

## **NOTE TO USERS**

**This reproduction is the best copy available.**

UMI<sup>®</sup>





uOttawa

L'Université canadienne  
Canada's university

**FACULTÉ DES ÉTUDES SUPÉRIEURES  
ET POSTDOCTORALES**



**FACULTY OF GRADUATE AND  
POSTDOCTORAL STUDIES**

**Bona Murty**

AUTEUR DE LA THÈSE / AUTHOR OF THESIS

**Ph.D. (Civil Engineering)**

GRADE / DEGREE

**Department of Civil Engineering**

FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

**Wind Uplift Performance Evaluation of Adhesive Applied Roofing Systems**

TITRE DE LA THÈSE / TITLE OF THESIS

**Bas Baskaran**

DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

**Hiroshi Tanaka**

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

**Elena Dragomirescu**

**David Lau**

**Gregory Kopp (University of  
Western Ontario)**

**Magdi Mohareb**

**Gary W. Slater**

Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

# **Wind Uplift Performance Evaluation of Adhesive Applied Roofing Systems**

**By**  
**Bona Murty**

Thesis submitted to the  
Faculty of Graduate and Postdoctoral Studies  
In partial fulfillment of  
the requirements for the degree of

**Doctor of Philosophy in Civil Engineering**

The PhD program in Civil Engineering is a joint program  
with Carleton University administered by the  
Ottawa-Carleton Institute for Civil Engineering

Department of Civil Engineering  
University of Ottawa  
Ottawa, Ontario, Canada  
2010

© Bona Murty, Ottawa, Ontario, Canada, 2010



Library and Archives  
Canada

Published Heritage  
Branch

395 Wellington Street  
Ottawa ON K1A 0N4  
Canada

Bibliothèque et  
Archives Canada

Direction du  
Patrimoine de l'édition

395, rue Wellington  
Ottawa ON K1A 0N4  
Canada

*Your file* *Votre référence*  
*ISBN:* 978-0-494-66003-4  
*Our file* *Notre référence*  
*ISBN:* 978-0-494-66003-4

#### NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

#### AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

---

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

---

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

  
**Canada**

## Abstract

Understanding how a roof performs under wind action is crucial to improve the roof design. The present study contributes to an ongoing collaborative research and development project, “*Evaluation of wind uplift resistance of Adhesive Applied Roofing Systems (AARS)*”. The objectives of the project are to develop wind uplift resistance standards and design guidelines for AARS. The project has the following tasks:

- Task 1: Pullout Testing
- Task 2: Peel Testing
- Task 3: Wind Uplift Testing
- Task 4: Numerical Modeling
- Task 5: Development of Design Guidelines

With respect to Task 1 and Task 2, Current (2009) and Wu (2008), respectively, developed new testing procedures. These testing procedures apply static tensile and shear loading to simulate wind uplift and peel forces on the AARS specimens. A dynamic testing procedure that accounts for the wind-induced pressure fluctuations is required for the comprehensive evaluation of the AARS wind uplift performance. The present dissertation contributes to the objective of the AARS project via Task 3 and Task 4. Accomplishments of this dissertation are grouped into two parts. Part 1 develops a laboratory dynamic-testing procedure for AARS wind uplift resistance evaluation and Part 2 presents a three dimensional finite element (3D FE) model to analyze AARS performance.

Part 1: Currently, there is no dynamic testing procedure available to evaluate wind uplift performance of rigid roofing systems such as AARS. Towards the development of a dynamic testing procedure, the present study documented the performance of rigid systems under wind effects. Differences in roof system responses were studied by comparing the wind tunnel data of flexible roofs with that of rigid roofs. Analysis of the pressure time histories data using probability distribution function and the power spectral density verified that these two roof

types exhibited different system responses under wind forces. Wind-induced pressure fluctuations were found to be higher for flexible roofs in comparison to rigid roofs.

A new load cycle for the evaluation of rigid roofing system was developed by applying a rain flow counting method. The newly developed load cycle was validated with the experimental investigation. Thirty full scale mock-ups of AARS were constructed and tested for the experimental investigations. The experimental investigations provided key information on the wind uplift performances of AARS under static and dynamic loading, the effects of number of cycles, the variability of the components, the weakest links, the adhesive curing time, and the failure modes. It was concluded that the newly developed load cycle was more appropriate for the wind uplift performance evaluation of rigid roofing systems such as the AARS. It also was shown that the newly developed load cycle provided a similar wind uplift rating and had shorter testing time in comparison to the existing CSA 123.21-04 load cycle. This new knowledge will be incorporated into the future edition of the CSA 123.21-04 standard.

Part 2: A 3DFE model was developed and benchmarked with experimental investigation. The FE analysis showed that the use of different adhesive application techniques significantly influenced the uplift resistance capacity of AARS. The uplift resistance capacity in terms of stress can be estimated when different adhesive application methods are used. The FE analysis also demonstrated the effect of adhesive thicknesses and type of insulation joints on the AARS uplift resistance capacity. The results from the FE model simulations can be used for the development of design guidelines for AARS.

## Acknowledgments

Thanks to Allah SWT that finally this dissertation could be completed. The completion of this dissertation would have been impossible without the financial support from the Natural Sciences and Engineering Research Council (NSERC) that is provided through a collaborative research project, *Evaluation of wind uplift resistance of adhesive applied roof systems*, grant # CRDPJ 3065819-04, between the National Research Council Canada (NRCC) and the University of Ottawa. This research was supported by Canadian roofing industry partners (Bakor Inc., IKO Industries Ltd, Roofing Contractors Association of British Columbia, Soprema Inc. and Tremco Inc.) and their contributions are greatly appreciated.

I would like to thank my research and academic supervisors, Dr. Appupillai Baskaran & Dr. Hiroshi Tanaka, for their excellent supervisions.

**Dr. Appupillai Baskaran**, my supervisor, who provided valuable guidance, inspiration and ideas to overcome many obstacles encountered during the study. He introduced me to the world of roofing engineering, and provides steadfast encouragement and generous financial support. I would have been lost without him. His rich experiences in the field of roofing have helped me to solve many problems and completed the dissertation. I am indebted to him for the training as a researcher and being my mentor.

**Dr. Hiroshi Tanaka**, my co-supervisor, for providing invaluable insights and timely encouragement. Out of his busy schedule, he took huge effort and time to review the dissertation and offer succinct suggestions that pushed the dissertation toward completion. I owe my deepest gratitude for his kind assistances and continuous supports.

Sincere thanks go to:

**Dr. Beatriz Martin- Perez**, my committee member, for her kind assistances and suggestions on finite element modeling. Thanks also to other committee members, **Dr. David Lau and Dr. Magdi Mohareb**, for their insightful criticism and guidance during research proposal presentation.

**Dr. Ralph Paroli**, Director, Building Envelope & Structure, NRC, for allowing me to pursue my research work at NRC.

My colleagues at IRC/NRC, Amor, Ana, David, Fadi, Jay, Jun, John, Harry, Helen, Ian, Gordon, Kevin, Mostafa, Nicole, Pascal, Phalguni, Suda, Steven, Steve and Vivian for their good company and kind assistances.

My technical colleagues for the help on the experimental investigations. They include Mr. Dave Miller, Mr. Jim Watson, Mr. Marcel Lemieux, Mr. Mike Bisson, Mr. Paul Hastings, Mr. Paul Neville, Mr. Peter Saunders, Mr. Vincent Boisvert and Mr. Yvest Bradet.

Administrative assistants: Manon, Lise and Yolande at the Department of Civil Engineering, and Christine, Lize and Flavia at the Faculty of Graduate and Postdoctoral Studies, University of Ottawa for their kind cooperation and helps.

Special appreciations go to my lovely wife, Yeni, my kids, Tasya, Hafiz and Dhia, my parents, my brothers and sister, my aunties and my uncles for their continuous patient, prayer, supports and encouragements during the study.

Ottawa, December 2009  
Bona Murty

# Table of Contents

|                                |            |
|--------------------------------|------------|
| <b>Abstract .....</b>          | <b>i</b>   |
| <b>Acknowledgements .....</b>  | <b>iii</b> |
| <b>Table of Contents .....</b> | <b>v</b>   |
| <b>List of Tables .....</b>    | <b>x</b>   |
| <b>List of Figures .....</b>   | <b>xi</b>  |
| <b>Glossary .....</b>          | <b>xv</b>  |

## **Chapter 1. Introduction**

|                                                                |   |
|----------------------------------------------------------------|---|
| 1.1 Roof .....                                                 | 1 |
| 1.2 Advantages and Disadvantages of Different Roof Types ..... | 5 |
| 1.3 AARS Project at Glance .....                               | 8 |
| 1.4 Research Objectives.....                                   | 9 |
| 1.5 Dissertation Outline .....                                 | 9 |

## **Chapter 2. Literature Review**

|                                                                         |    |
|-------------------------------------------------------------------------|----|
| 2.1 Introduction .....                                                  | 12 |
| 2.2 Wind Effect on Roofs .....                                          | 12 |
| 2.3 Review of Existing Standards                                        |    |
| 2.3.1 North American Approval Testing Standards                         |    |
| 2.3.1.1 Factory Mutual (FM 4474-2004).....                              | 21 |
| 2.3.1.2 Underwriters Laboratory (UL 580-2006).....                      | 23 |
| 2.3.1.3 Canadian Standards Association (CSA 123.21-04).....             | 26 |
| 2.3.1.4 Other Testing Procedures                                        |    |
| 2.3.1.4.1. European Organization for Technical Approval (ETAG 006) .... | 29 |
| 2.3.1.4.2. Norwegian Standard (NBI 160-90).....                         | 31 |
| 2.3.1.4.3. Review of Other Testing Methods.....                         | 33 |
| 2.3.2 Limitations of the Current Testing Procedures .....               | 35 |
| 2.4 Concluding Remarks .....                                            | 36 |

## **Chapter 3. Adhesive Applied Roofing Systems**

|         |                                          |    |
|---------|------------------------------------------|----|
| 3.1     | Introduction .....                       | 37 |
| 3.2     | Roofing Components                       |    |
| 3.2.1   | Roof Deck.....                           | 39 |
| 3.2.2   | Vapour Barrier .....                     | 42 |
| 3.2.3   | Insulation.....                          | 44 |
| 3.2.4   | Cover Board .....                        | 47 |
| 3.2.5   | Membranes                                |    |
| 3.2.5.1 | Base Sheet .....                         | 49 |
| 3.2.5.2 | Cap Sheet .....                          | 50 |
| 3.3     | Mock-up Preparation                      |    |
| 3.3.1   | Overview .....                           | 51 |
| 3.3.2   | Roof Deck.....                           | 52 |
| 3.3.3   | Vapour Barrier .....                     | 54 |
| 3.3.4   | Insulation.....                          | 56 |
| 3.3.5   | Cover Board .....                        | 58 |
| 3.3.6   | Base Sheet .....                         | 61 |
| 3.3.7   | Cap Sheet .....                          | 63 |
| 3.4     | Fully and Partially Adhered Groups ..... | 65 |
| 3.5     | Concluding Remark .....                  | 66 |

## **Chapter 4. Wind Uplift Response of Rigid and Flexible Systems**

|       |                                                                |    |
|-------|----------------------------------------------------------------|----|
| 4.1   | Introduction.....                                              | 67 |
| 4.2   | Wind Tunnel Data on Models with Flexible Roofs.....            | 73 |
| 4.3   | Wind Tunnel Data on Models with Rigid Roofs.....               | 75 |
| 4.4   | Response of the Wind Tunnel Model with Rigid Roof.....         | 77 |
| 4.5   | Rigid Vs Flexible Roof Responses                               |    |
| 4.5.1 | Pressure Time Histories of PVC, EPDM and Rigid Models.....     | 83 |
| 4.5.2 | Probability Distribution Function of the System Response ..... | 87 |

|       |                                               |    |
|-------|-----------------------------------------------|----|
| 4.5.3 | Spectral Analysis of the System Response..... | 93 |
| 4.6   | Concluding Remarks .....                      | 99 |

## **Chapter 5. Development of Dynamic Load Cycle for Rigid Roofs**

|     |                                                          |     |
|-----|----------------------------------------------------------|-----|
| 5.1 | Introduction.....                                        | 100 |
| 5.2 | General Considerations and Simplifications .....         | 101 |
| 5.3 | Computation of Load Cycle Using Rain Flow Counting ..... | 104 |
| 5.4 | Development of Load Cycles for Rigid Roofs .....         | 111 |
| 5.5 | Generalization of Load Cycles for Rigid Roofs .....      | 118 |
| 5.6 | Proposed Load Cycles for Rigid Roofs Evaluation .....    | 121 |
| 5.7 | Concluding Remarks .....                                 | 125 |

## **Chapter 6. Application of Developed Load Cycle**

|       |                                                                  |     |
|-------|------------------------------------------------------------------|-----|
| 6.1   | Introduction.....                                                | 126 |
| 6.2   | Wind-uplift Resistance                                           |     |
| 6.2.1 | General .....                                                    | 127 |
| 6.2.2 | Wind-Uplift Resistance under Static Loading .....                | 127 |
| 6.2.3 | Wind-uplift Resistance under Dynamic Loading.....                | 128 |
| 6.2.4 | Performance of Static vs Dynamic Loading.....                    | 129 |
| 6.3   | Effect of Number of Cycles on the Wind Uplift Resistance         |     |
| 6.3.1 | General .....                                                    | 138 |
| 6.3.2 | Wind Uplift Resistances at 25%, 50% &100% of CSA Load Cycle..... | 139 |
| 6.3.3 | Failure Modes at 25%, 50% & 100% of the CSA Load Cycle.....      | 142 |
| 6.4   | Comparison of the Wind Uplift Resistance: Flexible Vs Rigid      |     |
| 6.4.1 | General .....                                                    | 144 |
| 6.4.2 | Comparison of Wind-uplift Resistance Performances .....          | 144 |
| 6.4.3 | Comparison of Failure Modes .....                                | 146 |
| 6.5   | Concluding Remarks .....                                         | 147 |

## **Chapter 7. Correlation between Pullout, Peel and Wind Uplift Tests**

|     |                                                                  |     |
|-----|------------------------------------------------------------------|-----|
| 7.1 | Introduction.....                                                | 150 |
| 7.2 | Pullout Test.....                                                | 151 |
| 7.3 | Peel Test.....                                                   | 153 |
| 7.4 | Pullout, Peel and Wind Uplift Tests: Performance Comparison..... | 154 |
| 7.5 | Future Direction: Bridging the Three Tests Together.....         | 158 |
| 7.6 | Concluding Remarks .....                                         | 160 |

## **Chapter 8. Development of Finite Element Model**

|       |                                                                  |     |
|-------|------------------------------------------------------------------|-----|
| 8.1   | Introduction.....                                                | 161 |
| 8.2   | Literature Review on Numerical Modeling of Roofing Systems ..... | 162 |
| 8.3   | Three Dimensional Finite Element (3D-FE) Model Development       |     |
| 8.3.1 | Modeling Background.....                                         | 168 |
| 8.3.2 | Model Details.....                                               | 169 |
| 8.3.3 | Model Outputs .....                                              | 172 |
| 8.4   | Mesh Sensitivity Study.....                                      | 173 |
| 8.5   | Experimental Study for 3D-FE Model Benchmarking                  |     |
| 8.5.1 | General .....                                                    | 174 |
| 8.5.2 | Preparation of Test Specimens .....                              | 174 |
| 8.5.3 | Experimental Setup .....                                         | 175 |
| 8.5.4 | Test Results .....                                               | 177 |
| 8.6   | 3D-FE Model and Experimental Study: Performance Comparison.....  | 179 |
| 8.7   | Investigation of Changing Boundary Condition of 3DFE Model ..... | 182 |
| 8.8   | Concluding Remarks .....                                         | 185 |

## **Chapter 9. Parametric Investigations Using the Developed 3D FE Model**

|     |                                       |     |
|-----|---------------------------------------|-----|
| 9.1 | Introduction.....                     | 186 |
| 9.2 | Effect of Adhesive Application Method |     |

|                                                        |                                       |            |
|--------------------------------------------------------|---------------------------------------|------------|
| 9.2.1                                                  | Modelling Background .....            | 187        |
| 9.2.2                                                  | Model Details.....                    | 189        |
| 9.2.3                                                  | Model Outputs .....                   | 191        |
| 9.3                                                    | Effect of Adhesive Thickness          |            |
| 9.3.1                                                  | Modeling Background.....              | 194        |
| 9.3.2                                                  | Model Details.....                    | 195        |
| 9.3.3                                                  | Model Outputs .....                   | 196        |
| 9.4                                                    | Effect of Insulation Joints           |            |
| 9.4.1                                                  | Modeling Background.....              | 199        |
| 9.4.2                                                  | Model Details.....                    | 201        |
| 9.4.3                                                  | Model Outputs .....                   | 203        |
| 9.5                                                    | Concluding Remarks .....              | 207        |
| <br><b>Chapter 10. Conclusions and Recommendations</b> |                                       |            |
| 10.1                                                   | Conclusions .....                     | 208        |
| 10.2                                                   | Recommendation for Future Works ..... | 212        |
| <br><b>References .....</b>                            |                                       |            |
| <b>Appendix A .....</b>                                |                                       | <b>224</b> |
| <b>Appendix B .....</b>                                |                                       | <b>226</b> |
| <b>Appendix C .....</b>                                |                                       | <b>242</b> |
| <b>Appendix D .....</b>                                |                                       | <b>247</b> |
| <b>Appendix E .....</b>                                |                                       | <b>279</b> |

## List of Tables

|                                                                                                 |     |
|-------------------------------------------------------------------------------------------------|-----|
| Table 2.1 FM 4474 Loading Sequences .....                                                       | 23  |
| Table 2.2 UL 580-2006 Load Sequences .....                                                      | 25  |
| Table 2.3 Some Differences Among Existing Test Methods .....                                    | 36  |
| Table 3.1 Examples for Vapour Barrier Materials used in Roofing .....                           | 43  |
| Table 3.2 Properties of <i>Polyisocyanurate</i> Insulation Types .....                          | 45  |
| Table 4.1 Test Condition and Configuration used for the Wind Tunnel Study with Rigid Roof ..... | 75  |
| Table 4.2 Wind Tunnel Model Configurations for Rigid and Flexible Roofs .....                   | 98  |
| Table 5.1 Typical M x R matrix (L/W = 1; H/W = 1; Wind = 0 degree) .....                        | 106 |
| Table 5.2 Typical M x R matrix (L/W = 1; H/W = 1; Wind = 45 degree) .....                       | 107 |
| Table 5.3 Typical M x R matrices (L/W = 1; H/W = 1) .....                                       | 108 |
| Table 5.4 Summary of Computed Load Cycle Group 1 and 2 for All Model Data Tested .....          | 112 |
| Table 5.5 Considered Level A - Load Cycle for Rigid Roof .....                                  | 115 |
| Table 5.6 Calculated Ratios for the Different Levels to the Level A of CSA Load Cycles .....    | 120 |
| Table 5.7 Calculated Load Cycle for Rigid Roof based on CSA Load Cycle Ratios .....             | 120 |
| Table 5.8 Number of Cycles at the 5 Levels .....                                                | 121 |
| Table 6.1 Static & Dynamic Failure Investigation Photos and Diagrams: M-1 .....                 | 134 |
| Table 6.2 Static & Dynamic Failure Investigation Photos and Diagrams: M-2 .....                 | 135 |
| Table 6.3 Static & Dynamic Failure Investigation Photos and Diagrams: M-3 .....                 | 136 |
| Table 6.4 Static & Dynamic Failure Investigation Photos and Diagrams: M-4 .....                 | 137 |
| Table 7.1 Uplift Resistance Performance Summary .....                                           | 155 |
| Table 8.1 Mechanical Properties for the Models (Rossiter and Batts, 1985) .....                 | 164 |
| Table 8.2 Model Properties Used for the Present Model Development .....                         | 170 |
| Table 9.1 FE Model Maximum Stresses .....                                                       | 206 |

## List of Figures

|                                                                                   |    |
|-----------------------------------------------------------------------------------|----|
| Figure 1.1 Adhesive Applied Roofing Systems (AARS).....                           | 2  |
| Figure 1.2 Mechanically Attached Roofing Systems (MARS).....                      | 3  |
| Figure 1.3 Fully Bonded Roofing Systems (FBRs).....                               | 4  |
| Figure 1.4 Balasted Roofing Systems (BRS).....                                    | 5  |
| Figure 2.1 Suction Distribution on Flat Roof .....                                | 14 |
| Figure 2.2 Pressure Classification Zones .....                                    | 16 |
| Figure 2.3 Pressure Variations at the Three Roof Zones for Roof Aspect Ratio 1.   | 17 |
| Figure 2.4 Pressure variations at the Three Roof Zones for Roof Aspect Ratio 2 .  | 18 |
| Figure 2.5 Comparison of Pressure Spectral from PVC and EDPM models.....          | 20 |
| Figure 2.6 FM 4474 Test Apparatus (FM Research 1992) .....                        | 22 |
| Figure 2.7 UL 580 Test Apparatus (UL580, 2006).....                               | 25 |
| Figure 2.8 CSA 123.21-04 Test Apparatus (CSA 123.21-04).....                      | 27 |
| Figure 2.9 CSA Load Cycle for Flexible Roofs (CSA 123.21-04).....                 | 28 |
| Figure 2.10 ETAG 006 Load Cycles (ETAG 2000) .....                                | 30 |
| Figure 2.11 NT BUILD 307 Test Apparatus (Paulsen 1989).....                       | 32 |
| Figure 2.12 NT BUILD 307 Load Cycles (Paulsen 1989) .....                         | 32 |
| Figure 3.1 Typical AARS Construction and Isometric Drawing .....                  | 38 |
| Figure 3.2 Typical Steel Deck Used in Roofing .....                               | 41 |
| Figure 3.3 Typical Kraft Paper Laminate & Self Adhered VB used for the study ..   | 44 |
| Figure 3.4 Insulation Boards and Different Facer .....                            | 46 |
| Figure 3.5 Typical Cover Board Used in the AARS .....                             | 48 |
| Figure 3.6 Typical Base Sheet Membrane for AARS.....                              | 50 |
| Figure 3.7 Typical Cap Sheet Membrane for AARS .....                              | 51 |
| Figure 3.8 Typical Installations and Two Adhesive Applications on Steel Deck .... | 53 |
| Figure 3.9 Typical Vapour Barrier Installation in the AARS Mock-up Construction   | 55 |
| Figure 3.10 Detail of the Insulation Board Installation and Layout.....           | 57 |
| Figure 3.11 Fibre Cover Board (FCB) Layout and Installation .....                 | 59 |
| Figure 3.12 Asphaltic Core Board (ACB) Layout and Installation .....              | 60 |

|                                                                                                                                                  |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 3.13 Base Sheet Layout and Installation .....                                                                                             | 62 |
| Figure 3.14 Cap Sheet Layout and Installation .....                                                                                              | 64 |
| Figure 3.15 Fully-Adhered and Partially Adhered (not to scale) .....                                                                             | 65 |
| Figure 4.1 Flexible Roof Response Under Wind Actions and Simulated Wind<br>Pressure Conditions .....                                             | 69 |
| Figure 4.2 Rigid Roof Response Under Wind Actions and Simulated Wind<br>Pressure Conditions .....                                                | 70 |
| Figure 4.3 Typical Field Failures of Rigid and Flexible Roofs .....                                                                              | 71 |
| Figure 4.4 Rigid Vs Flexible Roofs: Force Dissipation Diagram.....                                                                               | 72 |
| Figure 4.5 a) Pressure Coefficient Countour Plot for PVC and b) Pressure<br>Coefficient Countour Plot for EPDM (Baskaran and Savage, 2003) ..... | 74 |
| Figure 4.6 Typical Wind Tunnel Model with Rigid Roof, Aspect Ratio= 1, H/W= 1                                                                    | 76 |
| Figure 4.7 Pressure Tap Locations on the Wind Tunnel Model with Rigid Roof ....                                                                  | 77 |
| Figure 4.8 Typical Suction Coefficient Fluctuations for a Corner Pressure Tap ....                                                               | 78 |
| Figure 4.9 Peak Suction Coefficients with Different Wind Angles .....                                                                            | 80 |
| Figure 4.10 Worst Peak Suction Coefficients with Different Aspect Ratios.....                                                                    | 82 |
| Figure 4.11 Pressure Time Histories for Rigid, PVC and EPDM Models .....                                                                         | 84 |
| Figure 4.12 Pressure Time Histories of Rigid and Flexible Roofs at Three Different<br>Roof Zones for H/W =1 .....                                | 85 |
| Figure 4.13 Pressure Time Histories of Rigid and Flexible Roofs at Three Different<br>Roof Zones for H/W =3 .....                                | 86 |
| Figure 4.14 A typical of PDF Pressure Fluctuations .....                                                                                         | 88 |
| Figure 4.15 PDF of Pressure Fluctuations for Rigid, EPDM and PVC roofs at the<br>Corner Zone.....                                                | 89 |
| Figure 4.16 PDF of Wind Pressure for Rigid and Flexible Roofs at the Three<br>Different Zones with the H/W = 1 .....                             | 91 |
| Figure 4.17 PDF of Wind Pressures for Rigid and Flexible Roofs at the Three<br>Different Zones with H/W = 3 .....                                | 92 |
| Figure 4.18 PSD of Pressure Signals at the Corner Zone for H/W ratio of 1 .....                                                                  | 94 |
| Figure 4.19 PSD Function of Rigid and Flexible Roofs for the Three Different Zone<br>with the ratio of H/W = 1 .....                             | 96 |

|                                                                                                                            |     |
|----------------------------------------------------------------------------------------------------------------------------|-----|
| Figure 4.20 PSD Function of Rigid and Flexible Roofs for the Three Different Zone with the Ratio of $H/W = 3$ .....        | 97  |
| Figure 5.1 Simplified Representation of Wind-Induced Pressure for Testing.....                                             | 101 |
| Figure 5.2 Computed Load Cycle for Group 1 .....                                                                           | 110 |
| Figure 5.3 Computed Load Cycle for Group 2 .....                                                                           | 110 |
| Figure 5.4 Load Cycles Comparison between the Flexible and Rigid Roof Models .....                                         | 113 |
| Figure 5.5 Load Cycles for the Rigid Roof Evaluation .....                                                                 | 117 |
| Figure 5.6 Time Requirement for One Cycle .....                                                                            | 118 |
| Figure 5.7 Proposed Load Cycle for Rigid Roofing Systems .....                                                             | 124 |
| Figure 6.1 Static Pressure Time Histories for the Tested Mock-ups .....                                                    | 130 |
| Figure 6.2 Dynamic Pressure Time Histories of the Tested Mock-ups .....                                                    | 131 |
| Figure 6.3 Typical Failure Investigation of the Tested Mock-up.....                                                        | 132 |
| Figure 6.4 Wind-Uplift Resistance at 25%, 50% & 100% of the CSA Load Cycle                                                 | 140 |
| Figure 6.5 Normalized Fatigue Damage Scale .....                                                                           | 142 |
| Figure 6.6 Failure Modes for Partially- Adhered Group .....                                                                | 143 |
| Figure 6.7 Failure Mode for Fully- Adhered Group .....                                                                     | 143 |
| Figure 6.8 Wind-uplift Resistance Rating of the AARS Mock-up Tested using the Load Cycle for Rigid and Flexible Roofs..... | 146 |
| Figure 6.9 Failure Modes Performance of the AARS Mock-up Tested using the Load Cycle for Rigid and Flexible Roofs.....     | 147 |
| Figure 7.1 Typical Pullout Test Setup (Current, 2009).....                                                                 | 152 |
| Figure 7.2 Typical Peel Test Setup (Wu, 2008) .....                                                                        | 154 |
| Figure 7.3 Uplift Resistance Performance Comparison .....                                                                  | 156 |
| Figure 7.4 Weakest Links for the Wind Uplift Test, Pullout Test and Peel Test ..                                           | 157 |
| Figure 8.1 Different Type of Gaps Considered in the Models .....                                                           | 163 |
| Figure 8.2 a) Roof Model, b) Loading Mechanism and c) Meshed Model.....                                                    | 165 |
| Figure 8.3 In Plane Bending of Membrane System .....                                                                       | 166 |
| Figure 8.4 FE-Model vs Experimental Results.....                                                                           | 166 |

|                                                                                           |         |
|-------------------------------------------------------------------------------------------|---------|
| Figure 8.5 Boundary Conditions Used for the Present Model Development.....                | 170     |
| Figure 8.6 Undeformed Shape of the 3D Model with the 108 Elements .....                   | 171     |
| Figure 8.7 Deformed 3D Model Shape of Stress Distribution .....                           | 172     |
| Figure 8.8 Computed Stresses with Different Mesh Sizes for the FE Model .....             | 173     |
| Figure 8.9 Specimen Preparation for the FE Model Benchmarking .....                       | 175     |
| Figure 8.10 Test Setup for the FE Model Benchmarking .....                                | 176     |
| Figure 8.11 Load vs Displacement for the Six Specimens Tested.....                        | 177     |
| Figure 8.12 Typical Failure Modes of the Experimental Specimen .....                      | 178     |
| Figure 8.13 Experiment Vs FE Model: Stress Comparison.....                                | 181     |
| Figure 8.14 Experiment Vs FE Model: Failure Mode Comparison.....                          | 181     |
| Figure 8.15 Stress Distribution Contours of 3DFE Model: Previous Vs Modified              | 184     |
| <br>Figure 9.1 Common AARS Adhesive Application Methods in AARS.....                      | <br>188 |
| Figure 9.2 Adhesive Techniques Considered for the Analysis.....                           | 190     |
| Figure 9.3 Stress Contour Diagrams: Model Output.....                                     | 192     |
| Figure 9.4 Stress Reduction Due to the Different of Adhesive Application Methods<br>..... | <br>193 |
| Figure 9.5 Variation in the Application of the Adhesive Thickness.....                    | 195     |
| Figure 9.6 Modeling Detail: Adhesive Thickness Investigation .....                        | 196     |
| Figure 9.7 Typical Stresses Contours Due to the Different Adhesive Thickness              | 197     |
| Figure 9.8 The Effect of Adhesive Thickness on the Stress .....                           | 198     |
| Figure 9.9 Type of Insulation Joints Considered for the FE Simulations.....               | 200     |
| Figure 9.10 Typical Use of the Insulation Joints .....                                    | 200     |
| Figure 9.11 Types of Joints adopted for the 3D FE model.....                              | 202     |
| Figure 9.12 Stresses Contour Diagrams for the three Types of Joints Considered<br>.....   | <br>204 |
| Figure 9.13 Stress Distribution at Node 1, 2, 3, 273, 272 and 271 .....                   | 205     |
| Figure 9.14 Stress Reduction Due to the Different of Joint Types .....                    | 206     |

# Glossary

## Symbols:

|                          |                                                                                                             |
|--------------------------|-------------------------------------------------------------------------------------------------------------|
| 3D FE                    | Three dimensional finite element                                                                            |
| $\rho$                   | Air Density                                                                                                 |
| $\varepsilon_e$          | Nominal strain                                                                                              |
| $\sigma$                 | Stress                                                                                                      |
| T                        | Stress vector                                                                                               |
| $\sigma_e$               | Nominal stress                                                                                              |
| $\tau$                   | Shear stress                                                                                                |
| C                        | Corner region                                                                                               |
| C <sub>p</sub>           | Coefficient pressure                                                                                        |
| C <sub>p peak</sub>      | Peak coefficient pressure                                                                                   |
| C <sub>p Mean</sub>      | Mean coefficient pressure                                                                                   |
| C <sub>p RMS</sub>       | Root mean square coefficient pressure                                                                       |
| D                        | Model thickness                                                                                             |
| E                        | Young modulus                                                                                               |
| F                        | Field region                                                                                                |
| L                        | Model length                                                                                                |
| L/W                      | Length to width roof ratio                                                                                  |
| H/W                      | Height to width roof ratio                                                                                  |
| P                        | Perimeter region                                                                                            |
| P-1, P-2,...             | Test pressure reading from pressure tap # 1, Test pressure reading from pressure tap # 2, etc               |
| P <sub>ref</sub>         | Test pressure reference                                                                                     |
| P <sub>60, 90, ...</sub> | Test pressure rating that a roofing system can sustain, 60 psf or 90 psf, etc, during wind uplifts testing. |
| M-1, M-2,...             | Mock-up fabricated by Source 1, Mock-up fabricated by Source 2, etc                                         |
| t                        | Time interval                                                                                               |
| V                        | Wind speed                                                                                                  |
| $\nu$                    | Poisson ratio                                                                                               |
| W                        | Model width                                                                                                 |

**Abbreviations:**

|          |                                                                      |
|----------|----------------------------------------------------------------------|
| AARS     | Adhesive Applied Roof Systems                                        |
| ACB      | Asphalt Cover Board                                                  |
| Adh      | Adhesive Failure                                                     |
| AF       | Acrylic Facer Insulation                                             |
| ASTM     | American Society for Testing and Materials                           |
| BS       | Base Sheet Membrane                                                  |
| BUR      | Built Up Roofing Systems                                             |
| BRE      | Building Research Establishment                                      |
| BRERWULF | Building Research Establishment Real Time Wind Uniform Load Follower |
| BRS      | Ballasted Roofing Systems                                            |
| CB       | Cover Board                                                          |
| CRD      | Collaborative Research and Development                               |
| CRDPJ    | Collaborative Research and Development Project                       |
| CS       | Cap Sheet Membrane                                                   |
| CSA      | Canadian Standard Association                                        |
| CEN      | Comité Européen de Normalization                                     |
| DRF      | Dynamic Roofing Facility                                             |
| EDPM     | Ethylene-Propylene-Diene-Monomer                                     |
| FCB      | Fibre Cover Board                                                    |
| FFT      | Fast Fourier Transform                                               |
| FM       | Factory Mutual                                                       |
| FE       | Finite Element                                                       |
| IRC      | Institute for Research in Construction                               |
| ISO      | Polyisocyanurate Insulation                                          |
| LTTR     | Long Term Thermal Resistance                                         |
| MARS     | Mechanically Attached Roofing System                                 |
| NBCC     | National Building Code of Canada                                     |
| NOAA     | National Oceanic and Atmospheric Administration                      |
| NRCC     | National Research Council of Canada                                  |
| NSERC    | Natural Sciences and Engineering Research Council                    |
| NTBUILD  | Norwegian Standard                                                   |
| PDF      | Probability Distribution Function                                    |
| PF       | Paper Facer Insulation                                               |

|         |                                                                 |
|---------|-----------------------------------------------------------------|
| PSD     | Power Spectra Density                                           |
| PVC     | Polyvinyl Chloride                                              |
| REMA    | Reinforced Membrane Analysis                                    |
| RFC     | Rain Flow Counting                                              |
| RMS     | Root Mean Square                                                |
| SIGDERS | Special Interest Group for Dynamic Evaluation of Roofing System |
| UL      | Underwriter Laboratory                                          |
| UEAtc   | European Union of Agreement                                     |
| VB      | Vapour Barrier                                                  |

## **Terminologies Definitions:**

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

*Dynamic roofing facility:* The name of a laboratory testing facility for evaluating wind-uplift performance of roofing systems at the Institute for Research in Construction, National Research Council Canada.

*Dynamic load cycle:* a set of loading cycles that is used to evaluate wind uplift performance of roof systems. The dynamic load cycles are one way to simulate wind-induced pressure fluctuations on roof.

*Flexible roof:* A roofing system in which the waterproofing component (membrane) is flexible sheets. These sheets are normally fabricated from either compounded synthetic thermoplastic or thermoset.

*Flexible response:* A roofing system response of the flexible roof due to aerodynamic forces of wind.

*Predominant frequency:* A frequency in which the strong variations (energy) of wind-induced suction fluctuations occur.

*Load cycles for flexible roof:* A set of loading sequences that was established using wind tunnel data analysis and is used to evaluate roofing systems that exhibits flexible response due to wind induced pressure on roofs such as MARS.

*Load cycles for rigid roof:* A set of loading sequences that was established using wind tunnel data analysis and is used to evaluate roofing systems that exhibits rigid response due to wind induced pressure on roofs such as AARS.

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

*Minimum (Min) pressure:* the minimum suction recorded during wind tunnel testing.

*Pressure:* unless otherwise stated, the pressure in this dissertation refers to the suction pressure (negative pressure) that is happening on the surface of the roof model and recorded from pressure tap during wind tunnel testing.

*Peak (Max.) pressure:* the maximum suction recorded during wind tunnel testing.

*Rigid roof:* A roofing system in which the waterproofing component (membrane) is rigid sheets. These sheets are normally fabricated from modified bituminous materials.

*Rigid response:* A roofing system response of the rigid roof due to aerodynamic forces of wind.

*Roof designer:* A person or a 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 mock-up:* Full complete assembly of a roof that is used for testing and normally consists of structural deck, vapour barrier or air retarder, thermal insulation, cover board and the waterproof membrane that together constitute the roof.

*Roof systems:* The vapour barrier or air retarder, roof insulation, cover board, and the waterproof membranes that constitute the weather-resistant portion of the roof assembly.

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

*Wind uplifts resistance performances (wind uplift rating):* Uplifts resistance capacity of a roofing system to withstand aerodynamic forces due to simulated wind induced pressures.

# **Chapter 1. Introduction**

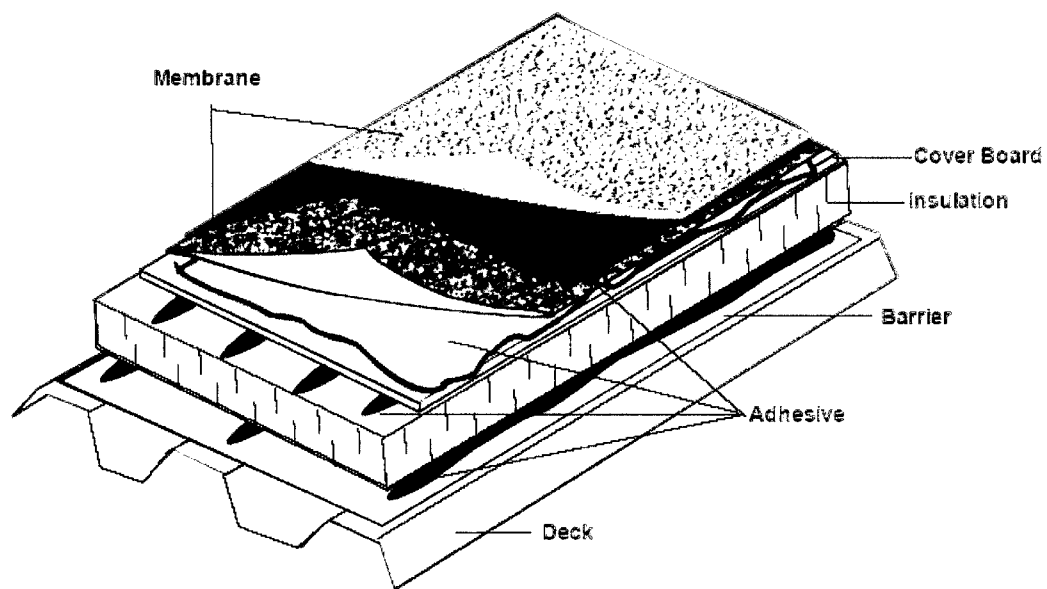
## **1.1 Roof**

A roof is an integral part of the building envelope that provides a physical separation between the indoor and outdoor environments. Its role is important for the protection of the indoor environment from the outdoor environment due to natural phenomena such as wind, rain, snow, temperature gradients, solar radiation, etc. Roofs can be classified as either low-slope or steep-slope. Low-slope roofs are often installed in commercial and industrial buildings such as warehouses and factories, while residential buildings mostly have steep-slope roofs. This dissertation focuses on the low-slope (flat) roofs. A typical commercial low slope roof system consists of several components, such as roof deck, vapour or air barrier membrane, insulation, cover board and waterproof membrane. These components are integrated together to form a compact roof system using various attachment methods. Based on the attachment methods, the low slope roof can be grouped as:

- Adhesive Applied Roofing Systems (AARS)
- Mechanically Attached Roofing Systems (MARS)
- Fully-Bonded Roofing Systems (FBRS)
- Ballasted Roofing Systems (BRS)

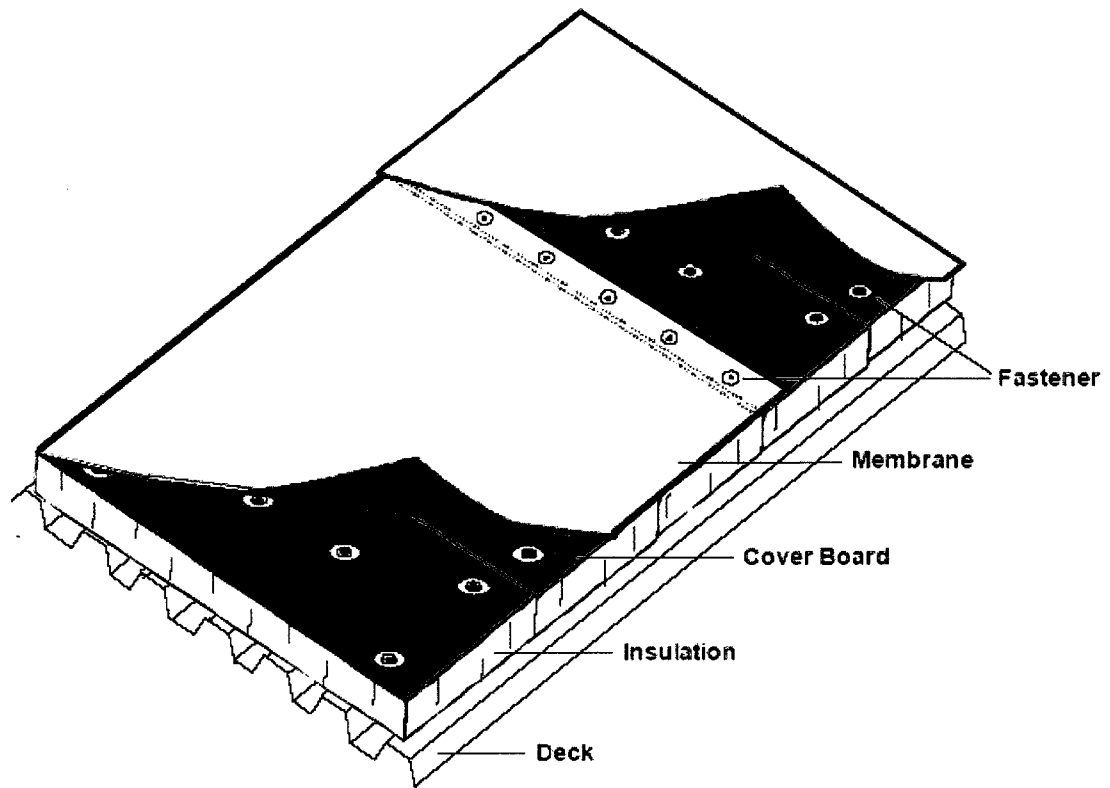
Figure 1.1 through Figure 1.4 present typical isometric drawings of roofs of these four attachment methods.

