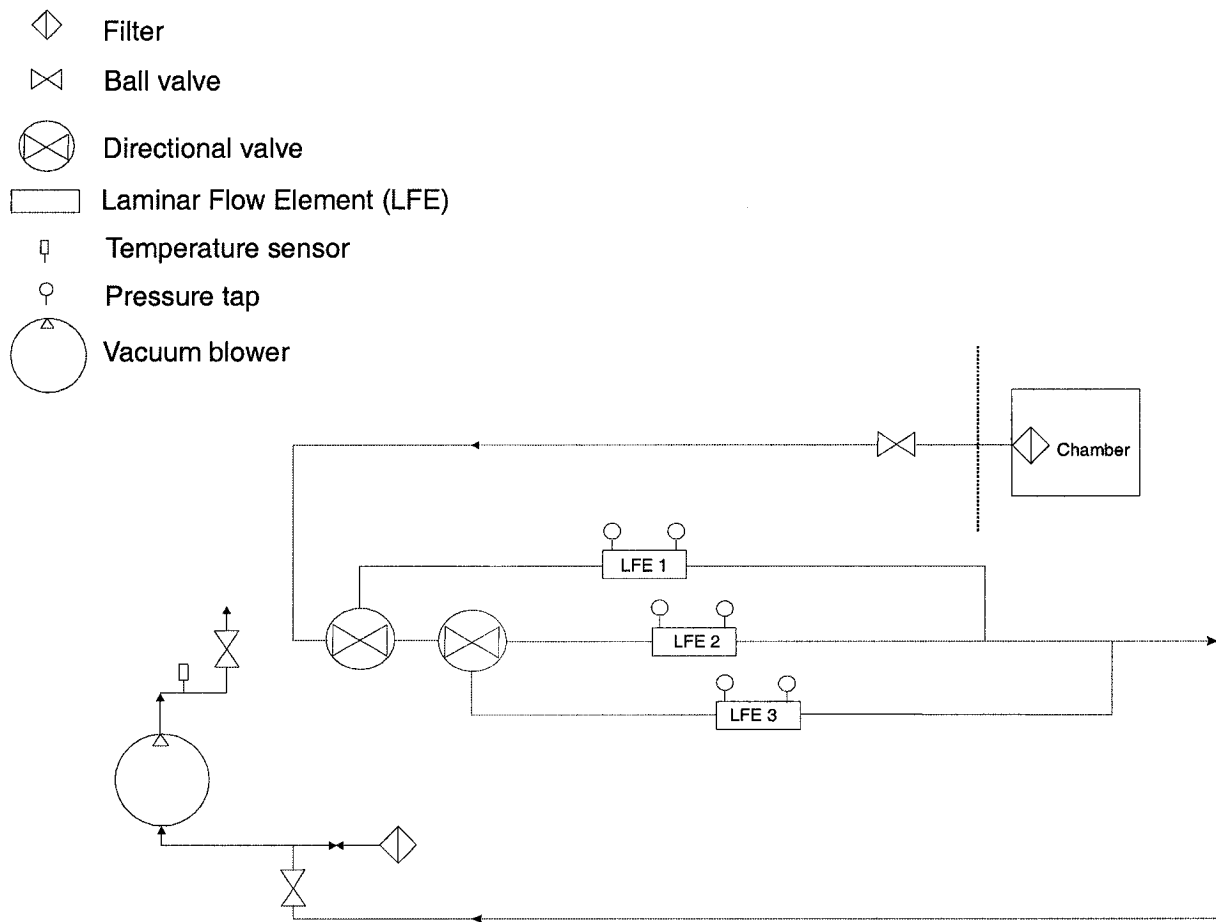


Figure 7.4: Schematic diagram of flow measuring setup

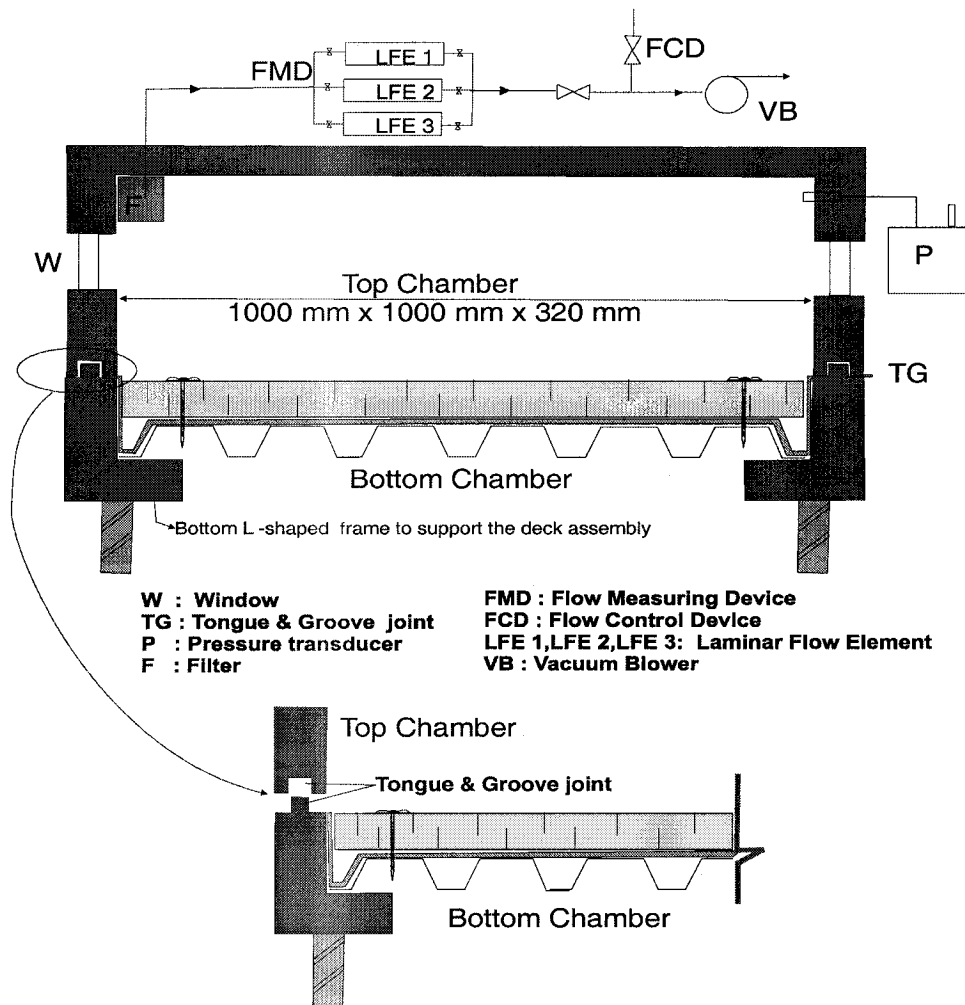


Figure 7.5: Air leakage testing apparatus schematic diagram

7.2.2 Test Assembly

Using the above mentioned air leakage testing apparatus three different roofing test assemblies were quantified for air leakage, which were

- Assembly 1 (A1) - Deck and insulation without any barrier (retarder)
- Assembly 2 (A2) - Deck, insulation and with a 6-mil polyethylene sheet as barrier (retarder)
- Assembly 3 (A3) - Deck, insulation and with a self adhered film (SAF) as barrier

The tested assemblies consisted of the following roofing components whose general physical and mechanical properties are:

Deck: 0.76 mm (22-Ga) thick corrugated steel deck with a profile height of 38 mm (1.5") and a flute width of 150 mm (5.9").

Insulation: 51 mm (2") thick polyisocyanurate (ISO) boards of 1200 mm x 2400 mm (4 8" x 96") with a compressive strength of 170 Kpa (25 psi). In order to accommodate in the testing chamber the insulation boards were cut to dimensions of 1000 mm x 1000 mm (39" x 39").

Barrier: In the present experimental setup, barrier means a component installed in the roofing assembly to prevent airflow into the system. Two types of barriers are used:

- 1) *Polyethylene film* -single layer of 6 mil (0.006 ") sheet was loose laid over the steel deck.
- 2) *SBS modified self-adhered film (SAF)* – 0.8 mm thick (1/32") sheets were self-adhered to the steel deck. They are composed of SBS modified bitumen and surface reinforced, and it comes in strips of 1140 mm wide (45").

As mentioned in the beginning of this section, the continuous waterproof membrane in the roofing assembly is airtight and therefore it is excluded from the investigation. Therefore, all the experimental mock-ups are constructed up to the insulation level. A detailed procedure of the test assembly construction is described below.

Assembly 1

Assembly 1 comprises steel deck, and insulation without any barrier. The steel deck was installed and fastened to the L-shaped frame of the bottom chamber. The steel deck has one seam with a v-shaped interlocking system as shown in the Figure 7.6. The cut insulation boards were installed and fastened to the steel deck with four fasteners equally placed from the chamber edges as shown in Figure 7.7. Fasteners were 127 mm (5 ") long with plastic plate 76-mm (3") diameter.

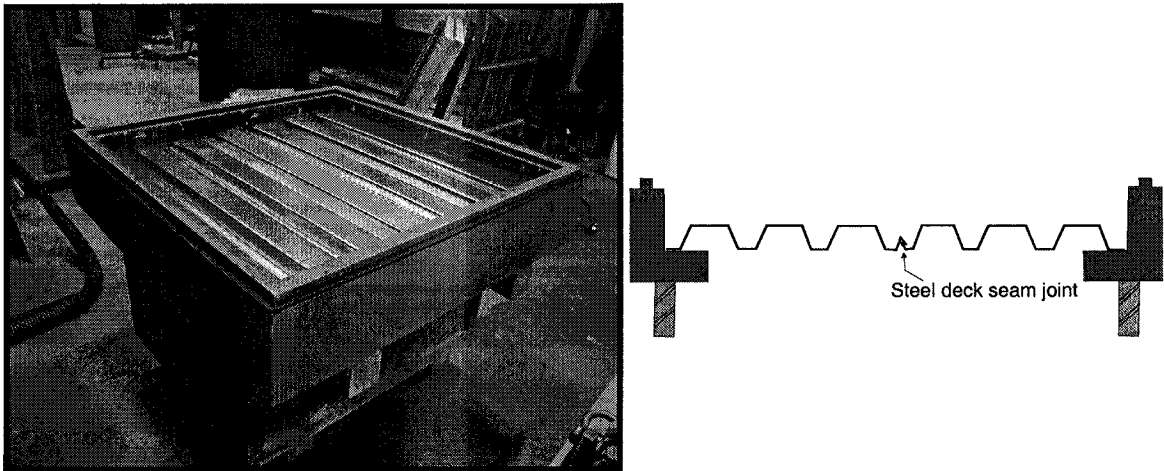


Figure 7.6: Installation of steel deck

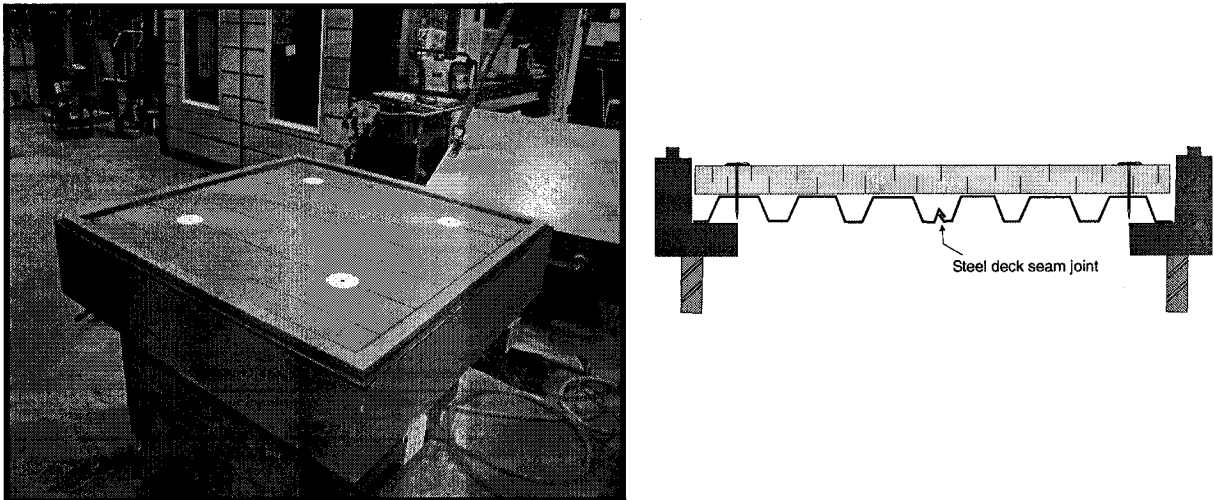


Figure 7.7: Fastening of insulation to the steel deck

Assembly 2

In Assembly 2, a 6-mil (0.006") polyethylene sheet was used as an air barrier. A new steel deck was installed and a continuous sheet of 6-mil (0.006") polyethylene sheet was laid over the steel deck as shown in Figure 7.8. With the polyethylene in position, a new insulation board is installed and fastened to the steel deck following the same procedure as S1. Similar fasteners and plates were used as in S1 and the insulation board was fitted tight in the bottom. The edge treatment of polyethylene is a critical issue when using polyethylene as a barrier because the major portion of airflow occurs at the edges. In this particular setup, the polyethylene was wrapped over the frame edges of the bottom frame as shown in Figure 7.9.

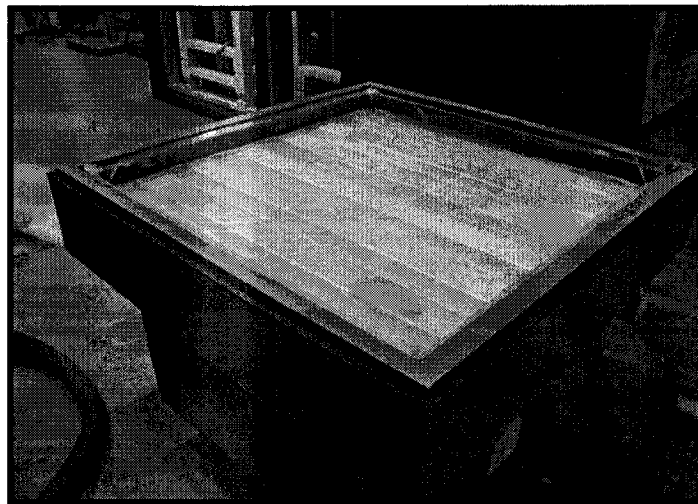


Figure 7.8: Polyethylene sheet laid over the steel deck

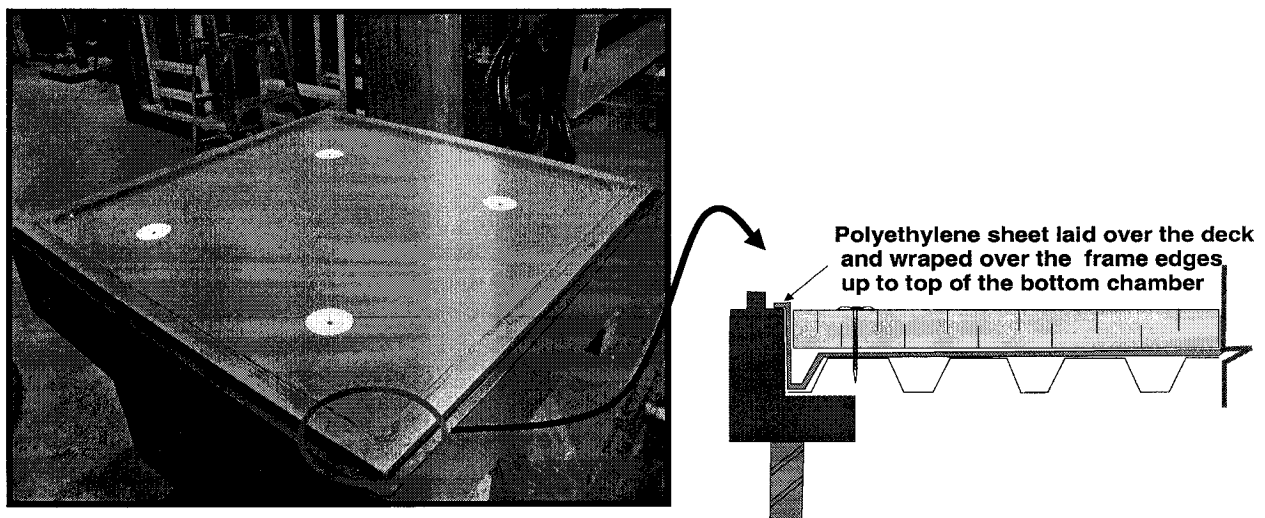


Figure 7.9: Edge treatment of polyethylene sheet

Assembly 3

Replacing the steel deck and insulation from A2 with a new set of steel deck and insulation a self-adhered film (SAF) was used as an air barrier in A3. The self-adhered membrane was a continuous strip without any joints as shown in Figure 7.10. The installation procedure for the insulation is similar to A1 and A2. To be consistent, the self-adhered membrane was adhered to the sides of the bottom frame as shown in Figure 7.11 thus making the edges sealed.

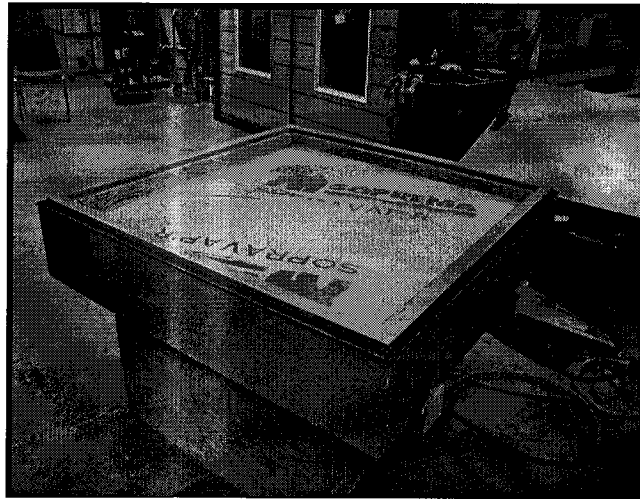


Figure 7.10: Self adhered membrane laid over the steel deck

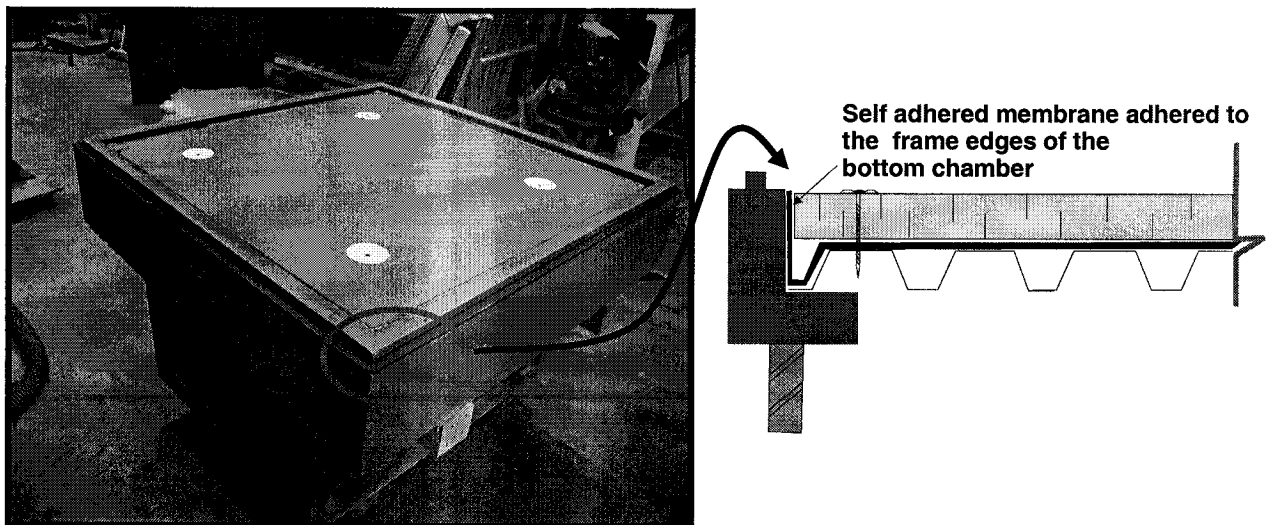


Figure 7.11: Edge treatment of self-adhered membrane

7.2.3 Experimental Procedure

With the installation of the test assembly in the bottom frame it is covered by the top chamber and by using clamping devices both the chambers are compressed as shown in Figure 7.12. The outlet pipe of the top chamber is connected to the vacuum fan and the test assemblies were tested using the following procedure:

1. A negative pressure differential of 240 Pa to 2400 Pa (5 to 50 psf) in the increments of 240 Pa (5 psf) is created across the test specimen.
2. At each pressure differential, after the test conditions are stabilized, the flow meter reading (Q) and test pressure difference (ΔP) were recorded.
3. The procedure was repeated by depressurizing from 2400 Pa to 240 Pa (50 to 5 psf) in the decrements of 240 Pa (5 psf), to determine if the measurement process has affected the air leakage of the test specimen.

For each roofing assembly configuration, minimum of two assemblies were tested.

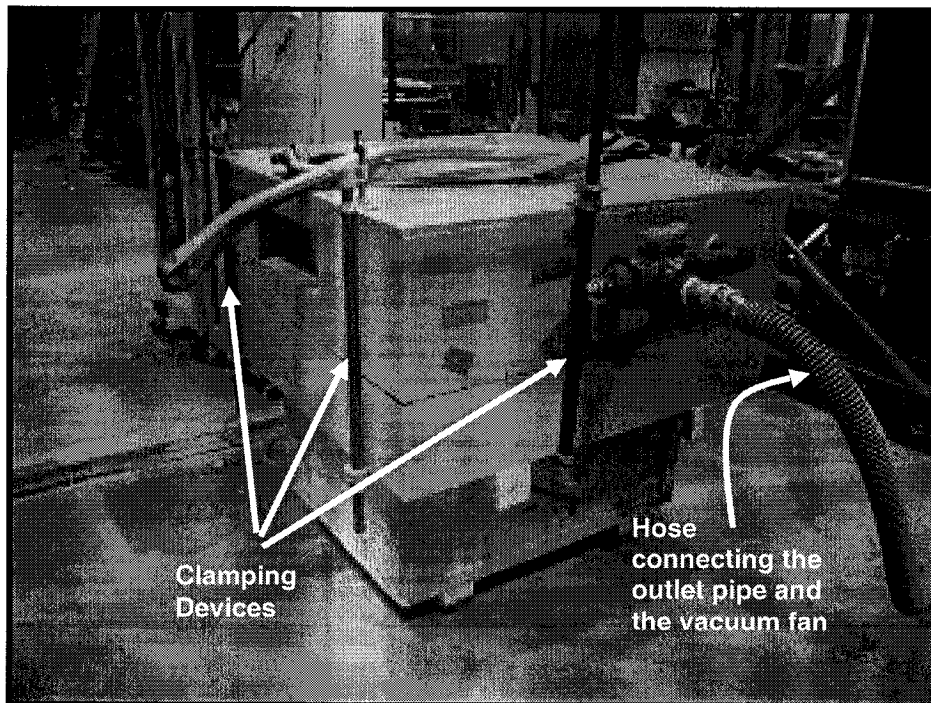


Figure 7.12 Test assembly installed and apparatus ready for quantifying air leakage

7.2.4 Results and Discussion

Extraneous Leakage

Despite all the efforts to make the testing chamber airtight, a small amount of air leakage can enter the envelope of the apparatus from the exterior environment. This is called the extraneous air leakage (Q_e). It represents all of the leakage entering the test chamber and although its complete elimination is impracticable it should be kept to the minimum as possible.

To determine the extraneous leakage of the chamber a 10 mm (0.4") thick polycarbonate glass was used as a test specimen between the bottom frame and top chamber. The polycarbonate glass was exactly cut to the dimension of bottom frame and by using screws it was fastened to the bottom frame. All the edges and the screw heads were well caulked such that no air seeps from the bottom frame into the top chamber and the extraneous leakage of the top chamber can be accurately determined. Following the test procedure mentioned in the Section 7.2.3, the airflow rates at different differential pressures were measured. In order to compare the results at the standard conditions irrespective of the lab conditions the measured airflow data was corrected for the standard flow conditions using equations 7.1 and the data is presented in Table 7.1. The relationship between the airflow rate and the differential pressure is plotted as shown in Figure 6.13.

$$Q_{std} = Q_{act} \times PCF \times TCF \quad (7.1)$$

where

Q_{std} = Standard air flow rate (L/s)

Standard conditions are defined as :

$$T_{std} = 20^\circ \text{C} = 293^\circ \text{K}$$

$$P_{std} = 101.3 \text{ Kpa}$$

Q_{act} = Actual air flow rate (L/s)

PCF = Pressure correction factor = $P_{lab \text{ pressure}} / P_{std}$

TCF = Temperature correction factor

Based on the data from Figure 7.13, the extraneous air leakage through the test chamber can be related to the pressure difference by a power function for the current setup:

$$Q_e = 0.0008(\Delta p)^{0.75}$$

where Q_e is in liters per second per square meter and Δp is expressed as pascals.

Table 7.1 Extraneous air leakage

Pressure Difference		Corrected Flow	
Pa	psf	(L/s)	(CFM)
239	5	0.05	0.10
479	10	0.08	0.17
718	15	0.11	0.23
956	20	0.14	0.29
1190	25	0.16	0.34
1438	30	0.18	0.39
1681	35	0.21	0.44
1909	40	0.23	0.48
2155	45	0.25	0.52
2394	50	0.27	0.57

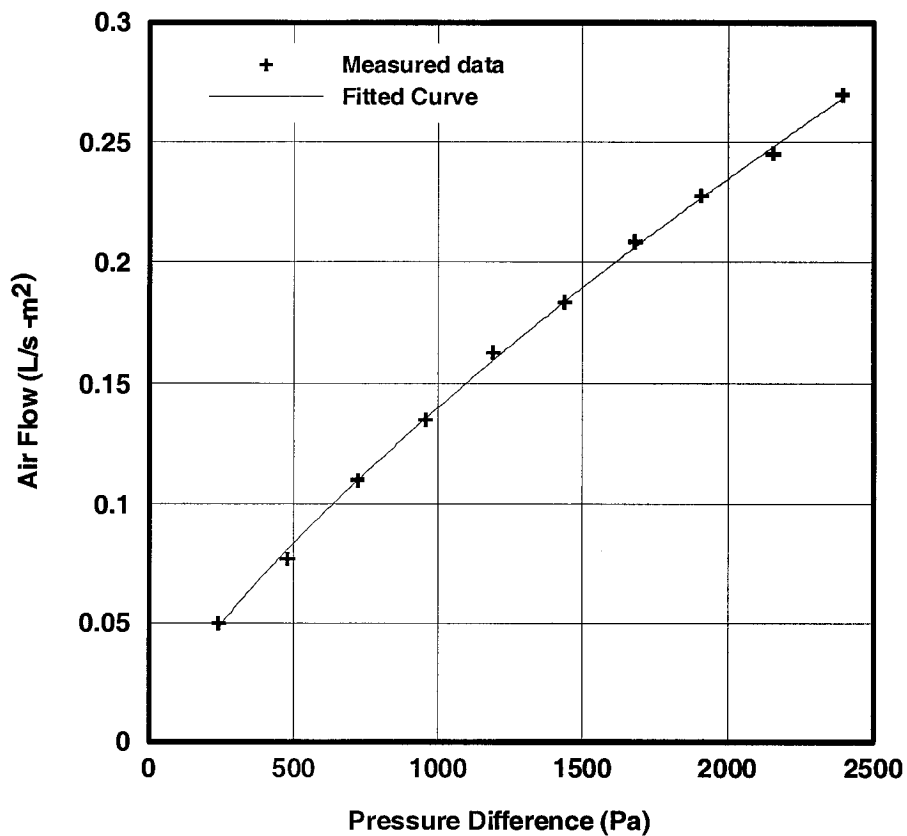


Figure 7.13: Extraneous air leakage of the testing apparatus

Air leakage of the tested specimens

The tested specimens can be categorized into two sets:

1. Assembly without barrier – A1
2. Assembly with barrier – A2 & A3

Following the experimental procedure described above, the three assemblies were quantified for air leakage by measuring the flow rates at various differential pressures. But the actual air leakage through the assembly (Q_A) is the difference between the total measured air flow (Q_t) and the extraneous air leakage (Q_e) i.e

$$Q_A = Q_t - Q_e \quad (7.2)$$

Therefore subtracting the extraneous leakage from the total assembly leakage gives the air leakage of each roofing assembly as shown in Table 7.2

Table 7.2 Measured air leakage of the tested assemblies

Pressure Difference (Pa)	Assembly 1 Q_{A1} (L/s)	Assembly 2 Q_{A2} (L/s)	Assembly 3 Q_{A3} (L/s)
239	1.00	0.08	0.02
479	1.67	0.18	0.04
718	2.17	0.26	0.06
956	2.53	0.36	0.08
1190	2.89	0.44	0.10
1438	3.20	0.54	0.12
1681	3.52	0.62	0.14
1909	3.83	0.71	0.16
2155	4.17	0.80	0.18
2394	4.61	0.88	0.20

* 1 L/s = 2.11 CFM

Data clearly indicates that A1 without barrier had a greater leakage rate when compared to A2 (Poly) and A3 (SAF). As discussed in Chapter 6, power law equation is commonly used to get an approximate relationship between air infiltration through the assembly (Q) and differential pressure across the system (ΔP).

$$Q = K A (\Delta P)^n \quad (7.3)$$

Where:

K = variable dependent on the intrinsic air permeability of the system

A is the cross sectional area of the system

n is the flow exponent, ranges from 0.5 (turbulent flow) to 1.0 (laminar flow).

Based on this relationship, the measured data was fitted with power function as shown in Figure 7.14. and the following functions were obtained for the three assemblies:

$$Q_{A1} = 0.0317 (\Delta P)^{0.64} \quad (7.4)$$

$$Q_{A2} = 0.0003 (\Delta P)^{1.02} \quad (7.5)$$

$$Q_{A3} = 0.0001 (\Delta P)^{0.96} \quad (7.6)$$

For A1, the flow exponent was 0.6, indicating a turbulent flow through the assembly due to the absence of barrier. The presence of barrier in A2 and A3 reduced the air leakage and disturbance in the flow, thereby the flow exponent had a value close to 1.0, suggesting a laminar flow through these assemblies.

As per the NBCC (2005), the maximum recommended air leakage rate for an air barrier systems is 0.15 L/s.m^2 at a differential pressure of 75 Pa. Based on this recommendation the air leakage rate for the three tested assemblies at a pressure difference of 75 Pa was obtained from equation 2. A1 with no barrier had a leakage rate of 0.49 L/s.m^2 while A2 (Poly) and A3 (SAF) had a leakage rate of 0.024 L/s.m^2 and 0.006 L/s.m^2 respectively. Comparison of these air leakage data with the NBCC recommended system leakage clearly indicates that both the assemblies A2 and A3 with barriers fall within the specified range of NBCC but the assembly without barrier A1 exceeded the limit by 200 %. Apart from providing good performance at the lower pressure of 75 Pa (1.5 psf), A3 also offered excellent resistance at higher pressures as illustrated in Figure 7.14 where the air leakage rate of the specimen performed linearly across the range of pressures. Further, the leakage rate of A3 was within the manufacturer's specified range of air leakage rating of the self-adhered film, which is less than 0.007 L/s.m^2 . This characteristic feature of the self-adhered film in A3

highlights the dual functionality of the self-adhered membrane both on material performance and system performance.

From the air infiltration measurements further calculations are made for determining the equivalent leakage area (ELA) and the equivalent orifice diameter (EOD), which represents the total of all the leakage paths in the roofing assembly. The ELA and EOD can be obtained from equation 6.16 and 6.17 respectively. Table 7.3 determines the ELA and the corresponding EOD for the three tested assemblies. For comparison purpose the table also includes ELA and EOD values at 75 Pa (1.5 psf). Starting at a low-pressure difference of 75 Pa, A1 has an EOD of 9.74 mm, which is reduced to 1.5 mm (on average) by the inclusion of barrier in the assembly i.e. A2 and A3. Similar trend could be observed at high differential pressure of 2394 Pa (50 psf) identifying the importance of barrier in the roofing assembly. These numbers provide a useful yardstick for comparing the air leakage characteristics in terms of geometry of the opening, which will be useful for the modeling characteristics of air infiltration into the roofing assembly and estimation of moisture migration.

Table 7.3 Equivalent Leakage Area (ELA) and Equivalent Orifice Diameter (EOD) of the three-tested assemblies (1" = 25.4 mm)

Pressure Difference (Pa)	A1		A2		A3	
	ELA (m ²) x 10 ⁻⁶	EOD (mm)	ELA (m ²) x 10 ⁻⁶	EOD (mm)	ELA (m ²) x 10 ⁻⁶	EOD (mm)
75	75e	9.74	3.65	2.16	0.91	1.08
239	85e	10.42	7.13	3.01	1.66	1.45
479	101	11.33	10.54	3.66	2.41	1.75
718	106	11.64	13	4.07	3.14	2.00
956	108	11.72	15.16	4.39	3.58	2.14
1190	110	11.85	16.99	4.65	3.76	2.19
1438	111	11.90	18.73	4.88	4.22	2.32
1681	113	12.00	20.01	5.05	4.44	2.37
1909	116	12.13	21.51	5.23	4.82	2.48
2155	118	12.27	22.63	5.37	5.19	2.57
2394	124	12.57	23.66	5.49	5.25	2.59

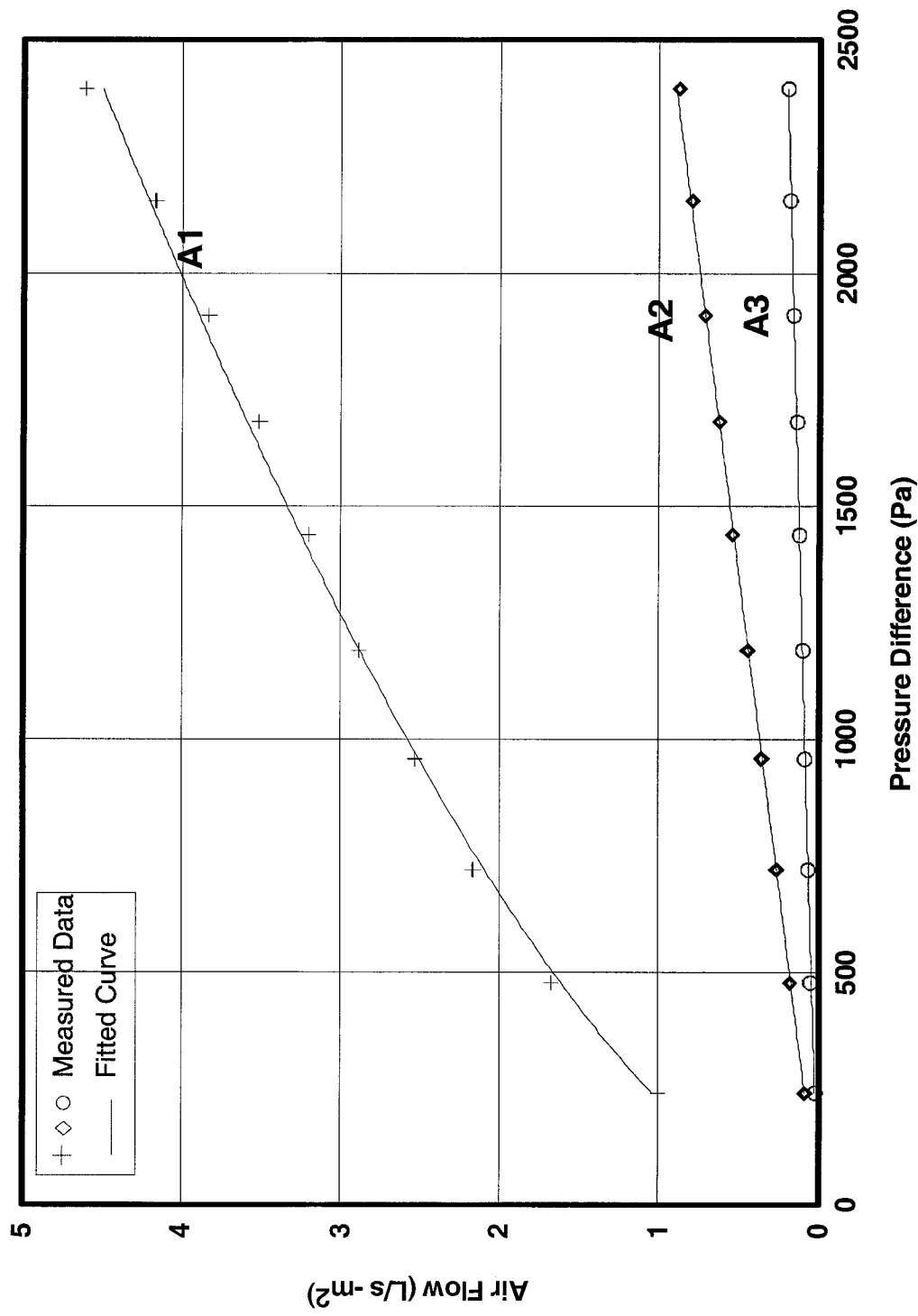


Figure 7.14 Air leakage rate through the three tested assemblies

Figure 7.15 compares relative airflow resistance of the three assemblies at three differential pressures. If it is assumed that A1 without any barrier had a 100% air leakage, with polyethylene as barrier A2 was able to reduce airflow by 80% while A3 with self-adhered film (SAF) was able to reduce it 90 %. The high leakage rate of A1 is attributable primarily to the channel flow occurring at the deck joints and secondarily due to the diffuse flow through the insulation material and fastener holes (fastener holes are probably minor air leaks if the holes are filled with screws). A2 with polyethylene sheet reduced the airflow rate into the system, however edge treatment of polyethylene sheet (refer to Figure 7.9) is critical and can cause certain amount of airflow into the system. A3 with self-adhered membrane provided higher resistance to airflow than the two others. The 10% of air leakage through this system is attributable to diffuse flow through the self- adhered film and the edge conditions.

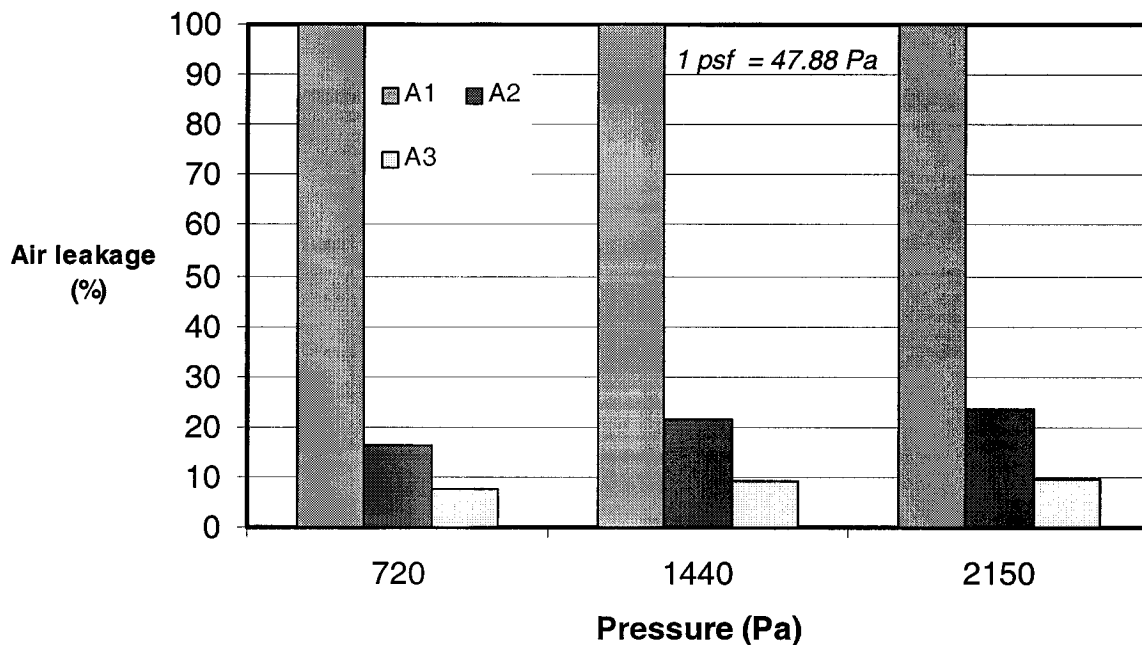


Figure 7.15 Relative comparison of the air leakage resistance of the three tested assemblies

7.3 Concluding Remarks

The chapter presented a newly developed test apparatus for the evaluation of air leakage through MAS. Three roofing systems were investigated for air leakage quantification. Data from these primary findings indicated that roofing systems without air barriers exceeded the limits of NBCC recommended values. On the contrary, roofing systems with air barriers provided good resistance to air leakage and were within the limits of NBCC recommended values. These results should throw light into the roofing industry, which is still in the state of conviction that the deck, insulation boards and cover boards can all serve to reduce air leakage instead of installing a single component that performs the role of an air barrier.

Although, the above observations are based on the small-scale setup in which the assemblies investigated were devoid of any localized leaks such as joints, junctions and penetrations, which add to the overall air leakage, the developed test method provides valuable data that can be used for comparison purposes. Nevertheless, there is an additional need for commissioning these air leakage tests on full scale systems incorporating all the possible localized leaks within the roofing systems and to correlate these results with NBCC recommended air leakage criteria. In this way a greater knowledge will be gained in constructing buildings to realistic or air tight standards.

Chapter 8

Effect of Barrier on Wind Uplift Resistance of Mechanically Attached Systems

8.1 General Review

Wind pressures developed on a mechanically attached roofing system lift the membrane and cause fluttering, introducing stresses at the attachment locations. As discussed in Chapter 1 the magnitude of the wind induced suction and the membrane's elastic property determines the billowing shape. Apart from performing their respective function each component offers a certain resistance to the wind uplift force. This can be illustrated through a force-resistance link diagram as shown in Figure 1.2.

As seen from the force resistance link diagram Figure 1.2, the barrier is one of the resistance links (Link 4) to wind uplift force. Depending on the barrier properties, it can act as both an air barrier and vapour barrier. The previous chapter highlighted the air leakage resistance of different barriers in MAS but the present chapter attempts to answer the following questions: Does the presence of a barrier in an assembly strengthen the force resistance chain and to what degree does the wind uplift rating increase? By constructing field mock-ups in the DRF, assemblies with and without barrier were tested under a dynamic environment. The responses from the roofing assemblies are measured based on two design factors: pressure and force. By presenting the comparison between the assemblies with and without barrier, the wind uplift related benefits of including a barrier in low slope roofing assemblies are addressed.

8.2 Experimental Approach

Experimental data for this study was obtained from the Dynamic Roofing Facility (DRF) located at the National Research Council of Canada (IRC/NRC). All the specimens were subjected to the SIGDERS (Special Interest Group on Dynamic Evaluation of Roofing Systems) dynamic load cycle. Section 2.4.6 discusses the experimental setup of the DRF and also presents a brief overview of the SIGDERS dynamic load cycle. Details of the method by which the load cycle was developed can be found in the publication of

Baskaran et al (1999) and, a detailed documentation of the DRF facility's features can be found in Baskaran and Lei (1997).

8.3 Assembly Details

Five roofing assemblies were constructed for the wind uplift evaluation testing, which were:

1. Assembly 1: A1 - No barrier
2. Assembly 2: A2 - Polyethylene
3. Assembly 3: A3 - Building paper
4. Assembly 4: A4 - Self Adhered Film 1 (SAF 1)
5. Assembly 5: A5 - Self Adhered Film 2 (SAF 2)

At least two specimens for each assembly were tested. The tested assemblies consisted of the following roofing components whose general physical and mechanical properties are:

Deck: 0.76 mm (22-Ga) thick corrugated steel deck with a profile height of 38 mm (1.5") and a flute width of 150 mm (5.9") was fastened at every flute to the wooden beams. The wooden beams are 152 mm x 152 mm (6" x 6") in size and spaced about 1829 mm (72") apart.

Insulation: 51 mm (2") thick polyisocyanurate (ISO) boards of 1.2 m x 2.4 m (48" x 96") are mechanically attached to the steel deck using 8 fasteners per board. The fasteners were 127 mm (5") long with plastic plate 76-mm (3") diameter.