In Adhesive Applied Roofing Systems (AARS), all components (vapour / air barrier, insulation, cover board and membrane) are integrated using adhesives only (Figure 1.1)



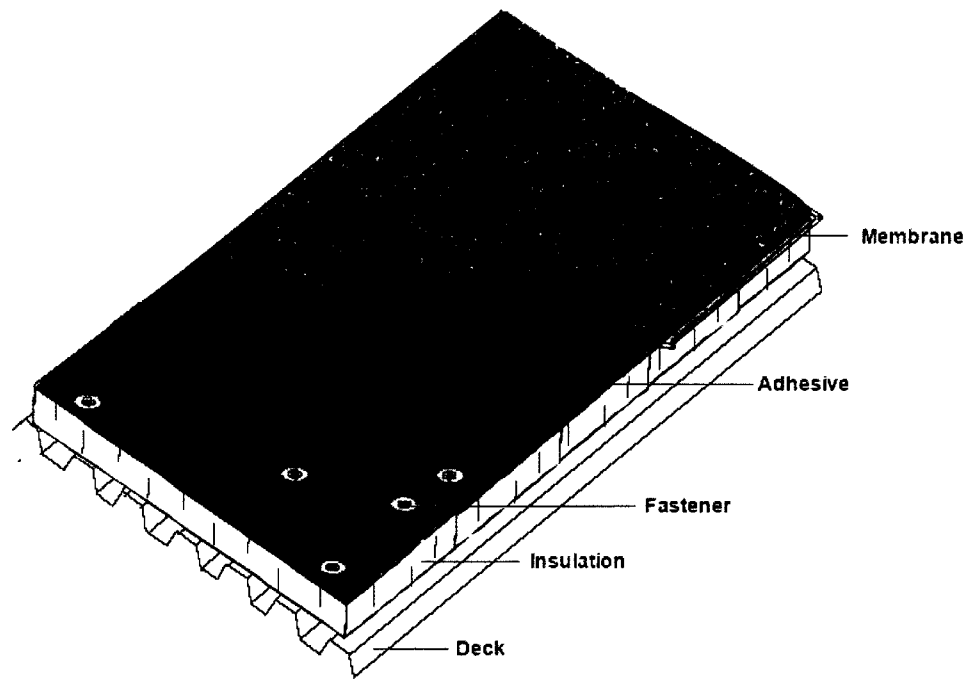
**Figure 1.1** Adhesive Applied Roofing Systems (AARS)

In Mechanically Attached Roofing Systems (MARS), all components are attached to the structural substrate using mechanical fasteners. This is done at discrete locations either using a combination of fasteners and plates, or using fasteners placed on long metal or polymer batten strips (Figure 1.2).



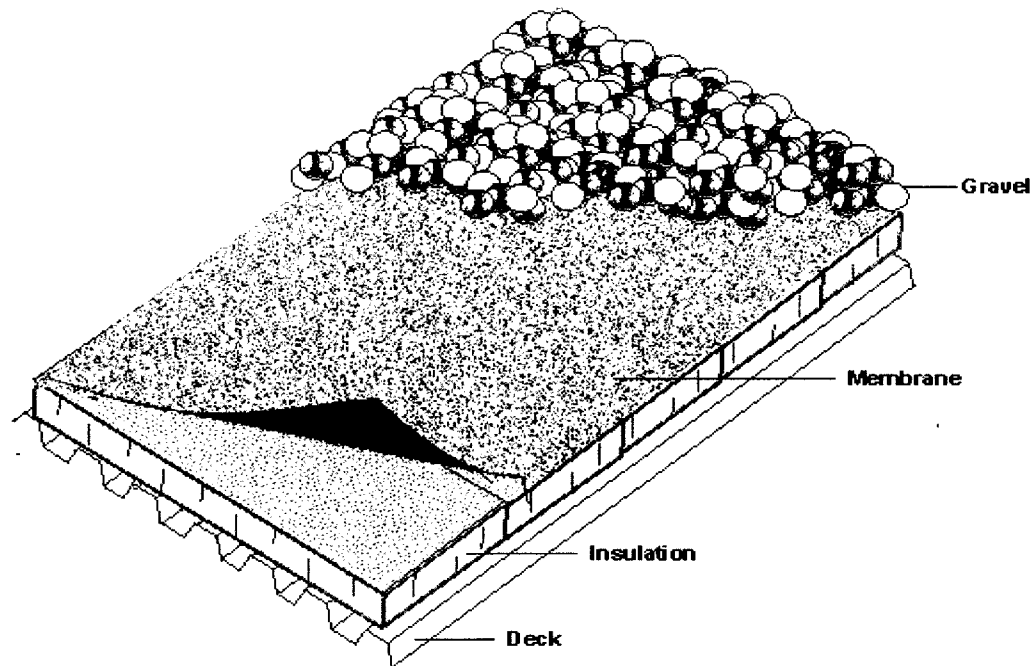
**Figure 1.2 Mechanically Attached Roofing Systems (MARS)**

In Fully Bonded Roofing Systems (FBRS), the waterproof membrane is fully bonded to the insulation, using either a solvent-based adhesive or a water-based adhesive or hot bitumen. The insulation and other components are attached to the structural deck using mechanical fasteners (Figure 1.3).



**Figure 1.3** Fully Bonded Roofing Systems (FBRS)

In Ballasted Roofing Systems (BRS), the waterproof membrane is loosely laid and held down by the weight of gravels or concrete pavers. The insulation and other components may be attached using fasteners or bonded to the deck (Figure 1.4).



**Figure 1.4** Ballasted Roofing Systems (BRS)

## **1.2 Advantages and Disadvantages of Different Roof Types**

The advantages and disadvantages of different roof types exist because of the differences in attachment methods and the type of material used for the roof components. They are typically summarized as follows,

The advantages of the AARS:

- No fastener corrosion
- Less moisture transport
- Less thermal bridging
- Less air intrusion

Disadvantages of the AARS:

- Labour intensive (Quality Assurance-QA and Quality Control-QC)
- Blistering

- Sensitivity to Ultra Violet (UV) radiation
- Slippage due to roof component movements
- Longer curing time

The advantages of the MARS are:

- Relatively quicker application since large seamless sheets of membrane are available.
- Relatively easy to install with no hot bitumen or open flames.
- Lighter due to mechanical attachments
- Less labour intensive by the use of robotic welders (QA and QC)
- No slippage of components
- Minimum curing time

Disadvantages of the MARS are:

- Moisture problems
- Fastener corrosion and penetration problem
- Thermal bridging
- Air intrusion problem due to membrane ballooning
- Easily punctured
- Susceptible to chemical or petroleum damage

The advantages of FBRS are:

- Relatively faster application compared to AARS due to the use of mechanical fasteners
- Relatively lower up-front cost.
- Compatible with most existing structures, flexible application

- Good redundancy factor due to multiple ply
- Maintenance relatively simple on smooth surfaced systems

Disadvantages of FBRS are:

- When hot asphalts are used, they create unpleasant fumes and their application requires heavy equipment; relatively dangerous compared to other systems.
- Fastener corrosion and penetration problem
- Moisture problems
- Thermal bridging
- Require curing time for the membrane components

The advantages of BRS are:

- Relatively fast to install in comparison to AARS, MARS and FBRS.
- Lowest life cycle cost
- Ballast can be easily maneuvered to fit aesthetic value for instance using round river stones or crushed stone or concrete paver.
- Capable of reducing storm water runoff
- Ballast protects membrane and help to reduce roof top temperature.

Disadvantages of BRS are:

- Relatively difficult to repair when problems arise at the substrates
- Relatively higher dead load in comparison to AARS, MARS and FBRS.
- Gravel can roll during stormy weather and fall off the roof when used
- Subject to insulation deterioration
- Frequent drainage system problems

In North America, AARS are gaining popularity because AARS can be used as a viable alternative to common low slope roofing systems such as MARS, FBRS and BRS. However, there are currently no testing methods available to quantify wind uplift performance of the AARS.

### **1.3 AARS Project at a Glance**

To develop wind uplift resistance standards for the AARS, a collaborative research and development project was initiated by the Department of Civil Engineering of the University of Ottawa and the National Research Council Canada (NRCC), in collaboration with Canadian roofing industry partners, Bakor Inc., IKO Industries Ltd, Soprema Inc., Tremco Inc., and the Roofing Contractors Association of British Columbia. The project is supported by the NSERC (Natural Sciences and Engineering Research Council) CRD (Collaborative Research and Development) grant (CRDPJ 3065819-04) and has the following tasks:

- Task 1: Pullout Testing
- Task 2: Peel Testing
- Task 3: Wind Uplift Testing
- Task 4: Numerical Modeling
- Task 5: Development of Design Guidelines

Task 1 objective was to establish a pullout testing procedure that can be used to evaluate small scale samples of AARS for uplift resistance performance evaluation. Similar to Task 1, Task 2 objective was to develop a peel testing procedure for peel resistance performance evaluation of AARS. Both Task 1 and Task 2 were

successfully completed by Current (2009) and Wu (2008), respectively. The testing procedures developed have been proposed to the American Society of Testing Material (ASTM) International to become a standardized test method. This dissertation contributes towards Task 3 and Task 4 which, focus on full scale testing and numerical modelling of AARS for wind uplift performance evaluation. Task 5 will be achieved by combining deliverables from all preceding tasks with input from the industry partners.

#### **1.4 Research Objectives**

The dissertation research objectives were to study, evaluate and establish a full-scale wind uplift testing procedure and to contribute to the development of design guidelines for adhesive applied low-slope roofing systems. To achieve the indicated objectives the following research were conducted:

- Experimentally developed a testing procedure to quantify the wind uplift performance of adhesive applied low-slope roofing systems; and
- Numerically developed a simplified finite element model that can be used for the parametric investigation of AARS.

#### **1.5 Dissertation Outline**

In addition to the present chapter, the following summarizes the content of this dissertation.

Chapter 2 provides information on wind effect on roofs and the literature review of the existing full-scale testing procedures commonly used in Canada, Europe and

United States of America for the evaluation of wind uplift performance of roofing systems. It indicates the absence of a dynamic testing procedure available for AARS wind uplift performance evaluation.

Chapter 3 presents the definition of AARS and describes commonly used roofing components. It includes material types, their functions, and mock-up construction information. In addition, it classifies AARS into two common groups namely, fully adhered and partially adhered systems.

Chapter 4 discusses the differences in the system response between rigid and flexible roofs. The results of the analyses of the wind tunnel test data which were made available for this study is also presented and discussed.

Chapter 5 presents the development of a new load cycle for the evaluation of the AARS wind uplift resistance using the wind tunnel test data from rigid models. The Rain Flow Counting method was used for the load cycle development using pressure time histories data.

Chapter 6 presents the application of the developed load cycle through experimental investigation and analysis of AARS performance, such as the uplift resistance under static and dynamic loading, the effects of the number of cycles applied and component variability. In addition, it also compares the performance of AARS mock-ups that were tested using the CSA load cycle and the newly developed load cycle.

Chapter 7 presents a summary of the peel and pullout tests and their comparison in terms of uplift resistance and failure modes with the full scale tests. In addition, a possible correlation between the three tests is also outlined.

Chapter 8 presents the development of a three-dimensional finite element (3D FE) model for the AARS. Prior to the development of the 3D FE model, a literature review on the use of numerical modelling techniques used for the roofing system evaluation is presented. It revealed minimal information regarding numerical models for AARS. This chapter outlines the development of a 3D FE model as well as its limitations. To benchmark the 3D FE model, an experimental study was also performed. The comparison of results between the modelling simulation and the experimental tests are also outlined in this chapter.

Chapter 9 demonstrates the use of the developed 3D FE model to investigate the effects of the adhesive application techniques, the adhesive thickness and the types of insulation joints on the AARS wind uplift resistance. 3D FE model information for the parameter investigations such as modeling background, detail and results are discussed in this chapter.

Chapter 10 presents the conclusions of the present research investigation, and proposes possible future extension of the research tasks to enhance the current developed full-scale testing procedures.

## **Chapter 2. Literature Review**

### **2.1 Introduction**

In order to achieve the objectives outlined in Section 1.4 for developing a laboratory testing procedure for the AARS wind-uplift performance evaluation and design guidelines, a literature review was performed. First, the wind effects on roofs were summarized and the existing laboratory testing procedures were reviewed. The literature review of the laboratory testing procedures focused on present practises commonly used in North America to evaluate the wind-uplift performance of roofing systems. Nevertheless, laboratory testing procedures practised in other parts of the world such as those from Europe, United Kingdom and Australia were also briefly reviewed.

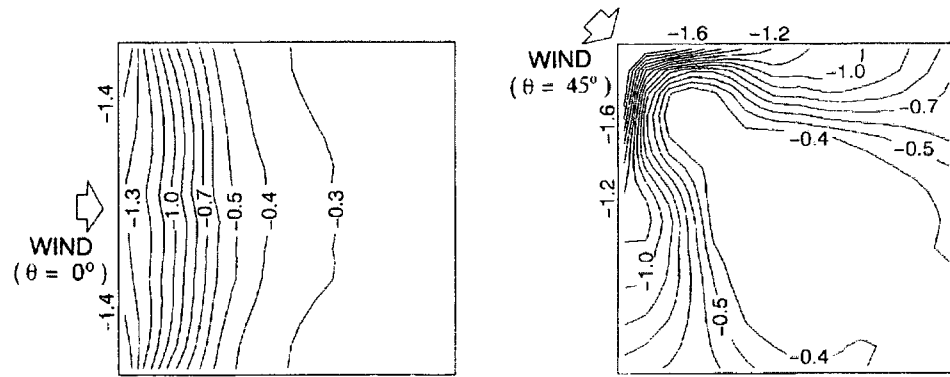
### **2.2 Wind Effect on Roofs**

Structural damage due to strong winds is the most obvious adverse effect of wind action on roofs. Wind flow over a building can create positive as well as negative pressures. The damages to roofs are mostly caused by suction, see, for example Baskaran (1986), Uematsu Y. & Isyumov N. (1999), Stathopoulus et al (1999) & Smith (2009). The wind-induced pressures on a roof are a complex phenomenon since the pressure and distribution depends upon wind flow patterns that are influenced by many factors such as wind speed, wind direction, building geometry, architecture features of the building, and surrounding topography (Lawson 1980;

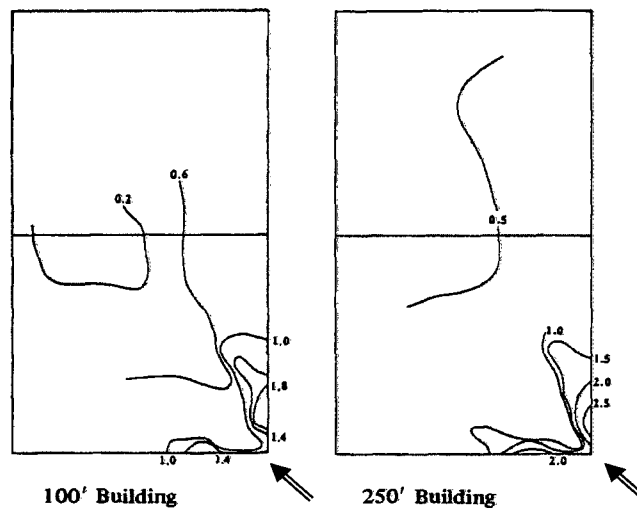
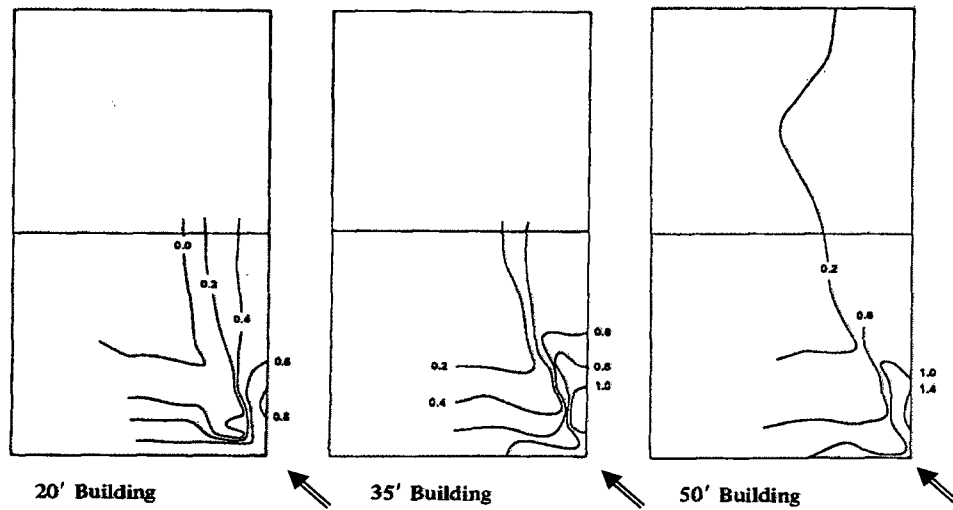
Baskaran 1986; Simiu and Scanlan 1986; Gerhardt and Kramer 1997; Ginger et al 2000; Holmes, 2001 & Ginger et al 2003).

Figure 2.1 illustrates contour plots of the pressure distributions on flat roofs from building models that were tested under open country exposure in the wind tunnel (Uematsu et al. 1996; Lythe and Surry 1983). Figure 2.1a shows the pressure distribution comparison between  $0^\circ$  and  $45^\circ$  approaching wind angles for a roof with an aspect ratio of 1. The worst suction for the  $0^\circ$  approaching wind angle is known to occur beneath the vortices that form in the separated flow along the roof edge, and are diverted away from the edge at irregular interval toward the other surfaces of the roof. For the  $45^\circ$  approaching wind angles, the worst suction is located near the roof corner. This is because of the development of dual conical vortices during the cornering winds. The vortices gradually become less critical toward the centre of the roof (Banks, 2000; Banks et al., 2000).

Figure 2.1b shows the pressure distributions for a roof aspect ratio of 2 for different building heights. Building heights of 20 ft (6m), 30 ft (9.2 m) and 50 ft (15.3 m), represent low-rise building category whereas building heights of 100 ft (30.5 m) and 250 ft (76.2 m) are considered to be in the high-rise building category. Similar observations of higher suctions at the roof corner were also observed during wind tunnel testing performed by Stathopoulos and Mohammadian (1986), Kind (1986), Blackmore (1988), Lin et al. (1995), Kawai (1996), Kawai (1997), Banks et al. (2000), Kawai (2002) and Richard and Hoxey (2008). Figure 2.1 clearly indicates that the pressure distributions on roof vary across the roof and depends on the approaching wind angle, building height and roof aspect ratio.



a) Roof Aspect Ratio 1



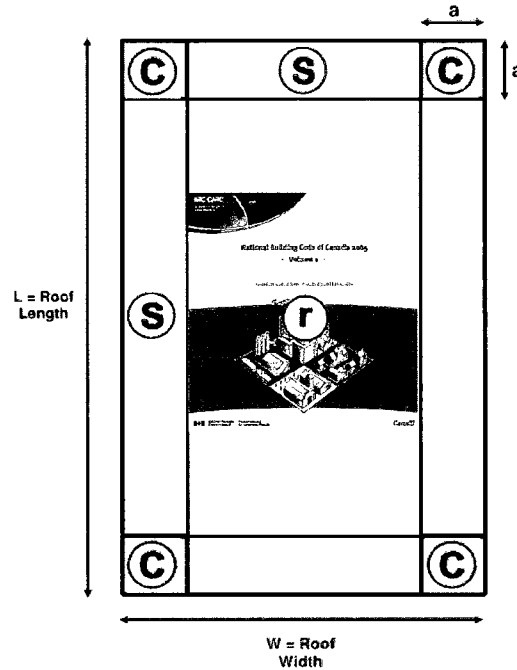
b) Roof Aspect Ratio 2

**Figure 2.1** Suction Distribution on Flat Roof  
(Uematsu et al. 1996; Lythe and Surry 1983)

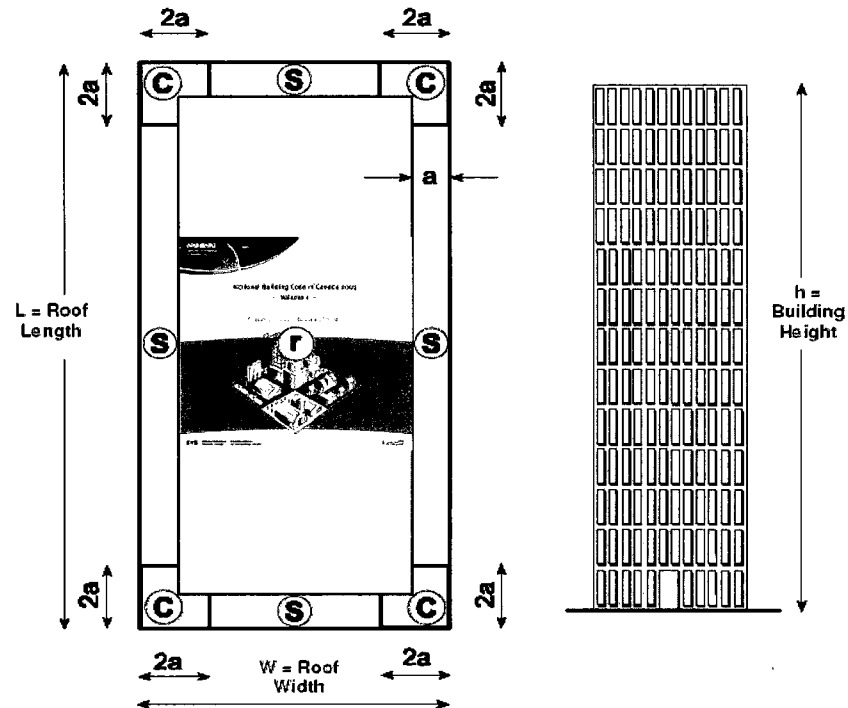
To account for the spatial pressure variations in the wind uplift design of roofs the National Building Code of Canada (NBCC, 2005) classifies roofs into three zones; corner (C), perimeter (S) & field (r) as shown in Figure 2.2. Figure 2.2a shows the three roof zones for low-rise buildings where the building height is less than 18.3 m (60 ft), while Figure 2.2b is for high-rise buildings with heights of more than 18.3 m (60 ft). The dimension “a” in Figure 2.2 is defined as either 10% of the roof width, W, or 40% of building height, h, which ever is less, cannot be less than 1 m (NBCC, 2005).

Figure 2.3 and Figure 2.4 show examples of pressure time histories on three different roof zones, corner, perimeter and field, for roof aspect ratios of 1 and 2, respectively (Savage et al 1996 and Stathopoulos 2008). It can be seen from Figure 2.3 and Figure 2.4 that the wind-induced pressures on roof are negative and vary with respect to time. It also can be seen that the pressures on the corner are always higher than the perimeter and field zones. The data presented in Figure 2.1, Figure 2.3 and Figure 2.4 indicate that wind-induced pressures on roofs have a dynamic characteristic which vary in terms of time and space.

From a time perspective, the wind dynamic characteristics are affected by wind speed, turbulence intensity and wind direction, while from the space perspective; it is affected by aspects such as building geometry, site topography and architectural features (Baskaran and Dutt 1995).

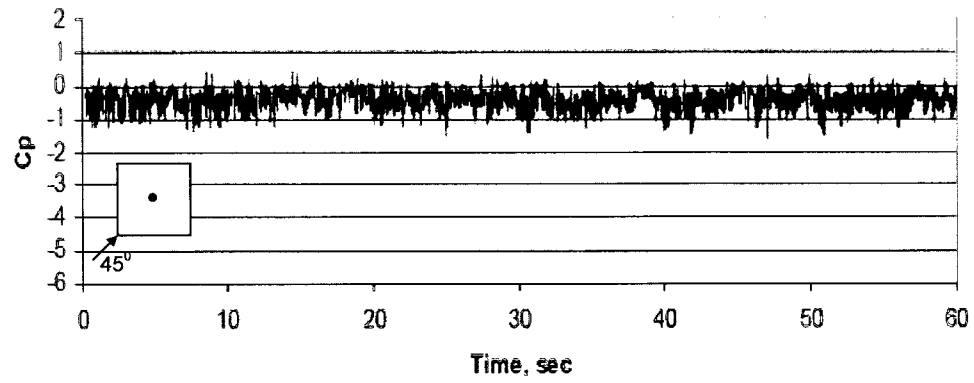


a) Three Roof Zones for Low Rise Building Category

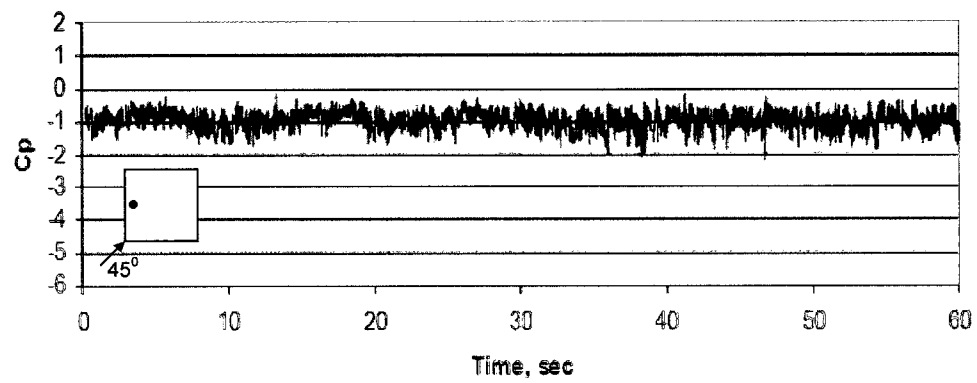


b) Three Roof Zones for High Rise Building Category

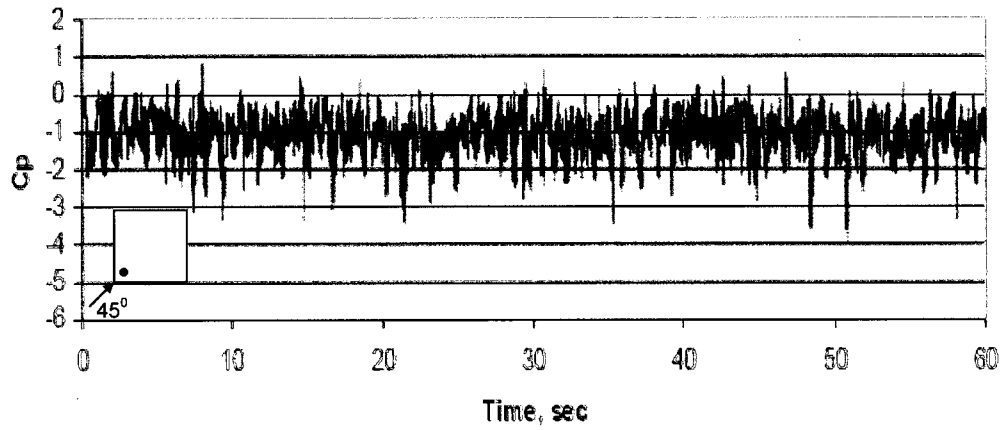
**Figure 2.2** Pressure Classification Zones: Corner (C), Perimeter (s) & Field (r)  
(NBCC, 2005)



a) Field zone (r)

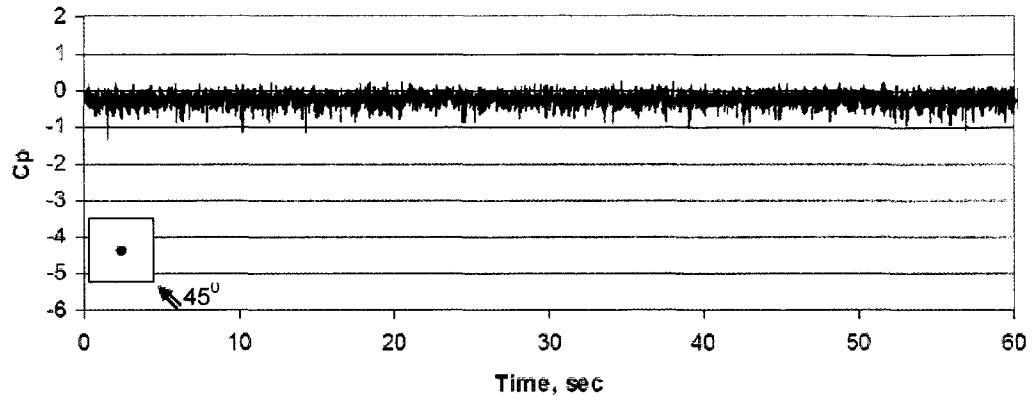


b) Perimeter zone (s)

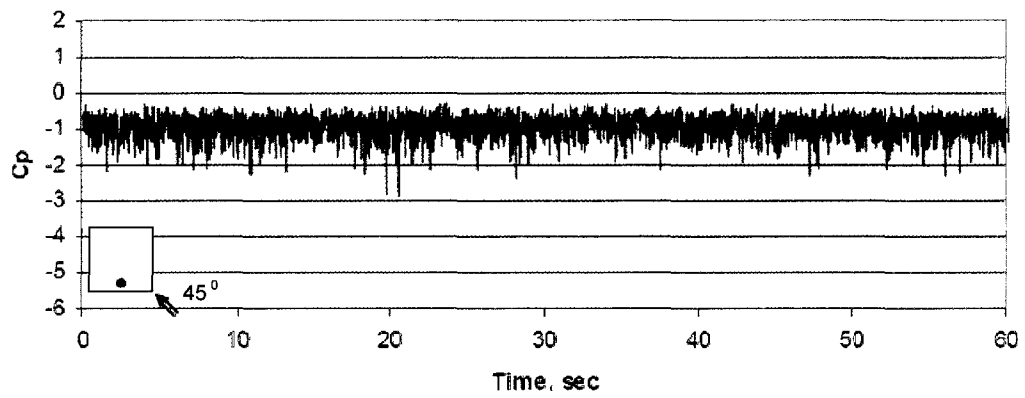


c) Corner zone (c)

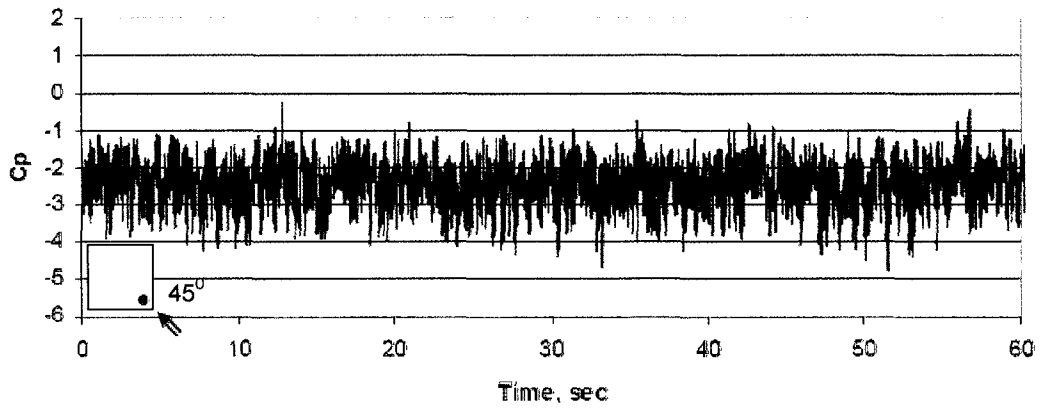
**Figure 2.3** Pressure Variations at the Three Roof Zones for Roof Aspect Ratio 1 (Savage et al. 1996)



a) Field zone (r)



b) Perimeter zone (s)



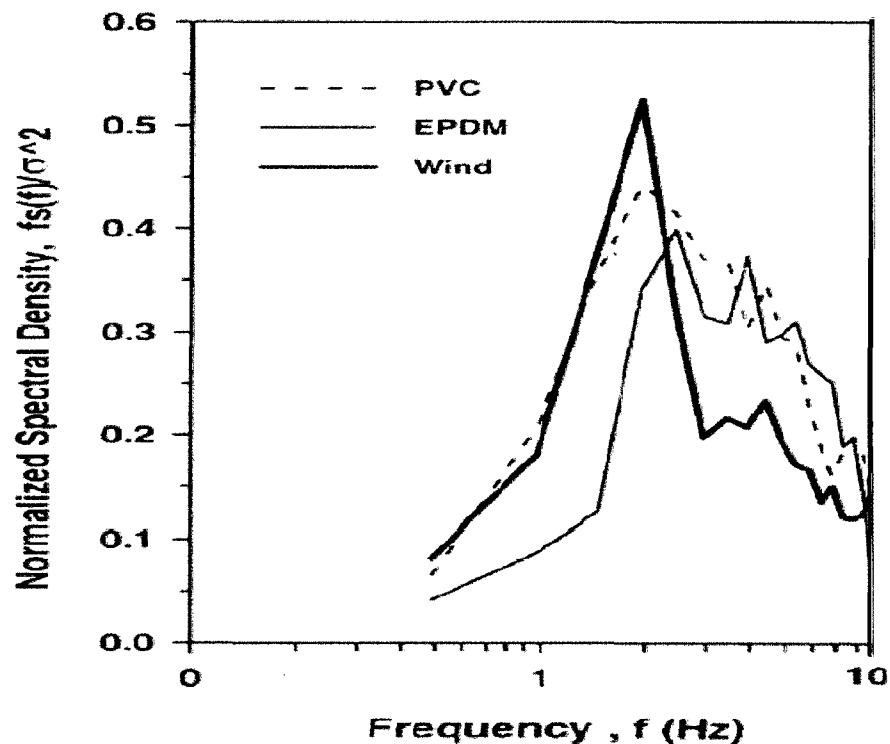
c) Corner zone (c)

**Figure 2.4** Pressure variations at the Three Roof Zones for Roof Aspect Ratio 2 (Stathopoulos 2008)

The dynamic characteristics of wind-induced pressures can be separated into static and fluctuating components. The static component is the mean pressure while the fluctuating component occurs as a random process in which the dominant frequencies depend on the frequency of the upstream wind and the geometry of the building. In addition, the distribution and magnitude of the pressures are also influenced by the structural response of the roof which mainly depends on the type of roofing system used on a building (Baskaran et al., 1994 and Baskaran, 1996). It is clear that the process of wind-induced pressures on roof is dynamic as it involves unsteady pressure responses that vary in terms of time and space.

To better simulate the forces due wind actions on roof in a laboratory, it is necessary to find the frequency in which the strong variations (energy) of wind-induced suction fluctuations occur on roofing systems. By knowing this frequency, an approximate time period for applying the forces during testing in laboratory can be determined. One way to quantify this frequency is by using spectral analysis so that the pressure time histories data can be converted into frequency domain instead of time domain. Baskaran and Savage (2003) studied the wind-induced pressure fluctuations on flat roof by using full-scale roof models. The study included performing spectral analysis to the pressure time histories data. Figure 2.5 shows the normalized spectral density of typical pressure records for Poly Vinyl Chloride (PVC) and Ethylene Propylene Diene Monomer (EPDM) roof models as well as the approaching wind measured at the perimeter region (Baskaran and Savage 2003). The study indicated that the frequency of the peak energy of the wind-induced pressures of PVC and EPDM roof models was less than 10 Hz. Lam

and To (1995) investigated the generation of wind loads on a horizontal roof with a large roof aspect ratio. In the study, they found that the frequency of the peak energy of wind-induced pressures for different wind approaching angles was less than 20 Hz and mostly occurred at a frequency of 8 Hz. Other applications of spectral analysis can also be found elsewhere, such as Kumar (1997) and Irwin (2008) for example.



**Figure 2.5** Comparison of Pressure Spectral from PVC and EPDM models (Baskaran and Savage 2003)

It is important that the development of full-scale testing procedure should consider for all or most of the aspects discussed in this section to better predict wind uplift resistance capacity of AARS. As a first step toward the development of full-scale

testing procedure for wind uplift evaluation of AARS, a review of existing full-scale testing procedures that are commonly used for the wind uplift evaluation of roofing systems was performed.

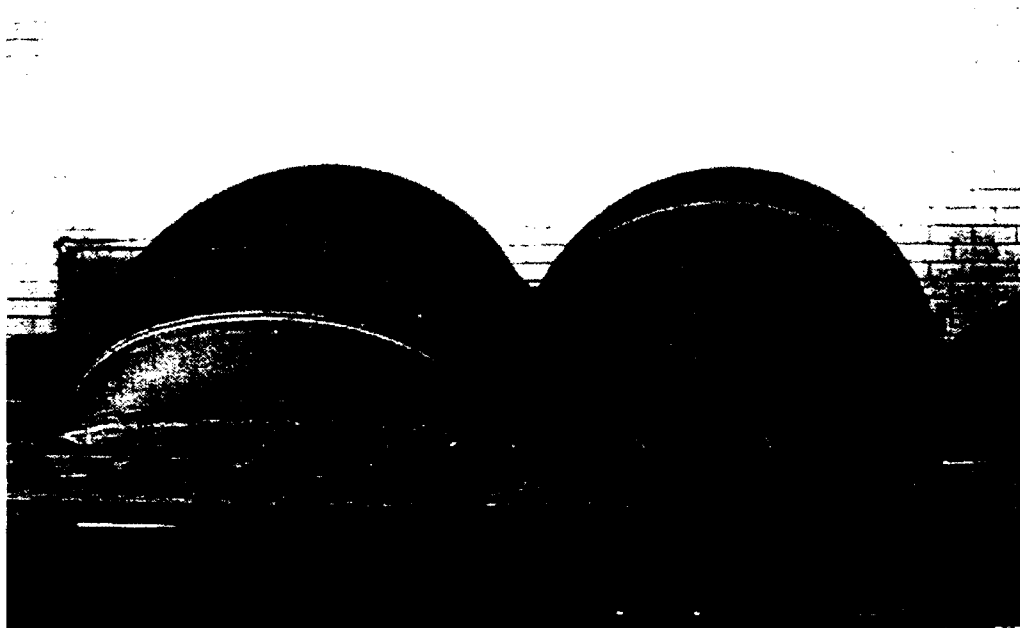
## **2.3 Review of Existing Standards**

### **2.3.1 North American Approval Testing Standards**

#### **2.3.1.1 Factory Mutual (FM) 4474-2004**

Factory Mutual (FM) is an insurance company that provides global commercial and industrial property insurance risk management solutions. In order for a roofing system to be insured by FM, it has to undergo tests in order to obtain the FM-rating. The FM rating is determined by performing static test in accordance with the FM 4474-2004. Prior to the issuance of FM 4474-2004, the FM 4470-1986 was used. The FM uplift pressure test apparatus are made by steel frames and are available in two sizes. The first table size is 1.5 m (5 ft) wide x 2.7 m (9 ft) long while the other table size is 3.7 m (12 ft) wide by 7.3 m (24 ft) long. The first test size can only be used to determine a roofing system rating up to 4.3 kPa (90 psf). For a roofing system rating more than 4.3 kPa (90 psf), the second test size should be used. The use of smaller table is limited to testing roofing systems subjected to certain conditions such as fastener row spacing, contributory fastener area, type of deck and the use of air barrier for example. Further information for the limiting conditions are described in FM4474-2004. A roofing system that has been fabricated according to the manufacturer's specification is placed on the test frame. Metal angles are attached around the assembly perimeter and are secured in place with C-clamps. Pressure is then applied to the bottom of the roofing system using

an air compressor (Figure 2.6). The initial test pressure of 1.4 kPa (30 psf) is applied and maintained for one minute. The pressure is then increased by 0.7 kPa (15 psf) increments each minute until failure. Table 2.1 shows an example of the FM loading sequence that is used for the uplift evaluation of roofing systems. The scope of the FM 4474 test method is to obtain a windstorm rating classification. The rating is provided when the tested roofing system successfully passes certain pressure levels as shown in Table 2.1 for one minute. For example, a “60 psf” windstorm rating classification is issued after a tested roofing system is capable of sustaining the 2.9 kPa (60 psf) pressure loading sequence for one minute. It should be noted that the FM 4474 is not a dynamic test and it is not applicable for rigid roofing systems. This is because of FM test applies static pressure loading and therefore differs significantly from the wind-induced pressure on roofs and the objective of the test was to test mechanically attached flexible roofing systems.



**Figure 2.6** FM 4474 Test Apparatus (FM Research 1992)

**Table 2.1 FM 4474 Loading Sequences**

| Time<br>(min) | Pressure Applied |       |
|---------------|------------------|-------|
|               | (psf)            | (kPa) |
| 0:00 to 1:00  | 30               | 1.4   |
| 1:01 to 2:00  | 45               | 2.2   |
| 2:01 to 3:00  | 60               | 2.9   |
| 3:01 to 4:00  | 75               | 3.6   |
| 4:01 to 5:00  | 90               | 4.2   |
| 5:01 to 6:00  | 105              | 4.9   |

#### 2.3.1.2 Underwriters Laboratory (UL) 580-2006

Underwriters Laboratories (UL) is an independent product safety certification organization that has established many test standards for product certification and evaluation. The UL 580-2006 test standard is intended to evaluate the uplift resistance of roofing systems consisting of a roof deck and roof covering materials. The test equipment dimensions are 3.05 m (120 in) by 3.05 m (120 in). The apparatus has three parts; a vacuum chamber, a test frame and a pressure chamber that are placed on the top, middle and bottom, respectively, as illustrated in Figure 2.7. The roofing system to be tested is placed on the test frame. The test is then performed by applying steady and oscillating negative pressures through the vacuum chamber, while a steady positive pressure is applied on the pressure chamber side. The test consists of five phases that should be completed in a period of 80 minutes. Phase 3 requires a period of 60 minutes, while other four phases take 5 minutes each. The oscillating suction is performed at Phase 3 at a frequency of 0.1 Hz. The order of applying static-fluctuating-static pressure in the procedure is intended to test the effect of internal pressure combined with the external pressure in a building. The UL 580-2006 testing procedure has a

classification designation of four ratings named as UL-15, UL-30, UL-60, UL-90. To obtain the UL-15 rating classification, a roofing system should successfully complete the following five testing phases without failure.

- Phase 1: Steady negative pressure of 0.45 kPa (9.4 psf) is applied through the vacuum chamber for 5 minutes
- Phase 2: A positive pressure of 0.45 kPa (9.4 psf) is added through the pressure chamber for 5 minutes
- Phase 3: Maintaining a positive pressure of 0.45 kPa (9.4 psf), a negative oscillating pressure of 0.27 kPa (5.7 psf) to 0.78 kPa (16.2 psf) is applied with the frequency of 0.1 Hz for a period of 60 minutes.
- Phase 4: Negative pressure of 0.7 kPa (14.6 psf) is applied for 5 minutes.
- Phase 5: In addition to the negative pressure of 0.7 kPa (14.6 psf), a positive pressure of 0.7 kPa (14.6 psf) is applied for 5 minutes.

Using procedures similar to the UL-15, other UL 580 rating classifications such as UL-30, UL-60 and UL-90 are established with a different sequence of both positive and negative pressures applied during each phase. Table 2.2 describes the specific pressure values that should be applied at each phase for the four UL 580 rating-classifications.



**Figure 2.7 UL 580 Test Apparatus**  
(UL 580, 2006)

**Table 2.2 UL 580-2006 Load Sequences**

| 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)                 |

### 2.3.1.3 Canadian Standards Association (CSA) 123.21-04

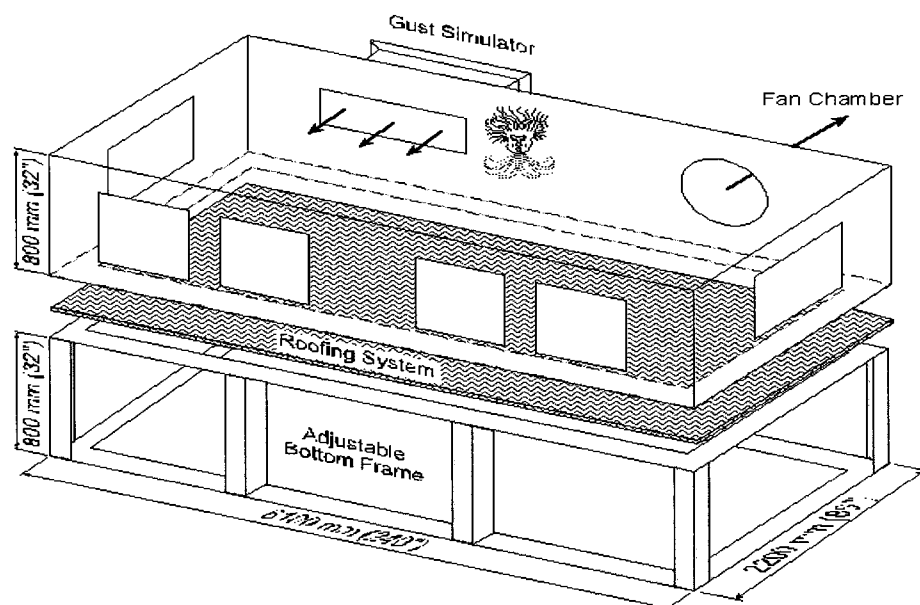
CSA A123.21-04 is a test standard issued by the Canadian Standards Association. The standard is currently used for evaluating the wind uplift resistance of Mechanically Attached Roofing Systems (MARS). The standard was developed based on the research that was performed by Special Interest Group for Dynamic Evaluation of Roofing System (SIGDERS). SIGDERS comprises roofing manufacturers, building owners and industrial associations.

The CSA 123.21 experimental apparatus consists of an adjustable bottom frame, a removable top chamber and a 37 KW (50HP) fan. The dimension of the bottom frame and top chamber are 6.1 m (240 in) long and 2.2 m (86 in) wide and 0.8 m (32 in) high. The top chamber is equipped with six viewing-windows and a cycle simulator (Figure 2.8). This apparatus is capable of producing a dynamic suction up to 10 kPa (209 psf) with a flow rate of 2500 L/sec (5300 cfm). Preparation and fabrication of the roofing system for the test is in accordance to the roofing manufacturer's specification. The test is then performed by placing the roofing system on the bottom frame and exposing it to dynamic suction in accordance with the loading sequences illustrated in Figure 2.9. Information about the development of the CSA A123.21-04 load cycles is summarized in Chapter 4. A summary of the CSA load cycle is outlined as follows:

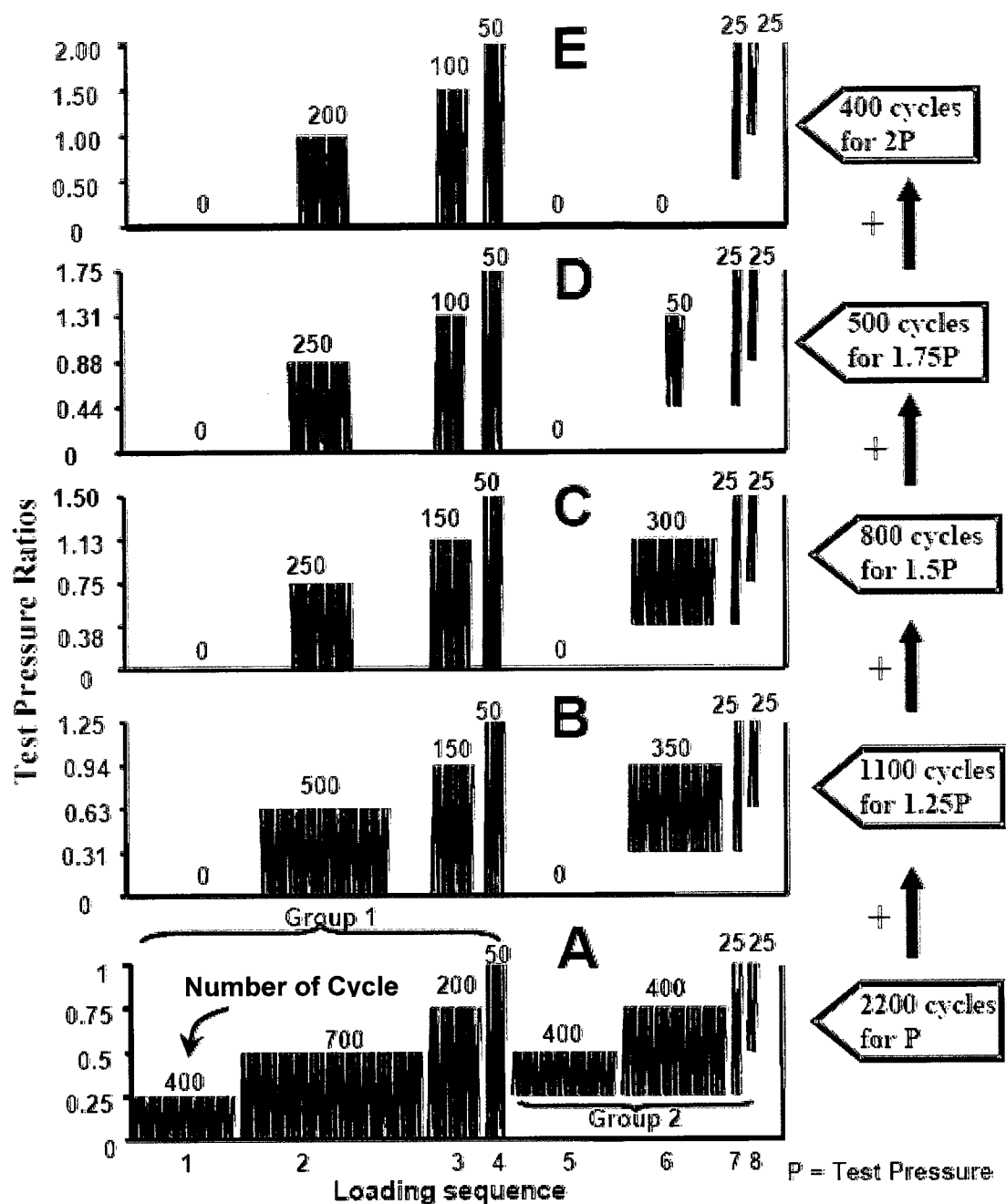
- As shown in Figure 2.9, the CSA load cycle has five rating levels (A to E). To evaluate a roof assembly for a specific wind resistance, all the cycles corresponding to Level A should be applied. One cycle takes about 8 seconds

to complete. One cycle consists of two processes, loading and unloading, each process takes about 4 seconds.

- Each level consists of eight load sequences with different pressure ranges, depicted in Figure 2.9. The eight load sequences are divided into two groups. Group 1 represents the wind-induced suction over a roof assembly. It consists of four sequences, where the pressure level alternates between zero and a fixed pressure. Group 2 simulates the effects of exterior wind fluctuations combined with a constant interior pressure on a building.
- The test pressure ratios (Y-axis) can be calculated from the design pressure, in accordance with local building codes or wind standards. The pressures for each load sequence are calculated as percentages of the applied test pressure.
- To evaluate the wind uplift resistance of the roof assembly, testing should be started at Level A and should be continued when moving from one level to another. To obtain a rating, all specified numbers of cycles in each level must be completed without failure.



**Figure 2.8** CSA A123.21-04 Test Apparatus  
(CSA A123.21-04)



**Figure 2.9 CSA Load Cycle for Flexible Roof  
(CSA A123.21-04)**

#### 2.3.1.4 Other Testing Procedures

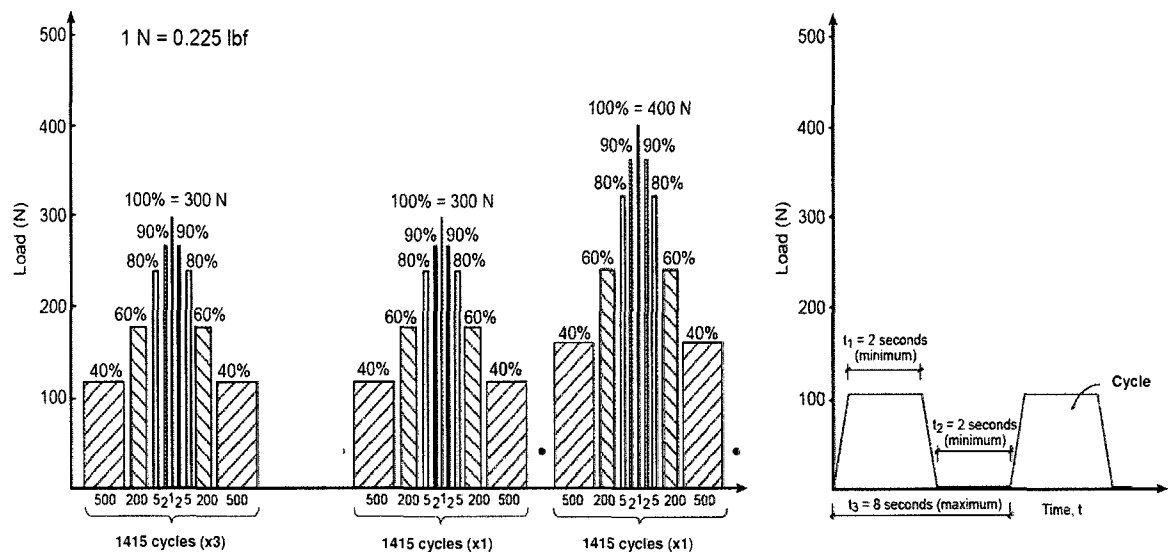
##### 2.3.1.4.1. European Organization for Technical Approval (EOTA) - ETAG 006

ETAG 006-2000 is a European guideline for the technical approval of roofing systems with mechanically fastened flexible waterproofing membranes. The European Union Agreement - UEA<sub>tc</sub>1991 test standard formed a basis for the ETAG 006-2000 guideline. The ETAG 006-2000 guideline was amended in April 2007 and, is referred to as the agreement document certificates for the assessment of materials used within the member countries including Denmark, Sweden, Belgium, Finland, France, Germany, Netherlands, Italy, Portugal, Spain, United Kingdom, Norway, Hungary, Poland, and three European industrial organizations (ETAG 006-2000). The three European industrial organizations are IFD-International Federation of Roofing Contractors, CEO- European Tool Committee and ESWA-European Synthetic Waterproofing Association. The testing procedure of ETAG 006-2000 for the wind uplift resistance performance evaluation was based on the research work performed by Gerhardt and Kramer (1986). The testing apparatus has dimensions of 0.75 m (29.5 in) high x 1.5 m (60 in) wide x 6.1 m (240 in) long consists of the testing chamber and a rigid frame. The test is performed by applying suction through the testing chamber. The test simulates dynamic pressure loading pressures by using load cycles but the procedure is very time consuming. Figure 2.10 shows an example of the ETAG 006-2000 load cycles for a five-year return period. One cycle shown in Figure 2.10 takes about 8 seconds to complete. The following procedures are performed for the test:

- Four cycles of 1415 cycles with a maximum load of 300 N (68 lbf) per fastener are applied.

- 1415 cycles are applied with a maximum load per fastener not exceeding 400 N (90 lbf).
- The maximum load per fastener is then increased with increments of 100 N (22.5 lbf) with 1415 cycles at each level until the system fails.

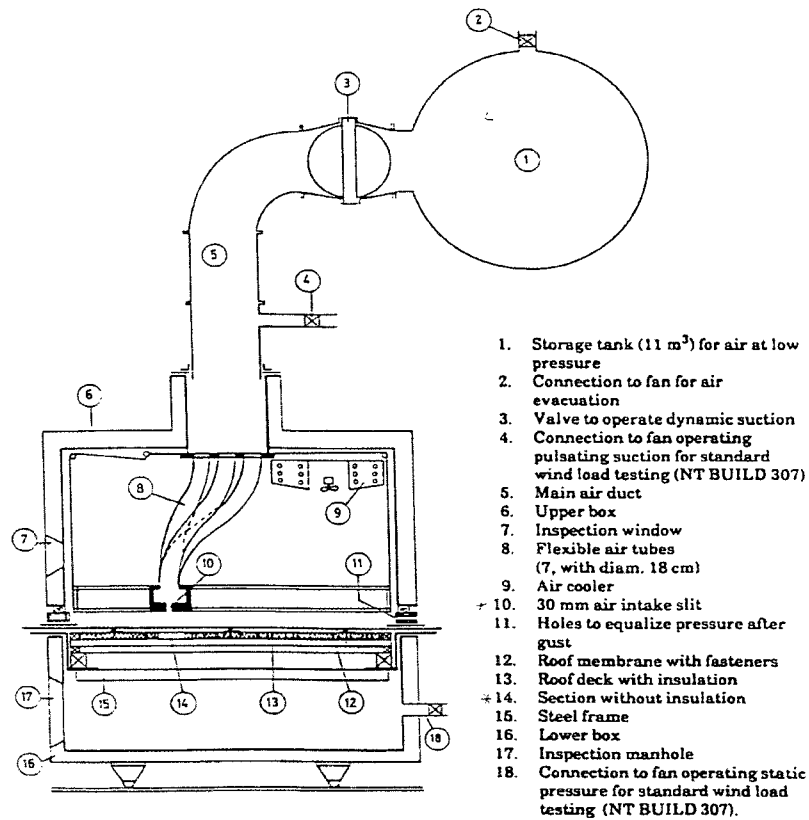
Prior to testing, the size of roofing system and fastener spacing are determined by the use of correction factors developed by Gerhardt and Gerbatch (1989). This testing procedure was verified by comparing the field failures and laboratory failures that yielded similar results (Gerhardt and Kramer, 1988).



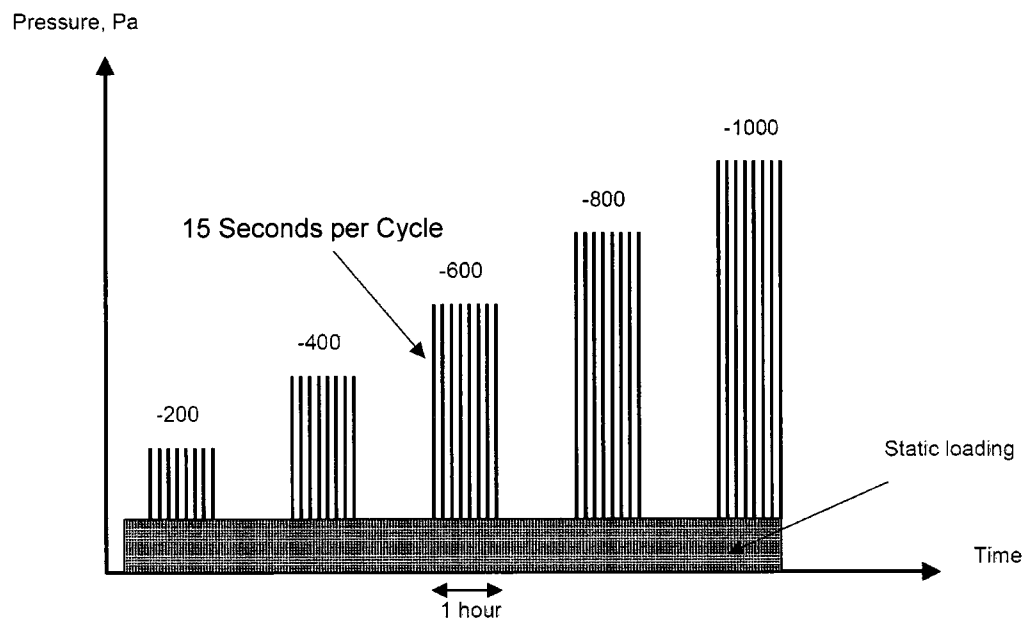
**Figure 2.10** ETAG 006 Load Cycles (ETAG 2000)

#### 2.3.1.4.2. Norwegian Standard (NBI 160-90)

A Norwegian testing procedure, NT BUILD 307 1986-11, "Roof Coverings-Wind load resistance" is a standardized test method that was commonly used for evaluating the wind uplift resistance of roofing systems (Paulsen 1989). The NT BUILD 307 1986-11 is a static test. During 1987, the NT BUILD 307 1986-11 standard was modified by the Norwegian Building Research Institute along with the other Scandinavian countries. After the modification, the NT BUILD 307 1986-11 standard was changed into a dynamic testing protocol to evaluate wind uplift resistance of mechanically attached roofing systems. The standard is later known as NBI 162-90, "Roof coverings-Dynamic wind load resistance", established by the Norwegian Building Research Institute. The test apparatus consists of a lower box and an upper box with the size of 2.4 m (96 in) x 2.4 m (96 in) as shown in Figure 2.11. The test is performed by applying a static suction of 0.1 Pa (2.1 psf) from the lower box. In addition, a pulsating suction initiated at 0.2 kPa (4.2 psf) is also applied from the upper box. Both pressures are applied at the same time and the test is continued until the roofing system fails. The pulsating pressure is applied in accordance with the load cycles presented in Figure 2.12. Each group has 240 load cycles of 15 seconds duration to complete on each cycle. Therefore, it takes one hour to complete a group of load cycles for the test.



**Figure 2.11 NT BUILD 307 Test Apparatus (Paulsen 1989)**



**Figure 2.12 NT BUILD 307 Load Cycles (Paulsen 1989)**

#### 2.3.1.4.3. Review of Other Testing Methods

The Building Research Establishment (BRE), UK, developed equipment called the “BRE Real Time Wind Uniform Load Follower (BRERWULF)”. The BRERWULF was designed to reproduce a long term history of wind pressure for evaluating the structural performance of buildings, primarily roofs (Cook et al., 1988). The test is performed by applying pressures to a roofing system. The pressure is generated 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. The static controller is used to control static pressure to either increase or lower the pressure rates, while the dynamic controller can be used to produce dynamic pressure that can be computed from a file containing programmed data such as field monitored wind pressure data, wind tunnel data, or data following a sinusoidal fluctuation. The target trace is sampled and normalized with the peak value corresponding to the design value in the range of  $\pm 8.5$  kPa.

Fatigue in material sciences can be defined as the progressive and localized structural damage that occurs when a material is subjected to cyclic loading (Wikipedia, 2009). Fatigue can damage roofing system and reduce its wind-uplift performance. Fatigue can occur due to wind-induced pressure fluctuations caused by natural turbulence in incident wind and the turbulence induced by the interaction between the incident wind and the structure (Xu, 1993). A testing procedure to evaluate the fatigue performance of mechanically attached single-ply membrane was introduced by Smith (1992). The sequences for number of loadings were developed using Weibull probability function based on wind data. Another method

of loading sequence computation using the level-crossing and mean-rain count analysis of recorded wind pressure data was presented by Letchford and Norville (1993). The developed loading sequences were applied to the test standard to determine the impact resistance against windborne debris, SBCCI (1994). In Australia, research investigations toward applying a dynamic loading to sheet metal roofing systems were performed by several researchers including Byrne (1976), Morgan and Beck (1977) and Mahendran (1990). Mahendran (1993) performed comprehensive study to investigate the fatigue behaviour of light gauge steel roof claddings under simulated cyclonic wind forces. Two types of fatigue tests, a random block loading test and the TR440 test, were applied to two types of steel roof claddings, namely corrugated roofing and trapezoid roofing profiles. The research concluded that extensive testing in the form of random load tests was required to study the fatigue behaviour of roofing and to develop appropriate tests. Later, Jancauskas et al (1994) developed an analytical model to simulate fatigue behaviour of roof cladding during passage of a tropical cyclone. The model was based on wind pressure data obtained from wind tunnel test and analysed using rain flow counting method. A modification of Miner's rule was also used to calculate a fatigue damage index of metal roof claddings. The results of these research investigations were used to update the Australian Standard (TR440). Clearly, it is important to consider wind-induced pressure fluctuations that can cause fatigue damage to roofing systems when developing a laboratory testing procedure.

### 2.3.2 Limitations of Current Testing Procedures

It is evident that there are no testing standards available to specifically evaluate the wind-uplift resistance of adhesive applied roofing systems (AARS). The following information provides the limitation of the current testing standards:

- All the testing standards were specifically developed to evaluate the wind uplift performance of mechanically attached roofing systems.
- The FM 4474 and UL 580 testing procedures do not consider fatigue effects due to wind induced pressure on roofs and roof system response behaviour.
- CSA 123.21 is the only dynamic testing procedure that incorporates the influence of roof system response behaviour.
- The ETAG 006 testing procedure provides the fastener design load, whereas FM 4474, UL 580 and CSA 1213.21 give ratings in terms of the design pressure.
- The ETAG 006 testing procedure is time consuming as it takes more than one day to complete each test.

Table 2.3 shows some of the differences on the existing test methods. These differences are attributed to the availability of test equipment, size of roofing materials, fastener arrangements, incorporating wind-induced pressure fluctuations to account for fatigue on roofing systems and compatibility to code requirements. For example, the FM 4474 has two table sizes. The use of table size depends on certain condition such as the fastener row spacing, contributory fastener area, type of deck and the use of air barrier. In addition, smaller table size is normally used to test fully bonded roofing system and the larger one is for mechanically attached roofing systems

**Table 2.3** Some Differences Among Existing Test Methods

| Description                                                         | FM 4474                              | UL580                               | CSA A123.21         | ETAG                 |
|---------------------------------------------------------------------|--------------------------------------|-------------------------------------|---------------------|----------------------|
| Table size                                                          | a) 1.5 m x 2.7 m<br>b) 3.7 m x 7.3 m | 3.05 m x 3.05 m                     | 2.2 m x 6.1 m       | 1.5 m x 6.1 m        |
| Method of loading                                                   | Static loading                       | Static-fluctuating – static loading | Fluctuating loading | Fluctuating loading  |
| Account for fatigue effect due to wind-induced pressure fluctuation | No                                   | No                                  | Yes                 | Yes                  |
| Account for System Response under wind action                       | No                                   | No                                  | Yes                 | No                   |
| Test output                                                         | Design pressure                      | Design pressure                     | Design pressure     | Fastener design load |

## **2.4 Concluding Remarks**

This chapter provided brief information on wind effects on roofs and reviewed the common standardized laboratory testing procedures that were available for wind uplift evaluation of roofing systems. It was clear that there was no standard available for the AARS wind uplift resistance evaluation. The literature review also showed that it was crucial to consider the effects of wind-induced pressure fluctuations and distributions on roofs. A method of evaluation should consider both wind-induced pressure fluctuations and distribution effects to better predict the wind uplift resistance of AARS.

## **Chapter 3      Adhesive Applied Roofing Systems**

### **3.1      Introduction**

Many types of roofing membranes and components are available in the roofing market. Selecting a roofing system that is suitable for a particular building application is a challenging task for any roof designer. In North America, there are four types of low-slope roofing systems commonly used. They are Adhesive Applied Roofing Systems (AARS), Mechanically Attached Roofing Systems (MARS), Fully Bonded Roofing Systems (FBRs), and Ballasted Roofing Systems (BRS). As illustrated in Chapter 1, one of the major differences among them is the method of attachment of various components. This chapter provides details of the AARS components and a typical example of the mock-up construction process.

AARS utilize adhesives as the method of attachment for all the components to form a compact roof assembly. The AARS roofing components include deck, vapour barrier, insulation board, cover board and membranes. The cap sheet can be attached with the base sheet by torching instead of applying adhesives. Figure 3.1 shows a field application and a typical isometric drawing illustrates the different AARS roof components and methods of layering the components together.

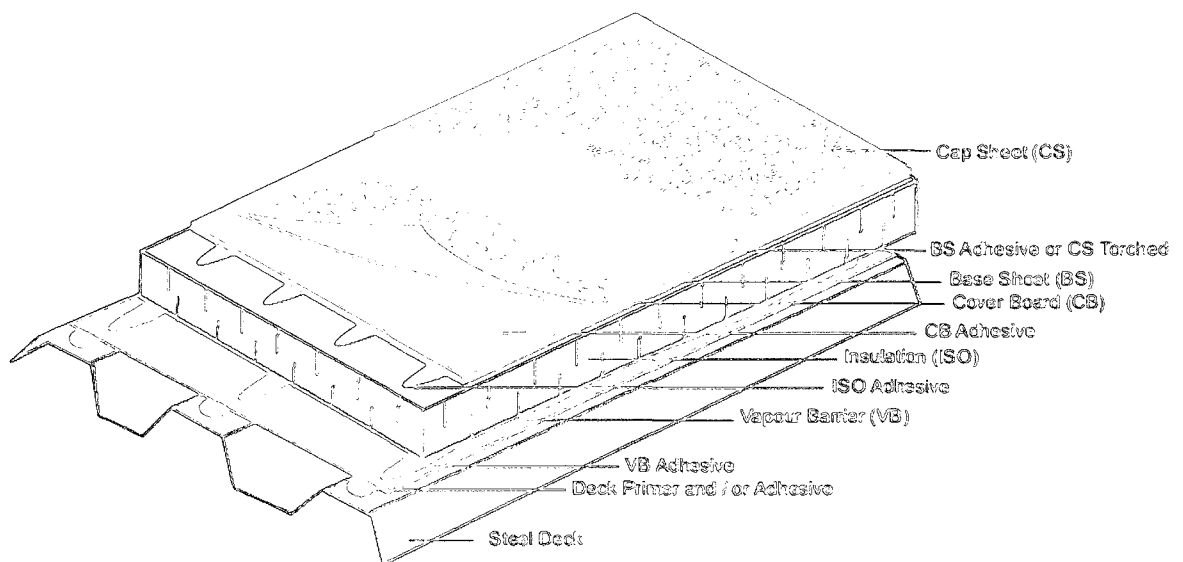


Figure 3.1 Typical AARS Construction and Isometric Drawing

## **3.2 Roofing Components**

### **3.2.1 Roof Deck**

Roof deck is the structural member upon which the roofing materials are placed together to form a compact roof assembly. Roof decks are normally constructed of either wood, concrete or steel. A wooden deck is normally used in residential applications while concrete and steel decks are mostly used in commercial and industrial building applications (Laaly 1991). Like other structural components, roof decks have to serve several functions. Roof decks need to:

- Act as structural components to transfer the weight of live and dead loads to supporting members. Live loads include wind, rain, snow, construction equipment and workers, and ice. Dead loads include the weight of the deck, that of the roofing system, and any HVAC units. Most decks must also act as diaphragms, transmitting wind or seismic lateral forces to the structural framework.
- Act as a suitable substrate to which the roof membrane or roof system is attached.
- Be dimensionally stable and capable to accommodate any roof component movement.
- Sustain, in the event of a fire, the loads for a certain period at time to allow occupants to safely escape the building.
- Contribute to the building performance in resisting: heat flow, moisture penetration, air flow, and acoustical noise.

Among the types of roof decks available, a steel roof deck was selected for the present research investigation. This decision was made based on the following considerations:

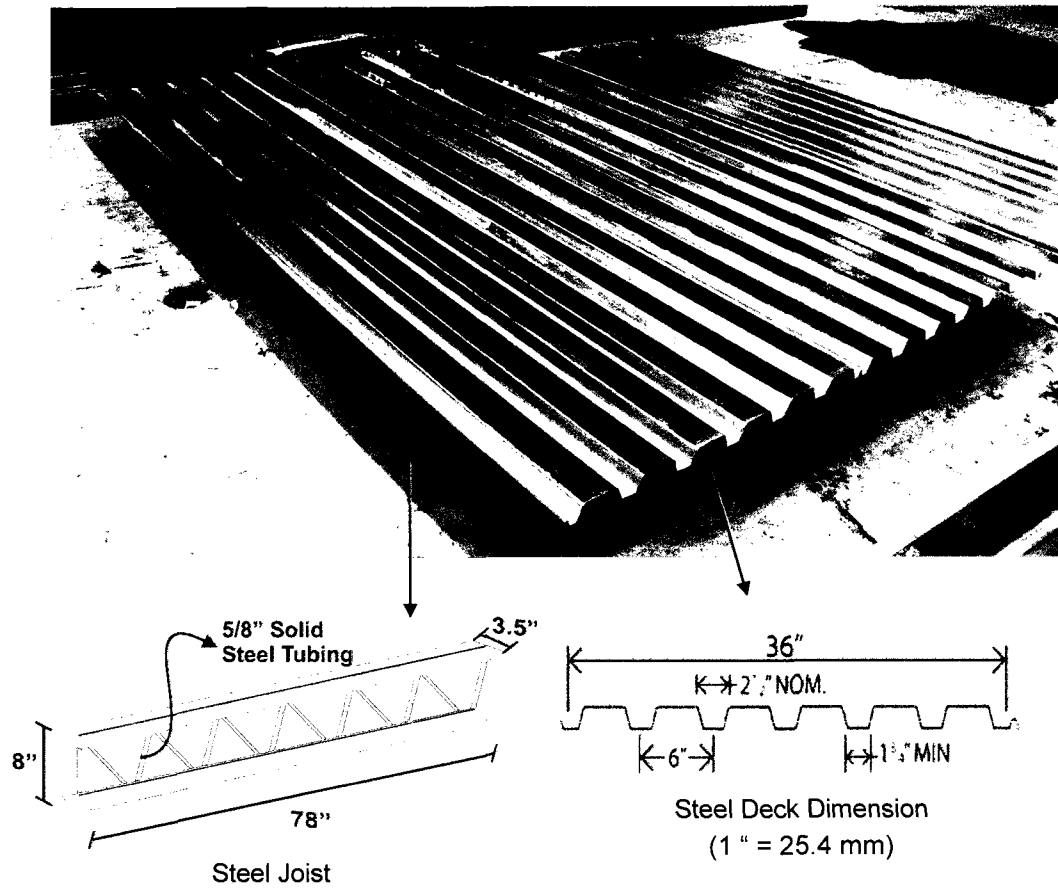
- For most commercial buildings, steel decks, rather than concrete or wood decks, are used.
- The volume weight of the steel deck is much lighter compared to concrete and wood decks.
- Steel decks are easily constructed and relatively fast to install.
- Based on small scale pull out test results (Current, 2009), AARS specimens with steel decks performed better than concrete decks in terms of bonding resistance. This is because the steel deck is more flexible in comparison to other two types of decks, and thus can absorb larger elastic energy during loading, resulting in a higher uplift resistance.

Steel decks used in roofs are manufactured using light gauge, typically 22, 20, or 18 gauge, cold-rolled steel panels that are usually galvanized. The panels are ribbed and are spaced at 150 mm (6") from centre to centre. The ribs provide the strength and rigidity to the panels. Figure 3.2 shows a typical example of a steel deck used during the full-scale mock-up construction. Steel decks are generally supported on an open-web steel joist framing and are welded or mechanically fastened to the panels. The steel deck used met the ASTM standards:

- ASTM Standard Specification A 653/A 653M-09, Steel Sheet, Zinc- Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process,

with a design thickness of 22 gauge (0.759 mm) or greater.

- ASTM Standard Specification A792 / A792M-09, Steel Sheet, Aluminium-Zinc Alloy-Coated by the Hot-Dip Process, with a design thickness of 22 gauge (0.759 mm) or greater.



**Figure 3.2** Typical Steel Deck Used in Roofing

### 3.2.2 Vapour Barrier (VB)

A vapour barrier is a layer or a laminate that can be used to reduce the diffusion of water vapour into a roof system. The rate of diffusion of water vapour depends on two factors: the water vapour pressure difference across the roof assembly and the vapour permeance of the materials along the migration path. Vapour permeance is the term used to measure the moisture flow or permeability through a material. International standards, define “perm” units as gr/day/m<sup>2</sup>/mmHg or 1 grain/hr/ft<sup>2</sup>/inHg. For example, the “perm” rating of a material that has a 0.1 grains of moisture (per ft<sup>2</sup>hr) under 0.36 inch differential pressure, is 0.27. The 27 perm rating is obtained by,

$$\text{Permeance} = \frac{0.1 \text{ grains}}{\text{hr} \times \text{ft}^2} \times \frac{1}{0.36 \text{ inches of mercury}} = 0.27 \text{ perms}$$

Materials less than 0.5 perms are suitable as a vapour barrier in roofing systems. Some materials have more resistance to vapour flow than others. Placing a material with high resistance to vapour flow in a roof assembly will help control water vapour migration.

Currently, there are many types of vapour barrier available in the roofing market. Table 3.1 shows several examples of materials that can be used as vapour barrier. However, the research herein only uses two types of vapour barrier that are commonly used in AARS application; namely the self-adhered woven polyethylene and kraft paper laminates. These two types of VB were selected based on their

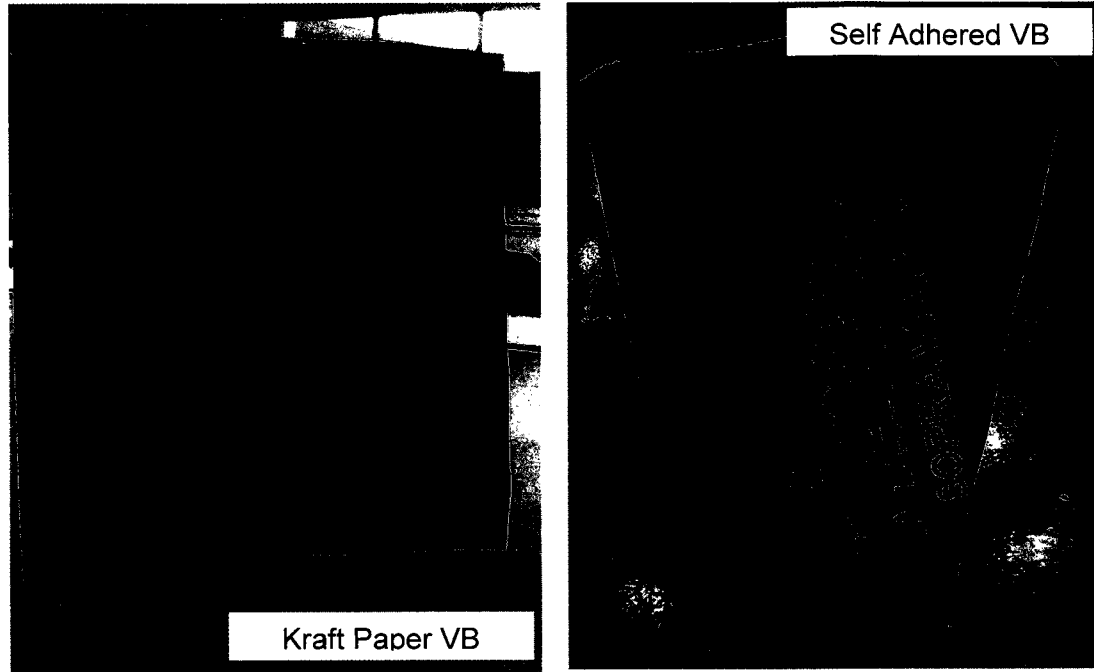
compatibilities with other AARS roofing components. Figure 3.3 illustrates these two types of vapour barrier. The self-adhered woven polyethylene vapour barrier is made from tri-laminated woven polyethylene in combination with a silicone release film that covers the self-adhesive underface. The width of the membrane is normally 1.14 meters (45 inches). Liquid primer was used on the deck prior to installation of the woven polyethylene vapour barrier<sup>1</sup>. The kraft paper laminate vapour barrier is made from two layers of kraft paper bonded together using asphalt with strands of fibreglass reinforcement intertwined near each edge for the enhancement of strength and tear resistance enhancements<sup>2</sup>.

**Table 3.1** Examples for Vapour Barrier Materials Used in Roofing

| <b>Material</b>                           | <b>Permeance Rating<br/>(perm)</b> |
|-------------------------------------------|------------------------------------|
| <i>Woven polyethylene-Self Adhered</i>    | <i>0.02</i>                        |
| 4-mil polyethylene                        | 0.08                               |
| 6-mil polyethylene                        | 0.06                               |
| 4-mil poly (vinyl-chloride) PVC           | 0.5                                |
| <i>Kraft Paper</i>                        | <i>0.25</i>                        |
| No. 43 Asphalt- saturated and coated felt | 0.3                                |
|                                           |                                    |

<sup>1</sup> Soprema -TDS# 061101CAN2E

<sup>2</sup> IKO-TDS#130059



**Figure 3.3** Typical Kraft Paper Laminate & Self Adhered VB used for the Study.

### 3.2.3 Insulation

In modern building construction, many types of insulation are available such as acoustical, radiant, reflective and thermal insulations. This section deals with thermal insulation for roofing applications. Thermal insulation can be made from mass, organic or inorganic, reflective or foil-faced, or a combination of both. As with other roofing components, thermal insulation for use in roofing applications should meet several criteria. For example, it should meet the design requirements for compressive, tensile and flexural strength, resist degradation from moisture; and should not be nor become corrosive to metals. Common types of thermal insulation available for roofing applications are *Polyisocyanurate*, Expanded Polystyrene EPS and Extruded Polystyrene (XEPS or XPS).