Barriers: Four types of barriers are used:

- 1) *Polyethylene film* -single layer of 6 mil (0.006 in.) thick sheet loose laid on the steel deck over on the entire length of the table.
- 2) *Building Paper* - 15mil thick (0.015") asphalt-impregnated paper loose laid on the steel deck. It comes in a length of 44 m (144') and width of 914 mm (36").
- 3) *Self-Adhered Film 1 (SAF 1)* – 3 mil thick (0.03") sheets were self-adhered to the steel deck. They are composed of SBS modified bitumen and surface reinforced, and is available in strips of 1140 mm wide (45"). According to the

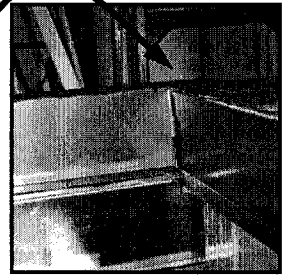
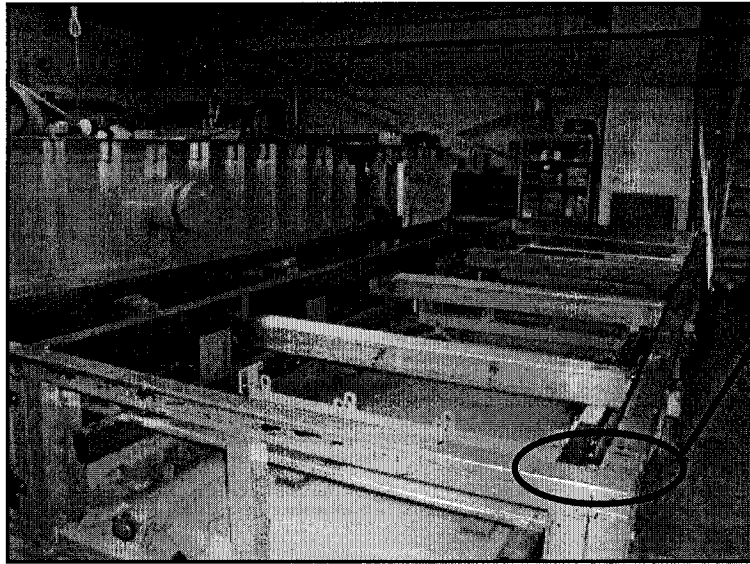
manufacture specification, these films can be directly applied over the steel deck without gypsum boards.

- 4) *Self-Adhered Film 2 (SAF 2)* - It is composed of two water proofing materials- an aggressive rubberized asphalt adhesive backed by a layer of high density cross – laminated polyethylene. The film has a thickness of 4 mil (0.04”) and a width of 914 mm (36 “)

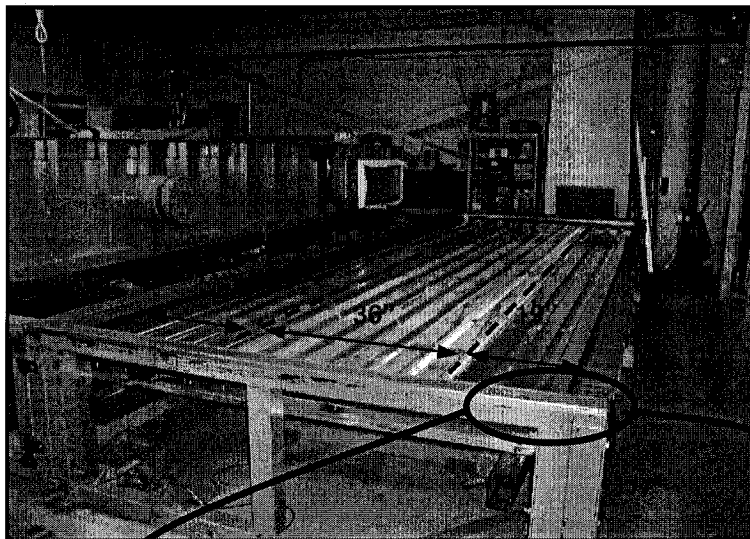
Membrane: Reinforced TPO membrane sheets were used for all the tests. The membranes have a thickness of 45 mil (0.045”) and width of 1981 mm (78”).

As the system installation is same for all the tested assemblies the construction procedure can be classified into five steps:

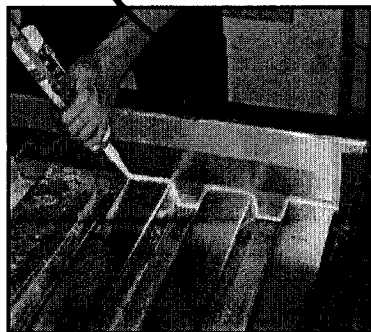
1. **Deck Installation:** This experimental set up is intended to measure the wind uplift resistance associated with the field zone of the roof. In order to achieve this, for all the assemblies L-channels were installed along the four edges of the SIGDERS testing table. As the width of table was 2006 mm (79”), one full sheet of 914 mm (36”) wide and two cut pieces of 610 mm (24”) and 483 mm (19”) wide steel decks were installed along the table length as shown in Figure 8.1. The black dotted lines indicate the deck overlaps. The edges of the steel deck along the perimeter of the table and the L-channel edges were treated with caulking and peel and stick membranes.
2. **Barrier Installation:** Figure 8.2 shows the installation of the four barriers. For A2 with polyethylene as barrier, a continuous sheet of polyethylene was installed on the steel deck. In order to avoid any leakage at the corners the poly was pulled over the bottom test frame and was adhered to the frame using adhesive tape. A3 had building paper as barrier and as the building paper comes in width of 914 mm (36”) two full sheets of 914 mm (36”) and one cut sheet of 457 mm (18”) were laid on the steel deck. The sheets had an overlap of 152 mm (6”) and by using adhesive (vapour-bloc glue) the overlaps were joined. Similar to A2 the building paper was pulled over the test frame edges all along the perimeter and adhered by tape to the frame edges. As SAF1 and SAF2 also come in sheet widths of 914 mm (36”) the installation procedure is similar to the building paper except these are self-adhered films, which adhere directly to the male flutes (top flanges) of the steel deck.



L-channels installed along the perimeter of the table

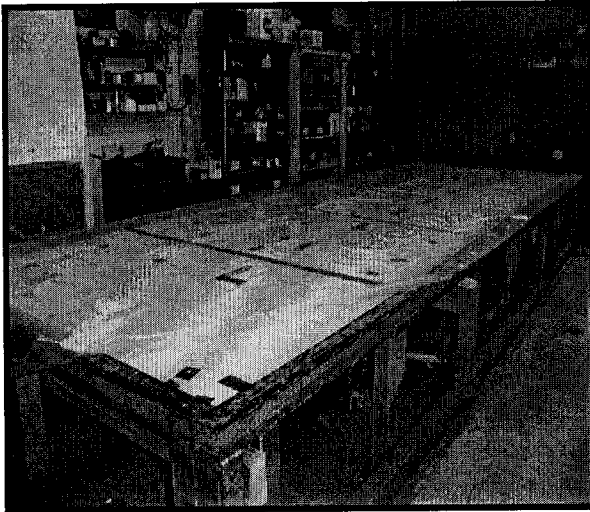


Steel deck installed

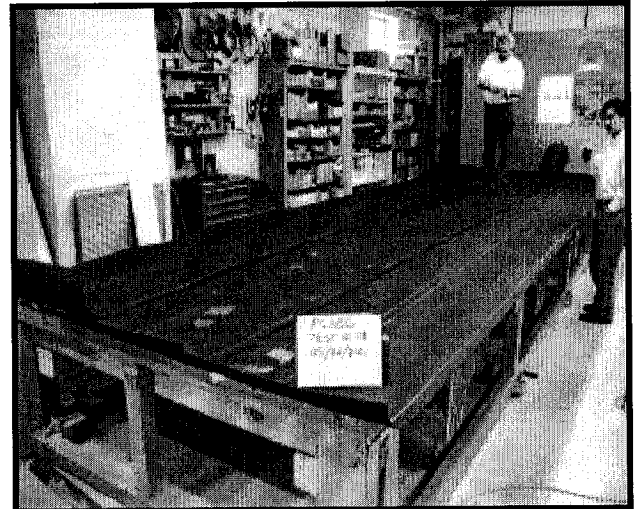


Edge treatment of the steel deck and L-channel

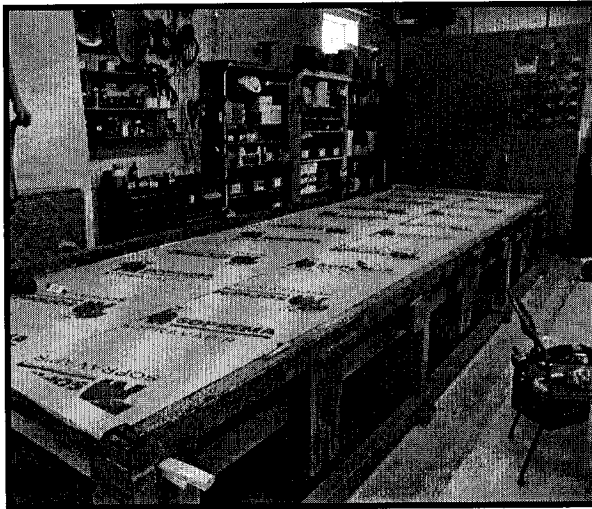
Figure 8.1 Installation procedure of the steel deck



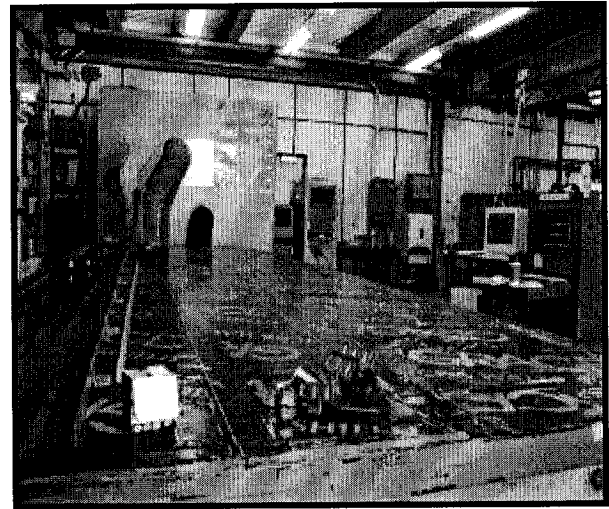
Assembly 2 – Polyethylene



Assembly 3- Building Paper



Assembly 4 – Self Adhered Film – SAF1



Assembly 5- Self Adhered Film – SAF2

Figure 8.2 Typical barrier installation on the steel deck

- 3. Insulation Installation:** 4 full boards of 1219 mm x 2006 mm (48" x 79") and one cut board of 1118 mm x 2006 mm (44" x 79") were used. The insulation boards were mechanically fastened to the steel deck with 76 mm (3") diameter circular plastic plates and 127 mm (5") long fasteners. All the assemblies had a fastener density of 8 per board. Figure 8.3 shows the typical layout of insulation attachment.

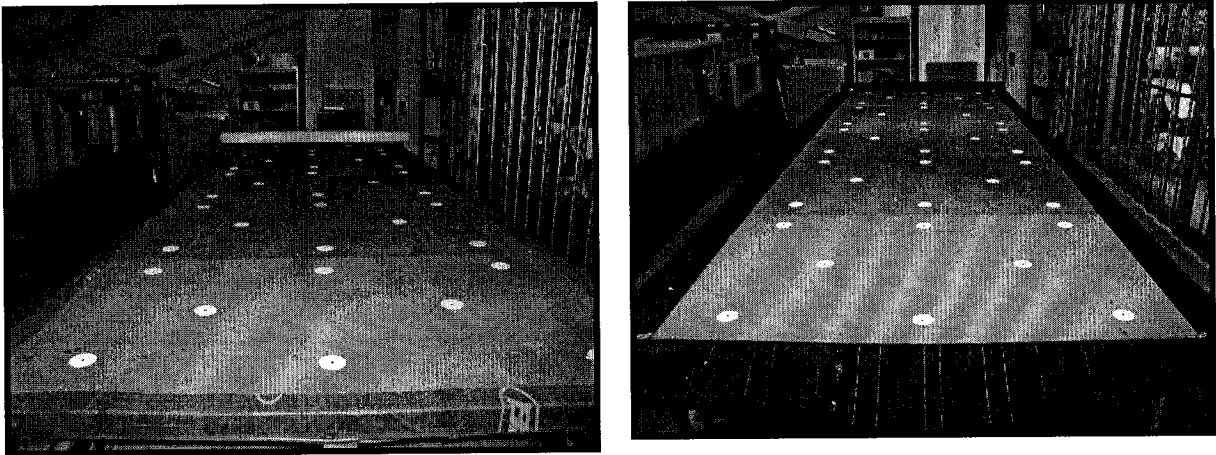


Figure 8.3 Typical layout of insulation attachment to the steel deck

4. Membrane Installation: Geometric details of a typical tested assembly are depicted in Figure 8.4. This figure shows the top view of the test assembly installed in the DRF with three full-width sheets and a dummy sheet at either end. The four seams shown in the Figure 8.4 indicate the fastener locations. For the tested assembly, membrane sheets were fastened at 305 mm (12") spacing (F_s) along the seam, resulting in 7 fasteners per seam. The distance between any two-fastener rows is known as fastener rows spacing ($\{F_r = 1790 \text{ mm (70.5")}\}$). Fasteners were 127 mm (5") long with metal plates of 61mm (2.4") diameter. Figure 8.4 also depicts the details of a typical seam. Each seam had an overlap of (S_w) 139mm (5.5"), with the fastener placed 38 mm (1.5") from the edge of the under sheet, and 73 mm (2.9") from the edge of the overlapping sheet. The portion of the seam beyond the fastener row was welded with hot air such that a waterproof top surface was obtained. The width of the welded portion varied between 38 mm and 45 mm (1.5" and 1.75"). P, L and D respectively represent pressure, force and deflection measurement locations. Figure 8.5 illustrates the typical installation procedure of the roofing membrane on one of the roofing assembly.

5. Data Instrumentation: Two parameters were monitored during this investigative study namely the pressure and fastener force. For measuring the pressure variation across the membrane and the insulation all the test assemblies were instrumented with four pressure transducers, two on top of the membrane and two on the insulation. Installing load cells on the middle seam membrane fastener and the

middle insulation fastener monitored the membrane fastener load and the insulation fastener load. Figure 8.6 illustrates a typical data instrumentation layout of the test assembly.

The above described construction procedure is same for all the tested assemblies except for Assembly 1. As the system configuration of Assembly 1 does not have a barrier, so with the exception of step 2 of the construction procedure all the other steps are same. Figures 8.7 to 8.11 show the system configuration of all the five tested assemblies.

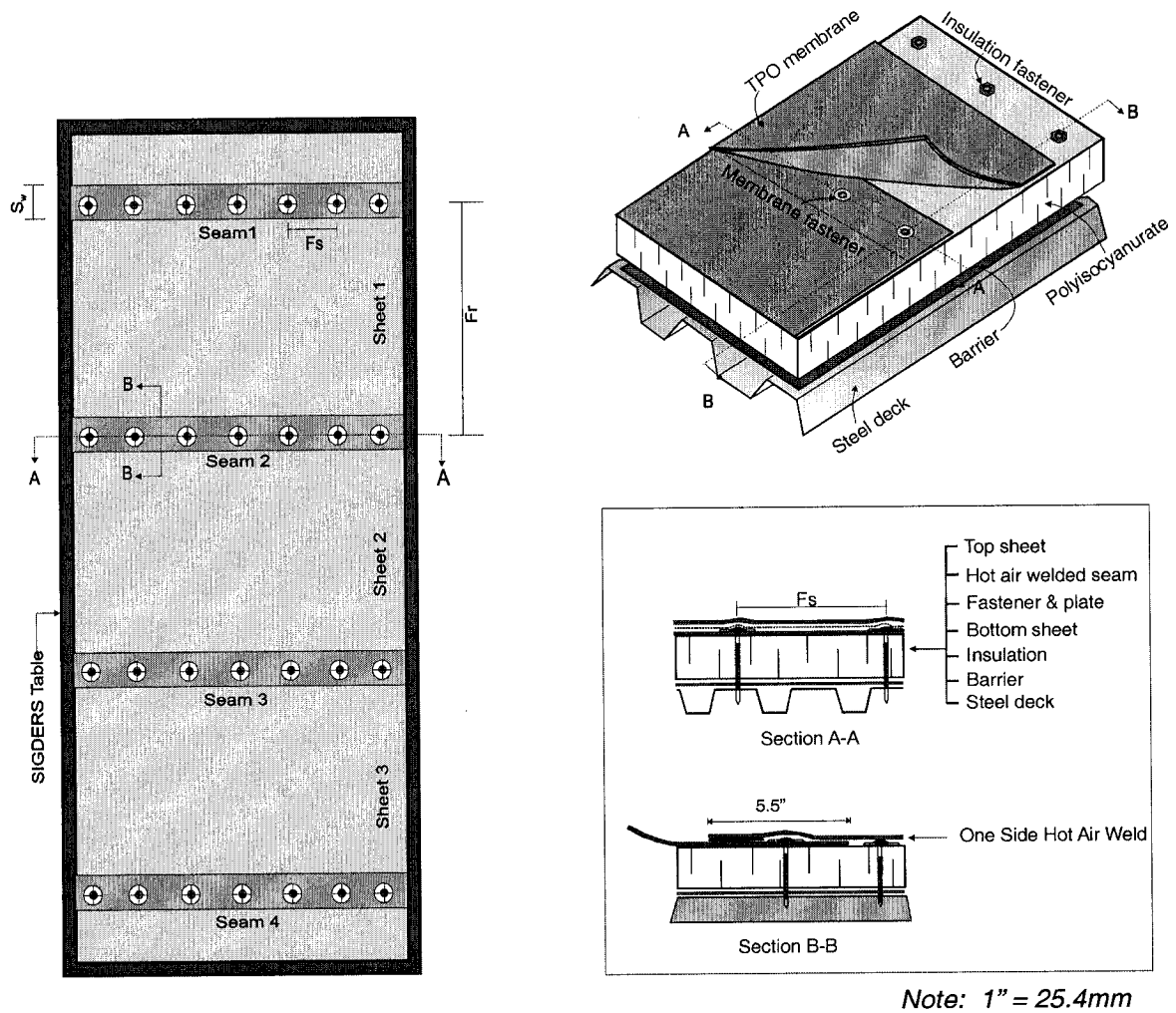
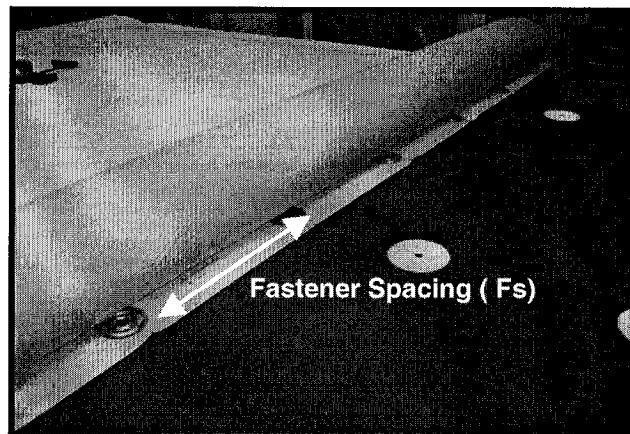
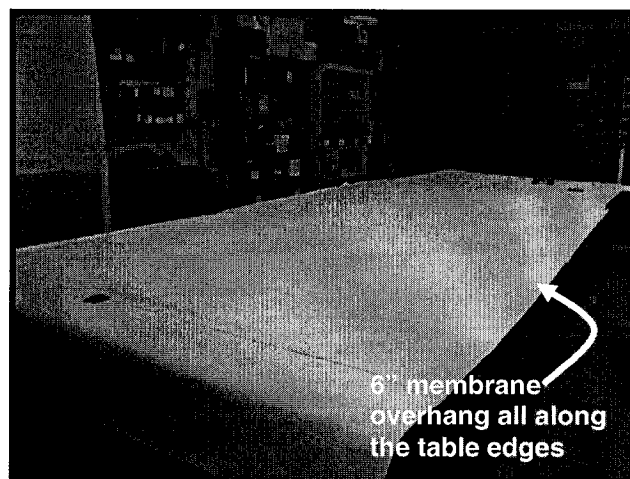


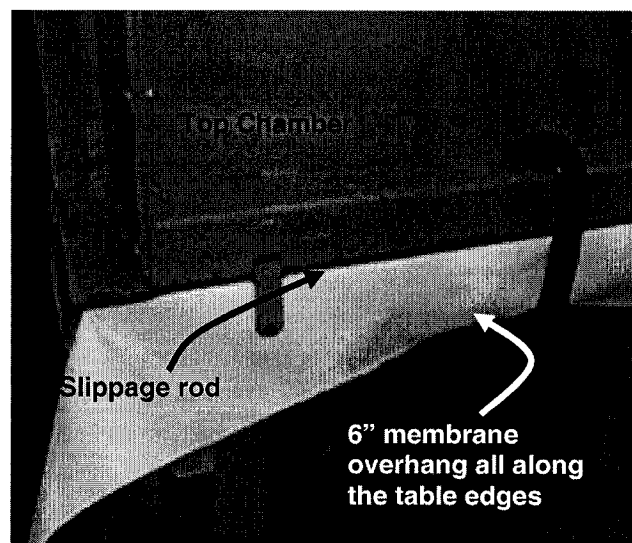
Figure 8.4: Membrane layout and sectional view of the membrane seams