*Polyisocyanurate* thermal insulation was selected for the study. This type of insulation is currently used in more than half of the commercial roofing market in North America (Singh et al 2005). It also has high thermal performance, is economical, has a high dimensional stability, is moisture resistant, is non-organic, has a good fire rating, and is widely available (Singh et al 2006). In addition, it is compatible with many roofing membranes and adhesive products which is a crucial factor for AARS applications which depend mainly on adhesives as the method of attachment. It is also placed directly on the steel metal deck and meets the internal burning criteria established by CAN/ULC S126M.

In Canada, the standard for the manufacturing of *polyisocyanurate* insulation is CAN/ULC S704-03, while in the United States, it has to meet with ASTM C1289. *Polyisocyanurate* insulation can be categorized into three types as shown in Table 3.2.

**Table 3.2.** Properties of *Polyisocyanurate* Insulation Types

| Property             | Type I  | Type II | Type III |
|----------------------|---------|---------|----------|
| Compressive strength | 110 kPa | 140 kPa | 170 kPa  |
| Tensile strength     | 24 kPa  | 35 kPa  | 35 kPa   |
| Flexural strength    | 170 kPa | 275 kPa | 275 kPa  |

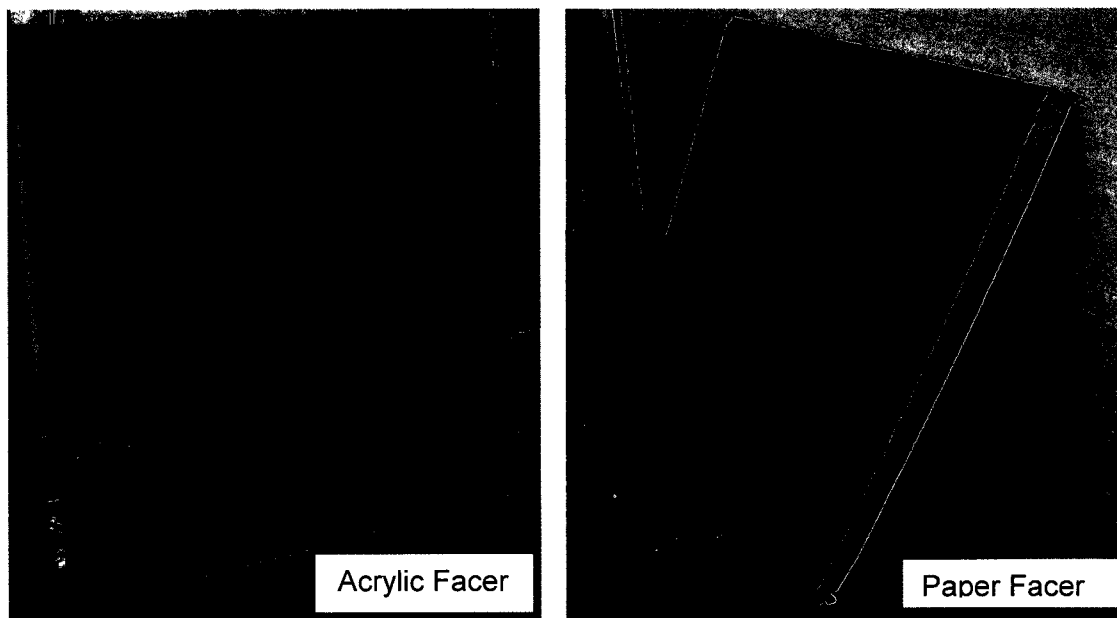
While based on the capability of water vapour, the *polyisocyanurate* insulation can be divided into three classes as below:

Class 1:  $\leq 15 \text{ ng}/(\text{pa.s.m}^2)$

Class 2:  $> 15 - \leq 60 \text{ ng}/(\text{pa.s.m}^2)$

Class 3:  $> 60 \text{ ng}/(\text{pa.s.m}^2)$

The water vapour capability depends on the nature of the facer rather than the foam. Typically this roofing insulation is made with an organic glass reinforced facer and supplied as a Type 2, Class 3 product. A relatively new facer, Acrylic Glass reinforced facers are non organic, have low water absorption and can be considered “low permeance”, suitable for accepting self-adhered membranes, hot asphalt and adhesives. This newest generation of facer *polyisocyanurate* has many desirable qualities that make it ideal for use in commercial construction.



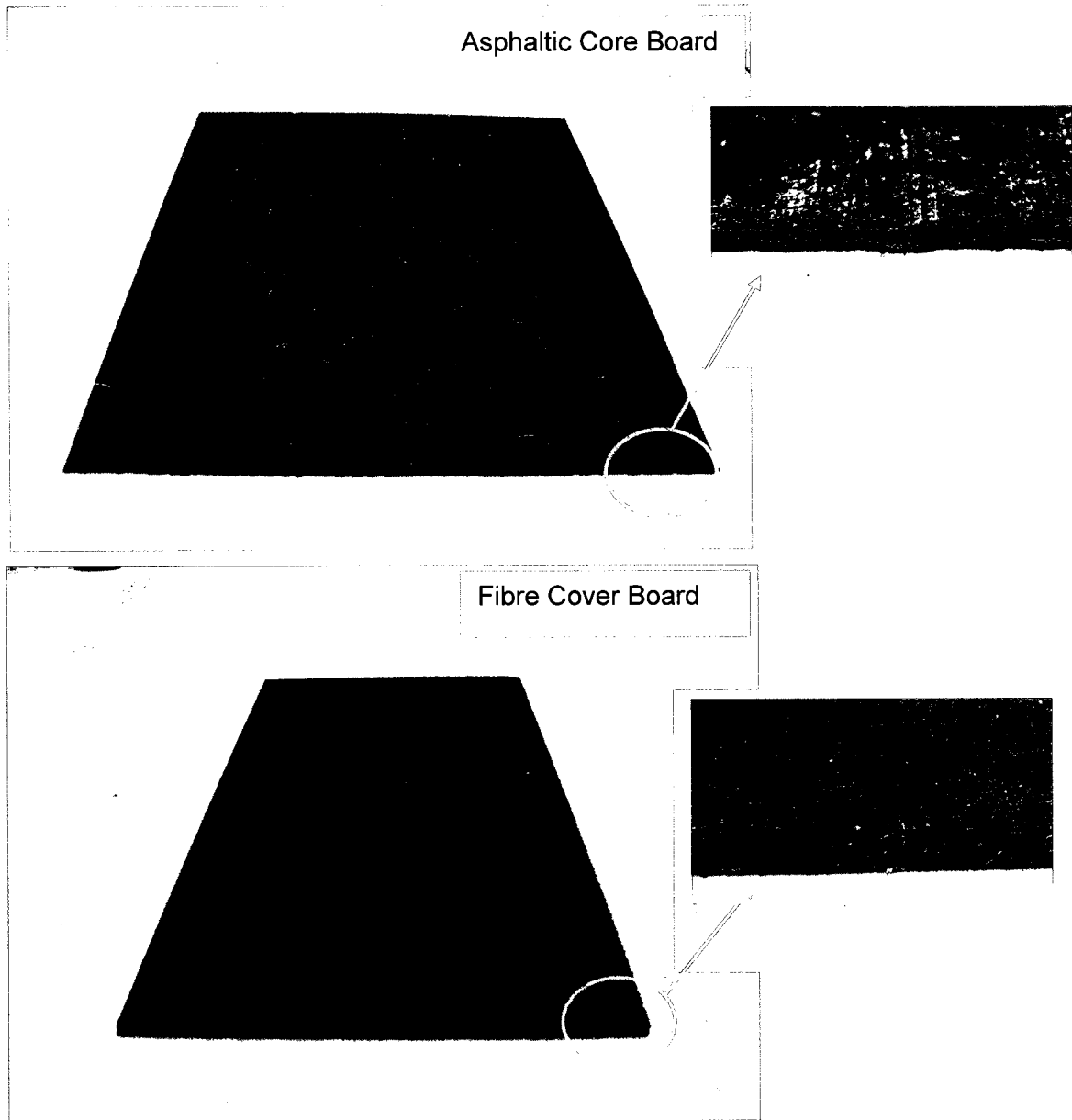
**Figure 3.4** Insulation Boards and Different Facers

### 3.2.4 Cover Board (CB)

Cover boards can enhance the performance of roof assemblies in terms of compressive strength, protection against mechanical damages, protection against heat during torch applications, reduction of the risk of performance problems associated with condensation within the roof assembly, and protection against solvent attack or chemical incompatibility. It also acts as a moisture buffer between the insulation and the membrane, enhancing thermal resistance as well as fire resistivity. There are several types of cover board available, such as asphaltic core board, wood fibre cover board, perlite cover board, gypsum cover board and cementitious cover board. The present study used two types of cover board; Asphalt and Wood fibre cover boards. These two types of cover board are the most commonly used for AARS.

- *Asphaltic Core Boards* comprise a asphaltic core between two non-woven glass fibre mats as indicated by ASTM D6506. It can be produced with a smooth surface on both sides or with plastic films for specific applications. Glass facers enhance fire resistivity while the asphaltic core promotes good membrane adhesion. They are commonly produced in 3mm (1/8"), 4.5mm (3/16") and 6mm (1/4") thicknesses.
- *Fibre Cover Boards* are made from wood fibres bonded together using heat, pressure and asphalt resin according to CAN/ULC S706-02. They are produced in various densities and can be coated or impregnated with asphalt emulsions

to increase moisture resistance and promote membrane adhesion. Common thicknesses are 11mm (7/16") and 12.5mm (½").



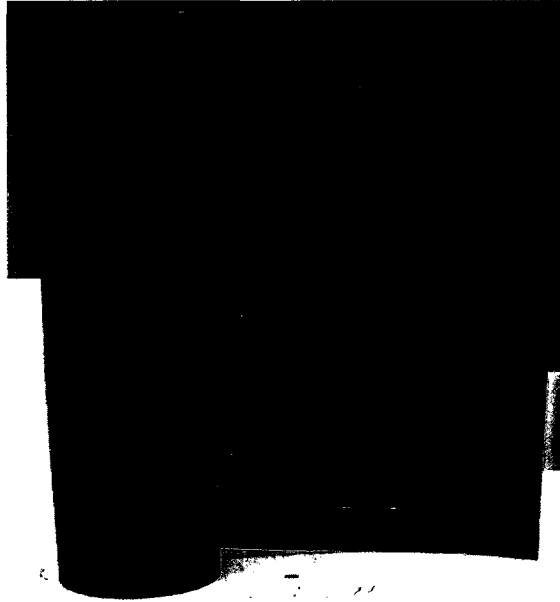
**Figure 3.5** Typical Cover Board Used in the AARS

### 3.2.5 Membranes

The membrane is the most essential part of the AARS assembly. This is because of its position at the top layer of the roof, this having direct interaction with the weather. Membranes need to be able to serve as waterproofing agents, sustain stresses from building movement and thermal changes. In AARS, membranes normally consist of two layers, the base sheet and the cap sheet. Section 3.2.5.1 and Section 3.2.5.2 briefly outline the constituent materials as well as their functions.

#### 3.2.5.1 Base Sheet (BS)

The base sheet membrane is constructed from an inorganic reinforcing mat of durable high strength non-woven glass fibres, which is coated and impregnated with *styrene-butadiene-styrene* (SBS) modified bitumen. SBS is a rubber-type modifier that gives bitumen the ability to stretch and resist damage, and improves its cold temperature flexibility (Liu et al 2000). The surface of the base sheet membrane is covered with thin poly-film while the underside is sanded to allow installation on heat sensitive substrates. The base sheet membranes, normally 1 meter in width, must satisfy the requirements of CGSB-37.56-M as well as ASTM D6163 for Type I, Grade S materials. Figure 3.6 illustrates the typical physical appearance of the base sheet membrane used for AARS application.



**Figure 3.6** Typical Base Sheet Membrane for AARS

#### 3.2.5.2 Cap Sheet (CS)

The cap sheet membrane is constructed using a reinforcing mat of durable non-woven polyester, same as the base sheet membrane. It is also coated and impregnated with the SBS modified bitumen. The main difference in comparison to the base sheet membrane is coloured ceramic mineral granules that cover the surface of the cap sheet membrane to provide protection against ultraviolet rays while at the underside is sanded to allow installation on heat-sensitive substrates via mopping asphalts or cold adhesive applications. The manufacturing of the cap sheet membrane should be in accordance with CGSB 37.56-M for Class G, Type 2, and Grade 2 materials and should also fulfil the requirements prescribed in the ASTM D6164 for Type I, Grade G materials. The width of the cap sheet membrane

is about 1 m similar to base sheet. Figure 3.7 illustrates the typical shape of cap sheet membrane.



**Figure 3.7 Typical Cap Sheet Membrane for AARS**

### **3.3 Mock-up Preparation**

#### **3.3.1 Overview**

This section presents the steps performed in the mock-up construction. It provides information on how the AARS components were layered to produce a complete AARS roof assembly. The techniques used to attach the roof-components as well as the adhesives are also described. Additionally, the detailed component layouts for the mock-ups are discussed. In total, 30 full-scale mock-ups were constructed for the study.

### 3.3.2 Roof Deck

The type of roof deck selected and used for the study was a steel deck rather than other available deck types. The profiled 22-gauge steel decks were cut and arranged to form a mock-up size of 1.98 m x 3.04 m (6.5 ft x 10 ft). Two steel joists were placed under the steel deck; one at the distance of 91.4 cm (3 ft) from centre-to-left and another at the same distance from centre-to-right. The two joist locations provided a joist-spacing of 1.82 m (6 ft) for the mock-up. The steel deck was attached to the steel joists using deck screws, *12/24-11/4 Hex Tek Screws*, as shown in Figure 3.8. The deck screws were installed on the female flutes of the deck with a spacing of 15.2 cm (6 in) parallel to length of the steel joists. Figure 3.8 illustrates the typical steel deck installation used for the study and the two methods of adhesive application that were used to attach the vapour barrier.

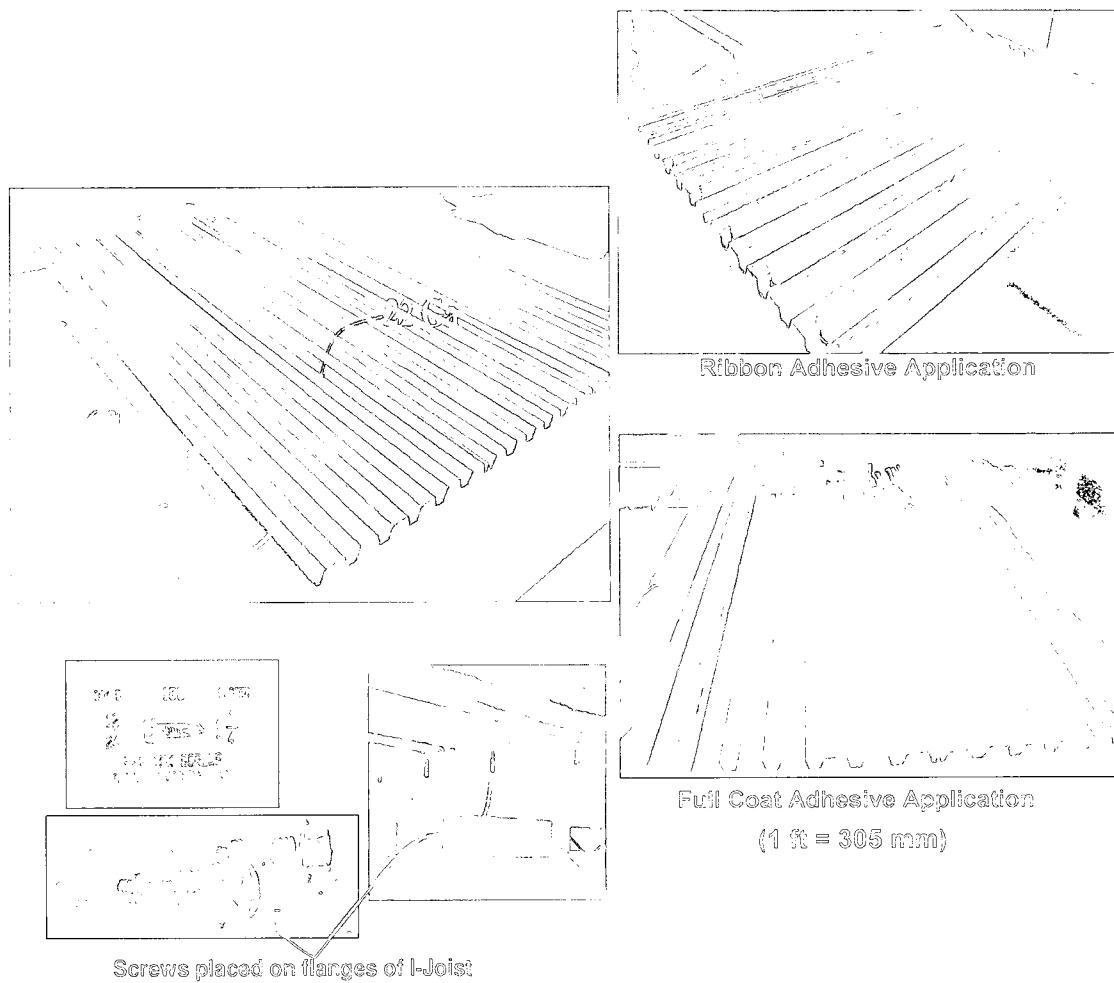
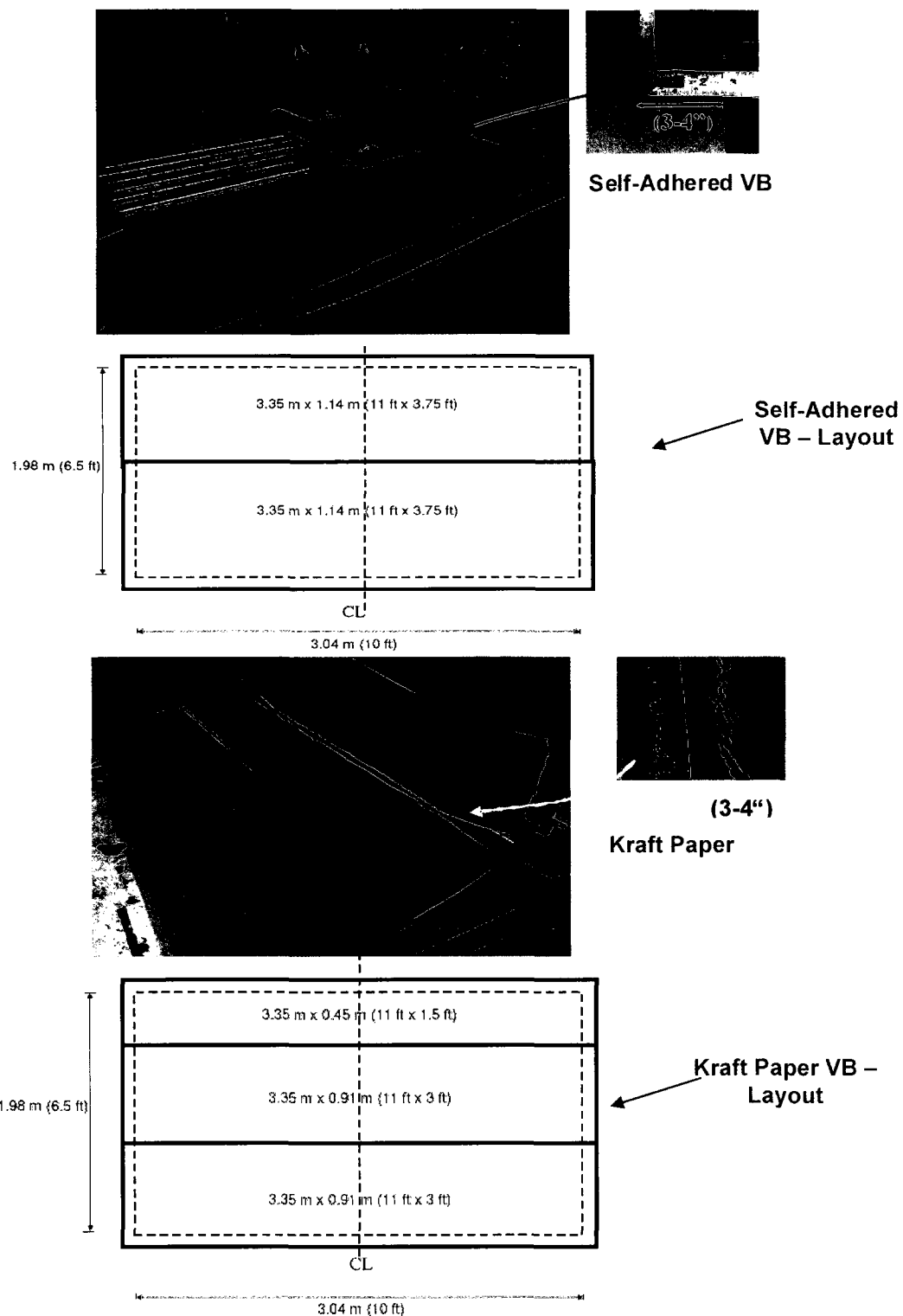


Figure 3.8 Typical Installations and Two Adhesive Applications on the Steel Deck

### 3.3.3 Vapour Barrier (VB)

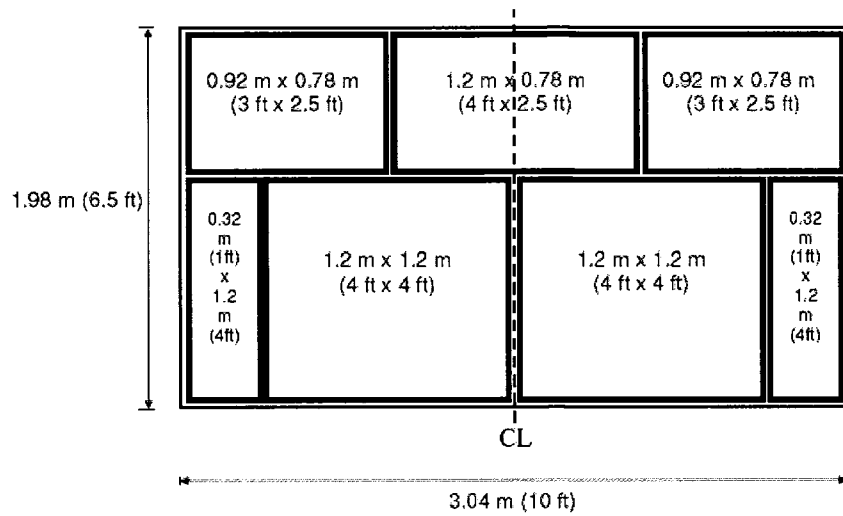
Two types of vapour barriers were used for the study, a self-adhered VB (Woven polyethylene) and an adhered VB (Kraft paper). Detailed information for both VB materials is found in Section 3.2.2. The installation of these VB materials was performed in a slightly different way for each type of VB. A primer was applied on the steel deck before the self-adhered VB was installed. In contrast, the primer liquid was not necessary when the adhered VB was used. The difference in VB size also led to two different VB-component layouts as shown Figure 3.9. Regardless of the VB type, the VB was cut to a length of 3.35 m (11 ft), about 0.3 m (1 ft) longer than the mock-up specimen length, this was 3.04 m (10 ft). This additional length was required to prevent air leakage during testing. To construct the mock-up in the width of 1.98 m (6.5 ft), the VB were placed overlapping each other. The overlap varied from 76.2 mm (3 in) to 101.6 mm (4 in) as shown in Figure 3.9. Similar way as the mock-up length was also used for the mock-up width, namely the width of VB was made about 0.3 m (1 ft) longer than the specimen size. Figure 3.9 also illustrates the two different adhesive application techniques used to attach the Kraft paper VB to steel deck. The ribbon or full-coat adhesive application technique shown in Figure 3.8 was used for adhering the Kraft paper VB.



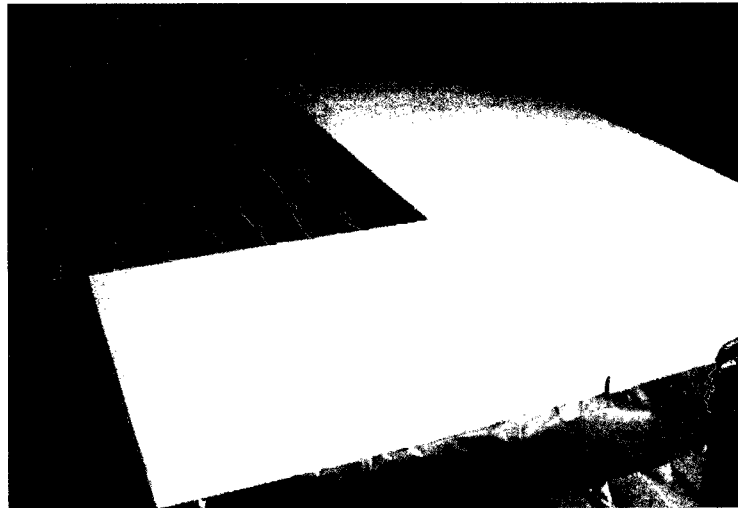
**Figure 3.9** Typical Vapour Barrier Installation in the AARS Mock-up Construction

### 3.3.4 Insulation

The *polyisocyanurate* (ISO) thermal insulation with two different facer types, a paper facer and an acrylic facer, was used as explained in Section 3.2.3. The insulation was cut from its original full board size of 1.2 m x 1.2 m (4 ft x 4 ft) into smaller board sizes. This was done to provide at least two joints along the mock-up length (3.04 m /10 ft) and one joint along the mock-up width (1.98 m /6.5 ft). Insulation adhesives were applied on vapour barriers of the mock-up and then the boards were placed in accordance with the insulation layout shown in Figure 3.10. Figure 3.10 also illustrates the adhesive application techniques used for attaching the insulation boards to the VB. The adhesive was applied in a way called the *ribbon* application technique. The ribbon technique applies the adhesive in lines or strips that are parallel to the length of the mock-up with about 0.3 m (1 ft) distance between one to another. The photo in Figure 3.10 shows the typical insulation installation process performed during the mock-up fabrication.



**Insulation Layout**



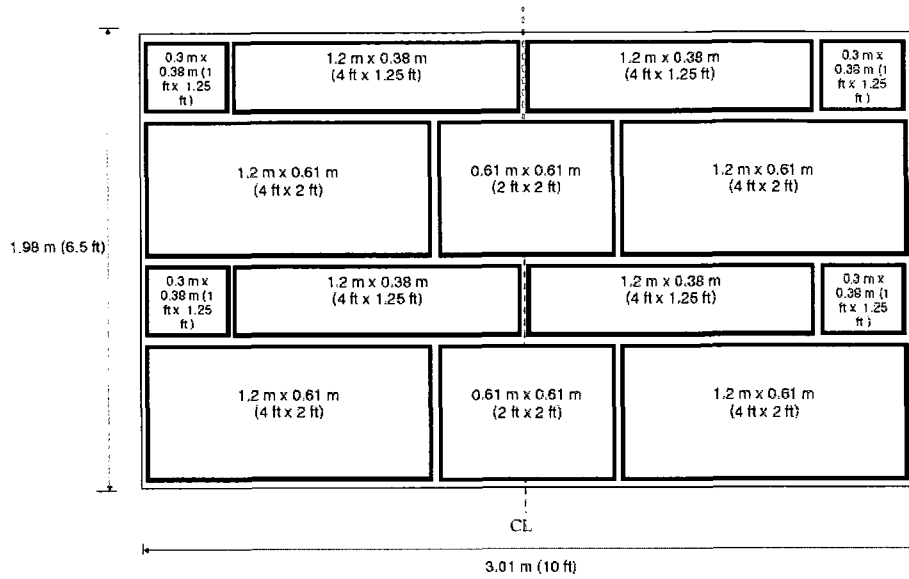
**Insulation Installation Process**

**Figure 3.10** Detail of the Insulation Board Installation and Layout

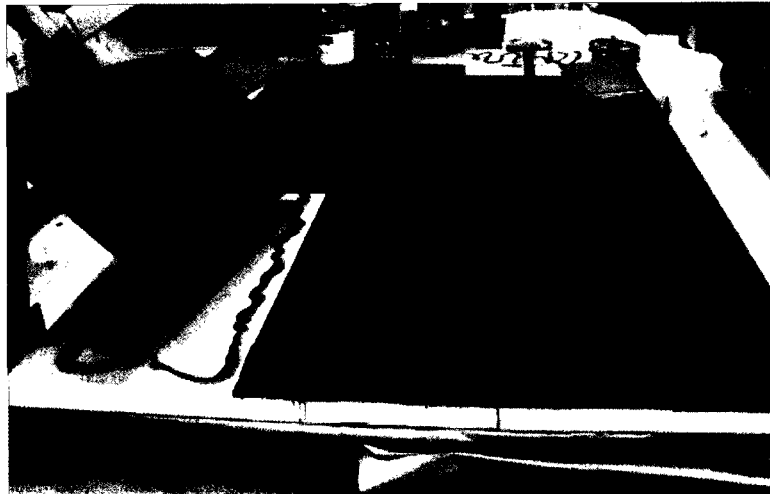
### 3.3.5 Cover Board

Two types of cover boards, asphaltic core board (ACB) and fibre cover board (FCB), were used in the study. Information about the two cover boards can be obtained in Section 3.2.4. The cover boards were also cut into smaller sizes. The boards were then placed on top of the insulation boards. Placement of the cover board followed either one of the two cover-board layouts depending on the type of cover board selected for the test mock-up. Figure 3.11 and Figure 3.12 illustrate the layout used for FCB and ACB, respectively. Two layouts exist because of the difference in board sizes of ACB and FCB. The full size of the FCB and ACB are 0.6 m x 1.21 m (2 ft x 4 ft) and 1.52 m x 1.21 m (5 ft x 4 ft), respectively.

Two methods of adhesive application technique were used for attaching the cover board to the insulation board as also shown in Figure 3.11 and Figure 3.12, the ribbon method and the full coating method. The bottom photo of Figure 3.11 illustrates the ribbon adhesive application while the bottom photo of Figure 3.12 shows the full coat application method. The ribbon method was a beading application method with a clearance of about 30 cm (12 in) between beads. The full coat adhesive application involves the application of adhesive over the whole surface of the insulation board. The adhesive thickness for both application methods was 2 to 3 mm. Note that it was not easy to control the thickness of adhesive during its application. To investigate the effect of adhesive thickness on uplift performance, a numerical study, using finite element modelling, was performed. This numerical study is explained in Chapter 9.

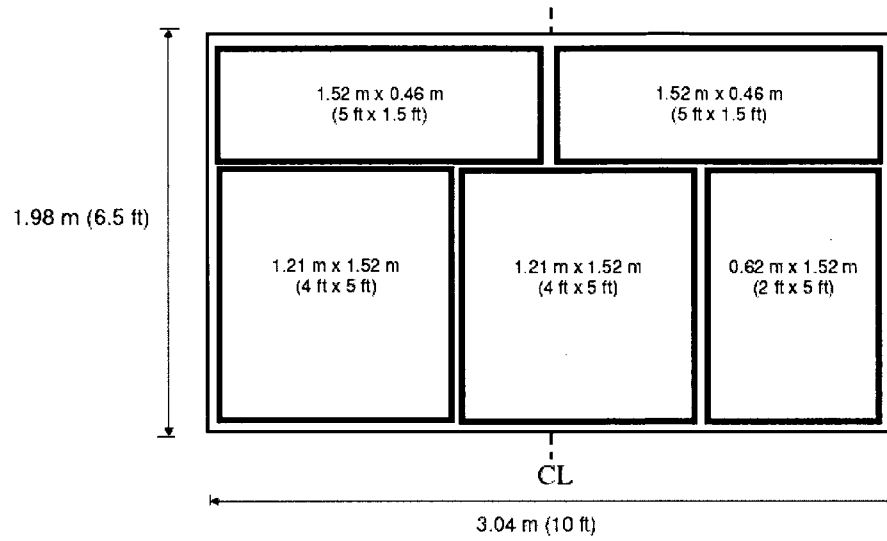


Fibre Cover Board Layout

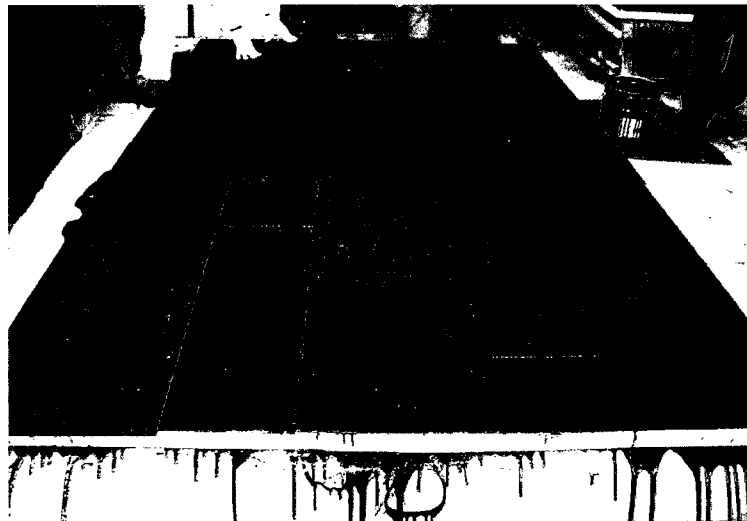


Fibre Cover Board Installation

**Figure 3.11** Fibre Cover Board (FCB) Layout and Installation



**Asphaltic Core Board Layout**

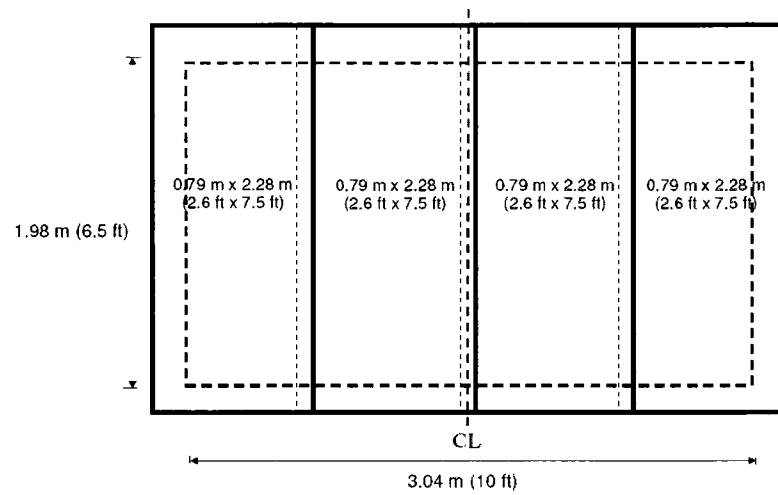


**Asphaltic Core Board Installation**

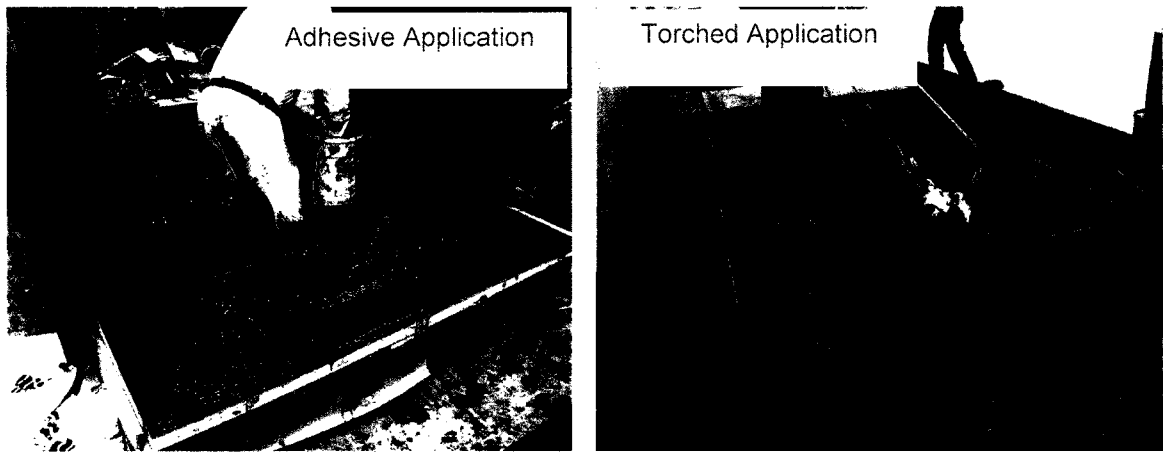
**Figure 3.12 Asphaltic Core Board (ACB) Layout and Installation**

### 3.3.6 Base Sheet (BS)

SBS modified bitumen membranes were used as the base sheet. Further information on the membrane can be found in Section 3.2.5.1. The base sheets were cut to 2.28 m (7.5 ft) in length and placed perpendicular to the steel deck flutes (Figure 3.13). Once the base sheets were cut, they were placed, overlapping, to form a length of 3.35 m (11 ft). The 3.35 m (11 ft) consisted of the 3.04 m (10 ft) mock-up length plus an extra of 0.3 m (1 ft) for the overhangs. Each of overhangs was 0.15 m (0.5 ft) from the edge of the testing mock-up. The overlap of membrane sheet was 0.076 m - 0.1 m (3 in - 4 in). For the attachment of the base sheets, two techniques were used. The first was to use adhesive on the whole surface of the cover board as shown in bottom left side of Figure 3.13. Second was to apply a torching method. This method was performed by torching the bottom side of the base sheet which is bonded to the cover board. The bottom right side photo of Figure 3.13 shows the torching technique for bonding the base sheet to the cover board. The overlapping size for the base sheet was the same in both cases. The only difference between these two methods was that when the adhesive technique was used, the adhesive needed to be re-applied on the overlapping seam membrane prior to laying down the other base sheet membrane, while the torching technique is performed only once during the torching process.



Base Sheet Layout

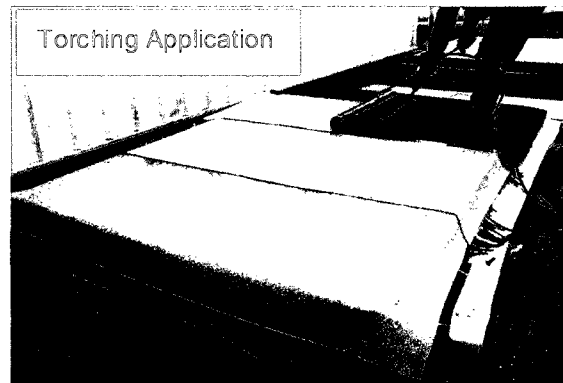
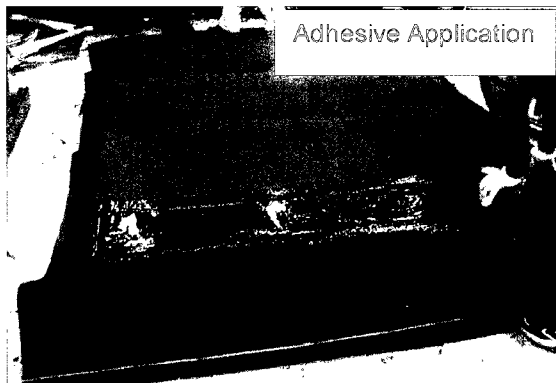
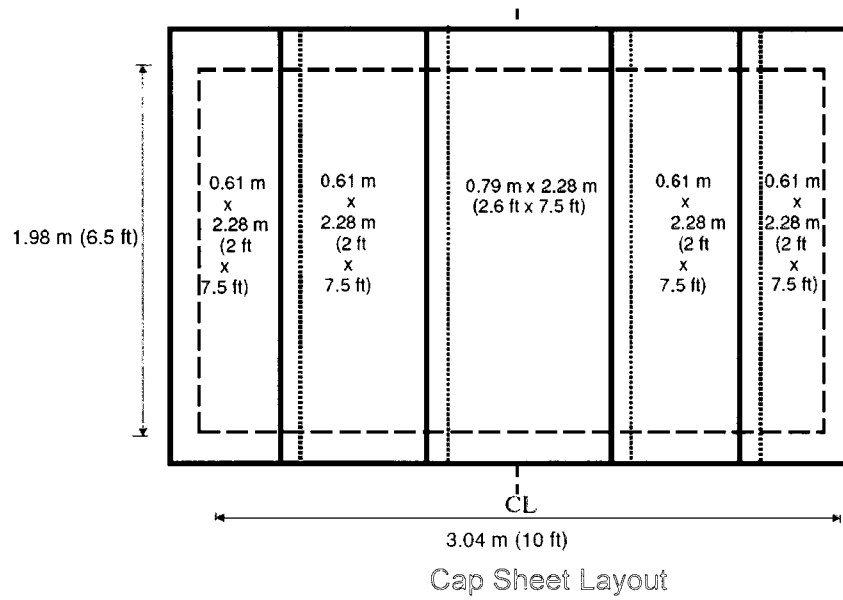


Base Sheet Installation

**Figure 3.13** Base Sheet Layout and Installation

### 3.3.7 Cap Sheet (CS)

SBS modified bitumen membranes were used as the cap sheet (CS) membranes. They were similar in type to that of the base sheet. They were cut into five pieces and each piece of cap sheet membrane was 2.28 m (7.5 ft) long. Out of five pieces of cap sheet membrane, four pieces were cut into the same width, 0.61 m (2 ft). This was done to create a staggered alignment of the base sheet and cap sheet membranes as shown in the cap sheet layout of Figure 3.14. The bottom photo of Figure 3.14 shows the cap sheet membrane application during the mock-up fabrication. The cap sheet membranes were placed perpendicular to the steel deck flutes in the same way as the base sheets. In order to form a properly size mock-up, the five cap sheet membranes were overlapped with a seam size of 0.076 m - 0.1 m (3 in - 4 in) and placed parallel to the steel deck flute. Similar to the base sheet membranes, two attachment techniques were used, namely, an adhesive application technique and a torching technique. The adhesive application technique used an adhesive membrane that was applied on the whole surface of the base sheet membranes prior to placing the cap sheet membranes. The torching technique used a gas torch to melt the asphalt portion from the back of the cap sheet membrane. The melting asphalt liquid produced a glue-like agent to adhere the cap sheet membrane to the base sheet membrane. The two techniques used to attach the cap sheet membrane to the base sheet membrane are shown in the bottom photo of Figure 3.14.