Fastening of the membrane sheet along the seam

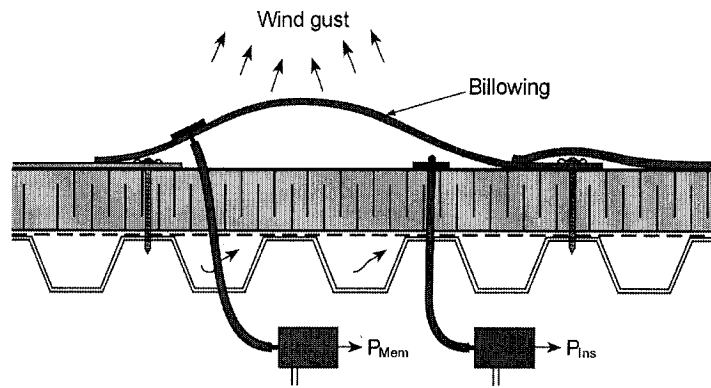


Membrane sheets installed on the table

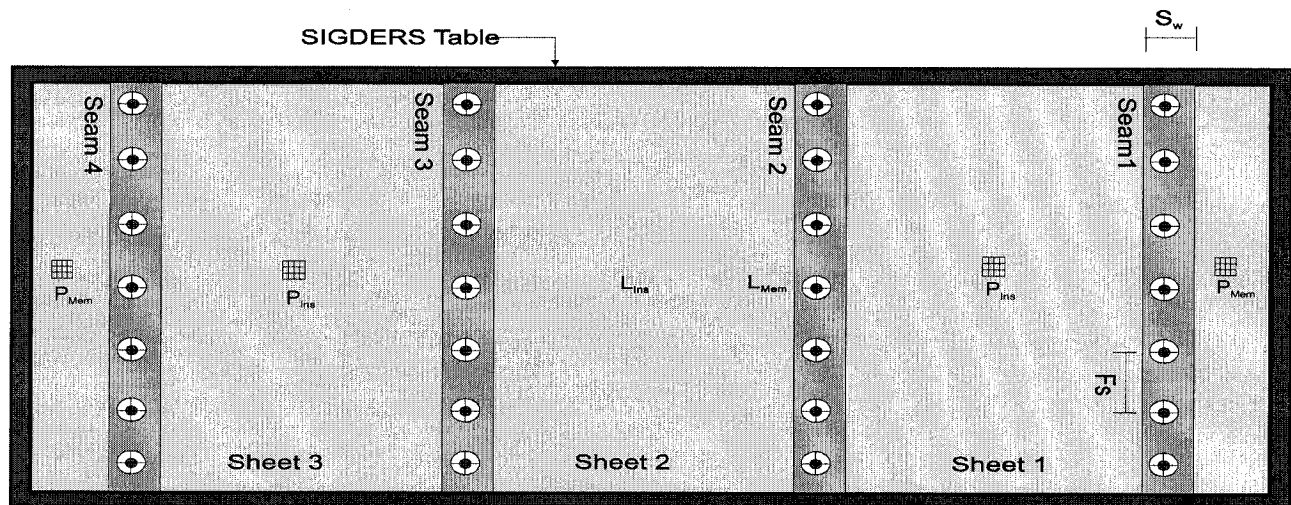


Edge treatment of the membrane

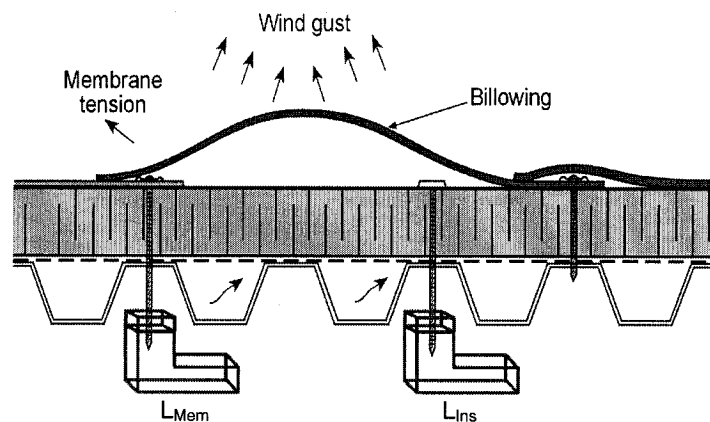
Figure 8.5 Installation of roofing membrane



Pressure transducers installed on the membrane and insulation

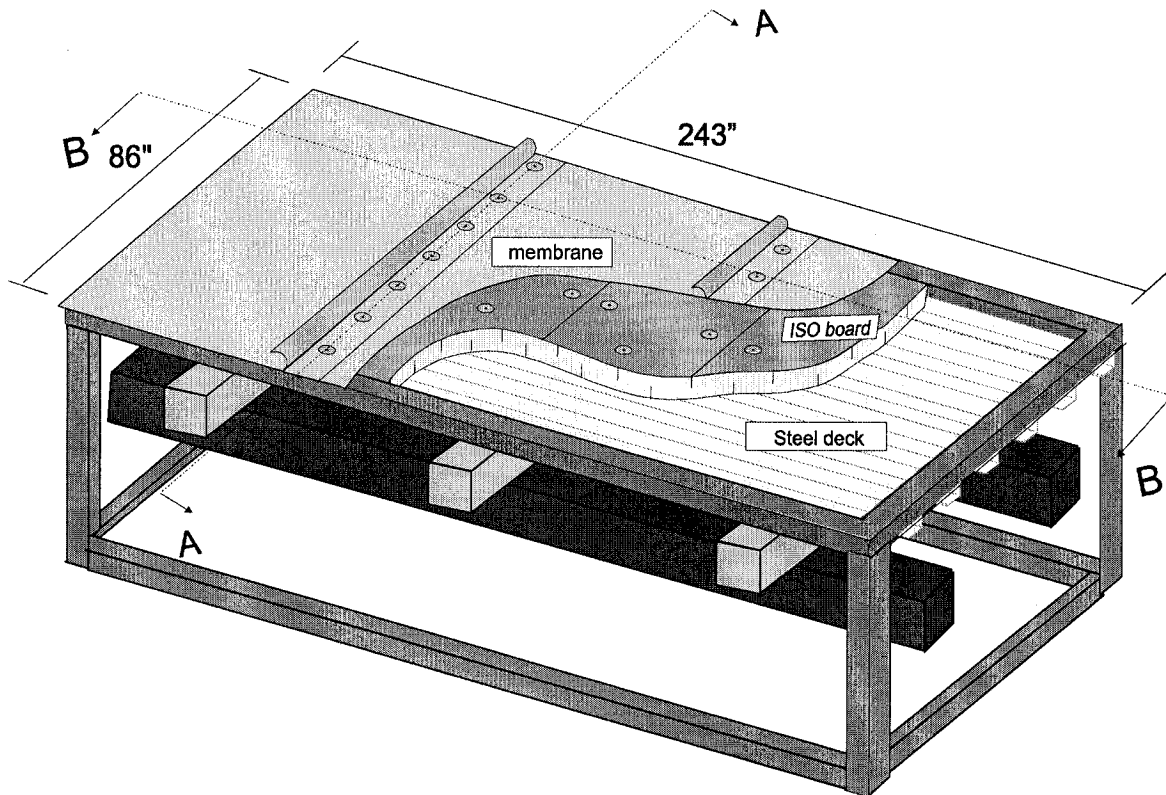


Where P_{Mem} = Membrane Pressure Sensor
 P_{Ins} = Insulation Pressure Sensor
 L_{Mem} = Membrane Load Cell
 L_{Ins} = Insulation Load Cell



Load cells attached to the membrane and insulation fastener

Figure 8.6 A typical instrumentation layout of the tested assembly



Note: 1" = 25.4mm

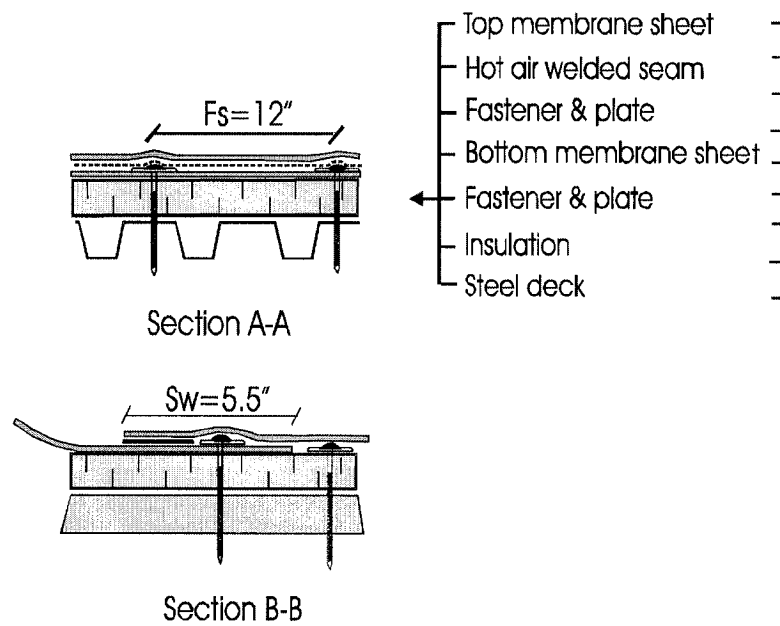
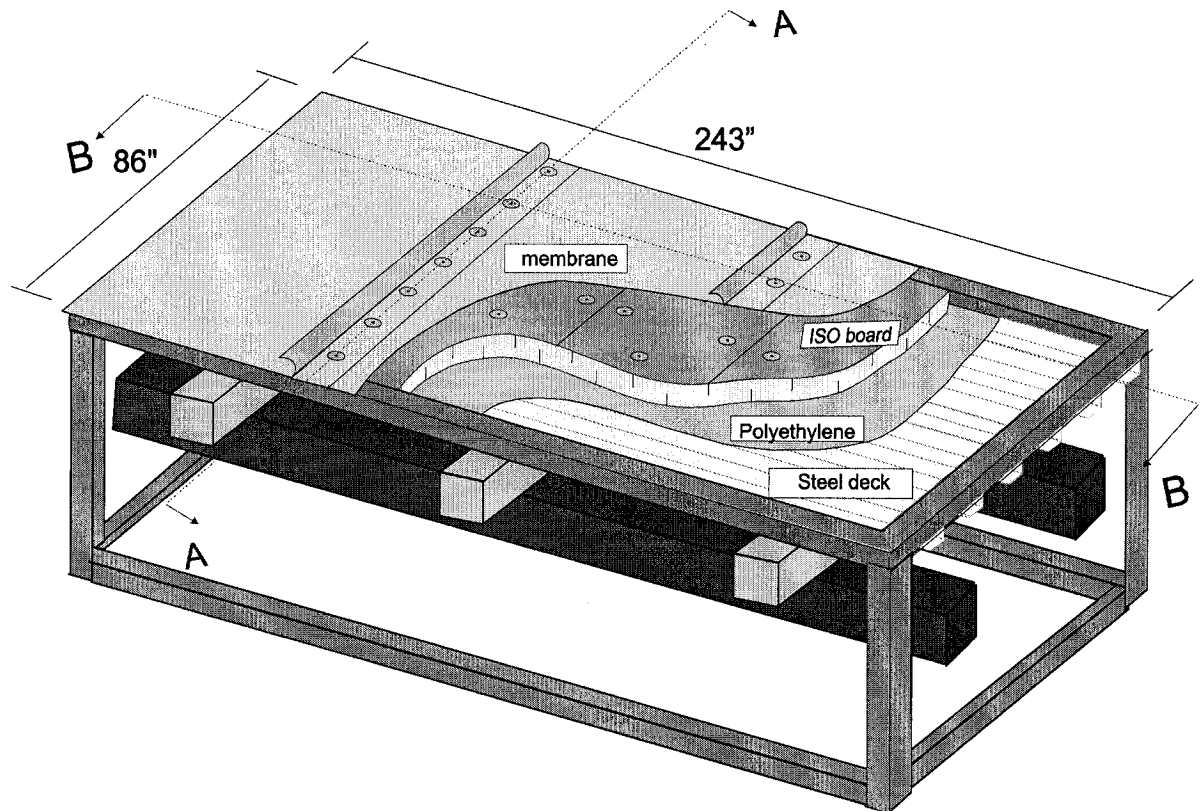
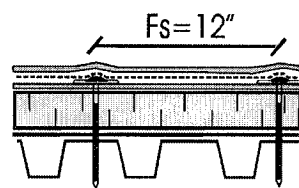


Figure 8.7 Assembly 1 – No barrier: set-up diagram

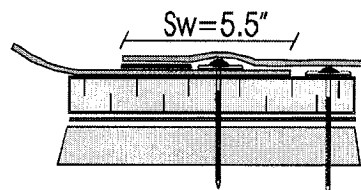


Note: 1" = 25.4mm



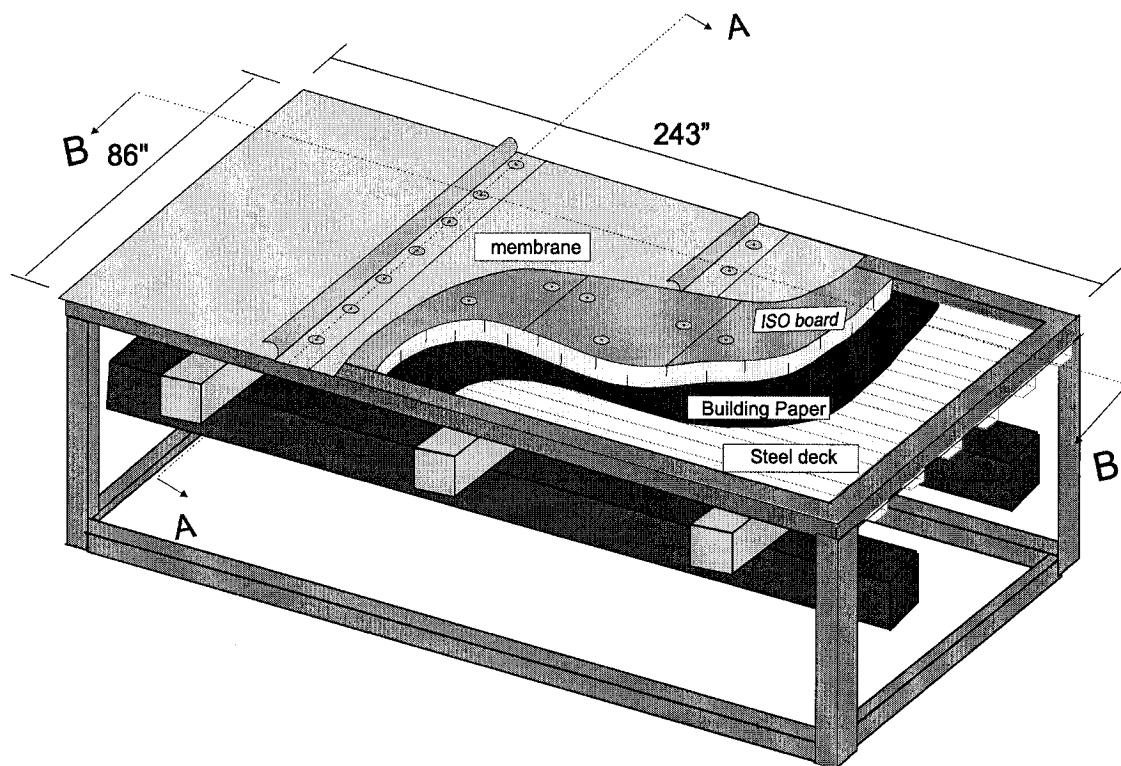
Section A-A

- Top membrane sheet
- Hot air welded seam
- Fastener & plate
- Bottom membrane sheet
- Fastener & plate
- Insulation
- Polyethylene
- Steel deck



Section B-B

Figure 8.8 Assembly 2 – with polyethylene sheet as barrier: set-up diagram



Note: 1" = 25.4mm

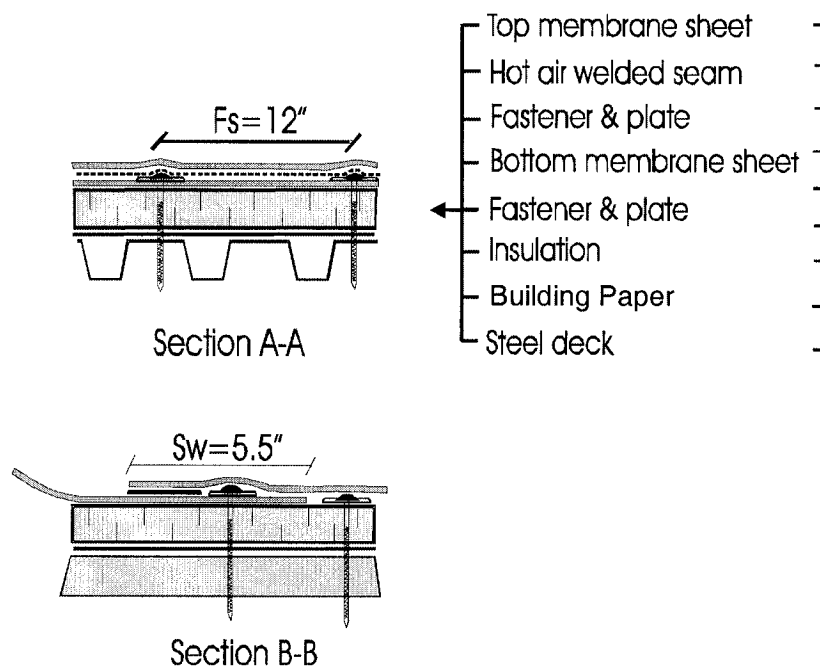
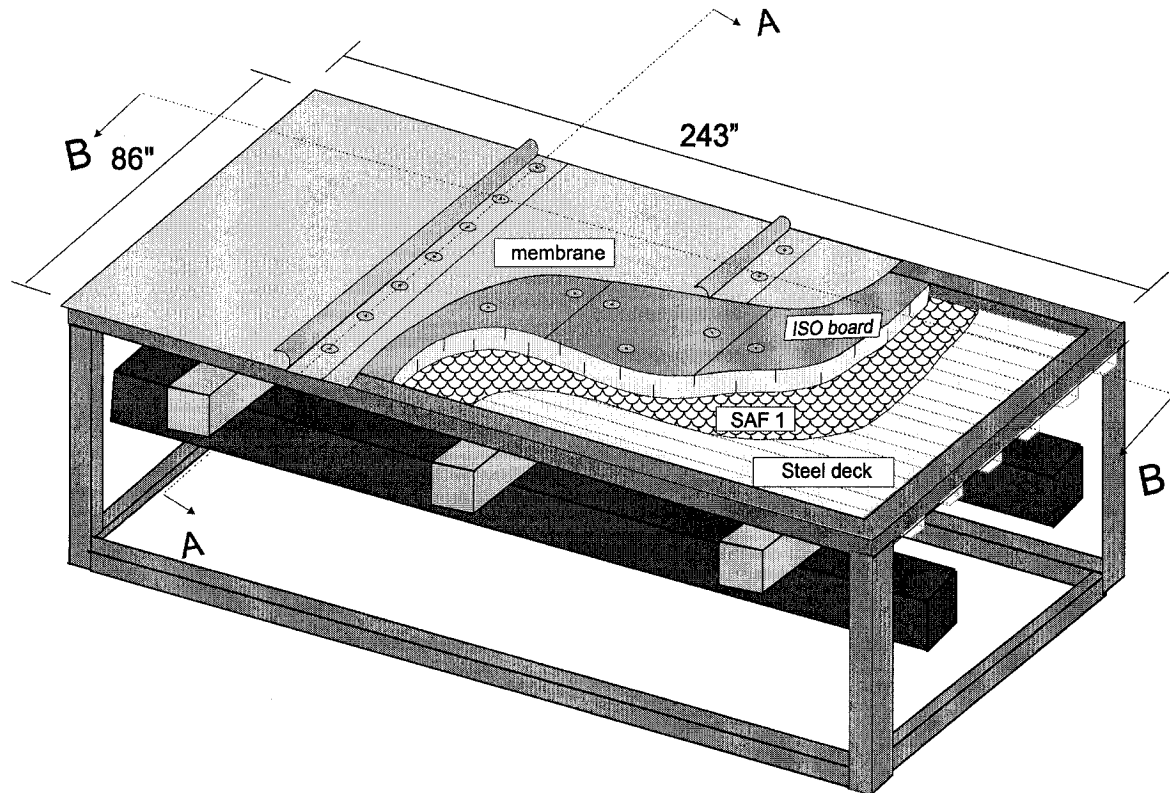


Figure 8.9 Assembly 3 –with building paper as barrier: set-up diagram



Note: 1" = 25.4mm

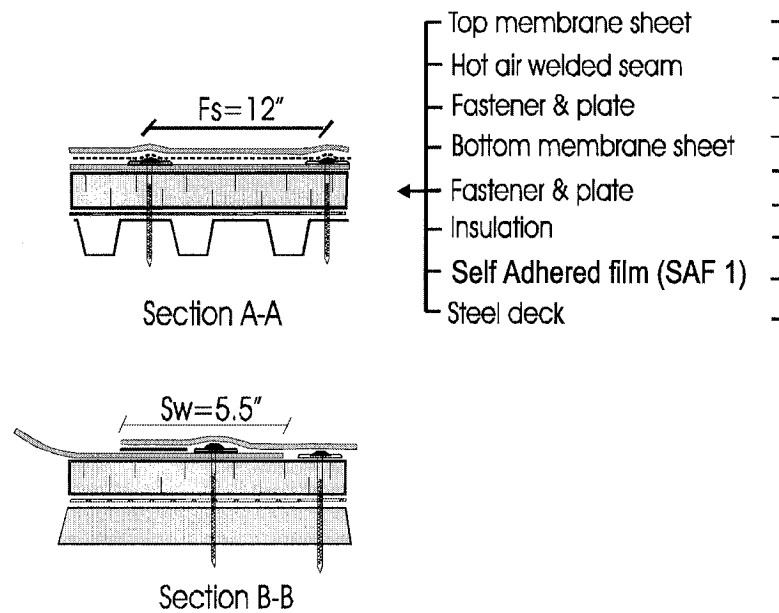
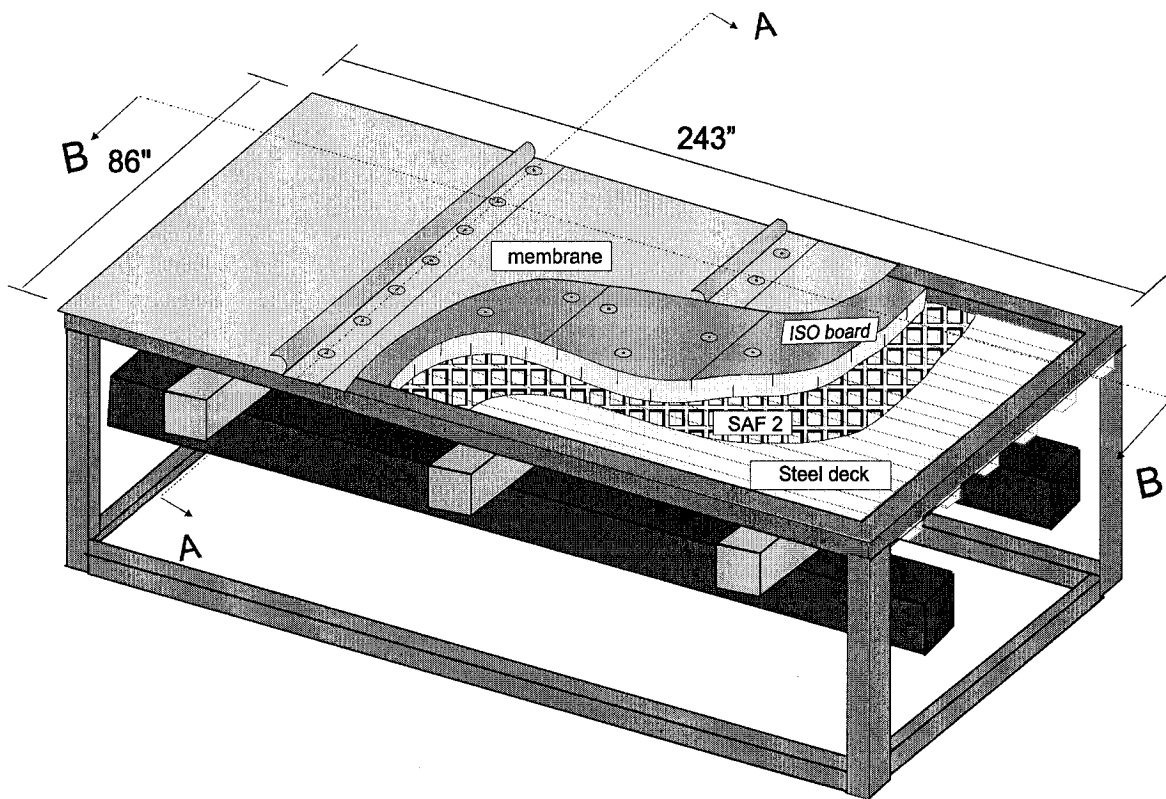


Figure 8.10 Assembly 4 –with Self Adhered Film (SAF 1) as barrier: set-up diagram



Note: 1" = 25.4mm

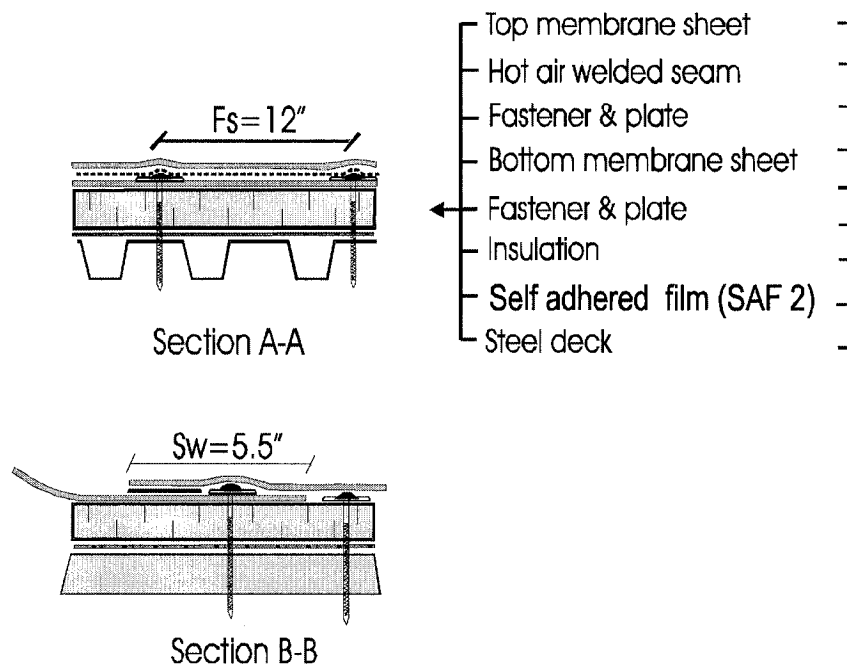


Figure 8.11 Assembly 5 –with Self Adhered Film (SAF 2) as barrier: set-up diagram

8.4 Results and Discussion

As mentioned above all the five tested assemblies were subjected to the SIGDERS dynamic load cycle (Figure 2.11). Figure 8.12 shows the measured response data for five assemblies. Assembly 1 (NOVB) sustained a maximum pressure of 4.3 kPa (90 psf) and passed all eight sequences of Level A of the SIGDERS test protocol. This means that the tested assembly passed the gusts applied over a constant static pressure component in Group 2 (refer to Figure 2.11), as well as those in Group 1. When the applied pressure was 5.0 kPa (105 psf), the system failed (failure mode discussed under Figure 8.13) at the loading sequence 4 gust number 12.