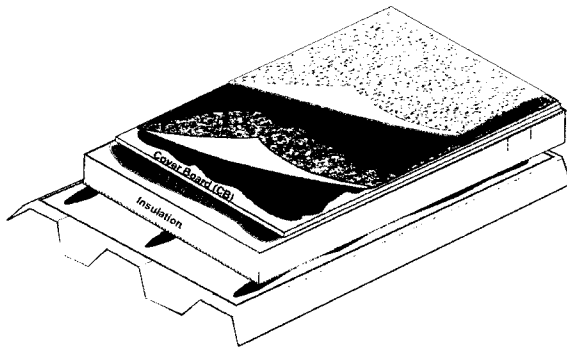


Cap Sheet Installation

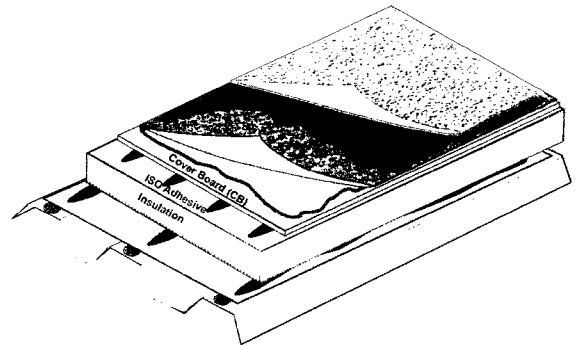
**Figure 3.14** Cap Sheet Layout and Installation

### 3.4 Fully and Partially Adhered Groups

The test mock-ups were classified into two groups, Fully Adhered and Partially Adhered. These were so-named because of the method of adhesive application between the insulation board and cover board. For the fully adhered mock-up group, adhesive was applied to cover the whole surface of the insulation board, whereas the partially adhered group has adhesive applied in beads or strips. In practise, the beads or strips adhesive application is also known as ribbon adhesive application. Figure 3.15 illustrates a typical example of these differences side by side. The fully adhered group consisted of the mock-ups M-2 and M-4, while the mock-ups M-1 and M-3 were called the partially-adhered group.



a) Typical Isometric Diagram of Fully-Adhered Group



b) Typical Isometric Diagram of Partially-Adhered Group

**Figure 3.15** Fully-Adhered and Partially-Adhered (not to scale)

### **3.5 Concluding Remark**

The AARS definition and features as well as the typical mock-up construction were outlined. In addition, this chapter also described the differences in AARS such as the difference in terms of roof components, method of adhesive application, type of adhesive, and the constructing ability of AARS assemblies. These differences could vary the AARS wind uplift resistance performance. To investigate the influence of these factors on the wind uplift resistance capacity, further research was needed. One way to deal with this issue was to establish an appropriate test method so that the AARS performance could be evaluated. In general, the information presented in this chapter could also be used by roof designers to understand the design characteristics of AARS for their suitability in roofing applications.

## **Chapter 4. Wind Uplift Response of Rigid and Flexible System**

### **4.1 Introduction**

Rigid roofs such as AARS response differently under wind action compared to flexible roofs such as MARS. Figure 4.1 shows a flexible roof system response due to wind actions and compares it with that of during full scale test under simulated wind loading conditions. Similarly Figure 4.2 illustrates the rigid system response. In the case of flexible systems, membrane deformation (ballooning) between attachment lines induces tensions on the membrane. The two figures show clearly that the two systems exhibit different responses due to aerodynamic forces. Figure 4.3 shows typical failures of flexible and rigid roof systems. Figure 4.4 shows force dissipation diagrams of rigid and flexible roofs. The wind uplift performance of rigid roof can be characterized as load transfer in which all components unite together and share the wind uplift forces. In the rigid roof, wind loads are distributed over a roof area. For the flexible roofs, the performance can be classified as structural load transfer or a linear load path in which most of membrane tension is transferred to the structural deck through fasteners. The different response between flexible roof and rigid roof may influence the wind-induced pressure fluctuations and distributions. Hence it could affect the CSA A123.21-04 loading test mechanism to determine the wind uplift resistance. The CSA 123.21-04 standard in its current version may need to be modified in order to evaluate the rigid system response.

In order to study the difference between rigid and flexible roof system response, two methods of analysis were performed. The first method analysed the probability distribution functions and the second method analysed the power spectral density functions on the pressure time histories from wind tunnel testing. The rigid model data were compared with the SIGDERS data representing the flexible system response (Savage et al, 1996 and Baskaran et al, 1996). This chapter discusses the comparison results between rigid and flexible roofs using the results obtained from these two analysis methods.

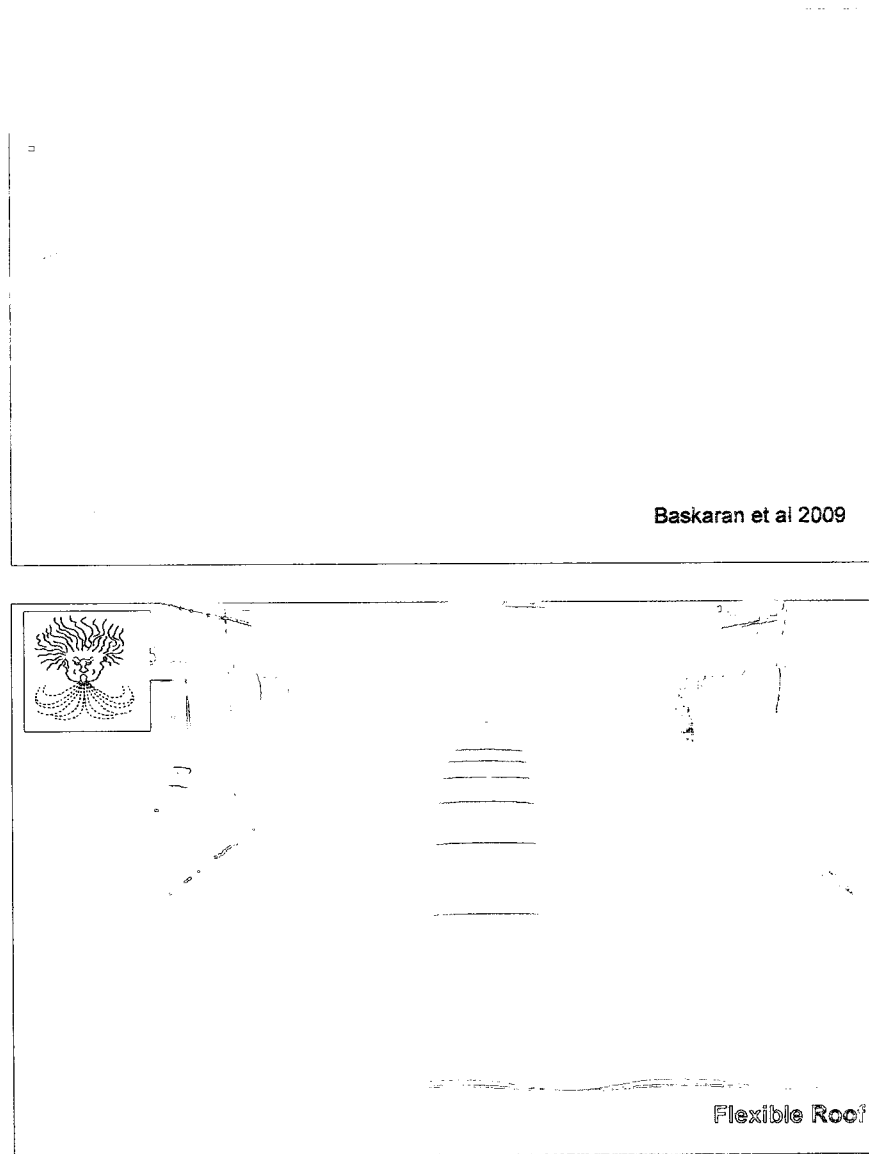
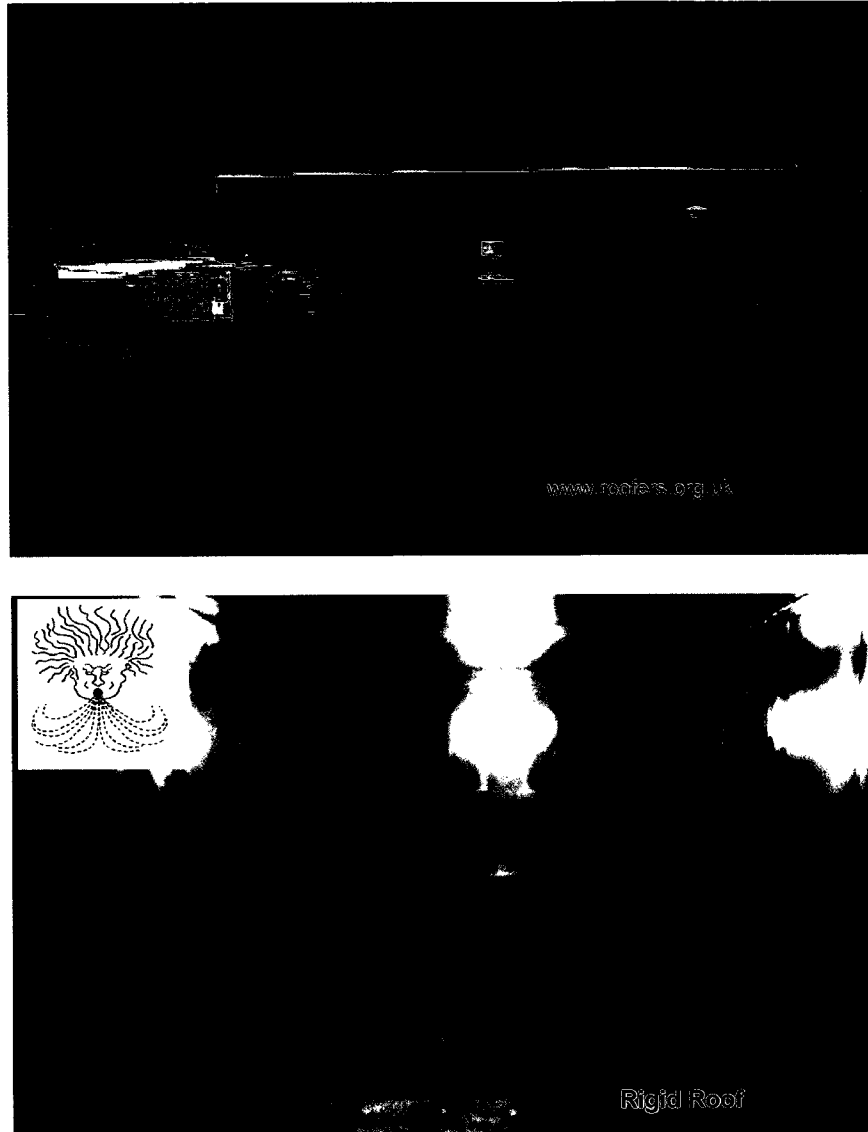
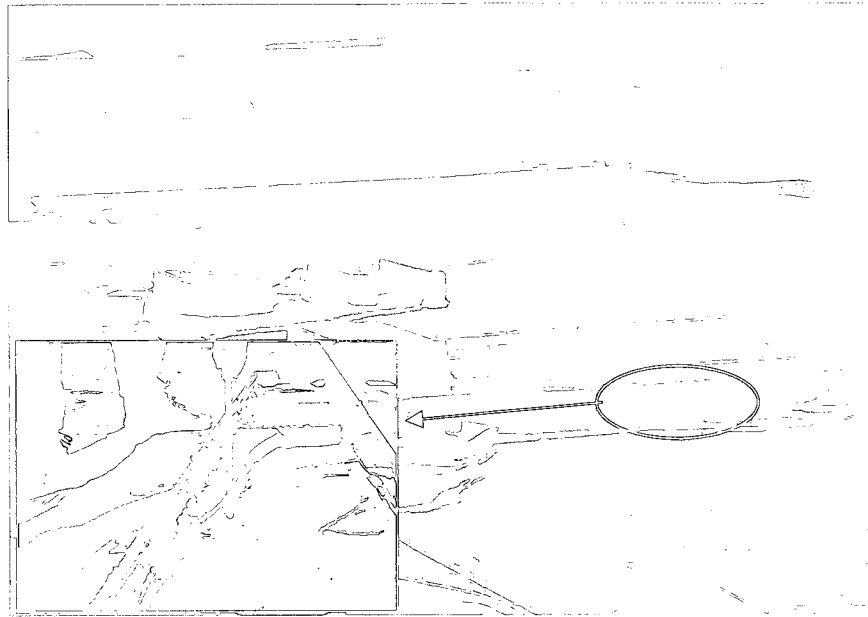


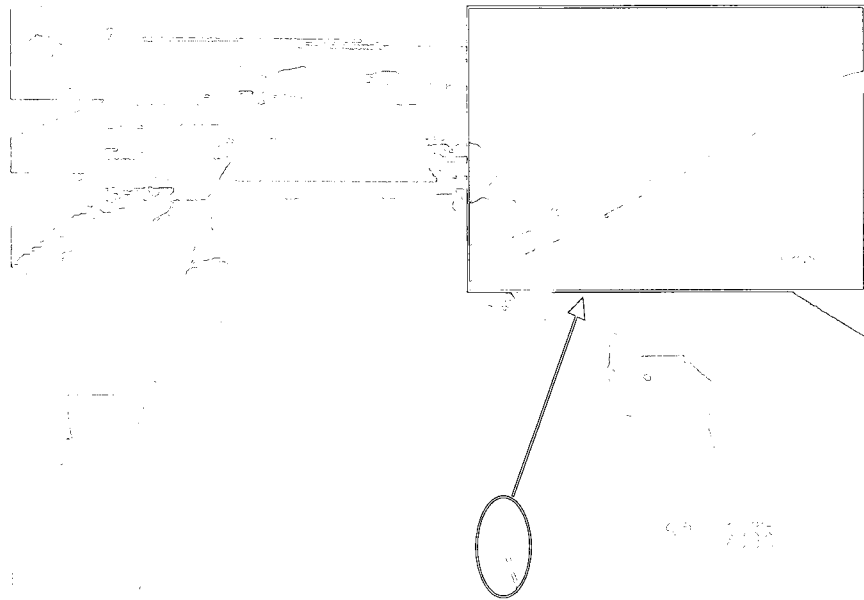
Figure 4.1 Flexible Roof Response Under Wind Actions and Simulated Wind Pressure Conditions



**Figure 4.2** Rigid Roof Response Under Wind Actions and Simulated Wind Pressure Conditions

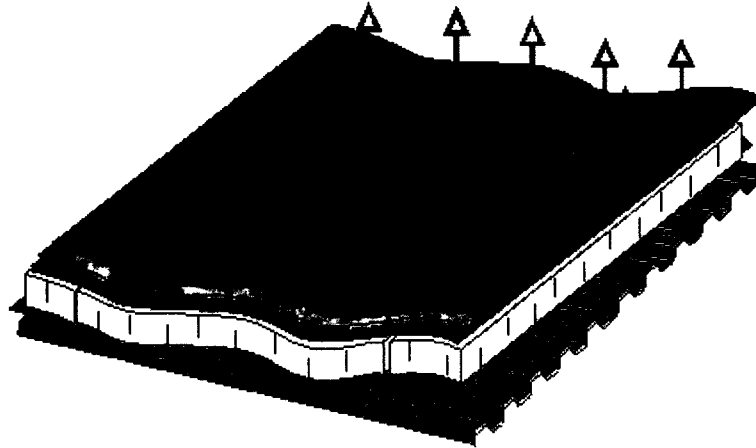


**Rigid Roof Failure**  
(Courtesy of RICOWI)

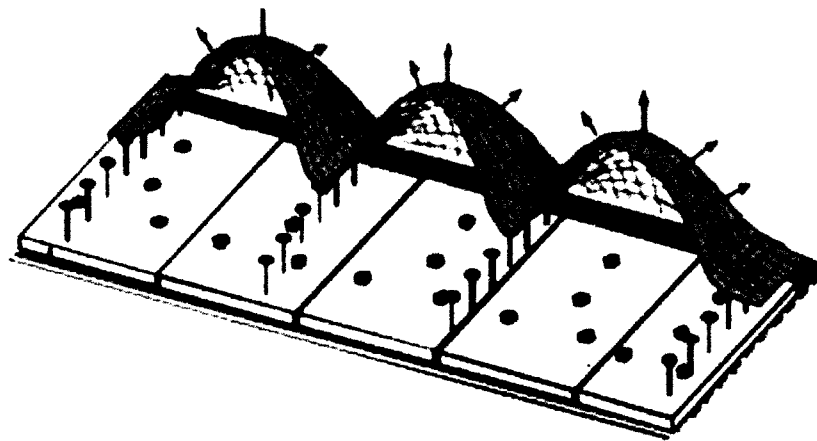


**Flexible Roof Failure**  
(Courtesy of RICOWI)

**Figure 4.3 Typical Field Failures of Rigid and Flexible Roofs**



Force Dissipation Diagram for Rigid Roof



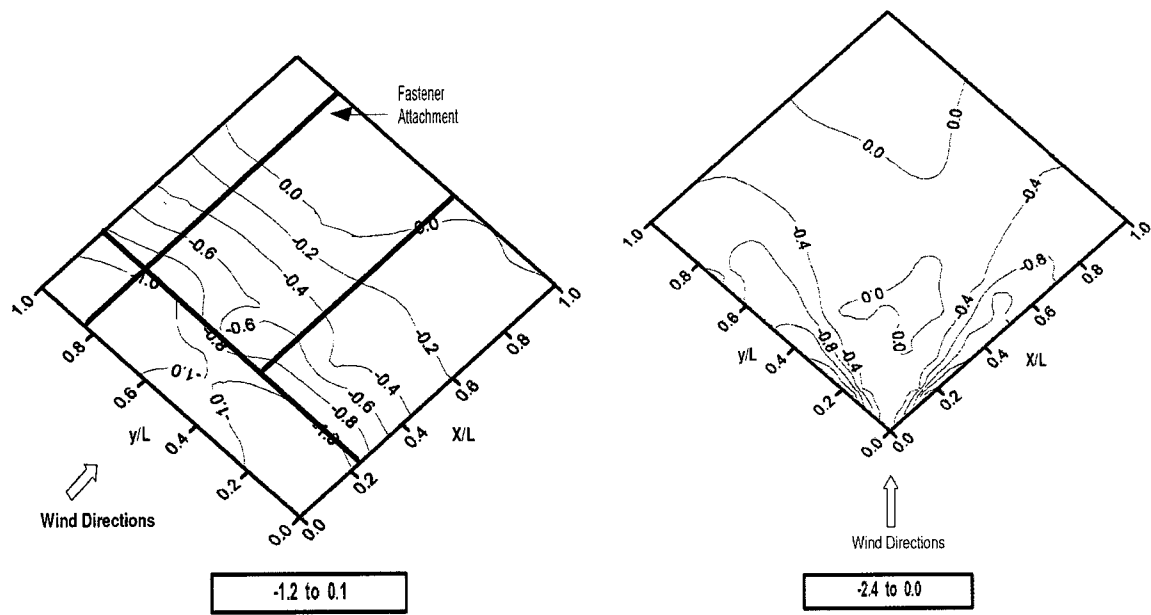
Force Dissipation Diagram for Flexible Roof

**Figure 4.4** Rigid vs Flexible Roofs: Force Dissipation Diagram

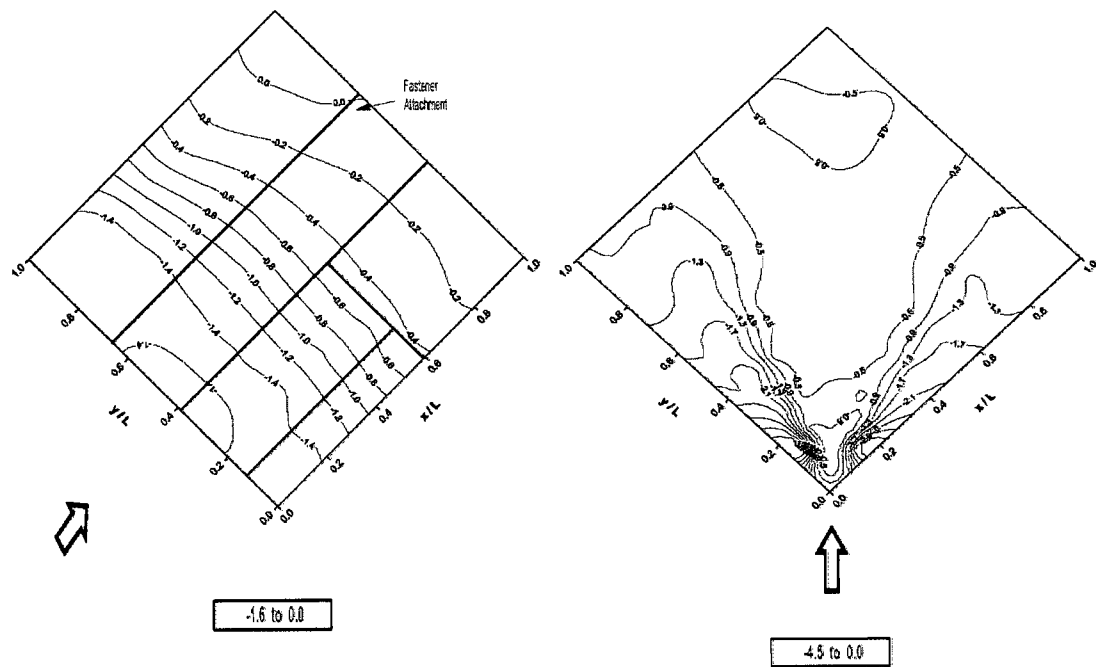
## **4.2 Wind Tunnel Data on Models with Flexible Roofs**

SIGDERS was formed in 1994 by the National Research Council Canada (NRCC) and its members include roofing contractors' associations, manufacturers, and building owners / managers. The research activities initiated by SIGDERS have made a significant contribution to the Canadian roofing community. Among them is the development of the dynamic testing procedures for the evaluation of the wind uplift performance of MARS (CSA A123.21-04). As mentioned in Chapter 2, this testing procedure is the only dynamic testing procedure available within the North America that considers simulated wind-induced dynamic effects. Thus, the response of roofing tested using this procedure can be compared to performance in the field.

The SIGDERS load cycle was based on wind tunnel studies using a full scale model of the flexible membrane roofing systems (3 m by 3 m). Wind tunnel experiments were carried out under open country exposure at the NRCC's 9 m by 9 m wind tunnel. Further details of the wind simulation data and configurations tested are available elsewhere (Savage et al 1996; Baskaran et al 1996; Baskaran et al 1997; Chen and Baskaran 1997; Baskaran et al. 1999a,1999b). Thirty and forty-eight roof configurations for PVC and EPDM, respectively, were tested. Figure 4.5 shows typical pressure coefficient contour plots from the two different types of membrane used during SIGDERS wind tunnel test. Pressure taps were installed on the roof assemblies and the data collected from the pressure taps were analyzed by the rain flow counting (RFC) method. The data analysis resulted in establishment of the SIGDERS dynamic load cycles as illustrated in Figure 2.6. The load cycle has been adopted by the CSA 123.21-04 as load testing protocol to evaluate MARS.



(a)



(b)

**Figure 4.5** a) Pressure Coefficient Contour Plot for PVC and b) Pressure Coefficient Contour Plot for EPDM (Baskaran and Savage, 2003)

### 4.3 Wind Tunnel Data on Models with Rigid Roofs

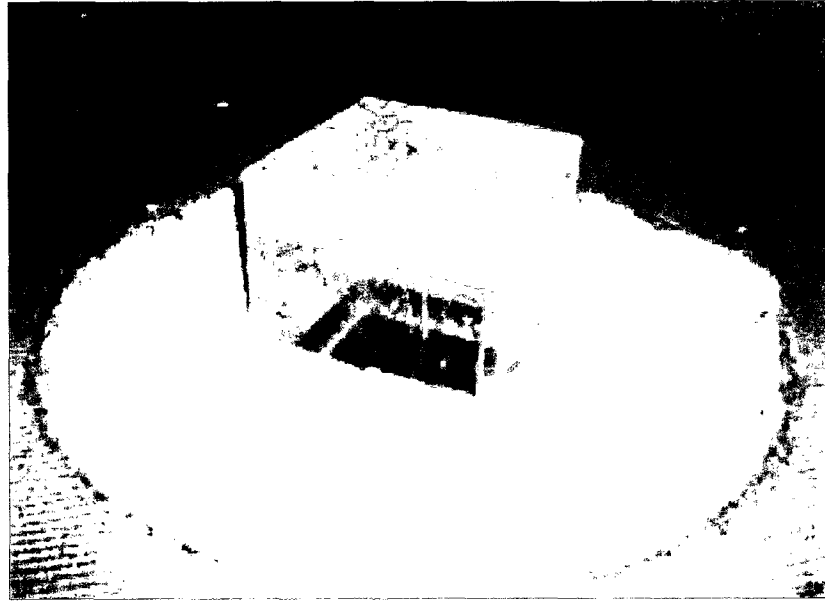
The results from the wind tunnel test carried out at the Concordia University by Stathopoulos (2008) were used in the present study. The wind tunnel model was rigid and was made of Plexiglas. The roof had 15 pressure taps and was tested under open exposure conditions for three different building heights, three different building aspect ratios and two different wind angles (Table 4.1). The time histories of measured pressure data obtained from the tests were converted into dimensionless pressure coefficients ( $C_p$ ) referenced to the building roof height. During the wind tunnel testing, the pressure time histories were collected using a sampling frequency of 418.75 Hz over a period of 64 seconds, resulting in 26800 data points for each pressure tap.

**Table 4.1** Test Condition and Configuration used for the Wind Tunnel Study with Rigid Roof

| Parameter               | Description                 |
|-------------------------|-----------------------------|
| Test condition          | Open exposure               |
| Height (ft / mm)        | 20/6.1, 40/12.2 and 60/18.3 |
| Roof aspect ratio       | 0.5, 1 and 2                |
| Wind angle (degrees)    | 0 and 45                    |
| Number of pressure taps | 15                          |

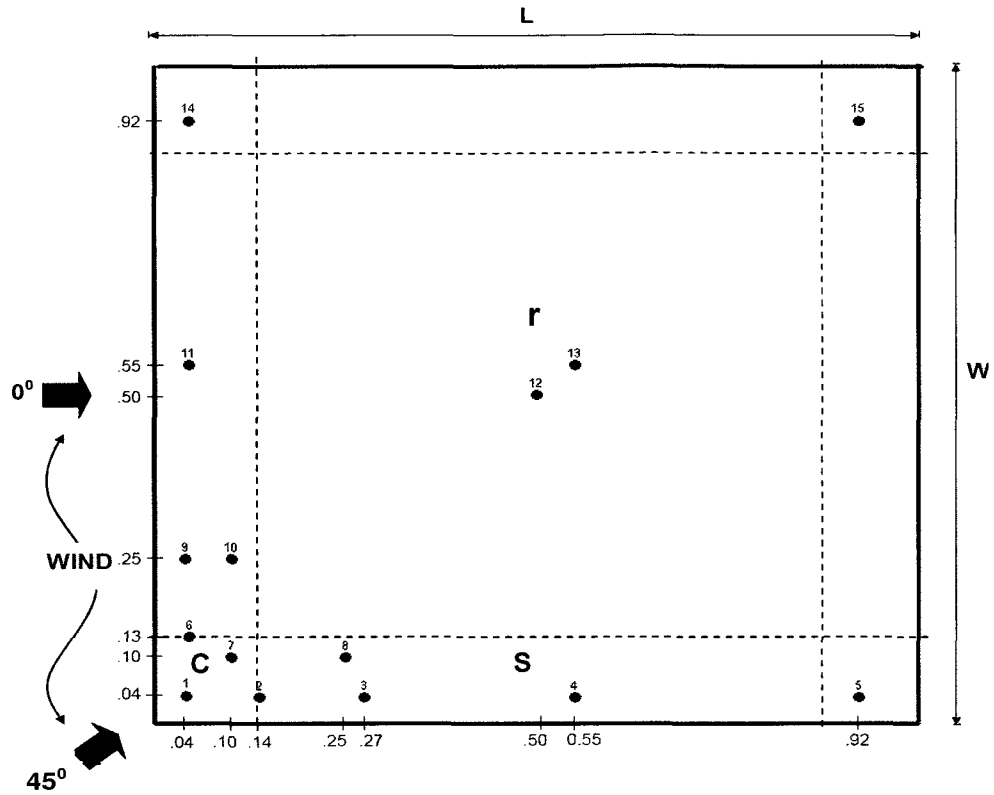
The test conditions and configurations presented in the Table 4.1 were specifically designed so that at a later stage these data could be compared with the previously collected data on flexible roofs. The open exposure was selected to be conservative; the selected building heights cover the different heights within the category of low-rise buildings. Three aspect ratios represent common building shapes conceivable for low slope application. The two wind angles were selected

to consider differences between the two extreme cases. Figure 4.6 shows the wind tunnel model with a rigid roof.



**Figure 4.6** Typical Wind Tunnel Model with Rigid Roof, Aspect Ratio =1,  $H/W=1$

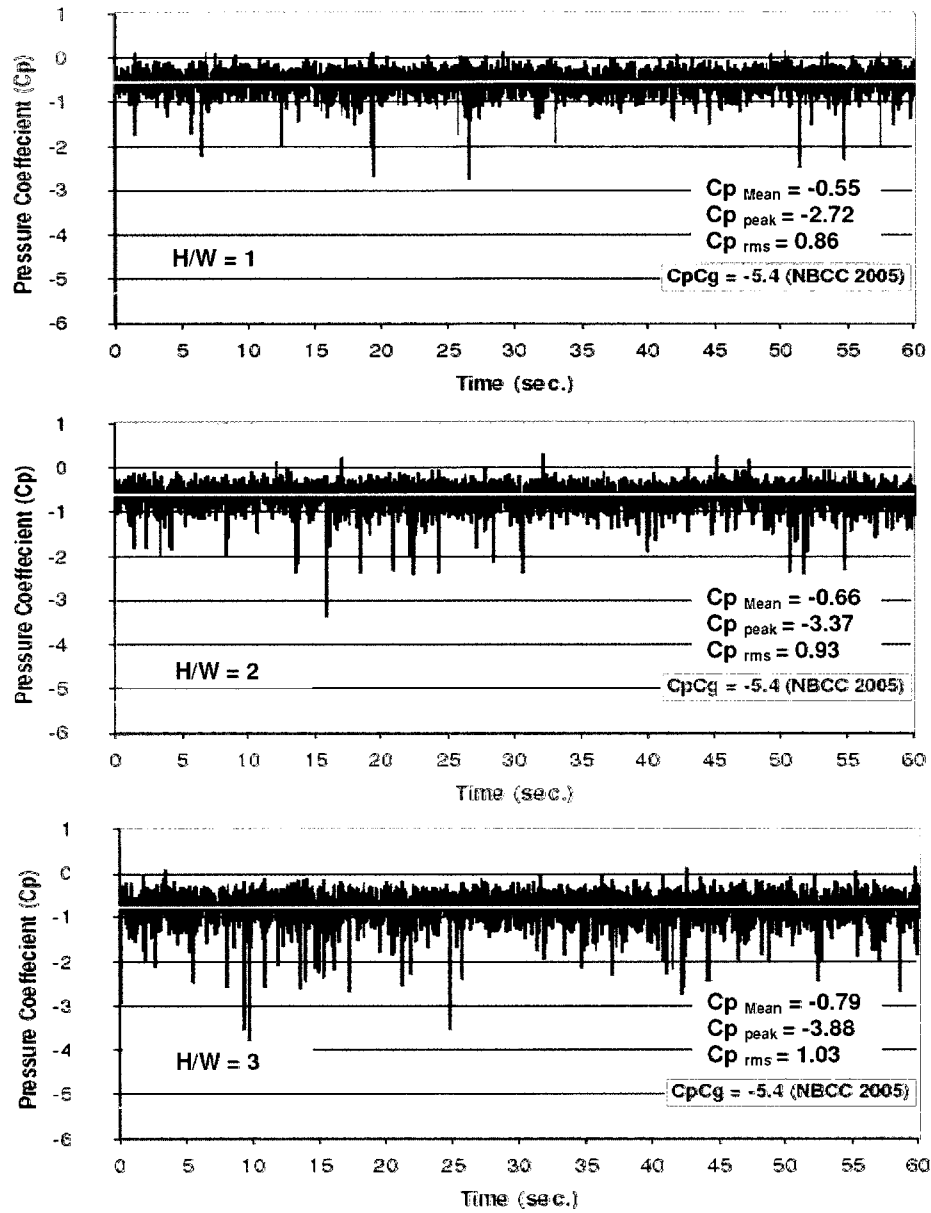
The locations of 15 pressure taps mounted on the wind tunnel model were determined in such a way that the collected data could be compared with the SIGDERS wind tunnel data to examine the difference of the wind effects between rigid and flexible roofs. Figure 4.7 indicates the locations of the 15 pressure taps. The coordinates are given in terms of the ratio to either building width ( $W$ ) or building length ( $L$ ). The intention was to provide general data that did not depend on the building width or length. Thus, the data collected can be compared to any wind tunnel data that has a similar set-up. For the purpose of data analysis, the pressure tap locations were divided into three roof zones, namely, corner (C), perimeter (S) and field (r) as illustrated in Figure 4.7.



**Figure 4.7** Pressure Tap Locations on the Wind Tunnel Model with Rigid Roof

#### 4.4 Response of the Wind Tunnel Model with Rigid Roof

In total, 270 time histories of measured pressure coefficients were obtained from the wind tunnel tests using rigid models for all test configurations and conditions in Table 4.1. Figure 4.8 illustrates a typical time history of a measured pressure coefficient. The graphs provide typical examples of the measured pressure coefficients time histories at three different heights. The data presented at each graph was collected from the same tap location (corner), roof aspect ratio (1), and wind direction ( $45^\circ$ ). The horizontal axis illustrates the time in seconds while the vertical axis gives the dimensionless pressure coefficients.

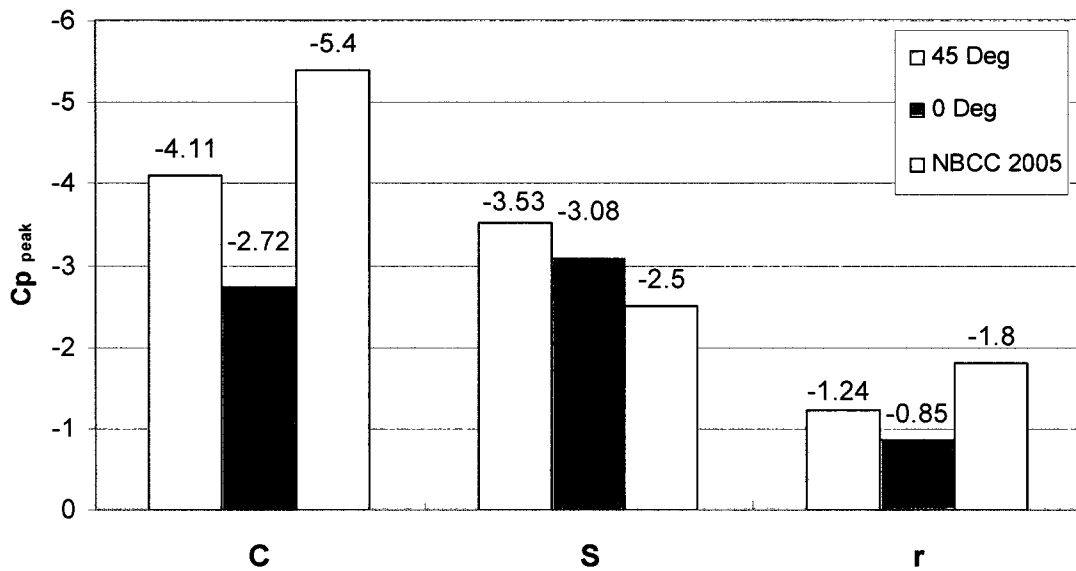


**Figure 4.8** Typical Suction Coefficient Fluctuations for a Corner Pressure Tap (roof aspect ratio = 1, wind direction = 45 degrees)

From the time histories, the mean, root-mean-square (rms) and peak values of the measured suction coefficient ( $C_p$ ) were calculated. Figure 4.8 indicates that the values of peak suction coefficient ( $C_{p\text{ peak}}$ ) were influenced by the building height. It also can be seen from the figure that for the ratio of building height over width of the building ( $H/W$ ) of 3 has the largest value of  $C_{p\text{ peak}}$  in comparison with the  $H/W$  ratio of 2 and of 1. The  $C_{p\text{ peak}}$  from the wind tunnel test can directly be compared to  $C_{pCg}$  value obtained from NBCC (2005). This is because the gust effect and aerodynamic shape factor have been incorporated during wind tunnel testing (Clause 20-structural commentary I, wind load and effects, NBCC, 2005). Regardless of  $H/W$  ratios, the value of  $C_{p\text{ peak}}$  was found to be lower than the value of  $C_{pCg}$  given in the National Building Code of Canada (NBCC, 2005).

Figure 4.9 shows the  $C_{p\text{ peak}}$  obtained from the pressure taps for the three roof zones, namely, Corner (C), Perimeter (S) and Field (r). This indicates that the  $C_{p\text{ peak}}$  varies across the roof surface. It was observed that the  $C_{p\text{ peak}}$  value was higher at the corner compared to other roof zones. This is due to the formation of vortices during wind flow. For the case of a  $0^\circ$  approaching wind angle, the worst pressure is known to occur beneath the vortices that form in the separated flow along the roof edge, while for the case of a  $45^\circ$  wind, it is caused by the dual conical vortices during cornering winds. Similar conditions in terms of pressure distribution contours were observed in other wind tunnel test investigations conducted by Simiu and Scanlan (1986), Lawson (1980), Chen and Baskaran (1997), Baskaran et al.(1997), Uematsu et al (1999), Stathopoulos et al (1999) and Banks et al (2000). Figure 4.9 also shows that the wind direction influences the

$C_{p_{peak}}$  values. For the perimeter zone, it was noticed that the  $C_{pCg}$  value based on NBCC (2005) was sometimes lower than the  $C_{p_{peak}}$  values obtained from the wind tunnel test. This could happen due to the vortex wind flows on roof. Nevertheless, the observed  $C_{p_{peak}}$  values from the wind tunnel tests were found to be lower than the corner  $C_{pCg}$  value of NBCC (2005).