Assembly 2 (Poly), Assembly 3 (Building paper), Assembly 4 (SAF1) sustained a maximum pressure of 6.5 kPa (135 psf) and passed all necessary sequences up to Level C of the SIGDERS test protocol. All the three assemblies failed at the loading sequence 7 of Level D {7.6 kPa (158 psf)}. Assembly 5 (SAF2) sustained a maximum pressure 7.6 kPa (158 psf) passing all sequences upto Level D and failed at Level E (8.6 Kpa (180 psf)). Reproducibility tests were also undertaken and they confirmed the above findings. After the wind test, failed assemblies were examined for the weakest link. Figure 8.13 shows a typical example of a failure mode. All five assemblies failed due to membrane tear around the fastener plate. Closer examination of the failure showed that the membrane had been stretched around the plate, and then torn completely away from around the plate, while the fasteners remained engaged with the deck. Examination of the system's seams after the test revealed that the membrane had experienced some stretching, and bore teeth marks from the metal fastener plates. Kramer (1994 and 1995) quoted the most common observed failure for membrane roofs as, *"Slippage of roof membrane from below attachment plate leading to loss of compression between roof membrane, insulation substrate, and fastening elements and ultimately to membrane failure by way of tear spread around the fastener shaft"*. This observation corresponds with SIGDERS failure mode and indicates that the SIGDERS load cycle is inducing representative wind dynamics on roof systems.

Presence of a barrier, as discussed above, improves the wind uplift rating. Also there is no change in the failure mode or in the weakest link on the force resistance chain. It is to be noted that components such as the membrane, insulation fastener and plates, membrane fastener and plates with similar physical and mechanical properties were used for all the five assemblies.

1 psf = 47.88 Pa

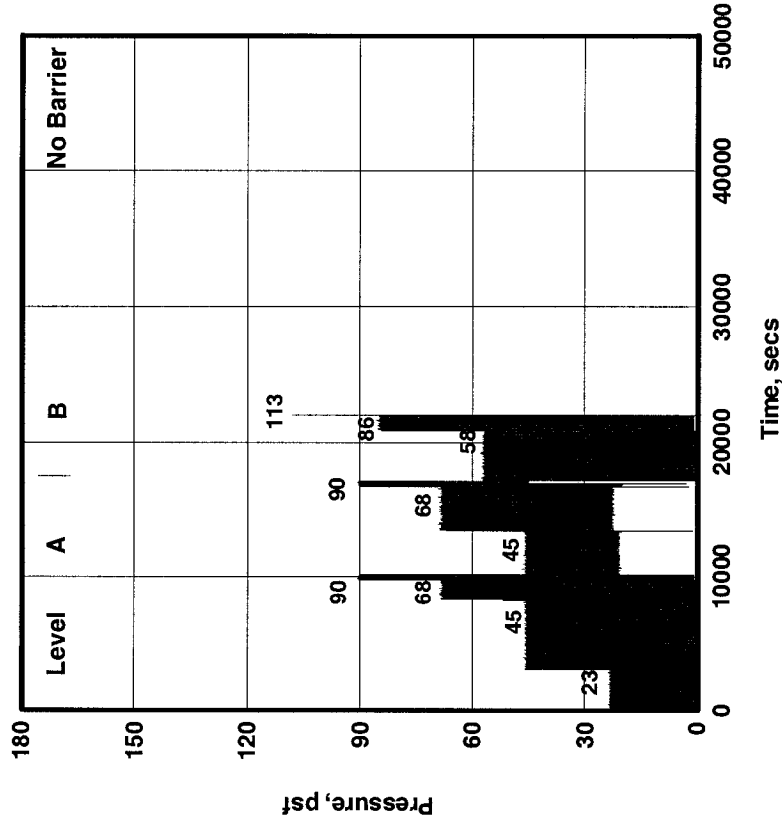


Figure 8.12 (a) Assembly 1 - with No Barrier

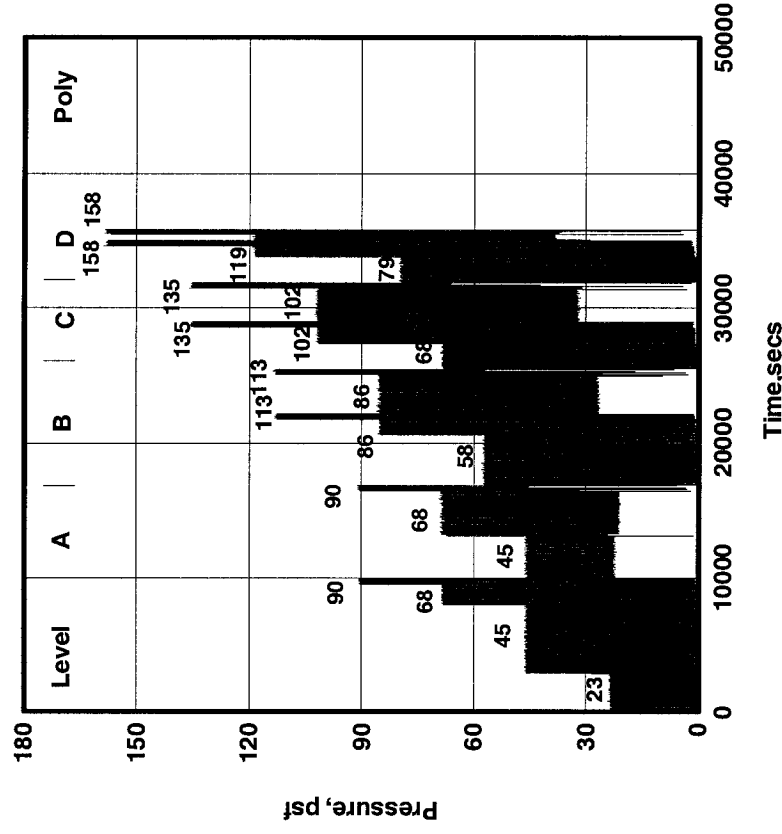


Figure 8.12 (b) Assembly 2 - with Polyethylene

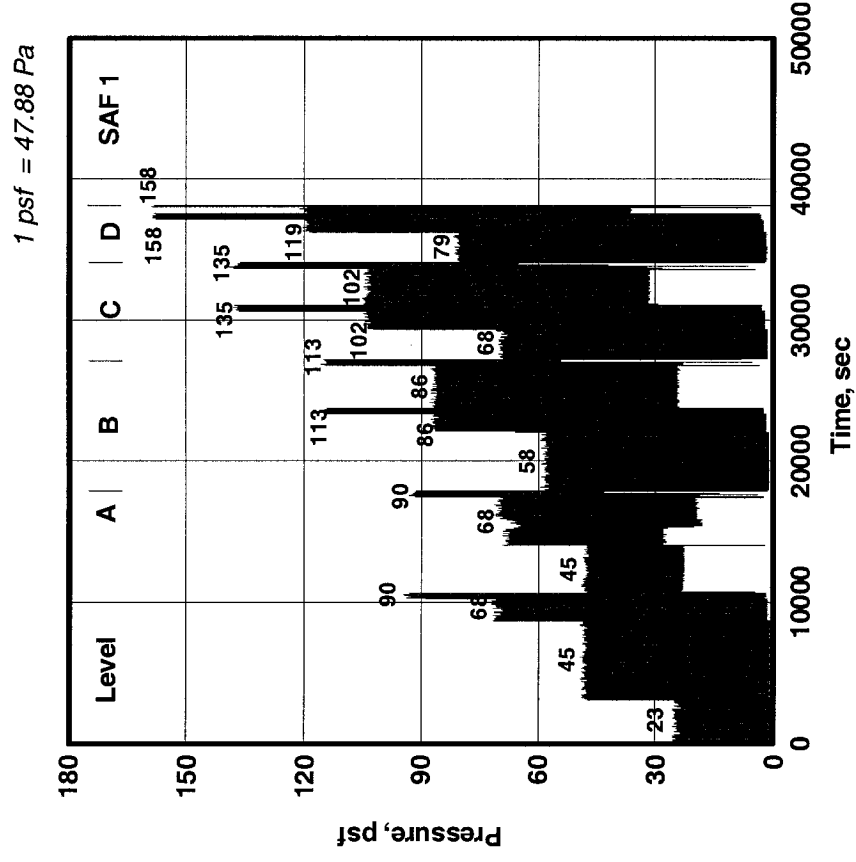


Figure 8.12 (d) Assembly 4 – with Self Adhered Film 1

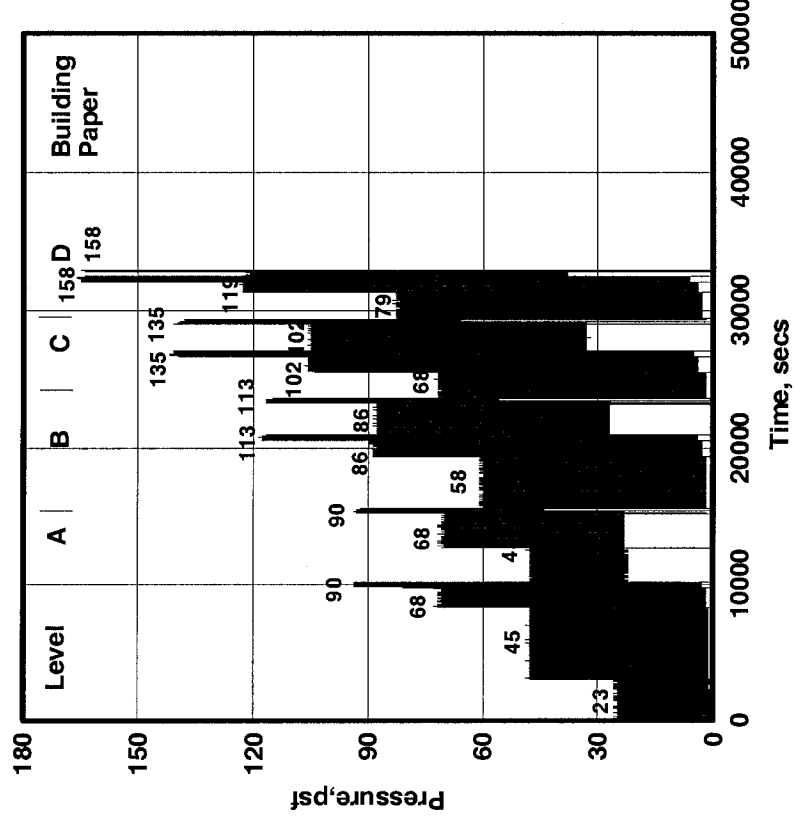


Figure 8.12 (c) Assembly 3 – with Building Paper

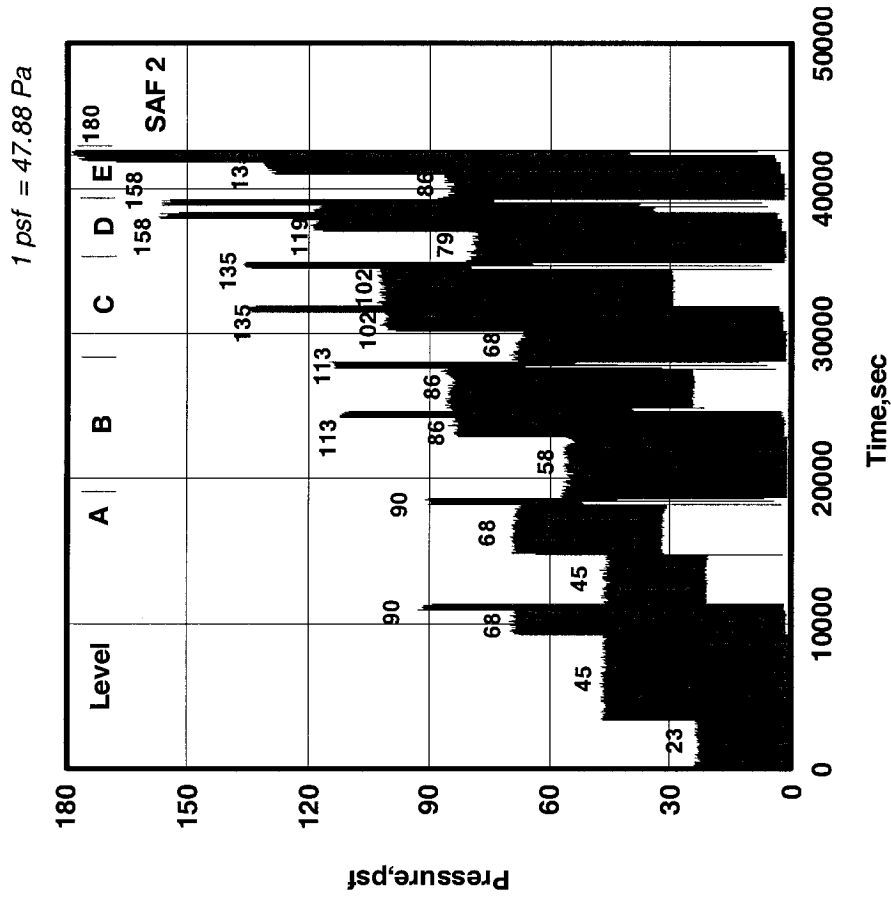


Figure 8.12 (e) System 5 – with Self Adhered Film 2

Figure 8.12 Wind uplift ratings of the assemblies with and without barrier

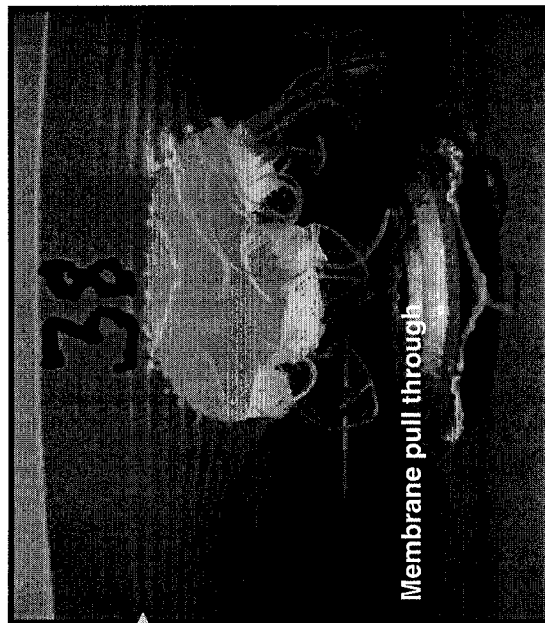
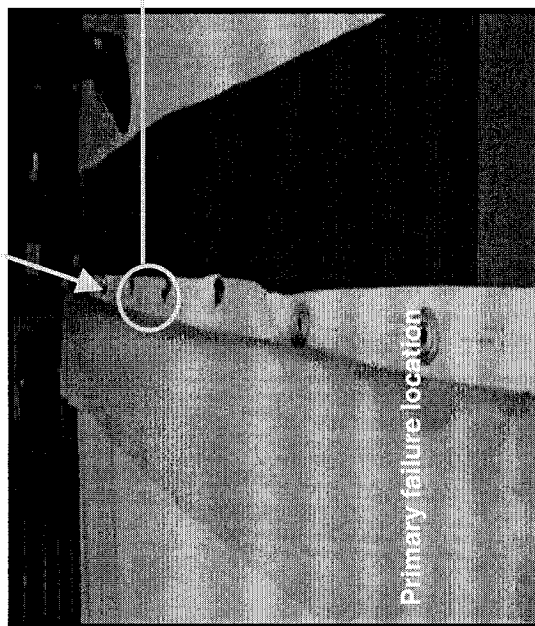
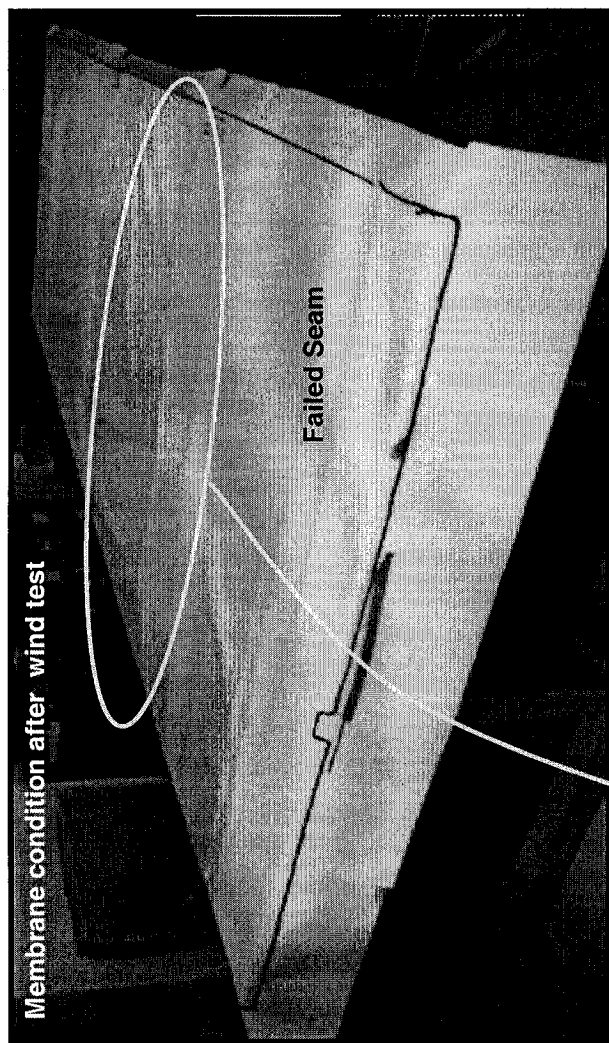


Figure 8.13 Failure mode of the tested assembly

However, these components were not from the same batch of the manufacturing production. Every effort was also made to have identical system layouts and instrument locations to those shown in Figure 8.4. If there is no change in the process and the weakest link, then how can the system resistance improve? To understand this, further data analysis was undertaken as discussed below.

A segment from the measured pressure time history is shown in Figure 8.14 and Figure 8.15. Figures 8.14 and 8.15 have five data sets representing NOVB, Poly, Building paper, SAF1 and SAF 2 assemblies at two pressure levels of 2.2 kPa (45 psf) and 4.3 kPa (90 psf) respectively. These pressures respectively represent the loading sequences 2 and 4 of Level A of the SIGDERS load cycle. In all cases, about five SIGDERS' wind gusts are shown, each having a duration of about 8 seconds. Within the 8-second period, the roofing membrane experiences the maximum pressure 2.2 kPa or 4.3 kPa (45 psf or 90 psf) for 2 seconds.

The membrane when subjected to suction at the top, billows and transfers the forces through the fastener to the structural deck. This is true irrespective of the system. It is interesting to note that in case of A1 (No Barrier), there is no pressure building up across the insulation and the insulation acts as a spacer between the membrane and deck. However, in the case of assemblies with barrier, the insulation boards share about one third of the applied suction, because these barrier types offer certain resistance to airflow thereby reducing the deflection of the membrane. The membrane load is transferred to the insulation, reducing the load on the membrane. This insulation pressure fraction partly elevates the stress on the membrane fasteners and plates and facilitates to increase the wind uplift rating of assemblies with barrier. Thus the variation in load sharing is higher on roofing assemblies with barrier. To confirm this observation, measured fastener forces are analysed and discussed below.

Figures 8.16 and 8.17 display the tensile forces measured from the fasteners of both membrane and insulation. Figures 8.15 and 8.16 have the same format as that of the Figures 8.13 and 8.14, with the exception that the vertical axis shows the forces. Several factors are evident from this Figure, some of which are outlined below.

- Only the waterproof membrane resists the induced forces in the case A1(No Barrier) and the sensor connected to insulation fastener is records no changes in the set preload irrespective of the 2.2 kPa (45psf) or 4.3 kPa (90 psf) wind gusts. This is similar to system response to applied suction.

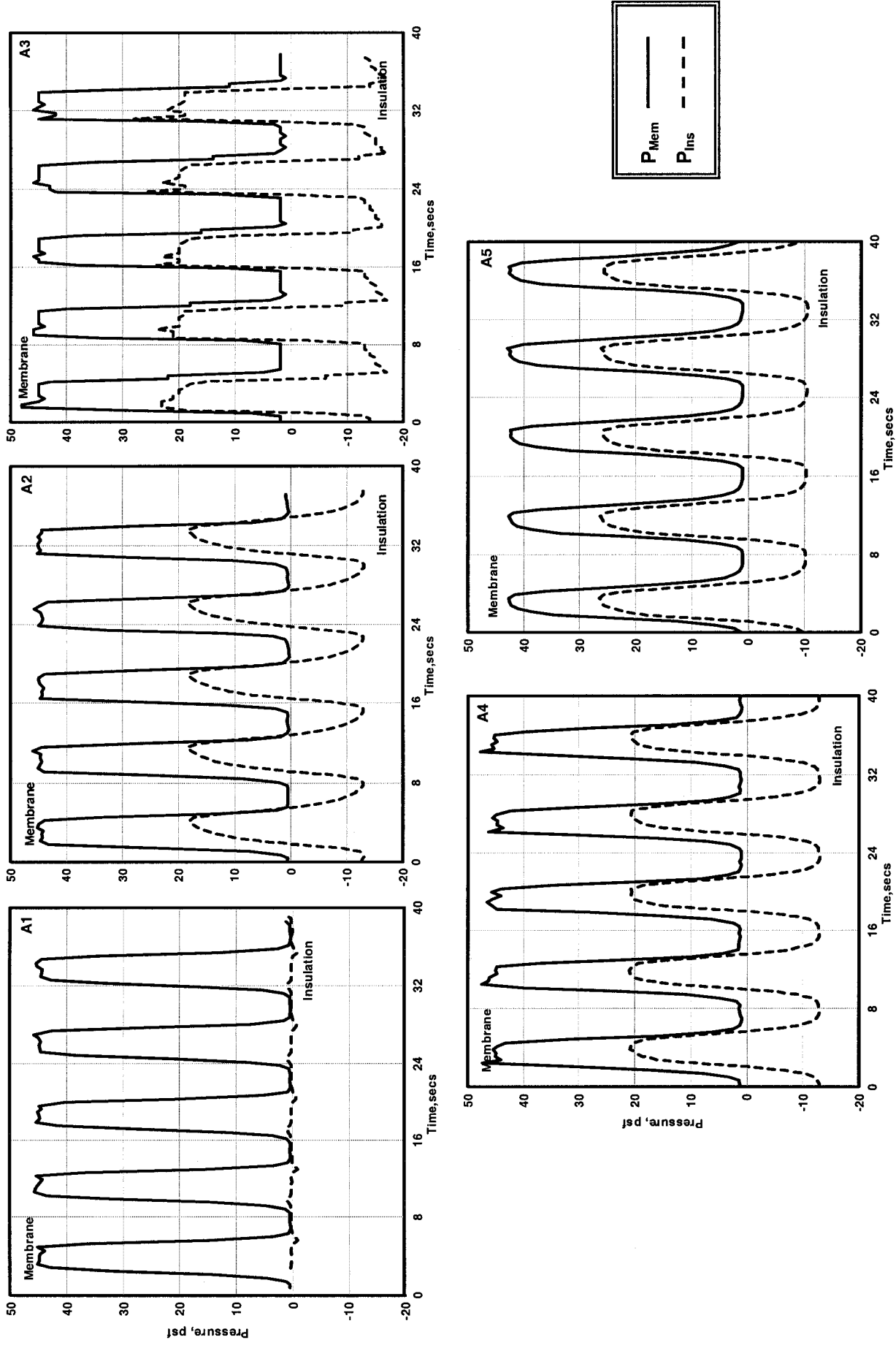


Figure 8.14 Pressure variation between the membrane and insulation for assemblies with and without barrier @ 45 psf ($1 \text{ psf} = 47.88 \text{ Pa}$)

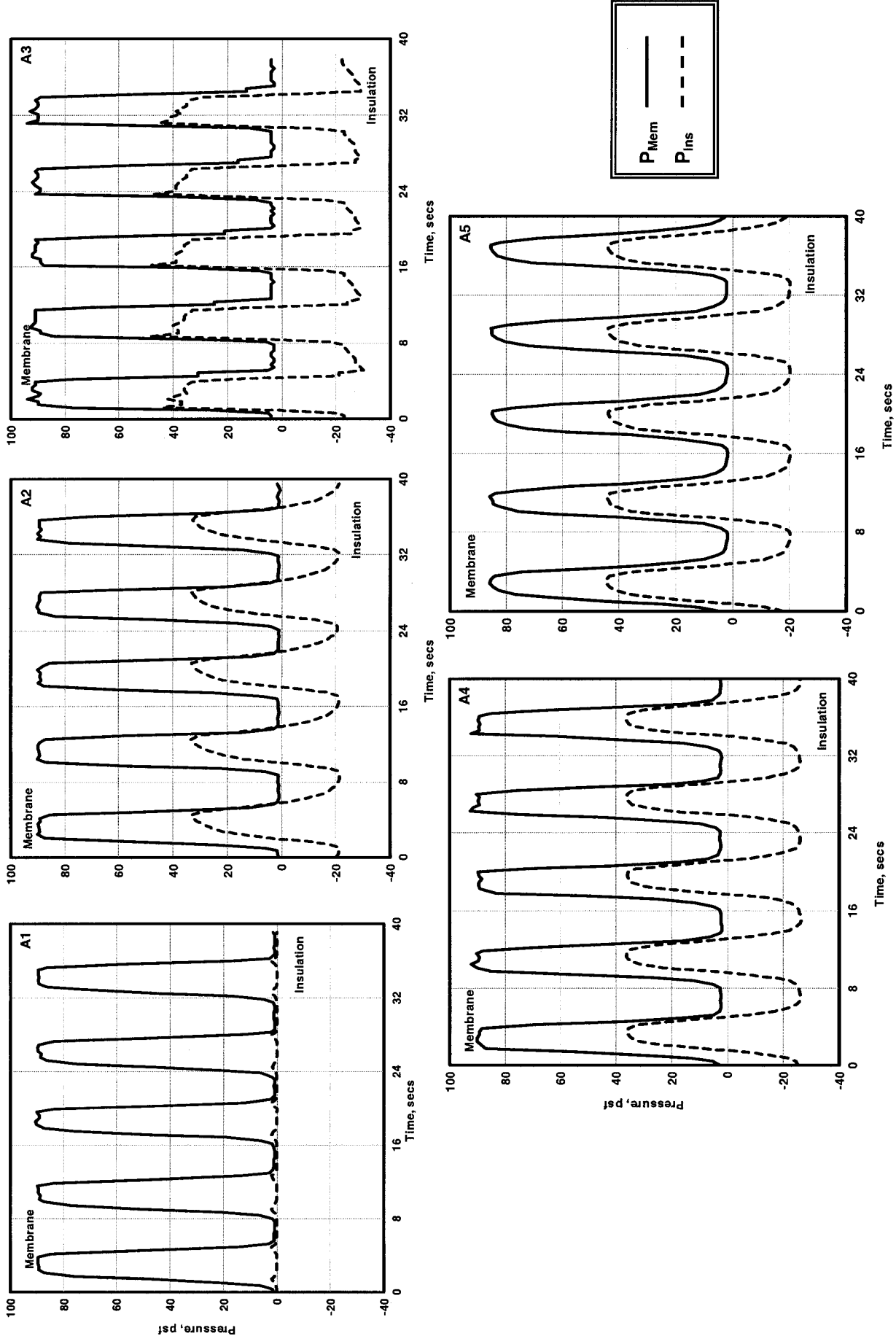


Figure 8.15 Pressure variation between the membrane and insulation for assemblies with and without barrier @ 90 psf (1 psf = 47.88 Pa)

- Not only the magnitude of the load on the membrane is greater in the case of the A1 but also the fluctuations. In the case of A1, the membrane fastener force varies from 0 to 889 N (0 to 200 lbf) or 0 to 1556 N (0 to 350 lbf) depending on 2.2 kPa (45psf) or 4.3 kPa (90 psf) wind gusts. For the same 4.3 kPa (90 psf) wind gusts, on the assemblies with barrier, the membrane fastener force ranges only between 445 to 1112 N (100 to 250 lbf).
- On assemblies with barrier, insulation fasteners take about one third or higher tensile forces from the membrane fasteners. For example, during the 4.3 kPa (90 psf) wind gusts in the A2, the membrane fastener force is 1112 N (250 lbf) and the insulation fastener force is 667 N (150 lbf).

Comparing the failure load difference between the membrane and insulation loads at the sustained pressures will emphasize the concept of load sharing mechanism. To illustrate this, a comparison has been made between four tested assemblies A1, A2, A3 and A5. Figure 8.18 shows the sustained pressures by the four tested systems and Figure 8.19 shows the corresponding membrane and insulation loads. In the case A1 without barrier, the system sustained a maximum pressure of 4309 Pa (90 psf), with membrane taking the maximum load, and zero loads on the insulation. On assemblies with barriers A2, A3 & A5, the wind uplift rating increased by 50 % as illustrated in Figure 8.18. This increase is mainly attributed to the presence of barrier in the assembly. The barrier retards air infiltration into the roofing system reducing the membrane deflection and distributing the wind load between the membrane and the insulation. The load distribution reduces the membrane stress thereby increasing the wind uplift pressure. The notion behind this load sharing mechanism is, the more air tight the system is constructed the higher will be the load distribution between membrane and insulation and higher the wind load it will sustain. Figure 8.19 clearly indicates this notion with A3 being the air tight system compared to A2 & A3.

During the wind uplift testing, the above-discussed force induced at the fastener was measured using a force balance specially developed at the NRC. The force balance has the capacity to measure simultaneously both vertical and horizontal forces. The measured horizontal component of the forces acting on the membrane fastener is compared between the assemblies with and without barrier at different pressures in Figure 8.20. The data indicate that the horizontal forces were reduced by about two third

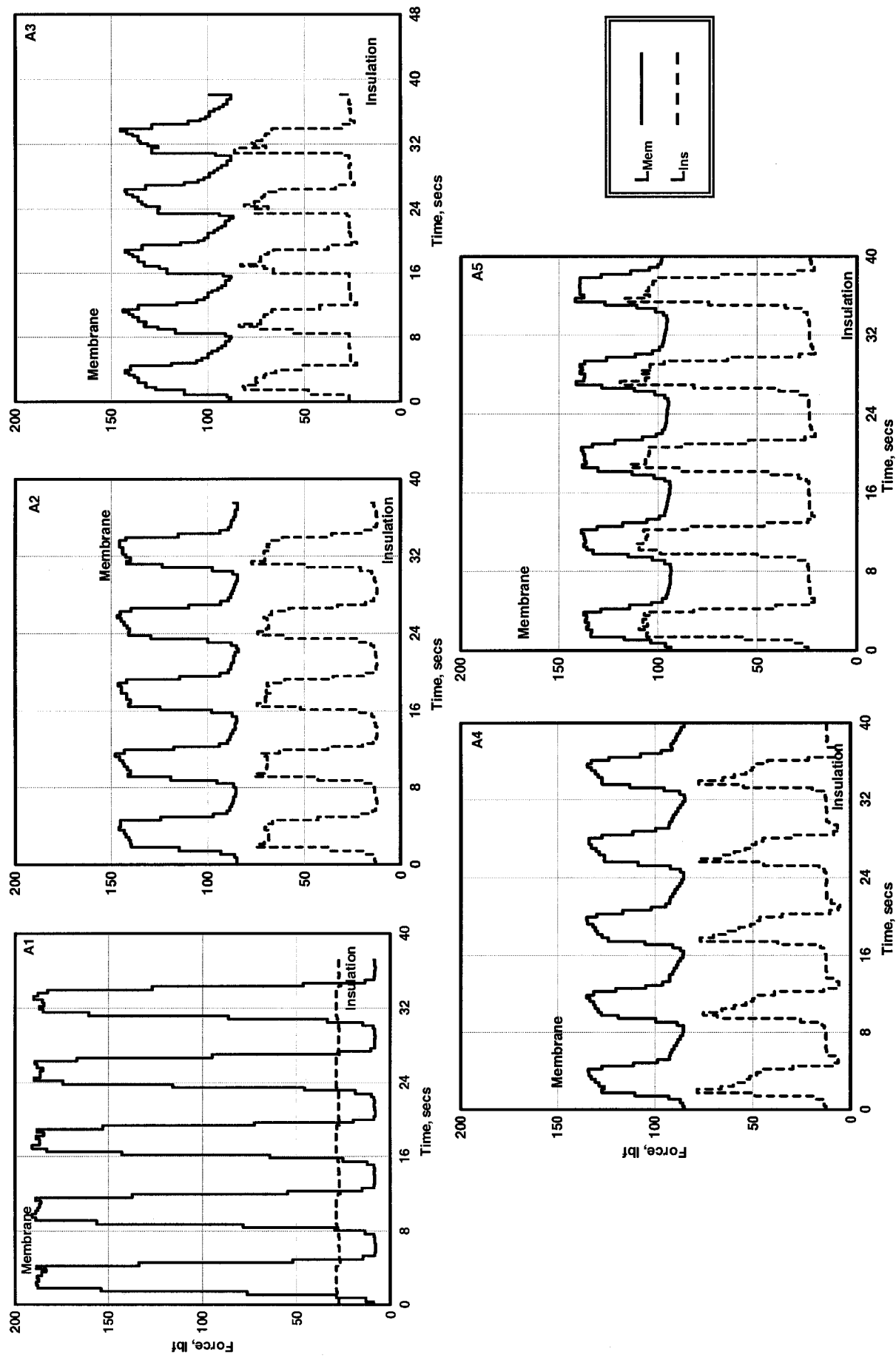


Figure 8.16 Load variation between the membrane and insulation for assemblies with and without barrier @ 45 psf (1 lbf = 4.4 N)

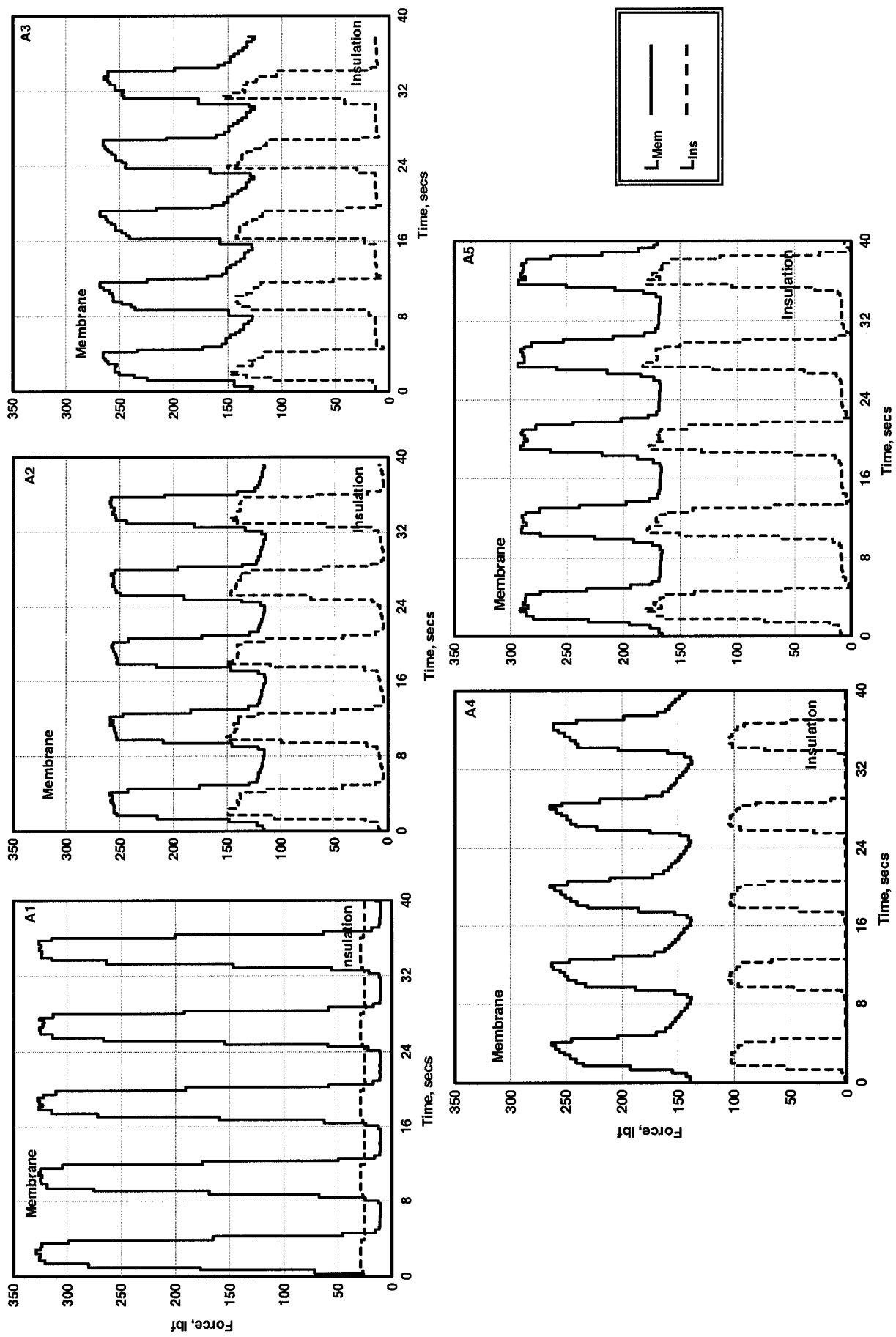


Figure 8.17 Load variation between the membrane and insulation for assemblies with and without barrier @ 90psf (1 lbf = 4.4 N)