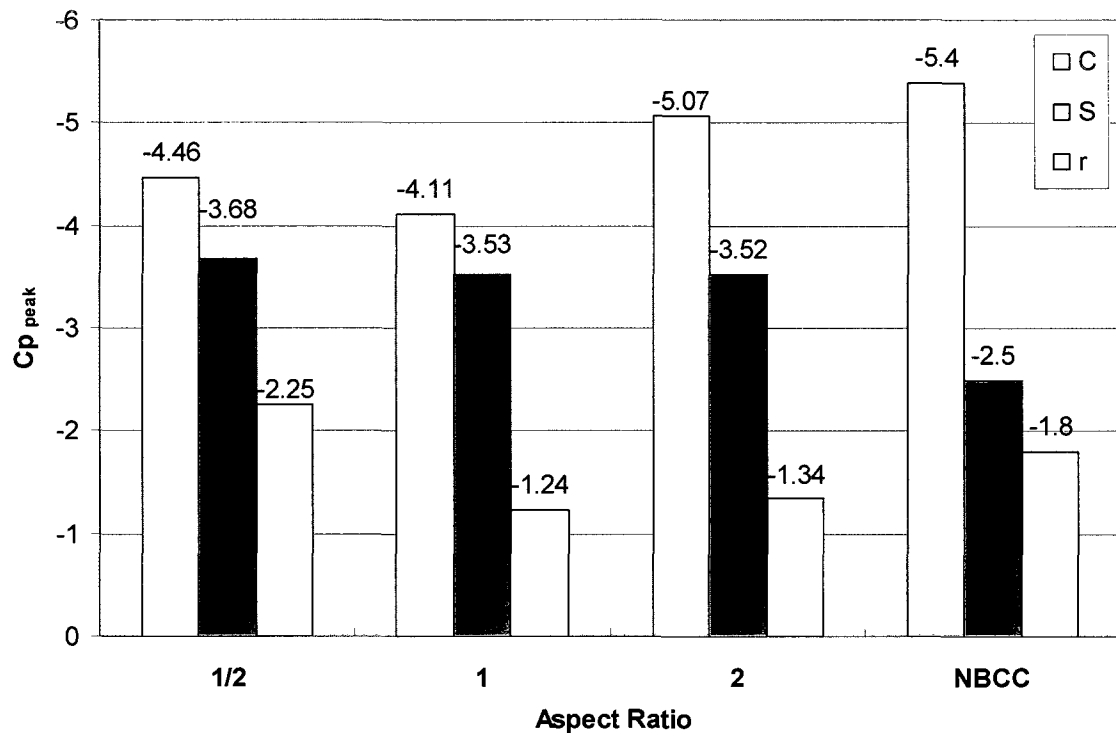
**Figure 4.9** Peak Suction Coefficients with Different Wind Angles (H/W Ratio of 1)

In addition to examining the effects of building height and wind direction, investigation was also extended to examine the influence of roof aspect ratio on the  $C_{p_{peak}}$  values and its distribution over various roof zones. Figure 4.10 illustrates the  $C_{p_{peak}}$  values with the three roof aspect ratios considered across the three roof zones. The  $C_{p_{peak}}$  values presented in the Figure 4.10 are the highest  $C_{p_{peak}}$  value from the two wind directions considered under the same roof aspect ratio, roof zone and building height. For example, the  $C_{p_{peak}}$  value of -4.46 for the aspect ratio of 1/2 at the corner location was the maximum measured  $C_{p_{peak}}$

value, when the model was tested at 0 and 45 degrees. Similarly, the other  $C_{p\ peak}$  values for the three roof zones and roof aspect ratios were determined.

Figure 4.10 illustrates that the  $C_{p\ peak}$  values at the corner roof zone are always higher than at the perimeter or the field zones for all roof aspect ratios. It also shows that the roof aspect ratio influences the  $C_{p\ peak}$  values in the same manner as the H/W ratio. Regardless of the roof aspect ratio, the  $C_{p\ peak}$  values shown in Figure 4.10 are lower than the corner  $C_{pCg}$  value from NBCC. With all of these test data, two important observations can be made:

- 1) Generally, the  $C_{p\ peak}$  values collected from the wind tunnel data are found to be lower compared to that of the maximum  $C_{pCg}$  value from NBCC (2005). This provides a level of confidence in the use of the data for further analysis.
- 2) It is evident that the roof aspect ratio, building height (H/W ratio) and the approaching wind angle significantly influence the wind-induced pressure fluctuations. These should be considered when using the wind tunnel data to establish rigid load cycles for the AARS wind uplift resistance performance evaluation. One solution is to always consider the pressure time histories data of the worst case scenario for the analysis from wind actions on roofs.



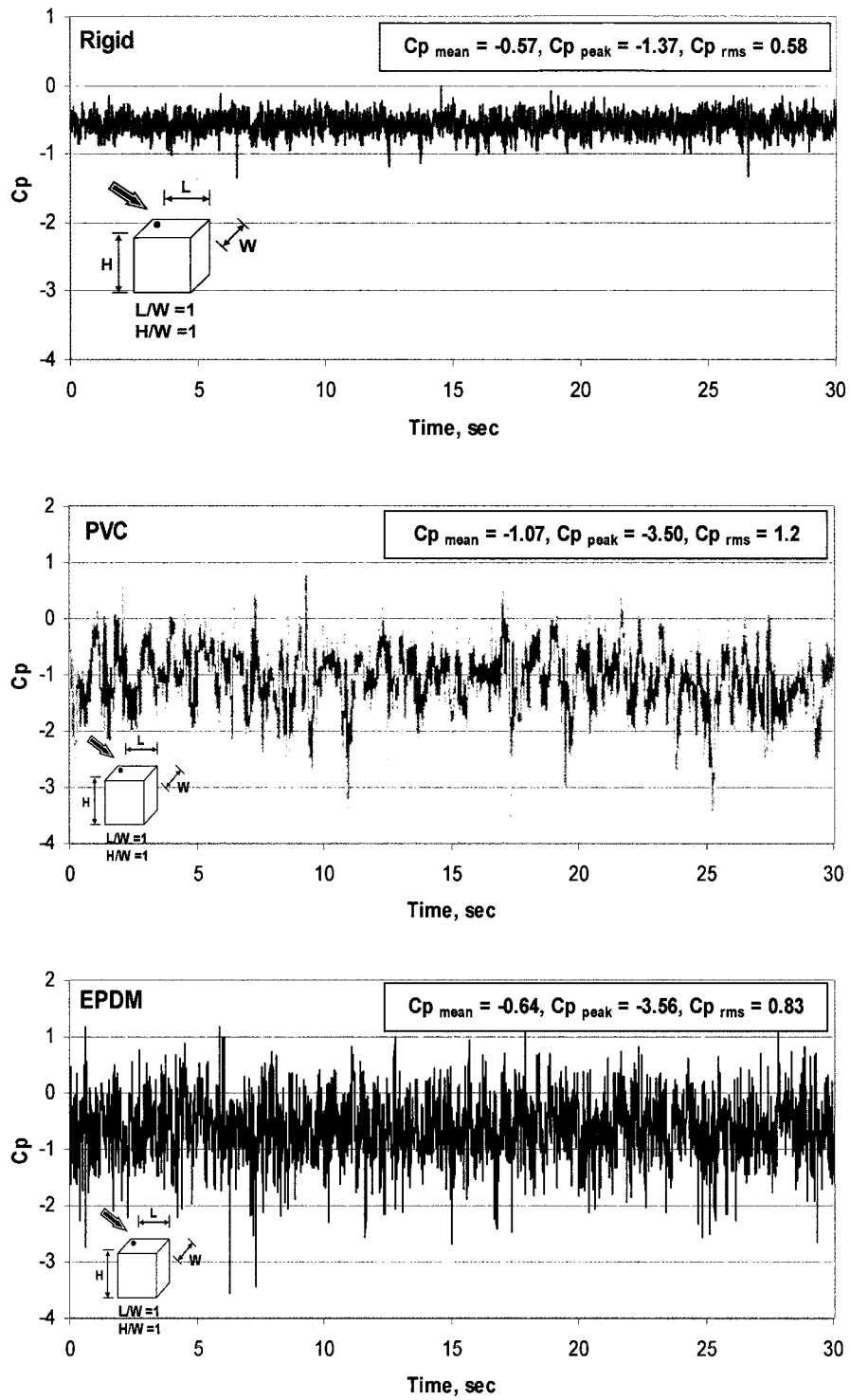
**Figure 4.10** Worst Peak Suction Coefficients with Different Aspect Ratios (H/W Ratio of 1)

## 4.5 Rigid vs Flexible Roof Responses

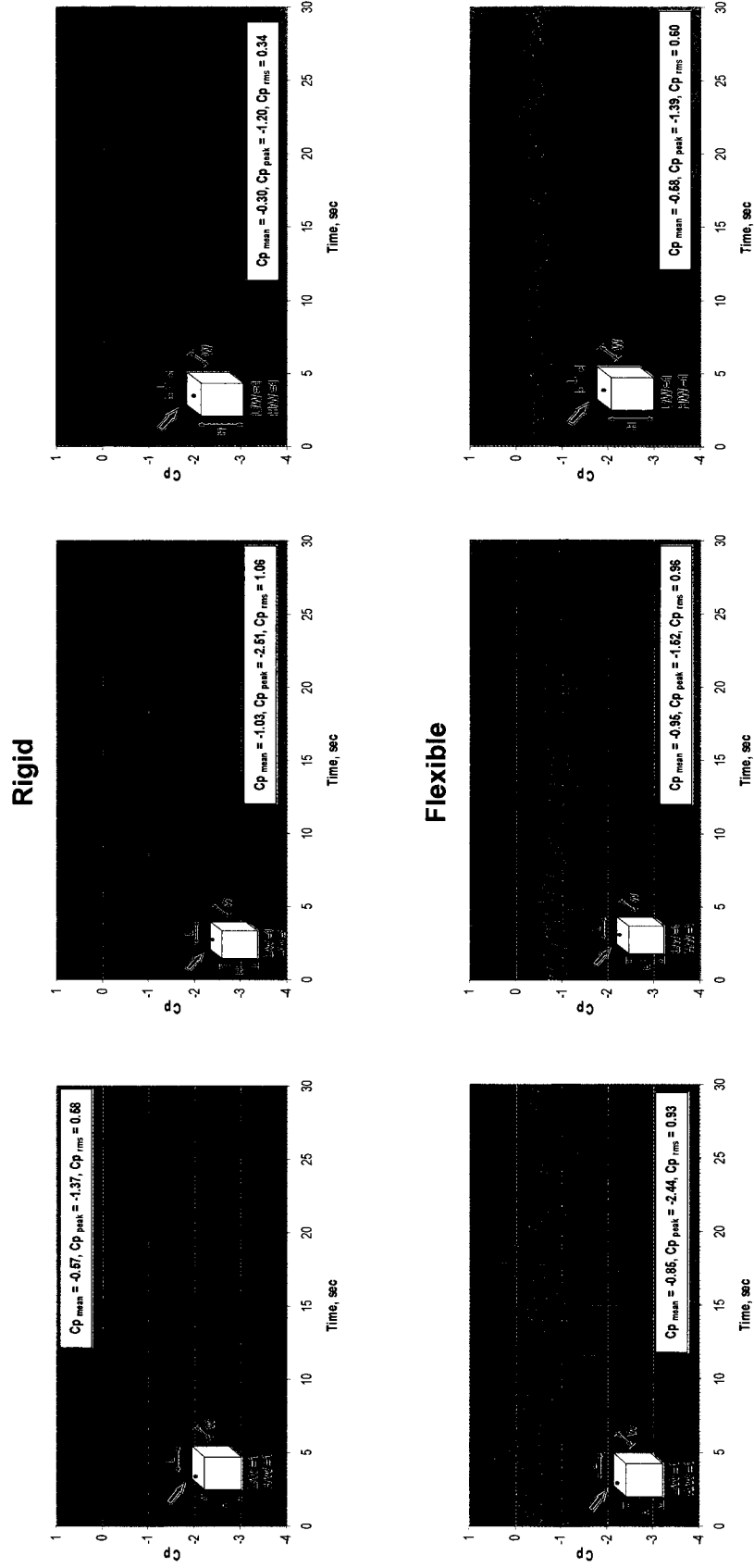
### 4.5.1 Pressure Time Histories of PVC, EPDM and Rigid Models

Figure 4.11 shows typical examples of pressure time histories from rigid and flexible (PVC and EPDM) roof models. The pressure time histories shown in Figure 4.11 are taken from a similar location (corner roof zone) and tested under open country exposure with 45 degree wind angle for a building height (H) to width (W) ratio of 1. Thirty second test durations were compared. The mean, peak and rms values from the three pressure time histories data are shown in Figure 4.11.

To represent a flexible roof response, the pressure time histories data of PVC and EPDM models were averaged. Figure 4.12 and Figure 4.13 show the comparison of the pressure time histories of rigid and flexible roofs at three different roof zones for the  $H/W = 1$  and  $H/W = 3$ , respectively. The mean, peak and rms values of the pressure time histories data were also calculated and presented. Using information such as the mean, peak and rms of the pressure time histories is not enough to capture the data variation and the frequency, in which strong energy variation occurs, in flexible and rigid roofs. In order to further study the system response between rigid and flexible roofs, statistical probability distribution function (PDF) and spectral analysis were used as analysis tools to characterize the responses of the two roofing systems.



**Figure 4.11** Pressure Time Histories for Rigid, PVC and EPDM Models



**Figure 4.12** Pressure Time Histories of Rigid and Flexible Roofs at Three Different Roof Zones for  $H/W = 1$

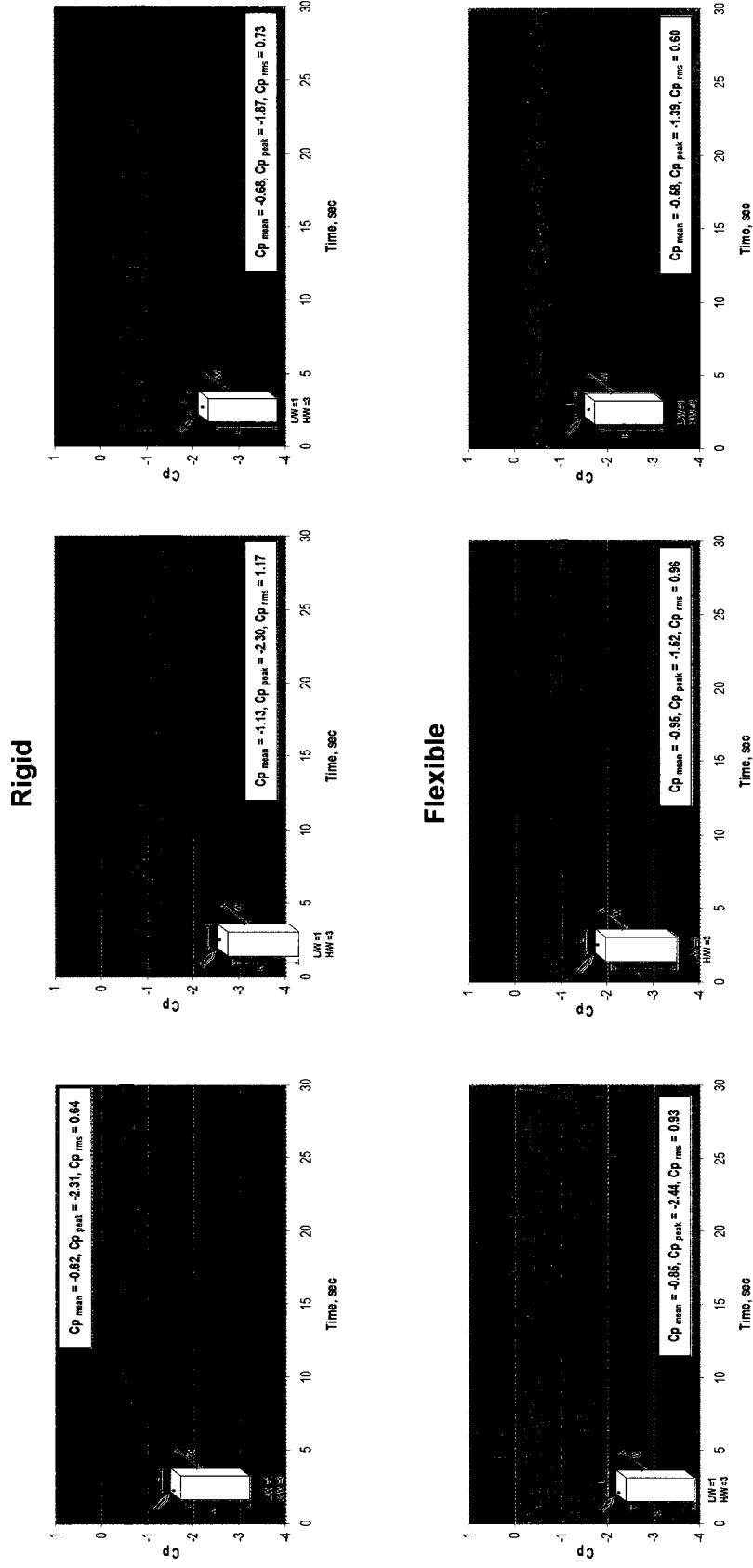
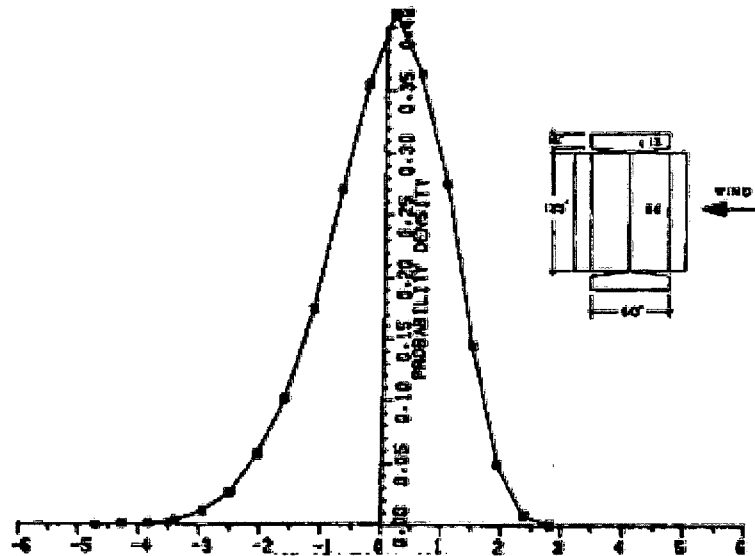


Figure 4.13 Pressure Time Histories of Rigid and Flexible Roofs at Three Different Roof Zones for H/W =3

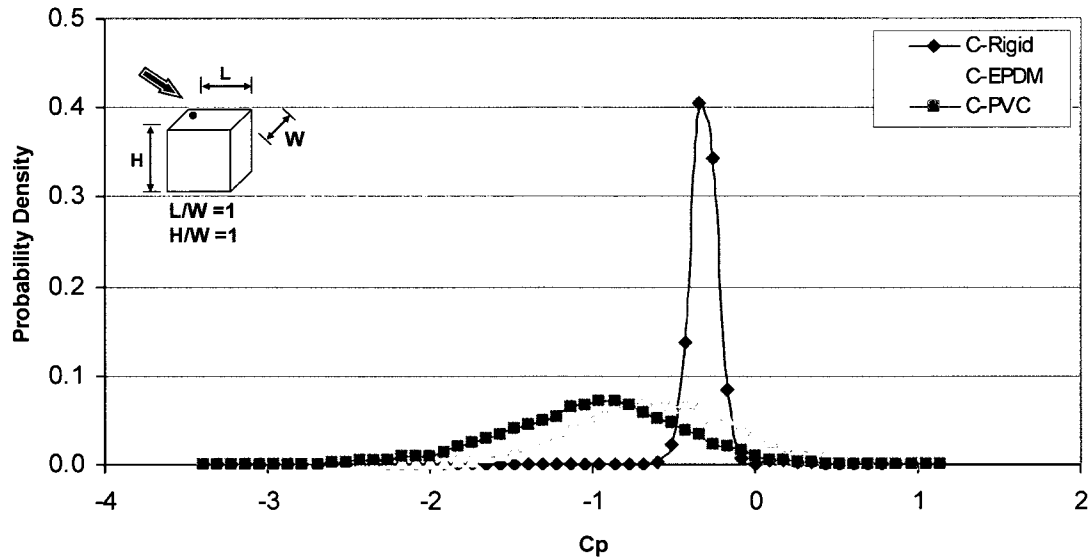
#### 4.5.2 Probability Distribution of the System Response

A probability distribution can be used to describe data variation and the probability of the possible values that a random variable can attain within any (measurable) subset of data. In terms of wind-induced pressure on roofs, the probability distribution can be used to estimate the number of occurrences of a particular pressure level at constant wind speed within a given time period and may also be used to account for the fatigue design of structural components (Stathopoulos, 1980). The probability distribution function (PDF) on roofs can follow either Gaussian or Non-Gaussian distributions. The Gaussian distribution function, sometimes called the normal distribution, is a curve which is symmetrical and has a bell shape. In Non-Gaussian distributions the curve is not symmetrical and normally skewed either to the right or left side. Figure 4.14 shows a typical non-Gaussian PDF observed on the edge of a gable roof building exposed to open country terrain at a 5 m building height (Stathopoulos, 1980). The dominant negative tail shows that the time series is negatively skewed. This was found to be the case in almost all time series measurements made on roofs. The PDF of the data used here shows similar characteristics, where the dominant negative tails are negatively skewed as shown in Figure 4.15 to Figure 4.17. The use of PDF to study wind-induced pressure characteristics can also be found elsewhere such as Dalglish (1970), Kumar (1997), Gullo et al. (1998), Gioffre et al. (2000) and Sadek and Simiu (2002).



**Figure 4.14** A typical of PDF Pressure Fluctuations  
(Stathopoulos 1980)

To understand the system response, the use of the PDF in the present study was only used for studying pressure time history data variation between rigid and flexible roofs. Understanding the pressure time history data variation of rigid and flexible roof is important since it can provide an idea about the variation of suction fluctuations due to aerodynamic forces during wind actions. Three sets of  $C_p$  data representing the corner, perimeter and field roof zones of the rigid and flexible roofs were selected. Figure 4.15 compares the PDF of the rigid roof with that of the flexible roof for the corner data set.

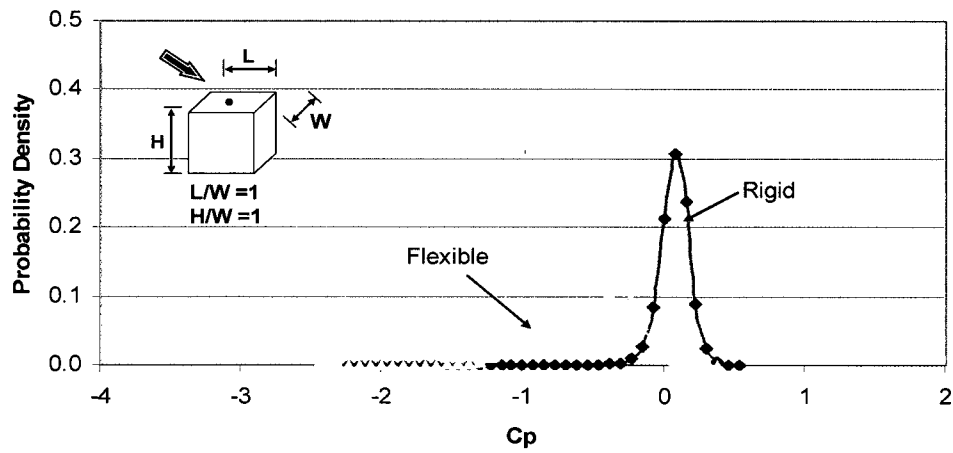
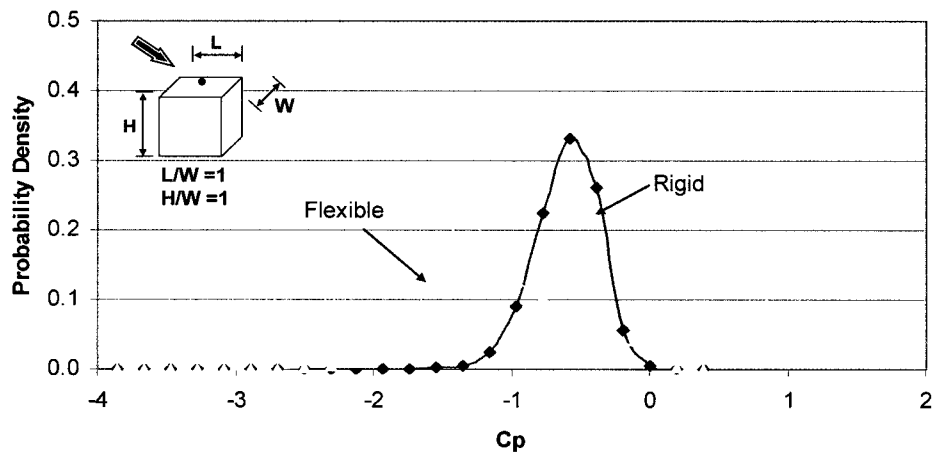
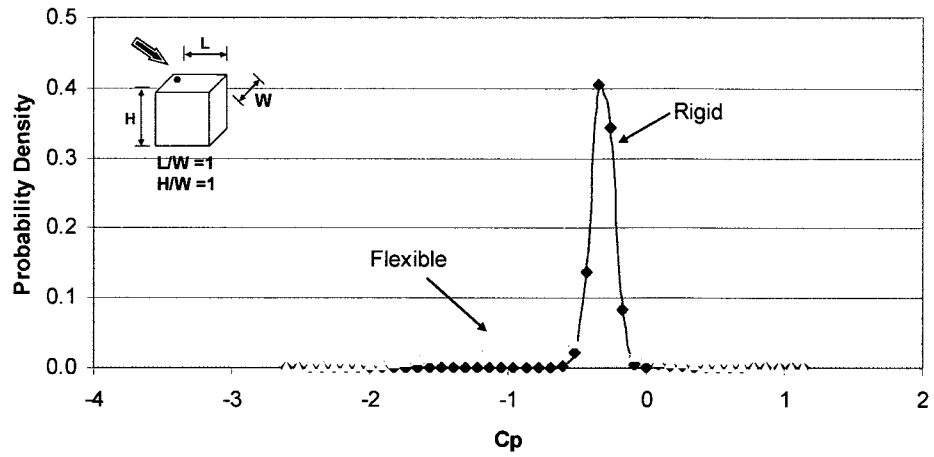


**Figure 4.15** PDF of Pressure Fluctuations for Rigid, EPDM and PVC roofs at the Corner Zone

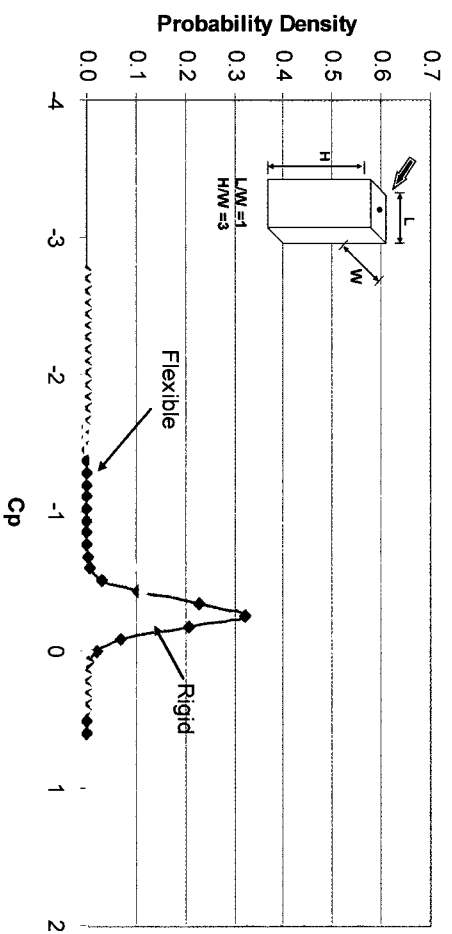
To compare the response, the PDF data analysis was performed by taking a common range of 10% from the lowest  $C_p$  data peak among the rigid and flexible (PVC and EPDM) data set. For example, the corner data set had peak suction coefficients of -0.87, -3.5 and -3.56 for rigid, PVC and EPDM respectively. Thus, data range used for this comparison was -0.087 ( $10\% \times -0.87 = -0.087$ ). The horizontal axis in Figure 4.15 represents the  $C_p$  data used for the PDF analysis. The  $C_p$  data for flexible roofs (PVC and EPDM) range from +1.2 to -3.6. This phenomenon illustrates that the  $C_p$  data variations are significantly wider in comparison to the rigid  $C_p$  data.

To represent the  $C_p$  data for the flexible roofs, the data of PVC and EPDM were averaged. Figure 4.16 and Figure 4.17 compare the distribution of the flexible and rigid roofs performance at the corner, perimeter and field zones for the ratio of H/W of 1 and 3, respectively. It is clear from the two figures that  $C_p$  data for flexible roofs have more variations of the wind-induced suction fluctuations. By comparing PDFs for the three zones, the following conclusions can be drawn:

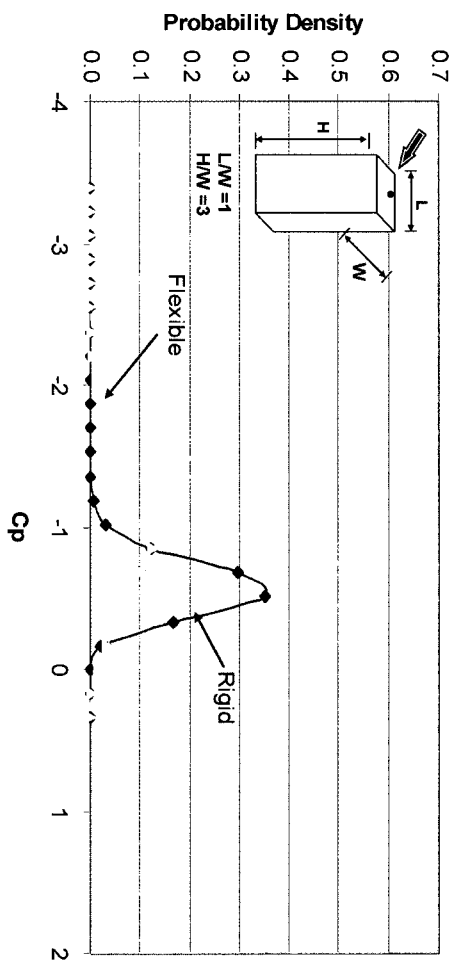
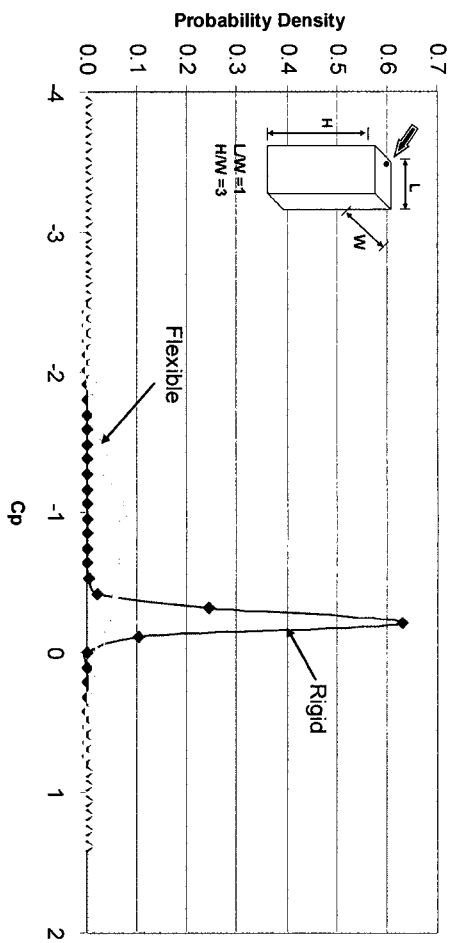
- The variation of the  $C_p$  data for flexible roof is higher than the  $C_p$  data for rigid roof as shown in Figure 4.16 and Figure 4.17. The variation is caused by the method of attachment used for the membrane. Flexible roofs use membranes that are attached, using fasteners, to the substrate at discrete locations. This causes the membranes to flutter during wind action. The fluttering effect creates high  $C_p$  data variation that represents suction fluctuations on roofs. In the case of rigid roofs, the membranes are adhered to the substrates such as on AARS. The membrane fluttering does not exist hence create lower  $C_p$  data variation. The  $C_p$  data variation can influence the number of cycles used for testing.
- The PDF of the  $C_p$  data series found in this study were non-Gaussian. The curves are negatively skewed especially at the corner and perimeter zones, while in the field zone the rigid data series seems to be Gaussian and for the flexible data series, the data distribution was non-Gaussian.



**Figure 4.16** PDF of Wind Pressure for Rigid and Flexible Roofs at the Three Different Zones with the  $H/W = 1$



**Figure 4.17** PDF of Wind Pressures for Rigid and Flexible Roofs at the Three Different Zones with  $H/W = 3$

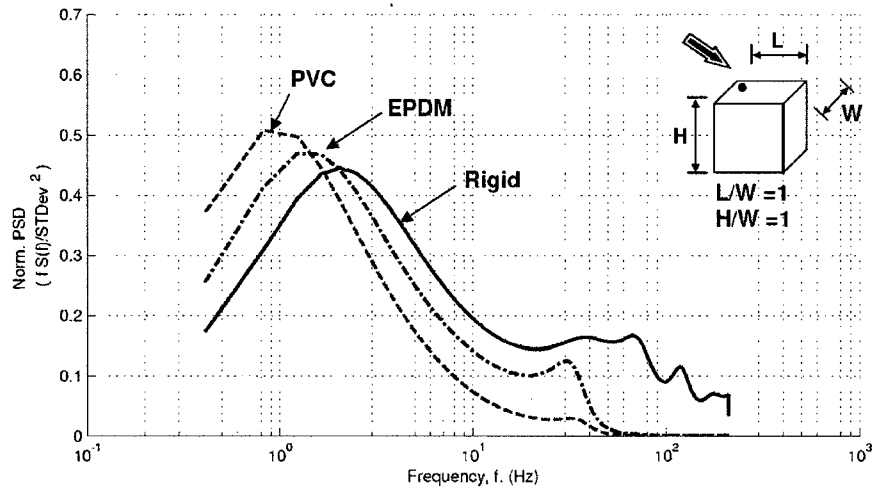


#### 4.5.3 Spectral Analysis of the System Response

Spectral analysis was also performed to study the difference in response and to determine a frequency for the peak energy of pressure time history data between rigid and flexible roofs. Finding a frequency for the peak energy of pressure time history data between rigid and flexible roofs is important since it gives an identification of the time period when the peak energy of wind-induced pressure occurs. For the comparison, three sets of data representing three different roof zones, corner, perimeter and field, were selected from the rigid, PVC and EPDM data. The three sets of data used for this analysis were chosen from similar pressure tap locations, model heights, roof aspect ratios and wind angle. The power spectral density (PSD) computations were performed by the developing a program using Matlab Version 7.0.1 (Mathwork Inc 2004). The Matlab program uses the Burg algorithm that incorporates the Fast Fourier Transform algorithm to obtain the power spectral density and the analysed data is plotted to give visual representation. A typical example of a calculation along with the program is presented in Appendix A.

Figure 4.18 compares the PSD functions of the three different selected data for a H/W ratio of 1 at the corner zone. The horizontal axis denotes the frequency (Hz) in log-scale while the vertical axis indicates the Normalized Power Spectral Density (NPSD). The solid line represents the result of the rigid roof model while the dashed line and the dash-dot line show the PVC and EPDM roof models, respectively. For the corner region, all three models show the similar energy

distribution up to a frequency of 10 Hz. The peak occurs at the frequency of less than 3 Hz as shown in Figure 4.18.



**Figure 4.18** PSD of Pressure Signals at the Corner Zone for H/W ratio of 1

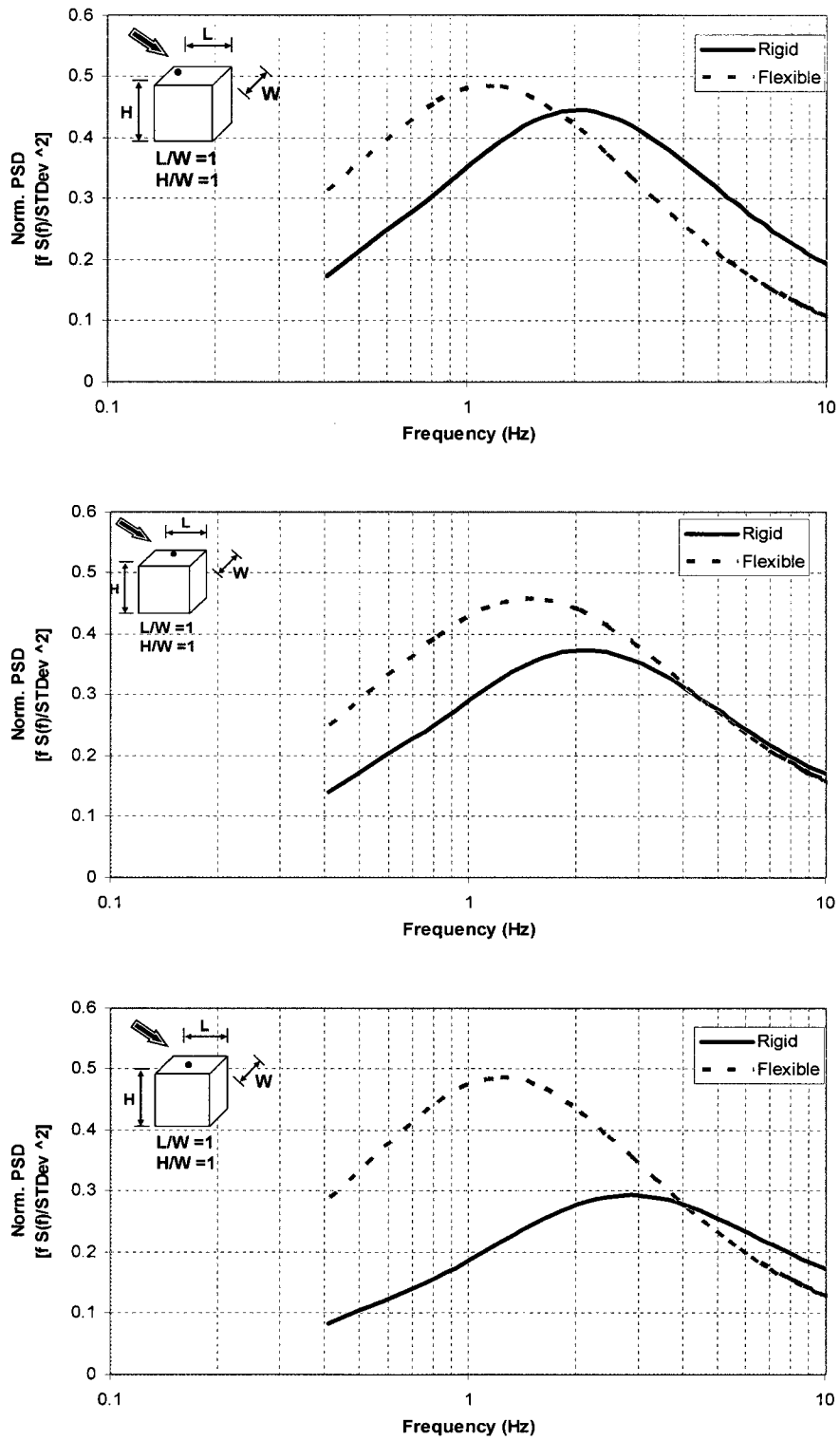
One of reasons for the difference of the PSD energy magnitudes and distributions shown in Figure 4.18 is because of the effect of membrane fluttering during dynamic forces due to wind action on roofs. The behaviour of membrane fluttering depends on the type of membrane material and the type of attachment used. The behaviour of membrane fluttering affects the wind-induced suction fluctuations and pressure distributions on the roof, influencing the number of cycles for the dynamic load cycle. The PSD data of PVC and EPDM models were averaged to represent as a data set for the flexible roof model. In view of the fact that the maximum of the PSD values were observed at the lower frequency range, a cut off frequency up to 10 Hz was used for this comparison.