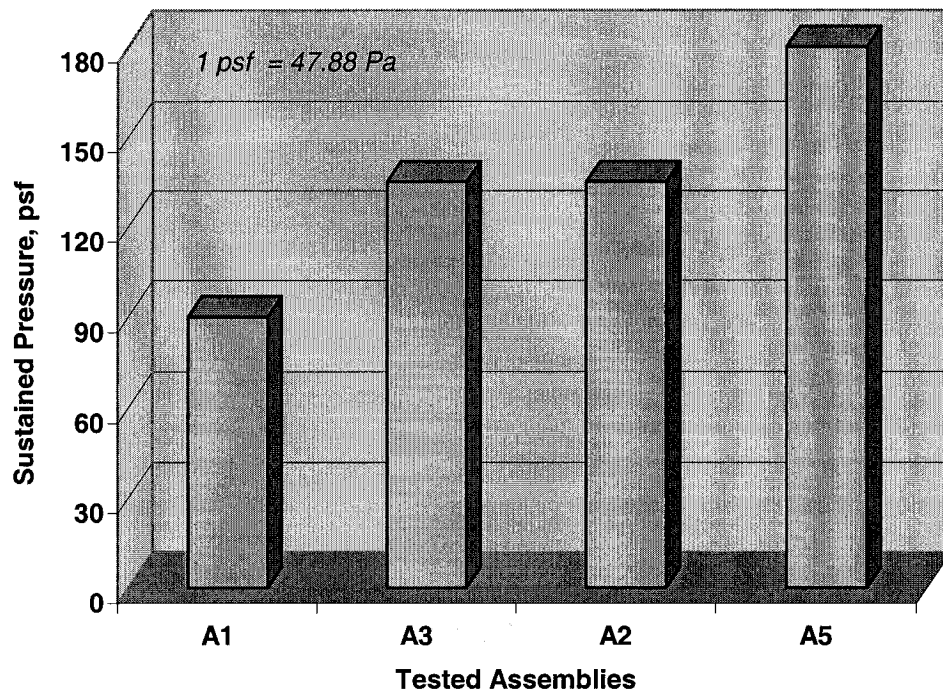


Figure 8.18 Sustained wind uplift pressures of the tested systems

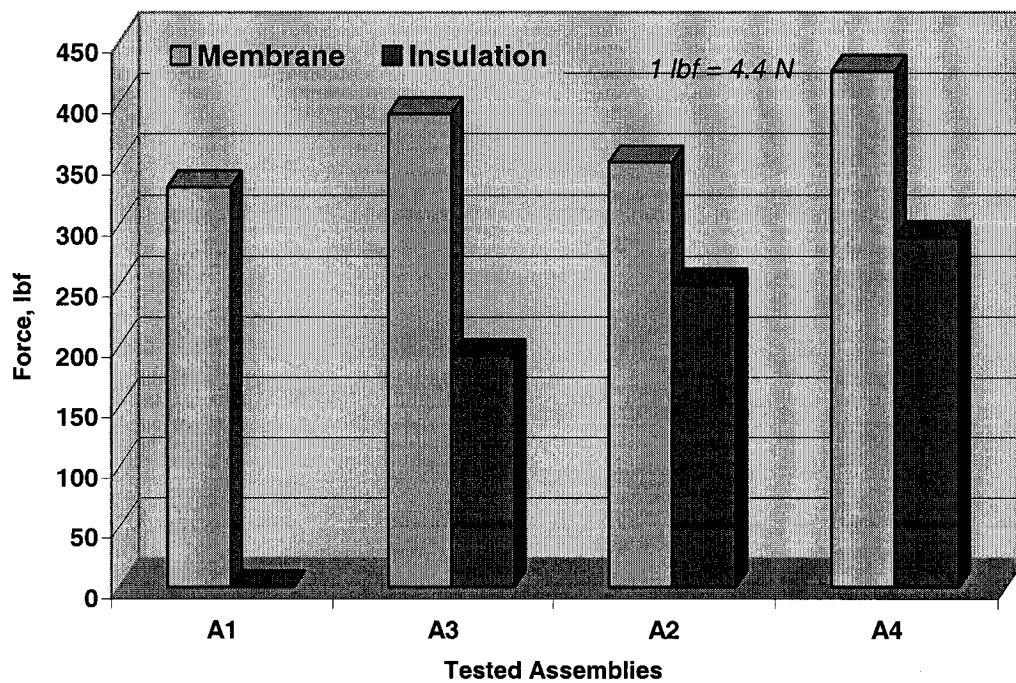


Figure 8.19 Load distribution between the membrane and insulation

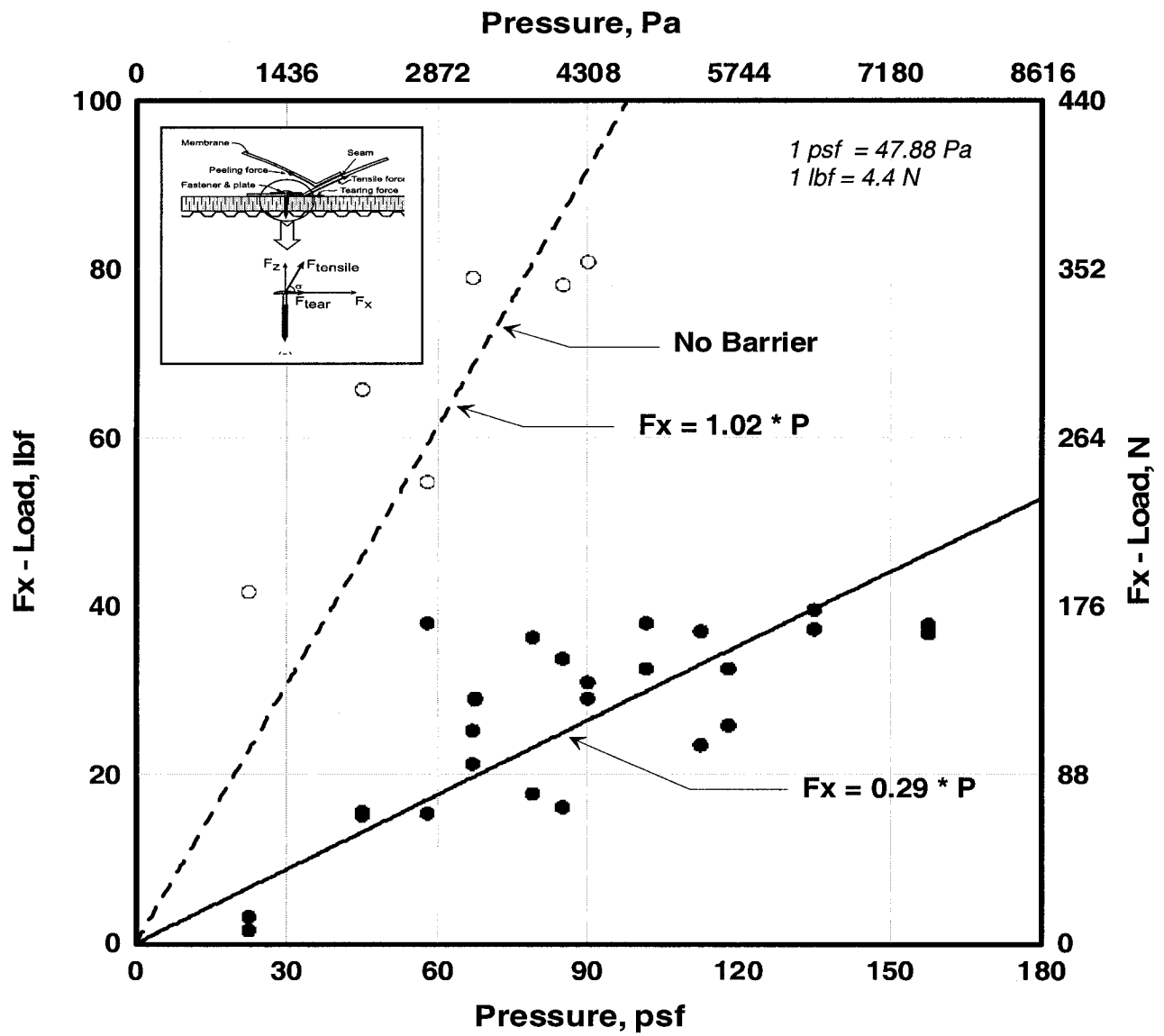


Figure 8.20 Reduction of the membrane horizontal force on assembly with barrier

due to the presence of barrier. In the assembly without barrier, due to higher deflection of the membrane the fastener plates can slide and the fastener shaft can tear the membrane around the vicinity of the fastener plates. On the other hand, in assemblies with barrier, the air barrier retards the air movement into the roof assembly thereby reducing the membrane deflection. With the reduction of the membrane deflection both the vertical and horizontal components of the membrane fastener force are reduced, which further reduces stress concentration around the membrane fastener plates. This stress localization causes either a fastener pullout from the deck if the membrane is strong enough, or membrane tearing around the plates. The latter was observed during this study.

8.5 Concluding Remarks

In summary, the present chapter investigated the impact of air infiltration on wind uplift resistance of MAS. Five systems were investigated with four different types of barriers. Data from these preliminary findings indicated that wind uplift performance is improved on systems with a barrier. An improvement of about 50% has been measured in the wind uplift rating for systems with barrier and also there is no change in the failure mode or in the weakest link on the force resistance chain. In the presence of a barrier the airflow is retarded and the rigid insulation boards share certain amounts of applied suction during the wind gusting. This load sharing mechanism minimizes stress concentration at the fastener attachment locations its wind uplift performance. This was found true for all barrier types.

Chapter 9

Conclusions and Recommendations

9.1 Conclusions

An ideal laboratory proof test of a roofing system's wind uplift resistance would consist of simulating the field performance of the roof. The best proof of any test involves correlation between the test result and field performance. Due to the limited size of the test apparatus, boundary conditions are imposed on the test specimen and thus the lab testing may not be able to replicate the performance of a field roof system. Task 1 of this dissertation focused on the application of an existing software and numerical techniques to understand the influence of the boundary effects on the wind uplift resistance of mechanically attached systems. The specific focus was on the behaviour of the membranes and not on the structural substrate.

Using the validated numerical model, simulations were performed to investigate the performance of wider roofing membranes, which are prevalent and most widely used in the current roofing market.

- Simulations were done for two system configurations using wider thermoplastic membranes and three system configurations using wider thermoset membrane. It was found that if roofing systems are tested on table widths narrower than the membrane width (Fastener row spacing) the table edges restrict the lateral deformation of the membrane. In addition, the dominant load transfer direction is along the table edges, thereby reducing the loads transferred to the fasteners.
- Attempts were made to identify a required table width for each of the five system configurations. The analysis of this numerical study reveals that wider tables are necessary to obtain realistic wind uplift evaluation of the systems with wider membranes. It was found that an increase in the table width beyond a level did not significantly change the system response. This specific limit (required table width) depends mainly on two system parameters, namely, fastener row spacing and fastener spacing. The influence of these two parameters on the required table width was also investigated.
- Based on the required table widths, correction factors were developed for testing tables less than the required table width to obtain the true fastener forces

- Effect of table length was also investigated and it was found that the table length has a minimal effect on the systems wind uplift response as long the table length can accommodate two full sheets with three seams.

The present study has been further extended to obtain generalized characteristic design curves or correction factor curves. The individual correction factors for various roofing system configurations were combined. A relationship was developed between the correction factors and parameters influencing the required table width, namely the fastener row spacing (F_r), the fastener spacing (F_s) and the table width (W). The combined correction factors were generalized based on the ratio of F_r/F_s (fastener row spacing/fastener spacing) to form design curves that can be of practical use to determine the wind loading on roofs. The following conclusions can be inferred from the development of generalized correction factor process:

- The RTW for different roofing layouts ranged from 2000 mm (79") to 5054 mm (199"). A minimum table width of 5359 mm (211") is necessary to evaluate all F_r/F_s combinations without applying any correction factor.
- The modified bituminous systems are free from correction factors as long as the membrane width remains constant as 1000 mm (39").

Task 2 of this research study addressed the issue of air leakage through mechanically attached roofing systems. In the literature, no measurement of air infiltration to the space underneath a billowed membrane in the MAS is reported. There are no formal performance criteria, standard specifications or test methods to quantify air leakage of MAS. An attempt to develop an experimental procedure to quantify air leakage through MAS was undertaken in the present research study. A new test apparatus was developed and three roofing assemblies with and without barriers were investigated for air leakage quantification. Data from these primary findings showed that:

- Systems with barriers were able to provide 80% to 90% air leakage resistance when compared to systems without barrier.
- Results have suggested that the high leakage rate of the systems without barrier may be attributed primarily to the channel flow occurring at the deck and insulation joints. In the case of systems with barriers, it was observed that the edge treatment

of barriers during installation could contribute for air seepage into the roofing assembly.

- Comparing the measured experimental data with the recommended air leakage resistance value of the NBCC (2005), it was found that systems without barrier exceeded the NBCC recommended value by three fold. (Note that, NBCC (2005) specifies a maximum allowable air leakage rate 0.15 L/s.m^2 at a differential pressure of 75 Pa).

Based on the quantification of air leakage through the MAS, its impact on the wind uplift resistance was also evaluated under a dynamic wind environment. Five roofing assemblies were investigated with four different types of barriers. Data from these primary findings indicated that:

- Wind uplift performance is improved on systems with a barrier. An improvement of about 50% was measured in the wind uplift rating for systems with barrier, which is found true for all barrier types. It is worth noting that the barriers used in the present experimental study are considered to be vapour barrier components in roofing design. Nevertheless the 50% wind uplift improvement is not due to their ability to reduce moisture diffusion; rather, it is due to their ability to retard air movement.
- Use of barrier introduces the load sharing mechanism between membrane and insulation thereby minimizing the stress concentration at the membrane fastener attachment locations. This minimizes asymmetrical stress concentration and improves the wind rating of MAS.
- One of the most common membrane layouts from field application was constructed and tested in the lab mock-up. Therefore, the above quantification may equally be valid for roof assemblies with other roof covers.

9.2 Recommendations for Future Work

Based on numerical investigations of single ply roofing systems, Task 1 of the present research study successfully developed the correction factors for estimating the true fastener load. The present model was benchmarked with the experimental data obtained from the smaller width membranes namely the 1219 mm (48") and 1829 mm (72"). Further research work is needed to benchmark the model with wider membranes. It is also necessary to validate the concept of required table width (RTW) experimentally,

which would verify the developed design curves such that they can be of practical use to the roofing community. The influence of the table edges affects the failure pressure of a roofing system and the present study correction factors only correct the edge effects and not the failure pressure. It would be ideal if studies could be conducted to obtain a correlation between the correction factors and failure pressure (i.e correlating the actual fastener load obtained from the correction factor graph with corresponding failure pressure when the system is tested on the required table width). In this way it would be possible to approximate the failure pressure depending on the membrane deflection and fastener load.

The present model is two-dimensional. It can be extended to incorporate the thickness of each component of the roofing assembly details such as deck, insulation and fasteners. An investigation for load combinations such as thermal and wind are also beneficial for Canadian weather conditions.

The primary findings obtained from Task 2 of the present research study illustrate the importance of air leakage. Though, the present research work was confined to the small-scale study, it is necessary that this small scale study should be extended to full scale assemblies incorporating the effects of non-uniformity such as deck joints, insulation joints and barrier joints. Attention should be focused on the interpretation of this data and to understand how these values correlate to the actual field performance of the roofing systems. The major sources of air leakage in a roofing system are: terminations, penetrations and junctions. It is recommended that the influence of these sources can be identified and air leakage studies be conducted to establish a limiting criteria for air leakage at these locations.

In the present study the experimental setup assumed that the continuous waterproof membrane is airtight and thus excluded from the investigation. It would be ideal if an experimental procedure could be developed, which includes the membrane deformations. The magnitude of the design wind pressure depends on the rate of infiltration into the space underneath the membrane and the size of the membrane that inflates to wind.

APPENDIX A: Typical ABAQUS input file for the simulation of MAS (Thermoplastic System)

A typical ABAQUS input file for the simulation of 144/12 wider thermoplastic system configuration on a 4445 mm (175") wide table and subjected to 1.44 kPa (30 psf) pressure is presented below. Critical explanations are highlighted in bold.

```
*HEADING
tpo,W=4445mm,L=7467.6mm,fastener spacing=12"
** Node definition and generation
*NODE,NSET=L1
1,0.0,0.0,0.0
*NODE,NSET=P2
2,0.0,0.0889,0.0
*NODE,NSET=P3
86,0.0,4.3561,0.0
*NFILL,NSET=L1
P2,P3,84,1
*NODE,NSET=L1
87,0.0,4.4450,0.0
*****
*NCOPY,CHANGE NUMBER=100,OLD SET=L1,SHIFT,NEW SET=DUMMY1
0.0762,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=DUMMY1,SHIFT,NEW SET=L2
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L2,SHIFT,NEW SET=L3
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L3,SHIFT,NEW SET=L4
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L4,SHIFT,NEW SET=L5
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L5,SHIFT,NEW SET=L6
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=L6,SHIFT,NEW SET=L7
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L7,SHIFT,NEW SET=L8
0.889,0.0,0.0
0.0,
```

```

*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L8,SHIFT,NEW SET=L9
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L9,SHIFT,NEW SET=L10
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L10,SHIFT,NEW SET=L11
0.889,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=L11,SHIFT,NEW SET=L12
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=100,OLD SET=L12,SHIFT,NEW SET=DUMMY2
0.0762,0.0,0.0
0.0,
*****
*NFill
DUMMY1,L2,4,100
L6,L7,4,100
L11,L12,4,100
*NFill,BIAS=0.8
L2,L3,7,100
L4,L5,7,100
L7,L8,7,100
L9,L10,7,100
*NFill,BIAS=1.15
L3,L4,7,100
L5,L6,7,100
L8,L9,7,100
L10,L11,7,100
*NSET,NSET=BC,GENERATE1
1,7001,100
87,7087,100
** Shell element definition and generation
*ELEMENT,TYPE=S4,ELSET=SHELL
1,1,101,102,2
*ELGEN,ELSET=SHELL
1,86,1,1,70,100,100
** Definition of spring elements
*ELEMENT,TYPE=SPRING1,ELSET=SPRING
9001,302
9002,308
9003,314
9004,320
9005,326
9006,332
9007,338
9008,344
9009,350
9010,356
9011,362
9012,368

```

9013,374
9014,380
9015,386
10101,3502
10102,3508
10103,3514
10104,3520
10105,3526
10106,3532
10107,3538
10108,3544
10109,3550
10110,3556
10111,3562
10112,3568
10113,3574
10114,3580
10115,3586
11101,6702
11102,6708
11103,6714
11104,6720
11105,6726
11106,6732
11107,6738
11108,6744
11109,6750
11110,6756
11111,6762
11112,6768
11113,6774
11114,6780
11115,6786

**** Definition of seam elements**

*ELSET,ELSET=SEAM,GENERATE

101,186,1
201,286,1
301,386,1
401,486,1
3301,3386,1
3401,3486,1
3501,3586,1
3601,3686,1
6501,6586,1
6601,6686,1
6701,6786,1
6801,6886,1

**** Definition of fastener plate elements**

*ELSET,ELSET=DISK,GENERATE

101,185,6
102,186,6
201,285,6
202,286,6
301,385,6
302,386,6
401,485,6
402,486,6

```

3301,3385,6
3302,3386,6
3401,3485,6
3402,3486,6
3501,3585,6
3502,3586,6
3601,3685,6
3602,3686,6
6501,6585,6
6502,6586,6
6601,6685,6
6602,6686,6
6701,6785,6
6702,6786,6
6801,6885,6
6802,6886,6
** Material definition
*SPRING, ELSET=SPRING
3
20000
*MATERIAL, NAME=TPO
*ELASTIC
**4.30E08, .40
3.0E08, 0.40
***PLASTIC
**10E06, 0.
**34.E06, 0.060
**34.427E06, 0.058
***DENSITY
** 7860.
*MATERIAL, NAME=PLASTIC
*ELASTIC
5.00E08, .40
*****
*SHELL SECTION, ELSET=SHELL, MATERIAL=TPO
0.00104
*SHELL SECTION, ELSET=SEAM, MATERIAL=TPO
0.00208
*SHELL SECTION, ELSET=DISK, MATERIAL=PLASTIC
0.0030
** Applied load and boundary condition
*STEP, NLGEOM, INC=550
***STEP
*STATIC
0.00001, 1.0, 1.0E-07, 0.51
*BOUNDARY
L1, 1, 3
DUMMY2, 1, 3
**1, 1, 1
**27, 1, 1
**1243, 1, 1
**1269, 1, 1
**L6, 1, 1, 0.01
BC, 1, 3
*DLOAD
SHELL, P, 1436.4
**17.5psf=837.9

```

```

**SHELL,P,1436.4
**SHELL,P,5745.75
**SHELL,P,4309.3
**30psf=1436.4Pa
***CLOAD
**L2,1,-10
**L5,1,10
**120psf=5745.75Pa
** Output format
*RESTART,WRITE,FREQUENCY=10
*NODE PRINT
U
*NODE FILE
U
RF
***NODE PRINT,NSET=L2
**RF
***NODE PRINT,NSET=MID
**RF
*EL PRINT,ELSET=SPRING
S11
*EL FILE,ELSET=SPRING
S
***EL PRINT,ELSET=ENDS
**S11
*END STEP

```

APPENDIX B: Typical ABAQUS input file for the simulation of MAS (Thermoset System)

A typical ABAQUS input file for the simulation of 120/12 wider thermoset system configuration on a 3835 mm(151") wide table and subjected to 1.44 kPa (30 psf) pressure is presented below. Critical explanations are highlighted in bold.

```
*HEADING
tpo,W=3835.4mm,L=7467.6mm,fastener spacing=12"
** Node definition and generation
*NODE,NSET=L1
1,0.0,0.0,0.0
*NODE,NSET=P2
2,0.0,0.0889,0.0
*NODE,NSET=P3
74,0.0,3.7465,0.0
*NFILL,NSET=L1
P2,P3,72,1
*NODE,NSET=L1
75,0.0,3.8354,0.0
*****
*NCOPY,CHANGE NUMBER=100,OLD SET=L1,SHIFT,NEW SET=DUMMY1
0.635,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=DUMMY1,SHIFT,NEW SET=L2
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L2,SHIFT,NEW SET=L3
0.7112,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=800,OLD SET=L3,SHIFT,NEW SET=L4
0.8128,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L4,SHIFT,NEW SET=L5
0.7112,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L5,SHIFT,NEW SET=L6
0.7112,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=L6,SHIFT,NEW SET=L7
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L7,SHIFT,NEW SET=L8
0.7112,0.0,0.0
0.0,
```

```

*****
*NCOPY,CHANGE NUMBER=800,OLD SET=L8,SHIFT,NEW SET=L9
0.8128,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L9,SHIFT,NEW SET=L10
0.7112,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=700,OLD SET=L10,SHIFT,NEW SET=L11
0.7112,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=400,OLD SET=L11,SHIFT,NEW SET=L12
0.1016,0.0,0.0
0.0,
*****
*NCOPY,CHANGE NUMBER=100,OLD SET=L12,SHIFT,NEW SET=DUMMY2
0.635,0.0,0.0
0.0,
*****
*NFILL
DUMMY1,L2,4,100
L6,L7,4,100
L11,L12,4,100
*NFILL,BIAS=0.8
L2,L3,7,100
L4,L5,7,100
L7,L8,7,100
L9,L10,7,100
*NFILL,BIAS=1.15
L3,L4,8,100
L5,L6,7,100
L8,L9,8,100
L10,L11,7,100
*NSET,NSET=BC,GENERATE1
1,7201,100
75,7275,100
** Shell element definition and generation
*ELEMENT,TYPE=S4,ELSET=SHELL
1,1,101,102,2
*ELGEN,ELSET=SHELL
1,74,1,1,72,100,100
** Definition of spring elements
*ELEMENT,TYPE=SPRING1,ELSET=SPRING
9001,302
9002,308
9003,314
9004,320
9005,326
9006,332
9007,338
9008,344
9009,350
9010,356
9011,362
9012,368

```

9013,374
10101,3602
10102,3608
10103,3614
10104,3620
10105,3626
10106,3632
10107,3638
10108,3644
10109,3650
10110,3656
10111,3662
10112,3668
10113,3674
11101,6902
11102,6908
11103,6914
11104,6920
11105,6926
11106,6932
11107,6938
11108,6944
11109,6950
11110,6956
11111,6962
11112,6968
11113,6974

**** Definition of seam and plate elements**

*ELSET, ELSET=SEAM, GENERATE

101,174,1
201,274,1
301,374,1
401,474,1
3401,3474,1
3501,3574,1
3601,3674,1
3701,3774,1
6701,6774,1
6801,6874,1
6901,6974,1
7001,7074,1

*ELSET, ELSET=DISK, GENERATE

101,173,6
102,174,6
201,273,6
202,274,6
301,373,6
302,374,6
401,473,6
402,474,6
3401,3473,6
3402,3474,6
3501,3573,6
3502,3574,6
3601,3673,6
3602,3674,6
3701,3773,6

```

3702,3774,6
6701,6773,6
6702,6774,6
6801,6873,6
6802,6874,6
6901,6973,6
6902,6974,6
7001,7073,6
7002,7074,6
** Definition of spring elements and materials
*SPRING,ELSET=SPRING
3
60000
*MATERIAL,NAME=EPDM
*ELASTIC
**4.30E08,.40
1.5E08,0.22
***PLASTIC
**10E06,0.
**34.E06,0.060
**34.427E06,0.058
***DENSITY
** 7860.
*MATERIAL,NAME=METAL
*ELASTIC
2.00E11,.20
*****
*SHELL SECTION,ELSET=SHELL,MATERIAL=EPDM
0.0011
*SHELL SECTION,ELSET=SEAM,MATERIAL=EPDM
0.0022
*SHELL SECTION,ELSET=DISK,MATERIAL=METAL
0.002
*STEP,NLGEOM,INC=550
***STEP
*STATIC
0.00001,1.0,1.0E-10,0.2
*BOUNDARY
L1,1,3
DUMMY2,1,3
**1,1,1
**27,1,1
**1243,1,1
**1269,1,1
**L6,1,1,0.01
BC,1,3
** Applied load and boundary condition
*DLOAD
SHELL,P,1436.4
**17.5psf=837.9
**SHELL,P,1436.4
**SHELL,P,5745.75
**SHELL,P,4309.3
**30psf=1436.4Pa
***CLOAD
**L2,1,-10
**L5,1,10

```

```
**120psf=5745.75Pa
** Output format
*RESTART,WRITE,FREQUENCY=10
*NODE PRINT
U
*NODE FILE
U
RF
***NODE PRINT,NSET=L2
**RF
***NODE PRINT,NSET=MID
**RF
*EL PRINT,ELSET=SPRING
S11
*EL FILE,ELSET=SPRING
S
***EL PRINT,ELSET=ENDS
**S11
*END STEP
```

APPENDIX C : Computed fastener forces and deflection from numerical modeling of wider membranes (Thermoplastic System)

Table Width mm (in)	144/12		144/12		144/24		144/24	
	Fastener Force		Deflection		Fastener Force		Deflection	
	N	lbf	mm	in	N	lbf	mm	in
5664 (223)					2465	555	378.5	14.9
5359 (211)					2405	541	370.2	14.6
5048 (199)	1332	303	337.7	13.3	2306	519	359.9	14.2
4743 (187)	1276	290	328.6	12.9	2162	486	347.8	13.7
4438 (175)	1221	277	317.3	12.4	2034	458	333.7	13.1
4134 (163)	1147	261	304.1	11.9	1936	436	317.5	12.5
3829 (151)	1077	245	288.1	11.3	1788	402	298.8	11.7
3524 (139)	985	224	269.7	10.6	1584	356	277.5	10.9
3219 (127)	904	206	248.5	9.8	1416	319	253.9	10.0
2914 (115)	803	182	224.7	8.9	1308	294	228.3	8.9
2610 (103)	718	163	198.9	7.8	1142	257	201	7.9
2305 (91)	614	139	171.5	6.8	912	205	172.5	6.8
2000 (79)	533	121	143.5	5.7	741	167	143.9	5.7

APPENDIX D: Computed fastener forces and deflection from the numerical modeling of wider membranes (Thermoset System)

Table Width mm (in)	120/12		120/12		120/18		120/18		120/24		120/24	
	Fastener Force		Deflection		Fastener Force		Deflection		Fastener Force		Deflection	
	N	lbf	mm	in	N	lbf	mm	in	N	lbf	mm	in
4438 (175)	1311	295	344	13.5	1909	429	355.8	14	2464	554	367.1	14.5
4134 (163)	1270	286	336.7	13.2	1865	419	347	13.6	2414	543	357.7	14
3829 (151)	1228	276	326.9	12.8	1783	401	336.1	13.2	2293	515	344.8	13.6
3524 (139)	1157	260	313.7	12.3	1652	371	321.8	12.6	2085	469	328.8	12.9
3219 (127)	1089	245	296.8	11.6	1562	351	300	11.8	1904	428	308.2	12.1
2914 (115)	987	222	275.4	10.8	1422	319	279.8	11	1800	405	284	11.2
2610 (103)	897	202	249.5	9.8	1226	277	252.3	9.9	1594	358	254.9	10
2305 (91)	776	174	219.2	8.6	1118	251	220.9	8.7	1289	290	222.2	8.7
2000 (79)	685	154	185.6	7.30	956	215	186.5	7.3	1058	238	187	7.4

APPENDIX E : Developed correction factors for the 144/12 and 144/24 thermoplastic system configuration

System Configuration : 144 / 12

Table width (mm)	Table width (in)	Force (N)	Force (lbf)	% Change	C _F
5048	199	1332	303		
4743	187	1276	290	4.22	
4438	175	1221	278	4.31	1.00
4134	163	1147	261	6.10	1.06
3829	151	1077	245	6.12	1.13
3524	139	985	224	8.46	1.24
3219	127	904	206	8.24	1.35
2914	115	803	182	11.24	1.52
2610	103	718	163	10.51	1.70
2305	91	614	139	14.59	1.99
2000	79	533	121	13.10	2.29

% Change: Change in fastener force with respect to the incremented table width

$$\text{Correction Factor, } C_F = \frac{\text{Computed Fastener Force (RTW)}}{\text{Computed Fastener Force (NarrowTable)}}$$

System Configuration : 144 / 24

Table width (mm)	Table width (in)	Force (N)	Force (lbf)	% Change	C _F
5664	223	2465	555		
5359	211	2405	541	2.46	
5048	199	2306	519	4.10	1.00
4743	187	2162	486	6.23	1.07
4438	175	2034	458	5.95	1.13
4134	163	1936	436	4.78	1.19
3829	151	1788	402	7.67	1.29
3524	139	1584	356	11.39	1.46
3219	127	1416	319	10.59	1.63
2914	115	1308	294	7.62	1.76
2610	103	1142	257	12.75	2.02
2305	91	912	205	20.13	2.53
2000	79	741	167	18.68	3.11

APPENDIX F : Developed correction factors for the 120/12 , 120/18 and 120/24 thermoplastic system configuration

System Configuration : 120 / 12

Table width (m)	Table width (in)	Force (N)	Force (lbf)	% Change	C _F
4438	175	1311	295		
4134	163	1270	286	3.13	
3829	151	1228	276	3.30	1.00
3524	139	1157	260	5.80	1.06
3219	127	1089	245	5.87	1.13
2914	115	987	222	9.43	1.25
2610	103	897	202	9.11	1.37
2305	91	776	174	13.44	1.58
2000	79	685	154	11.70	1.79

System Configuration : 120 / 18

Table width (mm)	Table width (in)	Force (N)	Force (lbf)	% Change	C _F
4438	175	1909	429		
4134	163	1865	419	2.30	
3829	151	1783	401	4.39	1.00
3524	139	1652	371	7.34	1.08
3219	127	1562	351	5.44	1.14
2914	115	1422	319	9.00	1.25
2610	103	1226	277	13.77	1.45
2305	91	1118	251	8.81	1.59
2000	79	956	215	14.45	1.86

System Configuration : 120 / 24

Table width (mm)	Table width (in)	Force (N)	Force (lbf)	% Change	C _F
4438	175	2464	554		
4134	163	2414	543	2.00	
3829	151	2293	515	5.01	1.00
3524	139	2085	469	9.09	1.10
3219	127	1904	428	8.66	1.20
2914	115	1800	405	5.46	1.27
2610	103	1594	358	11.48	1.44
2305	91	1289	290	19.10	1.78
2000	79	1058	238	17.95	2.17

% Change: Change in fastener force with respect to the incremented table width

$$\text{Correction Factor, } C_F = \frac{\text{Computed Fastener Force (RTW)}}{\text{Computed Fastener Force (NarrowTable)}}$$

APPENDIX G : Calculation of admissible design fastener load based on CSA 123.21-04 and UEAtc 1991

The appendix compares the correction factors developed by CSA and UEAtc for estimating the admissible design fastener load of single ply roofing systems. First, the procedure is defined for obtaining the design fastener load. Second, its application is presented through two examples., one for system with TPO membrane and other with EPDM membrane

CSA 123.21-04 Procedure

$$F_{adm} = F_{measured} \times C_f \times \frac{1}{F.S} \quad (G-1)$$

where:

$F_{measured}$ = Measured load

C_f = Correction factor

F.S = Factor of safety

F_{adm} , the design fastener load is obtained relative to the **measured load**.

UEAtc –1991 Procedure

$$W_{adm} = W_{test} \times C_a \times C_d \times C_t \times \frac{1}{\gamma_m} \quad (G-2)$$

where

W_{test} = **Tributary load = F.P x T.A**

C_a, C_d, C_t = Geometrical correction factor, Statistical correction factor
Temperature correction factor respectively

F.P = Failure pressure

T.A = Tributary Area = Fastener row spacing x Fastener spacing ($Fr \times Fs$)

γ_m = Safety factor relating to the effects of materials and defective
quality of installation

W_{adm} , the admissible design fastener load is obtained relative to the **tributary load**. Tributary area, ($Fr \times Fs$) is assumed for inducing load on fastener.

These limited comparisons shown in table G1 and G2 reveal that irrespective of the system, admissible fastener load computed by UEAtc is always lower than that of CSA. Underestimation by UEAtc is higher for the systems tested on a narrow table. This may be due to the use of tributary load in the UEAtc procedure. Further experimental data are needed towards verifying correction factors on systems with wider membranes and to identify the influence area

TableG1 : System with TPO membrane

Data Reference	CSA	UEATc
<u>Prevatt (1997)¹</u> Tested Table: 3600 mm (144") x 7300 mm (288") System: Fr = 1980 mm (78") Fs = 305 mm (12") Data: Failure Pressure: 2.7 kPa (57 psf) Measured Load: 1730 N (393 lbf) Tributary Load = F.P x T.A = 2.7 x 1.98 x 0.3 = 1650 N (376 lbf)	$m = Fr/Fs = 1980/305 = 6.6$ $n = W/Fs = 3600/305 = 12$ $C_f = 1$ (Figure 2, CSA,2004) $F_{adm} = F_{measured} \times C_f \times \frac{1}{F.S}$ $= 1730 \times 1 \times \frac{1}{1.5} = \mathbf{1150\ N}$ $\mathbf{(262\ lbf)}$	$Fr/Fs = a/b = 1980/305 = 6.6$ $W/Fs = m/b = 3600/305 = 12$ $C_a = 1$ (Table 8, UEATc,1991) $W_{adm} = W_{test} \times C_a \times C_d \times C_t \times \frac{1}{Y_m}$ $= 1650 \times 1 \times 0.9 \times \frac{1}{1.5} = \mathbf{990\ N}$ $\mathbf{(225\ lbf)}$ C_t is assumed 1
<u>Baskaran et. al (1999)²</u> Tested Table: 2000 mm (79") x 6000 mm (240") System: Fr = 1980 mm (78") Fs = 305 mm (12") Data: Failure Pressure: 3.6 kPa (75 psf) Measured Load: 1317 N (299 lbf) Tributary Load = F.P x T.A = 3.6 x 1.98 x 0.3 = 2147 N (488 lbf)	$m = Fr/Fs = 1980/305 = 6.5$ $n = W/Fs = 2000/305 = 6.6$ $C_f = 1.37$ (Figure 2, CSA,2004) $F_{adm} = F_{measured} \times C_f \times \frac{1}{F.S}$ $= 1317 \times 1.37 \times \frac{1}{1.5} = \mathbf{1200\ N}$ $\mathbf{(273\ lbf)}$	$Fr/Fs = a/b = 1980/305 = 6.5$ $W/Fs = m/b = 2000/305 = 6.6$ $C_a = 0.71$ (Table 8, UEATc,1991) $W_{adm} = W_{test} \times C_a \times C_d \times C_t \times \frac{1}{Y_m}$ $= 2147 \times 0.71 \times 0.9 \times \frac{1}{1.5} = \mathbf{915\ N}$ $\mathbf{(208\ lbf)}$ C_t is assumed 1

¹ Prevatt, O.D., Schiff, S.D., Malpezzi, J.A. (1997), "Investigation of Chamber Size for Uplift Performance Testing of Single-ply Roof Systems", NRCA - Proceedings of the Fourth International Symposium on Roof Technology – Gaithersburg, Maryland –USA. pp – 163-167

² Baskaran, B.A., Lei, W., Richardson, C., (1999) "Dynamic Evaluation of Thermoplastic Roofing System for Wind Performance" Journal of Architectural Engineering, vol. 5, pp –16-24.

Table G2 : System with EPDM membrane

Data Reference	CSA	UEATc
<u>Prevatt (1997)¹</u> Tested Table: 3600 mm (144") x 7300 mm (288") System: Fr = 1980 mm (78") Fs = 305 mm (12") Data: Failure Pressure: 3.3 kPa (69 psf) Measured Load: 2002 N (455 lbf) Tributary Load = F.P x T.A = 3.3 x 1.98 x 0.3 = 1975 N (449 lbf)	$m = Fr/Fs = 1980/305 = 6.6$ $n = W/Fs = 3600/305 = 12$ $C_f = 1$ (Figure 2, CSA,2004) $F_{adm} = F_{measured} \times C_f \times \frac{1}{F.S}$ $= 2002 \times 1 \times \frac{1}{1.5} = \mathbf{1334\ N}$ $\mathbf{(303\ lbf)}$	$Fr/Fs = a/b = 1980/305 = 6.6$ $W/Fs = m/b = 3600/305 = 1$ $C_a = 1$ (Table 8, UEATc,1991) $W_{adm} = W_{test} \times C_a \times C_d \times C_t \times \frac{1}{Y_m}$ $= 1975 \times 1 \times 0.9 \times \frac{1}{1.5} = \mathbf{1185\ N}$ $\mathbf{(269\ lbf)}$ C_t is assumed 1
<u>Baskaran et. al (2000)³</u> Tested Table: 2000 mm (79") x 6000 mm (240") System: Fr = 1980 mm (78") Fs = 305 mm (12") Data: Failure Pressure: 3.6 kPa (75 psf) Measured Load: 1865 N (424 lbf) Tributary Load = F.P x T.A = 3.6 x 1.98 x 0.3 = 2147 N (488 lbf)	$m = Fr/Fs = 1980/305 = 6.5$ $n = W/Fs = 2000/305 = 6.6$ $C_f = 1.37$ (Figure 2, CSA,2004) $F_{adm} = F_{measured} \times C_f \times \frac{1}{F.S}$ $= 1865 \times 1.37 \times \frac{1}{1.5} = \mathbf{1703\ N}$ $\mathbf{(387\ lbf)}$	$Fr/Fs = a/b = 1980/305 = 6.5$ $W/Fs = m/b = 2000/305 = 6.6$ $C_a = 0.71$ (Table 8, UEATc,1991) $W_{adm} = W_{test} \times C_a \times C_d \times C_t \times \frac{1}{Y_m}$ $= 2147 \times 0.71 \times 0.9 \times \frac{1}{1.5} = \mathbf{914\ N}$ $\mathbf{(208\ lbf)}$ C_t is assumed 1

³Lei,W., Baskaran,A.Mihailovic,M., (2000) "SIGDERS Wind Uplift Data for Thermoset Roofing Systems", IRC Internal Report No. 807, National Research Council, Ottawa, Ontario,Canada.

APPENDIX H : Air Leakage Control

Air & Vapor Barrier

Water can be transported into the roofing cavity by the diffusion process and the provision of vapour barrier controls the moisture entry into the roof assembly. The other mechanism, which is considered more significant, is the air leakage. Both mechanisms may, of course operate at the same time. The function of the air barrier and the function of the vapour retarder are sometimes confused. It is important to note that there is a significant and important difference between these two functions and between the materials and systems providing these functions. The most important fact to recognize is that an air barrier and vapour barrier perform different functions.

The principal function of a vapour barrier is to stop or, more accurately, to retard the passage of moisture as it diffuses through the roofing system materials. Diffusion is the process by which water vapour migrates through a material. The rate at which water vapour diffuses depends on two factors: the difference between the water vapour pressure of the inside air to that of the outside air and the resistance of the material against diffusion. The moisture diffusion control property of a material is its “water vapour permeance”. This property is measured by using a test procedure according to ASTM E-96. On the other hand, the principal function of air barrier is to stop inside air from entering through the roof assembly. This applies whether the air is humid or dry, since air leakage can results in problems other than the deposition of moisture in cavities. In a way the air barrier controls the moisture that is transported along with airflow. Airflow is driven by air pressure differences, and it moves water vapour in the direction that the air pressure drives. Air barriers are needed in just about every type of roofing assembly, whereas specific vapour retarding layers are not needed in many situations. Air barriers must be sealed, continuous, strong, air impermeable and stiff. The flow rate through a material is measured in terms of air permeance. This rating is measured using the test procedure ASTM E-2178.

The widespread confusion between air barriers and vapour barriers has perhaps arisen because of some materials. Sometimes attempts have been made to achieve the requirements of both (air and vapour control) by using one material (Quirouette, 1985). However, the component properties and system performance should be considered

before deciding that one material can do two functions. The Canadian Roofing Contractor's Association's Specification Manual considers materials for air and vapour control separately. (CRCA, 2002) However, it is recognized that air leakage in a roofing assembly cannot be achieved by any single material due to the high air pressure differences. In order to counter these different mechanisms of air infiltration into roof assembly, a conceptual approach to air tightening is need, called an air barrier "system".

Air Barrier System

As seen from the previous sections, air leakage through a roofing assembly is a complex combination of different air leakage mechanisms. So an air barrier system is an essential component of the roofing assembly so that air pressure differences within the roofing assembly can be controlled. The air barrier system, as defined in the 1995 NBC, is "The assembly installed to provide a continuous barrier to the movement of air". A continuous air barrier system is the combination of interconnected materials, flexible sealed joints and components of the building envelope that provide the air tightness of the building enclosure and separation between conditioned and unconditioned spaces (Figure G-1). The concept is to select and target a component of the roof that is air impermeable and to deliberately make it an airtight "assembly" by sealing the joints and penetrations.

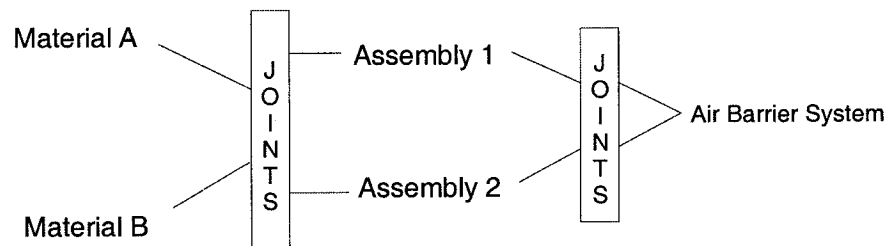


Figure G-1 Concept of air barrier system

Since the concept of air barrier system was introduced, much of the research has focussed on answering several fundamental questions:

- What is it's location in the assembly?
- What is its dimensional stability?
- How airtight should it be?

At present there is no data available in the literature about the air leakage characteristics of a roofing assembly. There is lot of uncertainty regarding the air permeance in a

roofing assembly and how it affects the life cycle performance. With advancement in roofing technology different types of commercial air barrier materials, vapour barriers and membranes are being introduced into the market. However, no standard specifications or test methods exist to address the air leakage in a roofing assembly. An air barrier system for the roofing assembly is not an option but it is a mandatory requirement to limit the uncontrolled air leakage. The important features of an air barrier system are:

1. Air Impermeability: Defining performance requirements for air barrier systems are not a simple undertaking. According to the Part 5 of NBCC, the material that provides the principal resistance to air leakage within the air barrier system is required to have an average leakage characteristic not greater than $0.02 \text{ L/(s-m}^2\text{)}$ at 75 Pascals pressure difference. This air leakage rate at 75Pa is not intended to represent typical leakage of the material in situ, since pressure differences across the building envelope are often much higher than 75 Pa. This reference pressure difference of 75 Pa is merely used to characterize a material property.

For the system requirements, the Appendix to the NBC provides a list of recommended maximum air leakage rates suitable for most weather conditions in Canada (Table G-1). These numbers are not the outcome of any experimental procedure due to the relatively few published data about the leakage of air barrier system. There were based on the perceived need to provide higher levels of air tightness than required at the time by American Architectural Manufacturers Association (AAMA) (1983) standard for metal and glass curtain walls.

Table G-1: Recommended maximum system air leakage (NBCC 2005)

Warm Side (% Relative Humidity at 21°C)	Recommended Air Leakage Rate $\text{L/(s-m}^2\text{)}$ at 75 Pa
< 27	0.15
27 to 55	0.10
> 55	0.05

The system air leakage rates are the leakage through the opaque insulated portion of the envelope, which is not to be confused with the overall air leakage rate of the building as measured by whole building air leakage tests.

2. Structural support: Effective structural support requires that an air barrier system must be designed to resist 100% of the wind load for which the wall or roof structure is designed. This load must then be safely transferred to the structure. The air barrier system must also be able to resist the stack pressure and the mechanical ventilation loads without exhibiting signs of detachment, rupturing or creep load failure. Design consideration must determine adequate resistance to these pressures by fasteners, adhesives, etc.

3. Durability: Materials selected for the air barrier system must be compatible with the adjoining materials and resistant to deterioration under the loads to which they are subjected during the expected service life of the structure. The Part 5 (NBCC) discusses at length the different deterioration mechanism that should be considered over the expected service life of the air barrier components including structural loading, freeze/thaw, differential movement, ice lensing, corrosion, solar radiation exposure, biological attack, and intrusion by insects and rodents.

4. Continuity: In an air barrier system, continuity should exist among the different components involved in the assembly. The air barrier system shall be continuous across all the joints, junctions and penetrations through the assembly. Thus not only is it important that no gaps exist in the individual components that comprise the system, but the components must be joined such that there is no gaps in the system as a whole. It is air leakage at the connections between air barrier components, and at penetrations through it, that usually determine the overall effectiveness of the system. The system's continuity is undoubtedly the most challenging characteristic to achieve, as it requires superior design, execution and quality control.

APPENDIX I : Air and vapour permeance data for common construction materials

Material	Thickness or Weight	Air Permeance, Measured leakage @ 75 Pa(L/s•m²)	Vapour Permeance (ng/Pa•s•m²)
Construction materials			
plywood sheathing	9.50 mm (3.8 in.)	0.00	15-50
plywood sheathing	8.00 mm (5/16 in)	0.0067	18-59
flakewood board	15.9 mm (5/8 in)	0.0069	30
flakewood board	11.0 mm (7/16 in.)	0.0108	44
particle board	15.9 mm (5/8 in.)	0.0260	
particle board	12.7 mm (1/2 in.)	0.0155	
cement board	12.7 mm (1/2 in.)	0.00	54-108
plain fiberboard	11.0 mm (7/16 in)	0.8223	
asphalt impregnated fiberboard	11.0 mm (7/16 in)	0.8285	772-2465
hardboard (standard)	3.00 mm (1/8 in)	0.0274	630
foil back gypsum board	12.7 mm(1/2 in)	0.00	0.00
gypsum board	12.7 mm (1/2 in.)	0.0091	1373
tongue and groove planks		19.1165	982
modified bituminous torch on grade membrane (polyester reinforced mat)	2.70 mm (3/32 in)	0.00	4.0
modified bituminous torch on grade membrane (glass fiber mat)	2.70 mm (3/32 in)	0.00	4.0
smooth surface roofing membrane	1.50 mm (1/16 in)	0.00	1.9
roofing felt	13.6 kg (30 lb)	0.1873	160
non-perforated asphalt felt	6.8 kg (15 lb.)	0.2706	320
perforated asphalt felt	6.8 kg (15 lb.)	0.3962	320

Plastic and Metal foils and films			
polyethylene	0.15 mm (6 mil)	0.00	1.6-5.8
aluminium foil	0.03 mm (1 mil)	0.00	0.00
reinforced non-perforated polyolefin		0.0195	
spunbonded polyolefin		0.9593	3646
spunbonded polypropylene		3.2186	884
Type I perforated polyethylene	0.10 mm (4 mil)	4.0320	
Type II perforated polyethylene	0.10 mm (4 mil)	3.2307	
Thermal Insulations			
extruded polystyrene	38.0 mm (1.5 in)	0.00	15-60
foil back urethane insulation	25.4 mm (1.0 in)	0.00	0.00
phenolic insulation board	25.4 mm (1.0 in)	0.00	133
phenolic insulation board	50.8 mm (2.0 in)	0.00	67
expanded polystyrene – Type II	25.0 mm (1 in)	0.1187	86-160
Glass fiber rigid insulation board with spunbonded polyolefin on one face		0.4880	1143
Expanded polystyrene – Type I	25 mm (1 in)	12.2372	115-333
Glass fiber wool insulation	152 mm (6 in)	36.7327	1110
vermiculite insulation		70.4926	1666
cellulose insulation (spray on)		86.9457	1666

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