Figure 4.19 and Figure 4.20 depicts a typical comparison of the PSD between the rigid and flexible models at the corner, perimeter and field roof zones for H/W ratios

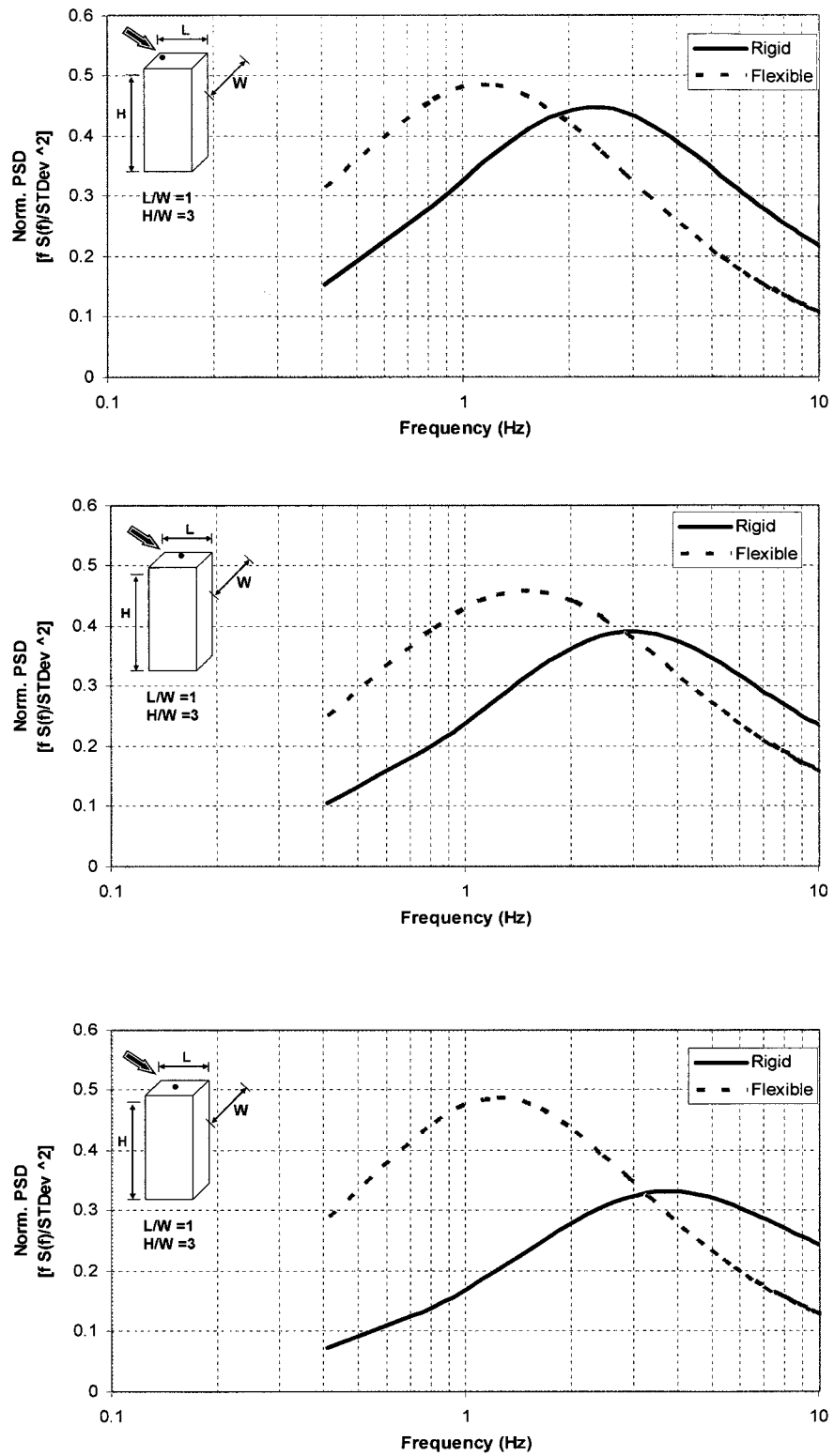
of 1 and 3, respectively. The solid line represents the PSD for the rigid model, while the dashed line signifies the flexible model. The PSD peaks for the rigid model at the corner region were seen at 2 Hz and 2.5 Hz for H/W ratios of 1 and 3, respectively, while it was at 1.25 Hz for the flexible model. The PSD energy at the peaks indicates that the flexible model has higher magnitude compared to rigid model. Similar to the data for the corner region, pressure data of the flexible model shows higher spectral peaks than those of the rigid model in the perimeter and field regions. From the comparison of Figure 4.19 and Figure 4.20, the following observations can be made:

- Spectral peaks for flexible roofs are always consistently higher than those of the rigid roofs, regardless of the zone examined.
- The PSD peaks of both flexible and rigid models are highest in the corner and lowest in the field of the roof.
- The PSD peaks recorded for both models occurred at a frequency lower than 4 Hz.
- The PSD energy of rigid roofs for  $H/W = 3$  at the frequencies above 3 Hz were consistently higher compared to flexible roof.

From both PDF & PSD analysis and observations, it is clear that the system responses of the rigid and flexible roofs are different. As previously indicated, the difference in roof system responses due to membrane fluttering affects wind-induced suction fluctuations on roof and eventually influencing the wind uplift resistance. This means that the wind effects on rigid systems are different from that of flexible systems.



**Figure 4.19** PSD Function of Rigid and Flexible Roofs for the Three Different Zone with the ratio of  $H/W = 1$



**Figure 4.20** PSD Function of Rigid and Flexible Roofs for the Three Different Zone with the Ratio of  $H/W = 3$

It is noted that the present study used the previously established wind tunnel data to investigate difference in system response between flexible and rigid roofs under wind-induced pressures. Despite efforts made when comparing the data, it was realised that both models were tested at different model scale and at different wind tunnel facilities. Although, the current models were performed under the same terrain condition, open country exposure, other differences in terms of tap layouts, tap numbers, Reynolds numbers and building shapes could affect the results. Further research using the same model configurations for flexible and rigid roofs tested at the same wind facility is necessary to review the results presented herein. Table 4.2 shows the present wind tunnel model configurations for rigid and flexible roofs used. To perform direct comparison between flexible and rigid roofs, wind tunnel testing using rigid model can be conducted at the NRC's wind tunnel test facility following similar configurations to that of the current flexible model.

**Table 4.2.** Wind Tunnel Model Configurations for Rigid and Flexible Roofs

| Description               | Flexible Model  |                 | Rigid Model                     |
|---------------------------|-----------------|-----------------|---------------------------------|
|                           | PVC             | EDPM            |                                 |
| Wind tunnel test facility | NRC wind tunnel | NRC wind tunnel | Concordia wind tunnel           |
| Model size (m)            | 3 x 3           | 3 x 3           | 0.466 x 0.466,<br>0.466 x 0.950 |
| Number of pressure taps   | 81              | 100             | 15                              |
| Model height (m)          | 1.37            | 1.37            | 0.466, 0.95,<br>1.4             |
| Model Scale               | 1:1             | 1:1             | 1:13                            |
| Wind angle                | 0° and 45°      | 0° and 45°      | 0° and 45°                      |
| Terrain condition         | Open country    | Open country    | Open country                    |
| Roof aspect ratio         | 1               | 1               | 0.5, 1, 2                       |

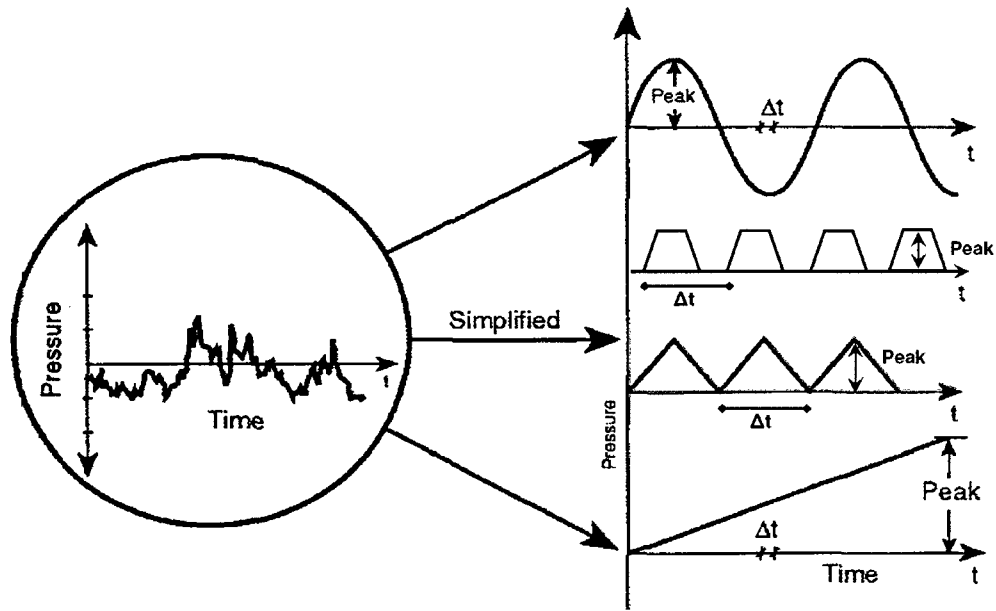
#### **4.6 Concluding Remarks**

The Probability Distribution Function (PDF) and Power Spectral Density (PSD) were used in this chapter as analytical tools to study the difference response of rigid and flexible roofs. Examination of the PDF and PSD analyses verified that rigid and flexible models exhibited different system response under wind action on roofs. The variation of the wind-induced suction fluctuations was found to be higher in the flexible model compared to the rigid model. The difference in roof system response provided clear understanding that each type of roofing system should be assessed differently to better predict their wind uplift resistance performances.

## **Chapter 5. Development of Dynamic Load Cycle for Rigid Roofs**

### **5.1 Introduction**

Wind-induced pressure on roof is random in nature. Simulating both the required amplitudes of pressure and the pressure variation with respect to frequency is necessary. Several simplified method for simulating wind-induced pressure fluctuations on roof are described in Figure 5.1. These methods normally are used as loading procedures during testing to quantify wind uplift resistance of roofing systems. As discussed in Chapter 2, the present North American roofing testing procedures such as FM 4474 and UL580 consider evaluation of the roofing systems based solely on the magnitude of the static pressure while the effect of wind-induced pressure fluctuations on roofs is not considered. This may be one reason why a roof, under the wind action, sometimes fails at much lower load than the wind uplift resistance capacity obtained from the two test methods (Baskaran et al., 1994; Smith 1996 and Prevatt 2008). A simple simulation of the highest magnitude of pressure or suction as static load does not represent the realistic pressure load which varies with time. In order to describe the wind loading process more realistically, simulation of the pressure spectrum is required. From the pressure spectrum, a frequency in which the strong energy variation of wind-induced pressure fluctuations can be determined. Once this frequency is known, the cycle duration,  $\Delta t$ , for the testing can be calculated. The dynamic energy of the wind-induced pressure signal is mostly contained in the frequency range up to 10 Hz (Baskaran and Dutt 1995).



**Figure 5.1** Simplified Representation of Wind-Induced Pressure for Testing  
(Baskaran and Dutt 1995)

## 5.2 General Considerations and Simplifications

As mentioned in Chapter 2, CSA 123.21-04 uses SIGDERS load cycles as a loading method during testing to represent simplification of wind-induced pressure fluctuations on roof. However, the load cycles for wind uplift resistance evaluation presented in CSA 123.21-04 cannot be used to evaluate wind uplift resistance for AARS. This is due to the fact that AARS response during wind action on roof is different when compared to that of the mechanically attached roofing systems (MARS). The development of load cycles for rigid roof evaluation such as AARS in this chapter follows a procedure similar to that of SIGDERS load cycles. Pressure time history data from rigid model presented in Chapter 4 were used herein to develop load cycle for rigid roof. In developing the load cycle for rigid roof, the following considerations and simplifications are made:

- There are several methods to simplify the pressure time history data for purpose of testing, as indicated in Figure 5.1, to evaluate the effect of wind-induced pressure fluctuations on roof. One of the best methods among them is a sinusoidal cyclic loading. This is because any dynamic wave forms including the wind-induced pressure fluctuations can be reconstructed using sine wave with different frequencies and amplitude. However, the newly developed load cycle follows a trapezoidal cyclic loading similar to CSA A123.21-04. The trapezoidal loading is close to sinusoidal cyclic loading.
- Application of the load cycle requires loading duration. The duration can be calculated by performing power spectral density analysis of pressure time history data. From the analysis, the strength of the data variations (energy) were observed within the frequency ranges of 2 Hz – 4 Hz. The newly developed load cycle for rigid roof evaluation uses loading duration of 8 seconds, similar to that of CSA A123.21-04.
- The calculated number of cycles were obtained by using the rain flow counting method as discussed later in terms of 10 x 10 matrices. The number of cycles is a function of not only the duration of the wind tunnel record, but also the mean wind speed at which the pressure measurements were made. Increasing the wind speed could increase number of cycles in a given time. The present study assumes that the normalized spectra of the pressure fluctuations are invariant with the mean wind speed so that the number of cycles in each cell is proportional to the mean speed.
- In order to evaluate ultimate strength of rigid roofs and to account for the effect of wind speed, five levels (Levels A, B, C, D and E) of loading cycles were

established. Ideally the establishment of these five levels required wind tunnel testing at different wind speeds to calculate total number of cycle required for a certain pressure. However, the present study uses the sequences ratios of Level A to Levels B, C, D and E of the CSA A123.21-04 load cycle to develop the five levels of loading cycle for rigid roofs.

- The development of dynamic load cycles for rigid roof evaluation requires several levels of generalization of the wind effects over a roof assembly that warrants compromise of the technical approach to produce practically acceptable procedures. The following conditions were considered when developing the load cycle for rigid roof evaluation:
  - Simulation of natural wind effects as realistically as possible
  - Simulation of the failure modes comparable to the field observation
  - Easiness of application in a common laboratory environment
  - A short testing time, not more than a day including the preparation time, for all practical purposes; and
  - Compatibility with the local building codes and wind standards.

### **5.3 Computation of Load Cycle Using Rain Flow Counting**

The dynamic response of measured suction coefficients from 270 time histories data were converted into discrete responses using the rain flow counting (RFC) method to account for wind-induced suction fluctuations. The RFC method has been proven to be a good method for predicting fatigue effects resulting from random processes (Downing and Socie 1982, Rychlik 1987, Glinka and Kam 1987 and Amzallag et al 1994). The RFC method has also been used by ASTM E1049-2005 as a standard practice for cycle counting in fatigue analysis. Detailed explanation and an example of the use of the RFC method for the prediction of wind-induced fatigue loading on roofs is found in Xu (1995).

For the purpose of the load cycle development for rigid roofs, a previously developed RFC computer program (Baskaran et al, 1997) was used to predict the wind-induced fatigue loading on the rigid model test data. The RFC method was rewritten using the Compaq Visual FORTRAN Version 6.6 (2001). Details of the RFC computer program used in this study can be found in Appendix B.

For the data analysis, the 270 time histories of measured suction coefficients were categorized into eighteen groups. They consist of nine groups of data based on a wind direction of 0 degree, three roof aspect ratios ( $L/W$ ) and three building heights ratio ( $H/W$ ). The other nine groups are for the same configurations under the 45 degree wind angle. The following four-step procedure was performed.

- Step 1: Classification of the time histories of measured pressure coefficients under the same group conditions, for example, the same  $L/W$  ratio,  $H/W$  ratio and wind approaching angle.

- Step 2: Application of the RFC method
- Step 3: Counting the number of cycles for each pressure tap
- Step 4: Identification of the maximum number of cycles under the same group condition.

The outcome of the data analysis based on the above procedure was presented in terms of 10 by 10 matrices that describe the occurrences of certain suction coefficient values based on test data (Table 5.1). The **M** in the rows represents the **Mean** normalized suction coefficient values, whereas the **R** in columns signifies the **Range** of normalized suction coefficient values. The values in the column matrix are the maximum number of cycles. Both M and R are tabulated from 0 to 1 with increments of 0.1. The 15 pressure taps were installed on the rigid models during wind tunnel testing to measure the dynamic system response. By combining the 10 x 10 matrices from the 15 individual pressure taps, other 10 by 10 matrices for specific group conditions were developed. The combining 10 x 10 matrices represent the maximum number of cycles for the specific group conditions.

Table 5.1 and Table 5.2 provide typical examples of the combined 10 x 10 matrices for the group with L/W and H/W ratios of 1. The data in Table 5.1 presents the maximum number of cycles for a wind angle of 0 degree, while Table 5.2 presents the data for the 45 degree wind angle. The values in columns and rows refer to the occurrence of number of cycle measured. For example, in the M1 (row) and R3 (column) of Table 5.1 for 0 degree wind, 57 cycles occurred with a mean suction value of 0.1 (M1) and suction range from 0.2 to 0.3 (R3). Table 5.1 and Table 5.2 show that the number of occurrences for a 0 degree wind is lower compared to the

data with a 45 degree wind for the same mean and range of the normalized suction coefficient values. This implies that wind-induced pressure fluctuations is higher and as a result, the roofing system exhibits more fatigue damage when the wind is in oblique direction irrespective of the pressure coefficient ranges. In addition, the distribution of the number of occurrence in terms of M x R matrices for the data of a 0 degree wind direction was more localized compared to that based on a 45 degree wind. The effect of wind direction on the data needed to be removed before using it for further analysis.

**Table 5.1** Typical M x R matrix (L/W = 1; H/W = 1; Wind = 0 degree)

|            | R1 | R2 | R3  | R4 | R5 | R6 | R7 | R8 | R9 | R10 |
|------------|----|----|-----|----|----|----|----|----|----|-----|
| <b>M1</b>  | 0  | 0  | 57  | 11 | 1  | 0  | 0  | 0  | 0  | 0   |
| <b>M2</b>  | 0  | 0  | 67  | 20 | 5  | 2  | 0  | 0  | 0  | 0   |
| <b>M3</b>  | 0  | 0  | 131 | 74 | 25 | 11 | 1  | 0  | 0  | 0   |
| <b>M4</b>  | 0  | 0  | 131 | 46 | 54 | 27 | 7  | 1  | 0  | 0   |
| <b>M5</b>  | 0  | 0  | 14  | 13 | 3  | 0  | 1  | 2  | 2  | 0   |
| <b>M6</b>  | 0  | 0  | 2   | 1  | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M7</b>  | 0  | 0  | 0   | 0  | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M8</b>  | 0  | 0  | 0   | 0  | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M9</b>  | 0  | 0  | 0   | 0  | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M10</b> | 0  | 0  | 0   | 0  | 0  | 0  | 0  | 0  | 0  | 0   |

**Table 5.2** Typical M x R matrix (L/W = 1; H/W = 1; Wind = 45 degree)

|     | R1 | R2 | R3  | R4  | R5 | R6 | R7 | R8 | R9 | R10 |
|-----|----|----|-----|-----|----|----|----|----|----|-----|
| M1  | 0  | 0  | 1   | 0   | 0  | 0  | 0  | 0  | 0  | 0   |
| M2  | 0  | 0  | 85  | 73  | 6  | 0  | 0  | 0  | 0  | 1   |
| M3  | 0  | 0  | 121 | 132 | 85 | 25 | 2  | 0  | 0  | 0   |
| M4  | 0  | 0  | 121 | 45  | 52 | 65 | 56 | 36 | 4  | 0   |
| M5  | 0  | 0  | 27  | 32  | 12 | 11 | 10 | 6  | 17 | 11  |
| M6  | 0  | 0  | 21  | 6   | 4  | 1  | 2  | 1  | 0  | 7   |
| M7  | 0  | 0  | 3   | 2   | 4  | 0  | 1  | 0  | 0  | 0   |
| M8  | 0  | 0  | 3   | 3   | 0  | 0  | 0  | 0  | 0  | 0   |
| M9  | 0  | 0  | 1   | 1   | 0  | 0  | 0  | 0  | 0  | 0   |
| M10 | 0  | 0  | 0   | 0   | 0  | 0  | 0  | 0  | 0  | 0   |

To simplify the analysis, the greater number of occurrence for the same mean and fluctuation of 10 x 10 matrices was taken for each specific area. The data used for further analysis represented the worst case scenario for each area of the roof. The result would be more conservative than accurate but it is consistent with the conventional approach often taken by design standards. One can obtain the maximum number of cycles for each data group corresponding to the respective mean and range pressures.

Table 5.3 presents a typical example of the 10 x 10 matrices for the data with the L/W and H/W ratios of 1. The 10 x 10 matrices data in Table 5.3 were calculated based on the data presented in Table 5.1 and Table 5.2. For example, the number occurrences for the M2R3 cell of Table 5.1 (0 degree) and of Table 5.2 (45 degree) are 67 and 85, respectively. Thus the occurrences used for the M2R3 cell in Table 5.3 is 85, taking the greatest number.

**Table 5.3** Typical M x R matrices (L/W = 1; H/W = 1)

|            | R1 | R2 | R3  | R4  | R5 | R6 | R7 | R8 | R9 | R10 |
|------------|----|----|-----|-----|----|----|----|----|----|-----|
| <b>M1</b>  | 0  | 0  | 57  | 11  | 1  | 0  | 0  | 0  | 0  | 0   |
| <b>M2</b>  | 0  | 0  | 85  | 73  | 6  | 2  | 0  | 0  | 0  | 1   |
| <b>M3</b>  | 0  | 0  | 131 | 132 | 85 | 25 | 2  | 0  | 0  | 0   |
| <b>M4</b>  | 0  | 0  | 131 | 46  | 54 | 65 | 56 | 36 | 4  | 0   |
| <b>M5</b>  | 0  | 0  | 27  | 32  | 12 | 11 | 10 | 6  | 17 | 11  |
| <b>M6</b>  | 0  | 0  | 21  | 6   | 4  | 1  | 2  | 1  | 0  | 7   |
| <b>M7</b>  | 0  | 0  | 3   | 2   | 4  | 0  | 1  | 0  | 0  | 0   |
| <b>M8</b>  | 0  | 0  | 3   | 3   | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M9</b>  | 0  | 0  | 1   | 1   | 0  | 0  | 0  | 0  | 0  | 0   |
| <b>M10</b> | 0  | 0  | 0   | 0   | 0  | 0  | 0  | 0  | 0  | 0   |

To develop the dynamic load testing procedure for the AARS performance evaluation, the 10 by 10 matrices data were reorganized into eight different pressure zones with their respective number of cycles. The eight pressure zones, subdivided into two groups were:

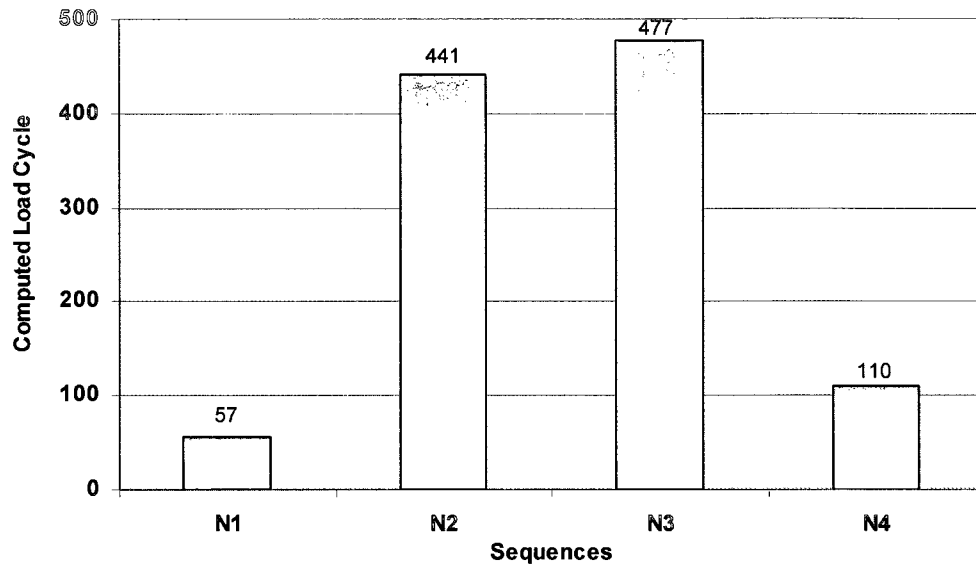
- Group 1: N1 (0.0 - 0.25), N2 (0.0 - 0.5), N3 (0.0 - 0.75), N4 (0.0 - 1.0), and
- Group 2: N5 (0.25 - 0.5), N6 (0.25 - 0.75), N7 (0.25 - 1.0) and N8 (0.5 - 1.0)

The number of cycles for each zone was then determined. Each cell of the M by R matrix was examined. If the combination of mean and range pressure fell into a particular zone, the corresponding number of cycles was counted for that pressure zone (Ns). The following procedures were used for the reorganization. A typical example of the calculation process is also presented in parenthesis corresponding to the data for cell M1R3 of Table 5.3.

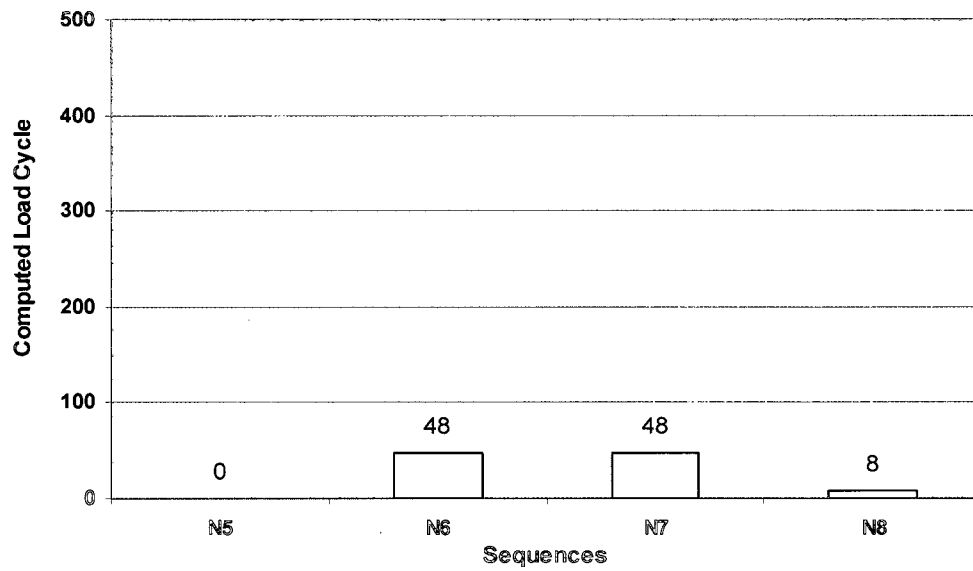
1. Calculate the highest range of suction pressure for the cell, (for M1R3, it is 0.3).

2. Calculate the lowest mean of suction pressure for the cell, (for M1R3, it is 0).
3. Determine the lowest suction pressure that is encountered by the cell. It is the lowest mean of suction pressure value subtracted by half of the highest range of suction pressure. If the value is negative, set it to zero (e.g., for M1R3, it is  $0 - 0.03 = 0$ ).
4. Calculate the highest mean of suction pressure for the cell (for M1R3, it is 0.1).
5. Determine the highest suction pressure that is encountered by the cell. It is the highest mean of suction pressure value added to half of the highest range of suction pressure, (for M1R3, it is  $0.1 + 0.15 = 0.25$ ).
6. Determine the suction pressure zone based on the suction pressure variation calculated in procedures 3 and 5, (for M1R3, it falls into the *N1* suction pressure zone [0.0-0.25]).
7. Calculate the total number of cycles from all cells that correspond to a particular suction pressure zone, (M1R1, M1R2, M1R3 and M2R1 contribute to *N1* for a total of 57 cycles [0+0+57+0] for Group 1 (Figure 5.2).

A computer program was developed to perform the above process (Appendix C). Figure 5.2 shows a typical load cycle for Group 1. The number of cycles for *N2*, *N3* and *N4* was calculated using a similar procedure to that for *N1*. Figure 5.3 depicts the typical occurrence for load cycles calculated for Group 2, which consists of the sequences, *N5*, *N6*, *N7* and *N8*. Groups 1 and 2 of Figure 5.2 and Figure 5.3, respectively, were obtained using the data presented in Table 5.3.



**Figure 5.2** Computed Load Cycle for Group 1



**Figure 5.3** Computed Load Cycle for Group 2

By comparing Figure 5.2 and Figure 5.3, it is noticed that the number of cycles for the Group 1 is significantly higher in comparison to the Group 2 and the number of cycles recorded for the N5 is equal to zero. This means that there was no system response recorded that had a suction pressure range of 0.25 – 0.5 during testing. This reflects the fact that the tested rigid models have different wind-induced response compared to the flexible roofs as described in Chapter 4.

#### **5.4 Development of Dynamic Load Cycles for Rigid Roofs**

To develop a generalised load cycle for the evaluation of rigid roof systems, a computational procedure similar to that described in Section 5.2 was applied for different configurations of the wind data. The results are presented in Table 5.4. The summarized load cycle data were computed by using 270 time histories of measured suction coefficients on the rigid models. They were classified into three different building heights ( $H/W$ ) and three different aspect ratios ( $L/W$ ). It was noticed that the effects of differences in  $H/W$  and  $L/W$  ratios on the data were minimal as shown in Table 5.4. The extreme load cycles highlighted at the bottom of Table 5.4 were selected for further data analysis.

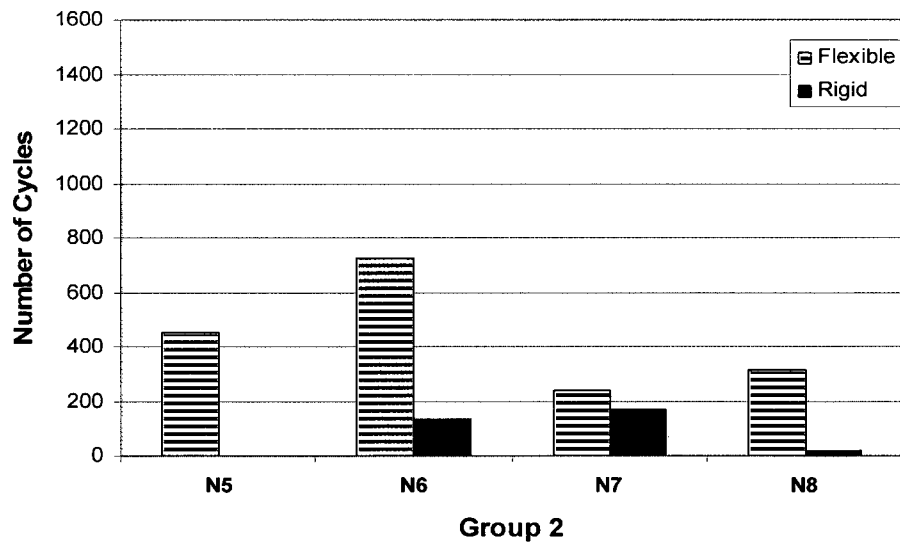
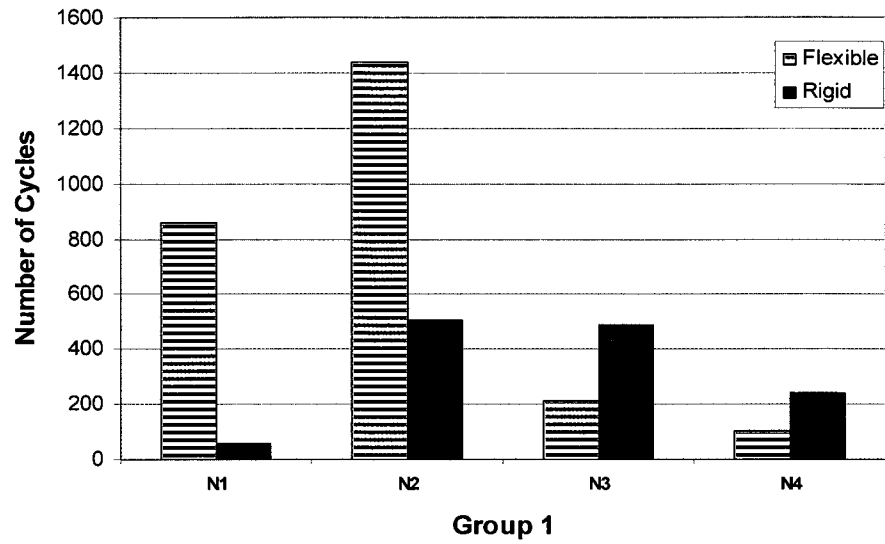
As previously mentioned in Section 5.2, the development of dynamic load cycles for rigid roof evaluation requires several levels of generalization of wind effects over a roof assembly. These generalizations compromise the technical approach but yield practical procedures that consider several conditions such as the simulation of natural wind effects as realistically as possible, simulation of the failure modes comparable to the field observation, ease of application in a common

laboratory environment, short testing times, and compatibility with the local building codes and wind standards.

**Table 5.4** Summary of Computed Load Cycle Group 1 and 2 for All Model Data Tested

| L/W Ratio                                | H/W Ratio | Number of Gusts |            |            |            |          |            |            |           |
|------------------------------------------|-----------|-----------------|------------|------------|------------|----------|------------|------------|-----------|
|                                          |           | Group 1         |            |            |            | Group 2  |            |            |           |
|                                          |           | N1              | N2         | N3         | N4         | N5       | N6         | N7         | N8        |
| 1                                        | 1         | 57              | 441        | 477        | 110        | 0        | 48         | 48         | 8         |
|                                          | 2         | 29              | 419        | 452        | 207        | 0        | 71         | 82         | 11        |
|                                          | 3         | 39              | 453        | 480        | 241        | 0        | 73         | 109        | 13        |
| 2                                        | 1         | 40              | 504        | 487        | 73         | 0        | 31         | 22         | 0         |
|                                          | 2         | 55              | 403        | 475        | 174        | 0        | 133        | 107        | 5         |
|                                          | 3         | 18              | 406        | 437        | 238        | 0        | 126        | 167        | 16        |
| 0.5                                      | 1         | 37              | 446        | 478        | 77         | 0        | 106        | 80         | 2         |
|                                          | 2         | 35              | 321        | 244        | 23         | 0        | 10         | 9          | 0         |
|                                          | 3         | 35              | 315        | 191        | 9          | 0        | 5          | 4          | 0         |
| <b>Extreme Load Cycle for Rigid Roof</b> |           | <b>57</b>       | <b>504</b> | <b>487</b> | <b>241</b> | <b>0</b> | <b>133</b> | <b>167</b> | <b>16</b> |

The extreme dynamic load cycles for rigid roof presented in Table 5.4 were simplified by studying the ratios between the established SIGDERS load cycles for the flexible roofs with the original SIGDERS data of PVC and EDPM roofs tested in the wind tunnel. Figure 5.4 compares the extreme load cycle data of the three models. The top bar chart provides a comparison of the number of calculated load cycles for Group 1 which consists of N1 to N4 while the bottom bar chart provides the data for N5 to N8 of Group 2.



**Figure 5.4** Load Cycle Comparison between the Flexible and Rigid Roof Models

Using the data presented in Figure 5.4, a load cycle for full scale AARS evaluation was developed. The procedure for calculating the number of load cycles is given below,

Computation of N1 to N8 of Level A, load cycles for rigid roof, can be calculated as follows,

$$NR_{std} = ( NF_{csa} / NF_{WT} ) \times NR_{WT}$$

where,

$NR_{std}$  = Calculated Number of Load Cycles for a N Rigid –Sequence

$NF_{csa}$  = CSA Number of Load Cycles for a N Flexible -Sequence

(Level A - Figure 4.1)

$NF_{WT}$  = Number of Load Cycles for a N Flexible –Sequence based on  
Wind Tunnel Test.

$NR_{WT}$  = Number of Load Cycles for a N Rigid –Sequence based on  
Wind Tunnel Test.

Example: The number of calculated load cycles for the N1 - Rigid ( $N_1R_{std}$ ) is 26  
[(400 / 863) x 57].

Table 5.5 summarizes the number of load cycles for the rigid roofs obtained using the procedure described above and referred to as “Considered Level A of Load Cycles for Rigid Roof”. The “Considered Level A of Load Cycles for Rigid Roof” was later used as the basis for establishing the Level A of the dynamic rigid load cycles for rigid roof.

**Table 5.5 Considered Level A - Load Cycle for Rigid Roof**

| Seq. | Load Cycles<br>Raw Data-<br>Flexible |      | NF <sub>WT</sub> | NF <sub>CSA</sub> | NR <sub>WT</sub> | Ratio of<br>NF <sub>CSA</sub> / NF <sub>WT</sub> | NR <sub>std</sub> | Level A -<br>Considered Load<br>Cycle -Rigid |
|------|--------------------------------------|------|------------------|-------------------|------------------|--------------------------------------------------|-------------------|----------------------------------------------|
|      | PVC                                  | EPDM |                  |                   |                  |                                                  |                   |                                              |
| N1   | 850                                  | 875  | 863              | 400               | 57               | 0.46                                             | 26                | 26                                           |
| N2   | 1300                                 | 1575 | 1438             | 700               | 504              | 0.49                                             | 245               | 245                                          |
| N3   | 225                                  | 200  | 213              | 200               | 487              | 0.94                                             | 458               | 458                                          |
| N4   | 80                                   | 125  | 103              | 50                | 241              | 0.49                                             | 118               | 50                                           |
| N5   | 380                                  | 525  | 453              | 400               | 0                | 0.88                                             | 0                 | 0                                            |
| N6   | 425                                  | 1025 | 725              | 400               | 133              | 0.55                                             | 73                | 73                                           |
| N7   | 50                                   | 425  | 238              | 25                | 167              | 0.11                                             | 18                | 18                                           |
| N8   | 25                                   | 600  | 313              | 25                | 16               | 0.08                                             | 1                 | 1                                            |

**Note:**

NF<sub>WT</sub> = Average of load cycle for flexible roof obtained from wind tunnel data

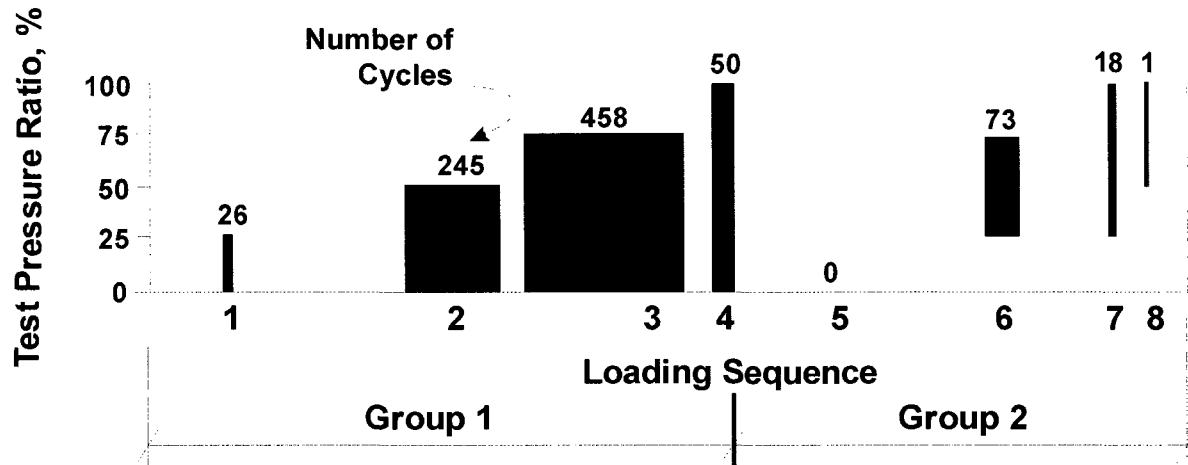
NF<sub>CSA</sub> = Establish CSA A123.21-04 load cycle for flexible roof

NR<sub>WT</sub> = Load cycle for rigid roof obtained from wind tunnel data

NR<sub>std</sub> = Calculated load cycle for rigid roof using ratios of  $(NF_{CSA} / NF_{WT}) \times NR_{WT}$

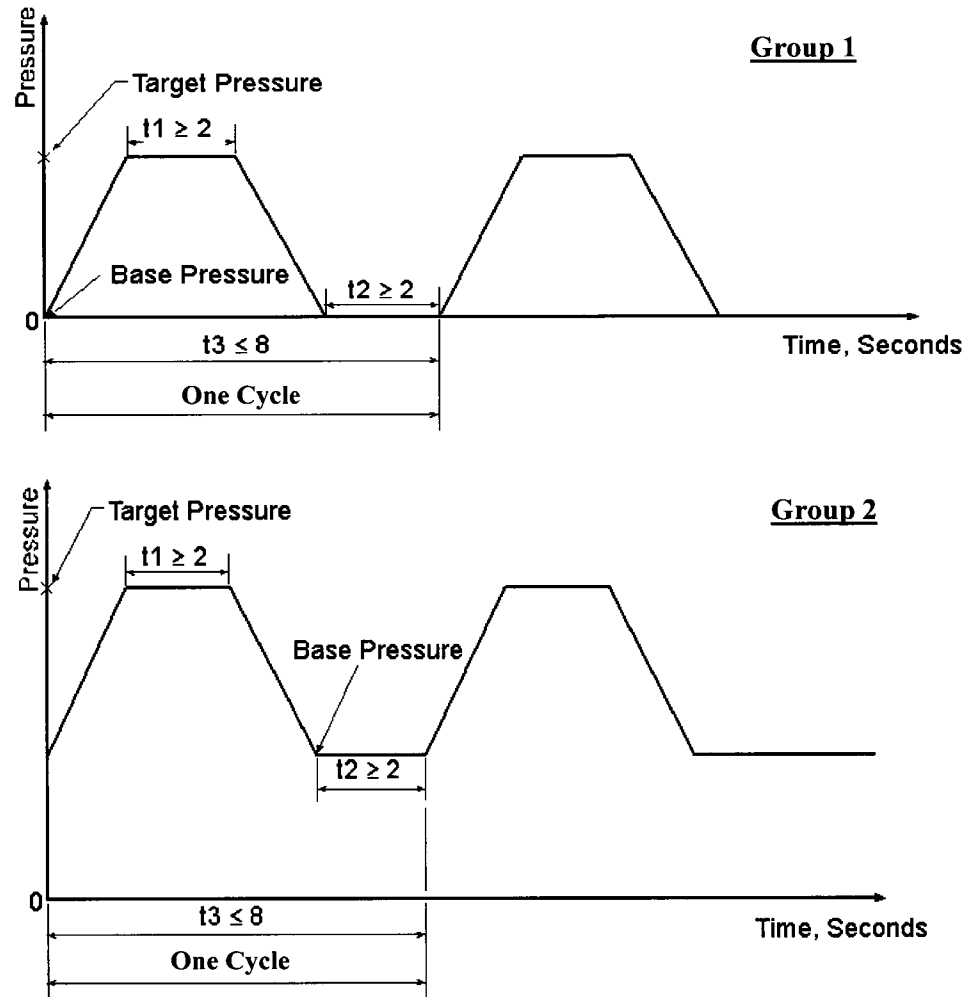
It was noted that while all values of  $NR_{std}$  were calculated using the above method, an exception was made only for the  $N_4R_{std}$  where 50 number of load cycles was maintained. The decision to maintain the  $N_4R_{std}$  - number of load cycles similar to the  $N_4R_{CSa}$  -SIGDERS number of load cycles was discussed with input from AARS project members. The selected number of load cycles (50) was believed to have represented enough fatigue effects on the system during testing.

The “Considered Level A of Load Cycles for Rigid Roof” consists of eight load sequences (N1 to N8) with different pressure ranges as shown in Figure 5.5. The vertical axis represents the percentage of the maximum pressure applied on each sequence of Level A. The maximum pressure corresponds to the design pressure prescribed in building codes or wind standards. The eight sequences (X-axis) were divided into two groups. Group 1 represents the wind-induced suction over a roof assembly that consists of four sequences (N1 to N4) where the pressure level alternates between zero to a fixed pressure. Group 2 characterizes the effect of exterior wind fluctuations combined with a constant interior pressure in a building. The effect of internal pressure variations were codified in the North American wind standards (ASCE, 2005; NBCC, 2005). In Group 2, a constant minimum static pressure is applied and the pressure level alternates between this minimum and the maximum pressures for each sequence.



**Figure 5.5** Load Cycles for the Evaluation of Rigid Roof

To be conservative, a time period of eight seconds was selected to complete one cycle loading. The eight seconds period duration was divided into two phases, the loading and unloading phases. The duration of these two phases are minimum of two seconds or longer. This time period was longer than the time period observed during the PSD analysis of wind-induced pressure of rigid roofs. As shown in Chapter 4, the frequency at which strong energy variations of wind-induced pressure occurred for rigid roofs was observed to range from 2 Hz to 4 Hz. This means that a minimum time period of 0.5 seconds is required. Another reason for the selection was to have a similar time period as the CSA 123.21-04 load cycle for to enable testing data comparison between rigid and flexible roofs. Figure 5.6 shows the time required to complete one cycle for Group 1 and Group 2 of Figure 5.5.



**Figure 5.6 Time Requirement for One Cycle**

## 5.5 Generalization of Load Cycles for Rigid Roofs

In order to evaluate the ultimate wind uplift resistance of a roofing system, that is major importance to roofing manufacturers for comparing their product with others, a method of load cycle generalization was developed. The generalization was required because the load cycle for rigid roof presented in Figure 5.5 may not be able to provide this information. Consider a particular situation of a roofing manufacturer who selected a system and tested it with test pressure of 60 psf.

According to Figure 5.5, if the system successfully passes all the load cycles, it can be certified as  $P_{60}$ . However, in this scenario, the client is not aware of the ultimate strength of the tested roofing system. On the other hand if the system failed before passing all the load cycles, the manufacturer is required to redesign the system's components. The developed load cycle is useful to those who have a clear understanding of the system strength or for those who have tested similar systems in the past. Based on past experience, they can select the appropriate test pressure at which the system can pass all the required cycles. This is not a viable solution when new products or new installation procedures are introduced. To overcome this situation, a method of load cycle generalization for rigid roof is presented in this section.

The method of load cycle generalization for rigid roof was introduced by utilizing ratios of the SIGDERS (CSA) load cycles to forecast the number of load cycles that would occur at pressure levels that were not tested in the wind tunnel. The following procedure gives an example of using the ratios method to forecast the dynamic load cycles of rigid roof for the Sequence N1 to N8 of Level B to Level E.

- Calculate the ratio of N2-Level B to N2-Level A of the CSA load cycles = 0.71  
[  $500 \text{ (N1-Level B)} / 700 \text{ (N1-Level A)} = 0.71$  ]. Table 5.6 encapsulates all of the calculated ratios from SIGDERS (CSA) load cycles for the determination of dynamic load cycles for rigid roof.
- Establish the N2 – number of cycle of the Level B for rigid roof by multiplying the obtained ratio (0.71) with the N2 of Figure 5.5. [  $0.71 \times 245 = 175$  ]

**Table 5.6** Calculated Ratios for the Different Levels to Level A of CSA Load Cycles

| Group # | Loading Sequence | Level A | Level B |            | Level C |            | Level D |            | Level E |            |
|---------|------------------|---------|---------|------------|---------|------------|---------|------------|---------|------------|
|         |                  | Cycles  | Cycles  | Ratio to A | Cycles  | Ratio to A | Cycles  | Ratio to A | Cycles  | Ratio to A |
| 1       | N1               | 400     | 0       | 0.00       | 0       | 0.00       | 0       | 0.00       | 0       | 0.00       |
|         | N2               | 700     | 500     | 0.71       | 250     | 0.36       | 250     | 0.36       | 200     | 0.29       |
|         | N3               | 200     | 150     | 0.75       | 150     | 0.75       | 100     | 0.50       | 100     | 0.50       |
|         | N4               | 50      | 50      | 1.00       | 50      | 1.00       | 50      | 1.00       | 50      | 1.00       |
| 2       | N5               | 400     | 0       | 0.00       | 0       | 0.00       | 0       | 0.00       | 0       | 0.00       |
|         | N6               | 400     | 350     | 0.88       | 300     | 0.75       | 50      | 0.13       | 0       | 0.00       |
|         | N7               | 25      | 25      | 1.00       | 25      | 1.00       | 25      | 1.00       | 25      | 1.00       |
|         | N8               | 25      | 25      | 1.00       | 25      | 1.00       | 25      | 1.00       | 25      | 1.00       |
| Total = |                  | 2200    | 1100    |            | 800     |            | 500     |            | 400     |            |

Using a similar procedure as N2 Level B other values of N2 for Level C to Level E were calculated as well as other sequences for Level B to Level E. The completed results are tabulated in Table 5.7. For the rigid system, the performed calculations provide a total number of cycles of 652, 555, 395 and 368 for Levels B, C, D and E, respectively.

**Table 5.7** Calculated Load Cycle for Rigid Roof based on CSA Load Cycle Ratios

| Group # | Loading Sequence | Number of Cycles Proposed |            |            |            |            |
|---------|------------------|---------------------------|------------|------------|------------|------------|
|         |                  | Level A                   | Level B    | Level C    | Level D    | Level E    |
| 1       | N1               | 26                        | 0          | 0          | 0          | 0          |
|         | N2               | 245                       | 175        | 88         | 88         | 70         |
|         | N3               | 458                       | 344        | 344        | 229        | 229        |
|         | N4               | 50                        | 50         | 50         | 50         | 50         |
| 2       | N5               | 0                         | 0          | 0          | 0          | 0          |
|         | N6               | 73                        | 64         | 55         | 9          | 0          |
|         | N7               | 18                        | 18         | 18         | 18         | 18         |
|         | N8               | 1                         | 1          | 1          | 1          | 1          |
| Total = |                  | <b>872</b>                | <b>652</b> | <b>555</b> | <b>395</b> | <b>368</b> |

## 5.6 Proposed Load Cycles for Rigid Roofs Evaluation

The calculated rigid load cycles presented in Table 5.7 were simplified and the values were rounded to the nearest number of load cycles as presented in Table 5.8. Following the number of load cycle simplifications, the load cycles for rigid roof shown in Table 5.8 was proposed to use for the evaluation of AARS wind uplift resistance performance. Under the proposed load cycles, the testing time required to complete Level A is less than 2 hours. While the total duration required for completion of all levels (Level A to Level E) is less than 6.5 hours. The total number of cycles to complete all five levels is 2886 cycles. This is about 40% less than the total number of CSA (flexible) load cycles and results in a reduction of testing time of about 4.5 hours.

**Table 5.8** Number of Cycles at the 5 Levels

| Group #        | Loading Sequence | <i>Number of Cycles Proposed</i> |            |            |            |            |
|----------------|------------------|----------------------------------|------------|------------|------------|------------|
|                |                  | Level A                          | Level B    | Level C    | Level D    | Level E    |
| 1              | N1               | 25                               | 0          | 0          | 0          | 0          |
|                | N2               | 250                              | 175        | 100        | 100        | 75         |
|                | N3               | 450                              | 350        | 350        | 225        | 225        |
|                | N4               | 50                               | 50         | 50         | 50         | 50         |
| 2              | N5               | 0                                | 0          | 0          | 0          | 0          |
|                | N6               | 75                               | 50         | 50         | 0          | 0          |
|                | N7               | 20                               | 20         | 20         | 20         | 20         |
|                | N8               | 5                                | 5          | 5          | 5          | 5          |
| <b>Total =</b> |                  | <b>875</b>                       | <b>650</b> | <b>575</b> | <b>400</b> | <b>375</b> |

Figure 5.7 presents the proposed load cycles for a rigid roof that consists of five levels (A, B, C, D and E). Each level has eight sequences (N1 to N8). Similar to SIGDERS (CSA) load cycles, the rating is established when all specified numbers of cycles in each level have been completed without any resistance link failures (Chapter 2). Similar to the SIGDERS (CSA) load cycle, the proposed load cycles can provide various options to the roofing community. Two of them are summarized below,

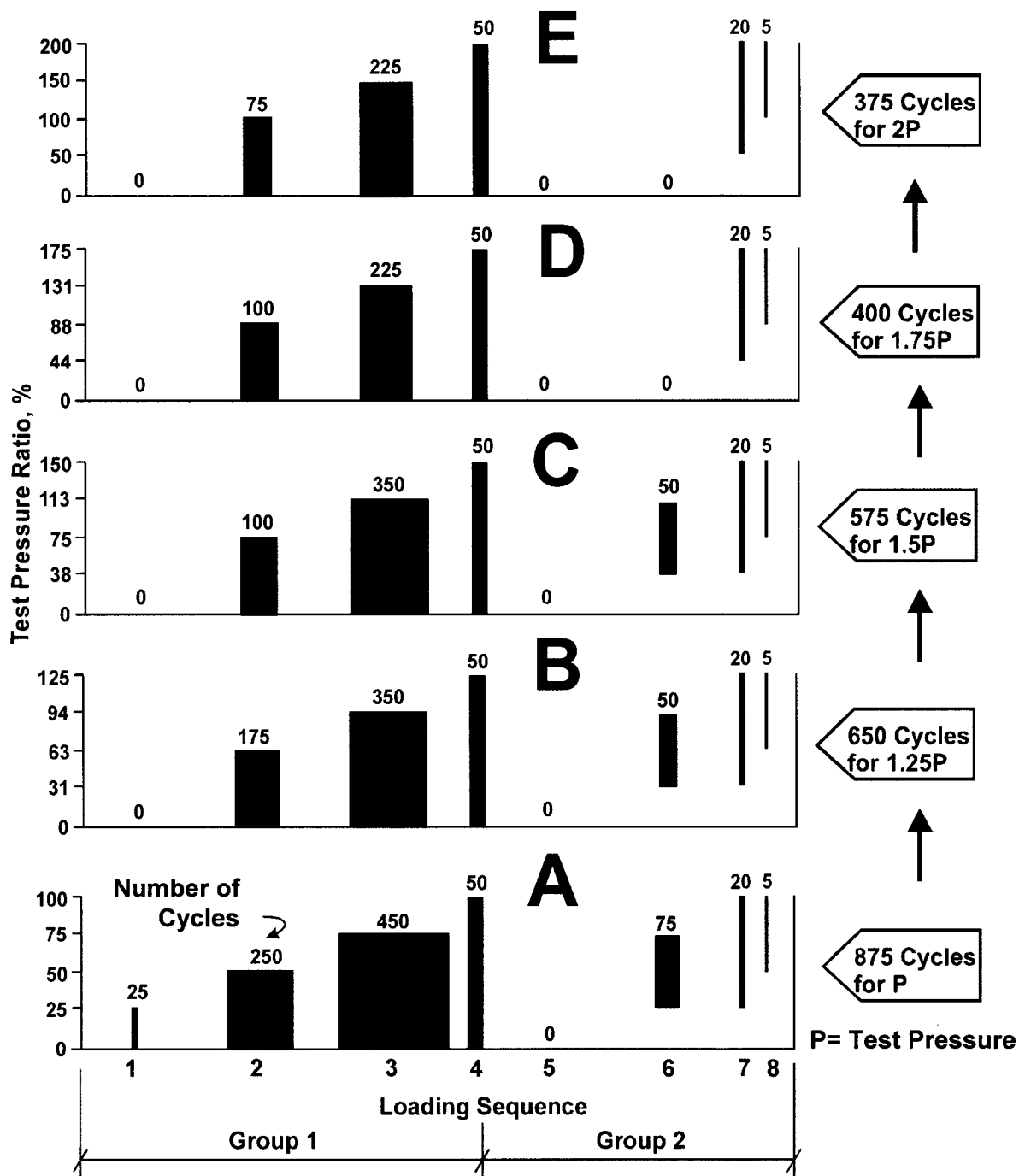
*Option 1: Introduction of Safety Factor in System Design*

The load cycle for rigid roof was developed to satisfy regulatory requirements. The design pressures are used to convert the ratios on the Y-axis of Figure 5.7. Such pressures are established in accordance with the local wind standards or building code minimum requirement recommendations. Systems that pass level A can be tested with the design pressure increased incrementally by 0.25. Thus it can provide roofing manufacturers with the safety factor, while the building codes or wind standards prescribe only “minimum design values.” The proposed load cycle distribution presents the safety factor of 2 for the design pressure. Other features of the load cycles, such as need for Group 1 and Group 2, remain the same as explained in Figure 5.5.

*Option 2: System Rating Certification*

This option provides roofing manufacturers a system rating. The system rating certification is needed to ensure that the roofing system meets the minimum design pressure prescribed in the building code requirements. The process of system

rating certification can be used to quantify either a new roof assembly or to verify a existing with new, substituted or enhancement components. The rating can be established when the system tested completes all sequences on each corresponding level. The established rating is used to determine whether or not, a roofing system can be installed at a specific location. This is performed by dividing the rating's with the factor of safety and compare this value with the design wind uplift pressure values (corner, edge and field) obtained from the building code (e.g. NBCC 2005, ASCE-07 2005). To use a roofing system at specific location, the pressure rating value should be larger than design wind uplift pressure values obtained from the building code.



**Figure 5.7** Proposed Load Cycle for Rigid Roofing Systems

## **5.7 Concluding Remarks**

In this chapter a set of load cycles was developed (Figure 5.7) for the evaluation of wind uplift resistance of the rigid roofing systems. The developed load cycles can be used to quantify any roof system performance that exhibits rigid system response such as AARS during wind actions. The developed load cycles will be used later as a load testing protocol to establish a full-scale laboratory testing procedure for the evaluation of the AARS wind-uplift resistance performance (Appendix D).

## **Chapter 6.      Application of the Developed Load Cycle**

### **6.1      Introduction**

In order to develop a full-scale test method for the AARS wind-uplift resistance performance evaluation, the experimental investigations have been performed and the test results were analysed. The tests were conducted under simulated static and dynamic loadings on 30 full-scale AARS mock-ups. The static test was performed in accordance with the testing procedure presented in the Section 2.3.1.1, while the dynamic test followed the procedure given in the Section 2.3.1.3. During dynamic testing, two load cycles were applied, the developed load cycle in Chapter 5 and the CSA 123.21-04 load cycle. The test mock ups for AARS were constructed following the procedure outlined in Chapter 3. The test setup including the mock-up handling and edge treatments, failure criteria and failure mode investigation for the tests are given in Appendix D.

This chapter discusses the AARS wind-uplift resistance performance under simulated static and dynamic loading conditions, the effects of the number of cycles, component variability, and the comparison of wind uplift performance between the developed load cycle herein with the CSA 123.21-04 load cycle. The information obtained from these investigations is being used to enhance the CSA 123.21-04 dynamic full scale test method to incorporate the test method for wind uplift resistance evaluation of rigid roofing systems such as AARS.

## **6.2 Wind-uplift Resistance**

### **6.2.1 General**

To study the wind-uplift resistance performance of AARS tested under simulated static and dynamic loading conditions, four sets of full-scale mock-ups using the same roof components and adhesive application techniques were fabricated. Each set consists of two full-scale mock-ups. Hereafter, the four set mock-ups are referred to as M-1, M-2, M-3 and M-4. A curing time of 21 days was given prior testing to allow adhesives to harden. For each set, two identical mock-ups were constructed. One was tested under simulated static loading conditions and another was tested under simulated dynamic loading conditions. Comparison of the test results between the eight mock-ups tested under both simulated loading conditions is discussed below.

### **6.2.2 Wind-Uplift Resistance under Static Loading**

The wind-uplift resistance under simulated static loading was measured by applying a static negative pressure as explained in the Section 2.3.1.1. Figure 6.1 shows the negative pressure time histories for the four mock-ups tested under static loading. The Y-axis gives negative pressure values that are achieved by the respective mock-ups as a function of time (X-axis). The M-1 and M-3 successfully sustained 2.87 kPa (60 psf) and failed at 3.59 kPa (75 psf). M-2 achieved a negative pressure of 3.59 kPa (75 psf) and was determined as the highest wind-uplift resistance rating under static loading, while the lowest pressure rating was achieved by M-4 at the suction of 2.15 kPa (45 psf). The suctions in the graphs (Y-

axis) are the reference pressures ( $P_{ref}$ ), and were measured by a pressure tap located in the middle of the DRF top chamber. The other two negative pressures, P1 and P2, measured at the dummy sections had the same readings as that of the control pressure to the  $P_{ref}$ .

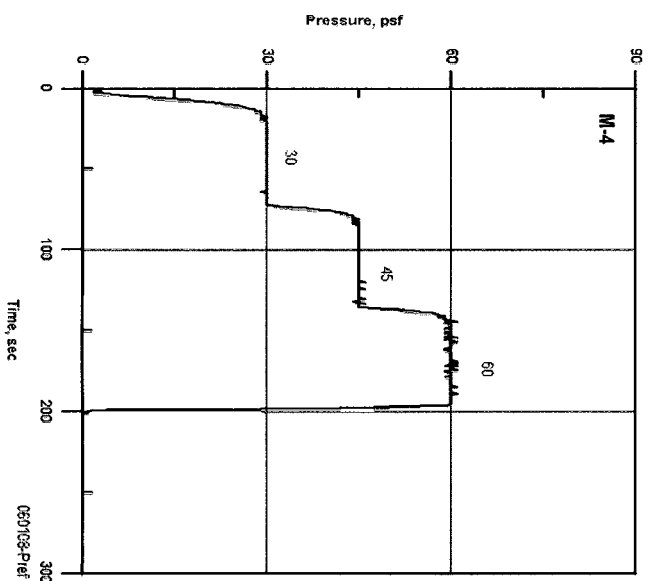
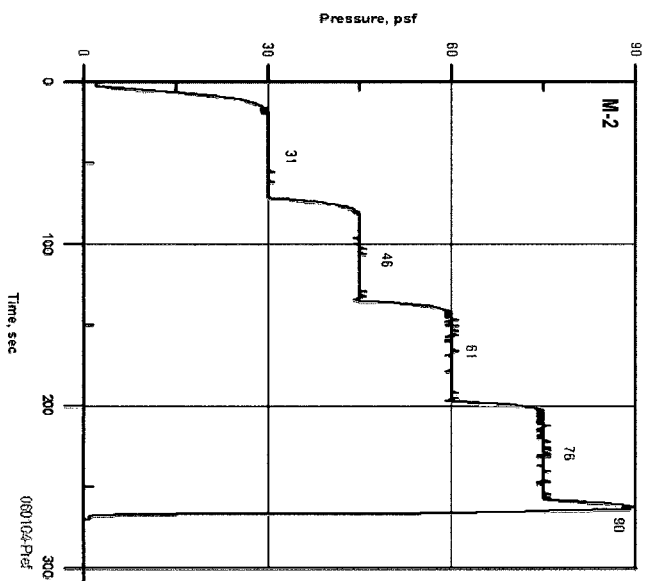
### 6.2.3 Wind-uplift Resistance under Dynamic Loading

The wind-uplift resistance under simulated dynamic loading was measured by applying suction cycles as indicated in Figure 2.9. Four graphs of negative pressure time history are shown in Figure 6.2. The Y-axis in the graph shows the dynamic wind-uplift resistance while the X-axis shows the corresponding time. In terms of the rating classification between dynamic testing and static testing, dynamic testing has different rating classification method in comparison to the static testing. The dynamic rating classification shows the maximum capability of a roofing system to withstand simulated wind-uplift pressure during testing in accordance with the testing procedure described in the Section 2.3.1.3. The dynamic rating classification was established when the mock-ups were tested under eight pressure sequences without any failures. As shown in the Figure 2.8, the Level A of “CSA 123.21-04 Loading Sequence” consists of 8 sequences, N1 to N8, and if there is a failure before completing the eight pressure sequences in Level A, no rating classification is assigned. This was experienced by M-1 as illustrated in Figure 6.2. However it should be mentioned that M-1 failed at Level A, sequence 5. Both M-2 and M-3 were able to sustain 2.15 kPa (45 psf) and failed at Level B, sequence 2 and sequence 3 respectively. Based on the M-1 performance which had no assigned rating, the lower test pressure of 1.44 kPa (30 psf) was

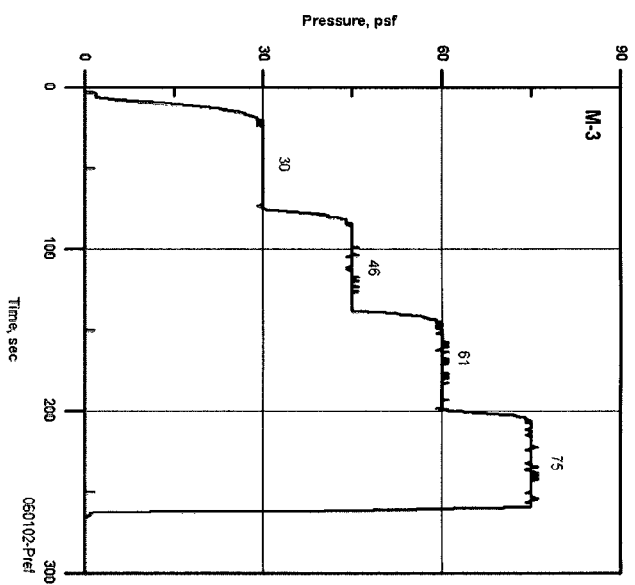
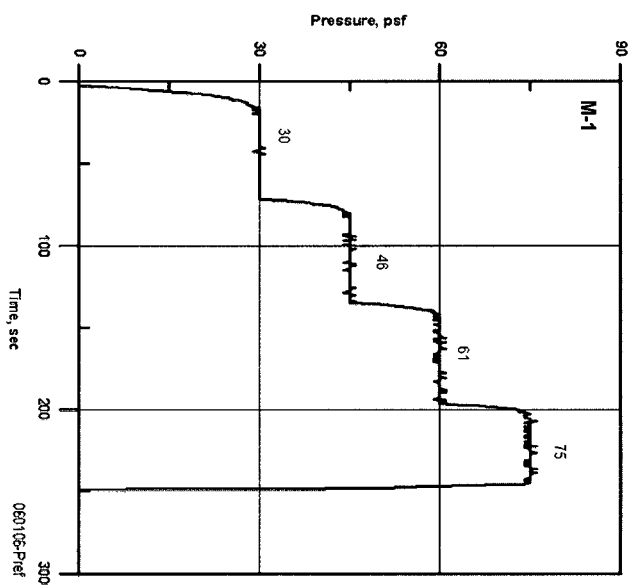
selected for the evaluation of M-4. Note that the ordinates vary based on the selected test pressure. M-4 passed all required sequences of Level A and Level B. This indicates that M-4 sustained 1.82 kPa (38 psf) and failed at Level C sequence 2.

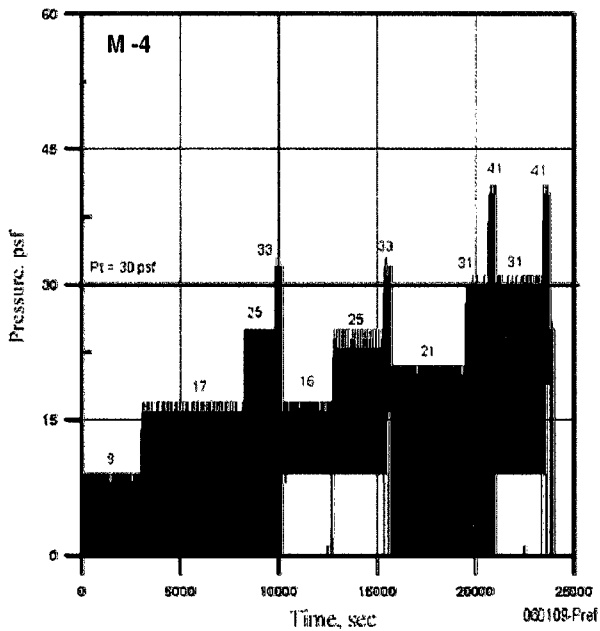
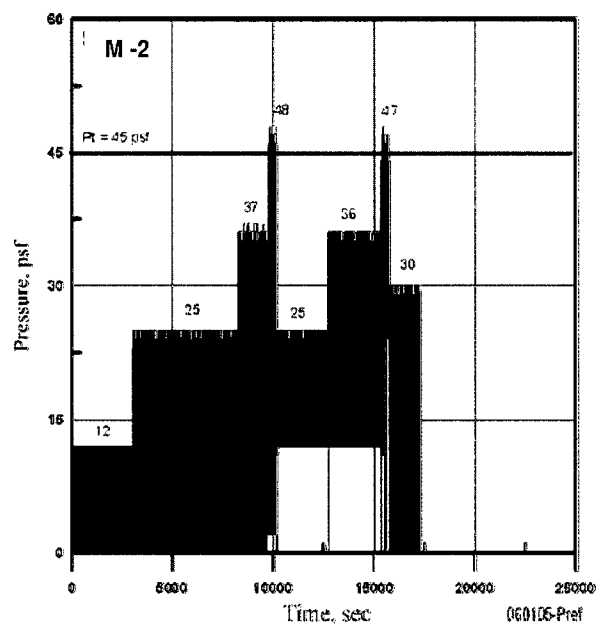
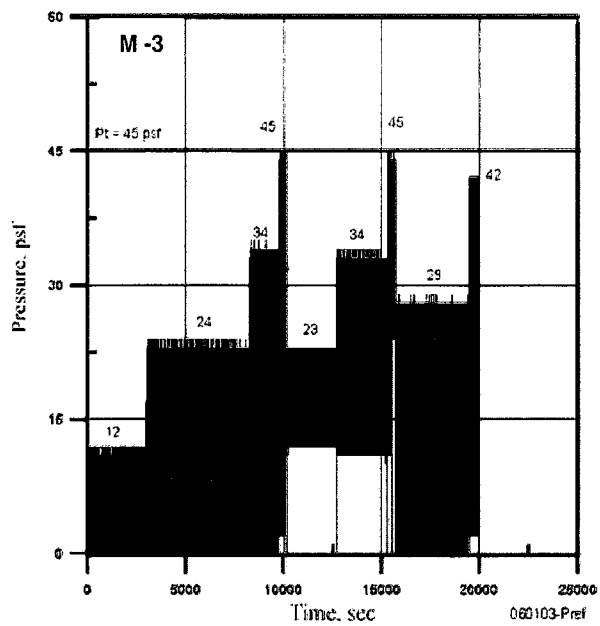
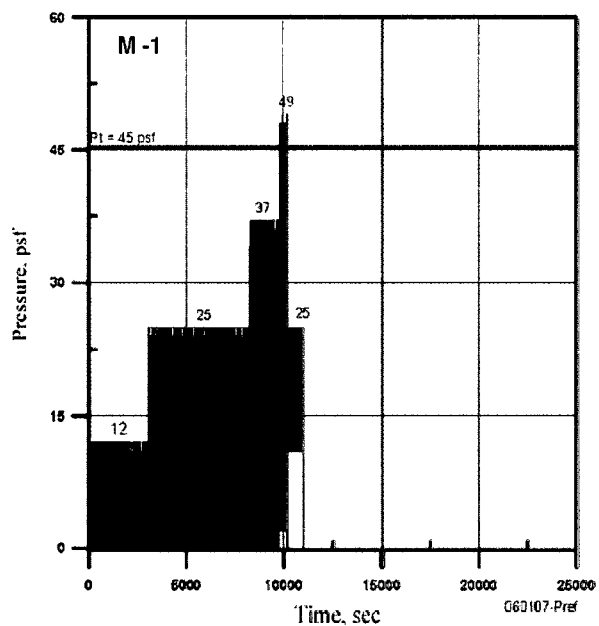
#### 6.2.4 Performance of Static vs Dynamic Loading

A comparison of the static pressure ratings with that of the dynamic pressure ratings indicated that the static test overestimated the wind-uplift resistance. This is because the static test does not simulate the wind-uplift forces over the roof assembly. The dynamic test, as explained in the Chapter 5, considers the effect of wind-induced pressure fluctuations on roofs through load cycles. Wind-induced pressure fluctuations on roofs need to be taken into consideration because they can cause fatigue of the roofing system components and eventually reduce the wind uplift resistance of roofing system (Baskaran et al. 1999). In order to study the failure modes, failure investigations were carried out by cutting the mock-up at the failure location. This is shown in Figure 6.3. During testing, the mock-ups were closely observed to identify the failure location. To identify failure location more precisely, the mock-up top surface was divided into nine segments of equal squares, and was colour marked (Appendix D). The size of each segment was approximately 660 mm x 1016 mm (26 in x 40 in). Note that the total mock-up area was 1981 mm x 3048 mm (78 in x 120 in). The nine segments drawn over the mock-up surface helped the DRF operator observe the extent of failure, as explained in Appendix D. Once the percentage of blister area reached 20% of the total surface area, the test was stopped and the top chamber was removed. This is shown in Figure 6.3.



**Figure 6.1** Static Pressure Time Histories of the Tested Mock-ups





**Figure 6.2** Dynamic Pressure Time Histories of the Tested Mock-ups

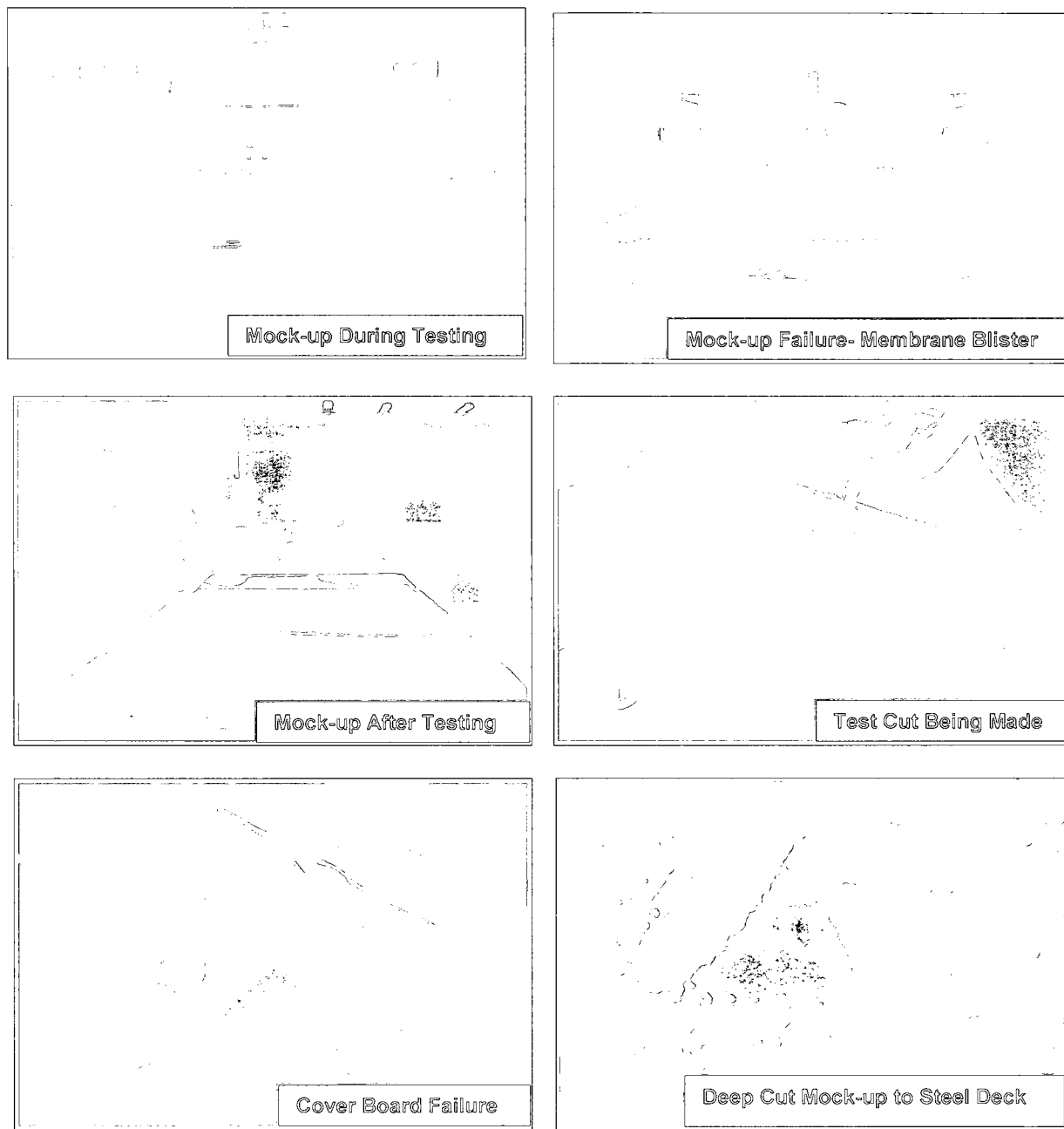


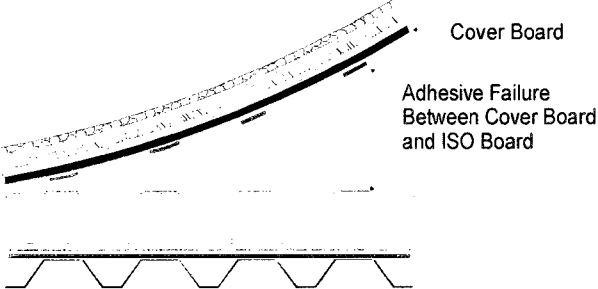
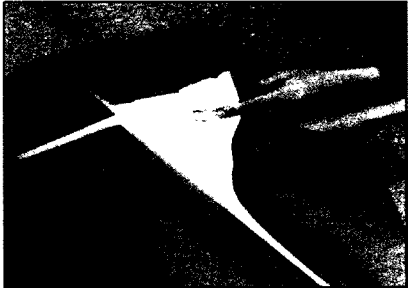
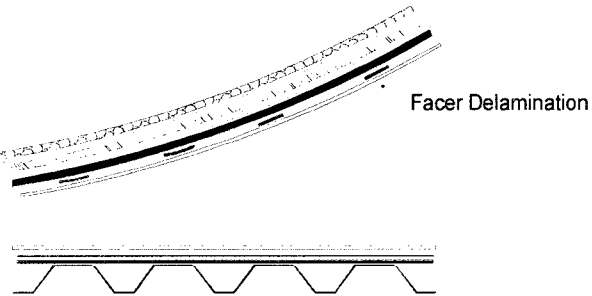
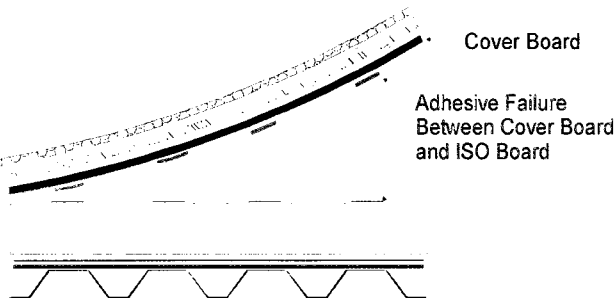
Figure 6.3 Typical Failure Investigation of the Tested Mock-up

The mock-up was then cut at the observed failure location to identify the weakest link of the system. In the case of the mock-up shown in Figure 6.3, the system failed due to adhesive failure between the base sheet and the cover board. This has been classified as Failure #1. Further deep cuts were made up to the steel deck level to verify the integrity of the other components, or if any other failure also occurred. If another failure is observed then it is labelled as Failure # 2 and so on. Note that by doing so, this does not mean that Failure #1 has occurred before Failure #2. In other words, it only showed the sequence of the failure investigation.

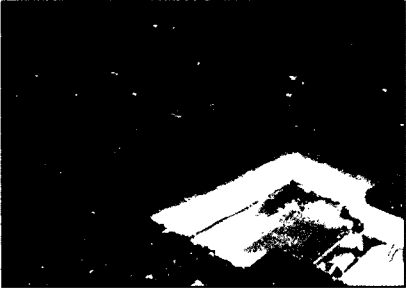
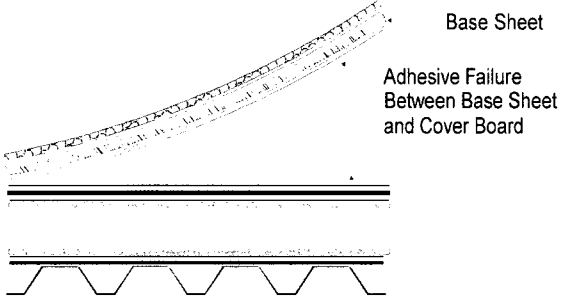
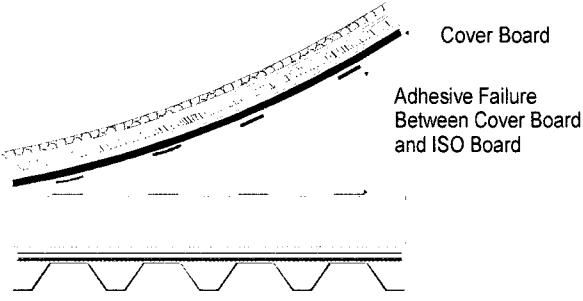
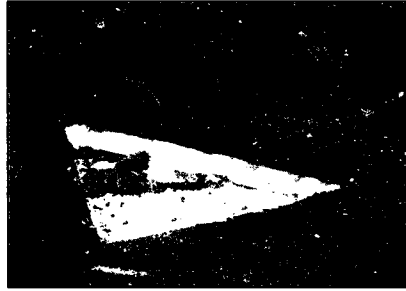
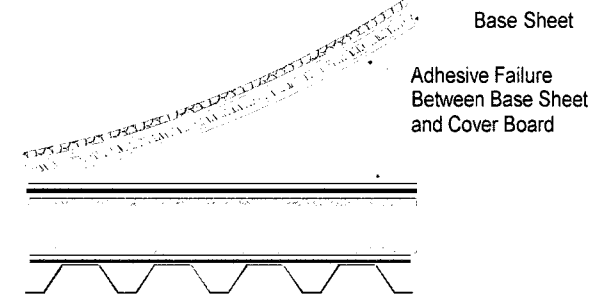
Static and dynamic failure modes are illustrated and compared in Table 6.1 to Table 6.4. The tables have photographs showing the failure mode investigation from the tested mock-ups, as well illustrate the isometric diagrams on the right hand side of the table. Dynamic test failure modes were found similar to that of static test failure mode for the M-1, M-2, and M-4 cases as shown in Table 6.1, Table 6.2 and Table 6.4, respectively. Most failures occurred at the adhesive between the base sheet and the cover board, the cover board and the insulation board or a combination of both. Interestingly, M-3 had a different failure mode than others (Table 6.3). This might be caused by the adhesive application, which was manually applied using the “ribbon” adhesive application technique for this mock-up. As a result, the amount of adhesive applied was difficult to control and was inconsistent from one bead to another. Other failure modes observed were insulation top facer delamination and the failure of uncured adhesives at certain places. It was also noted that during failure investigations, when mock-ups were cut, the uncured adhesive was found in several locations. This indicates that the 21 day curing time of the present study was not sufficient and needs to be modified in

future investigations. Eliminating this condition can affect the performance of the AARS wind-uplift resistance due to the fact that the adhesives were not cured yet hence the roofing system may not show have the optimum wind uplift resistance capacity during testing.

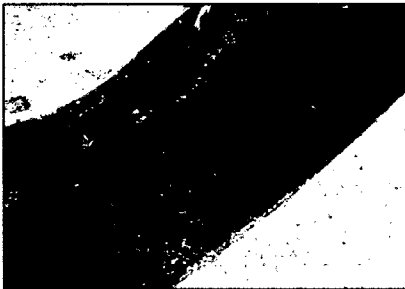
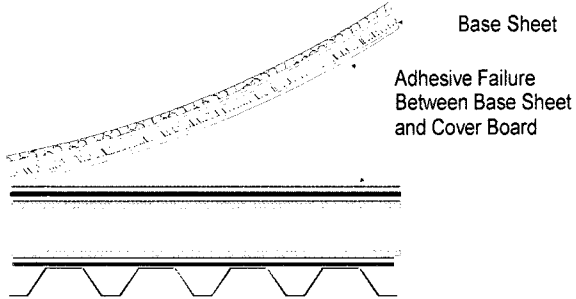
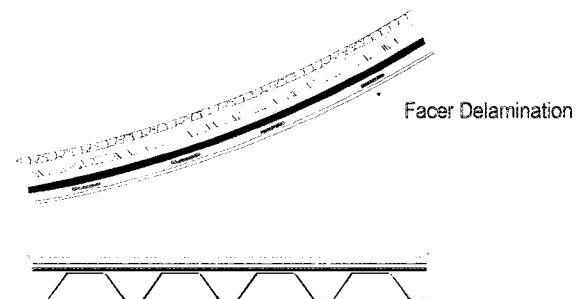
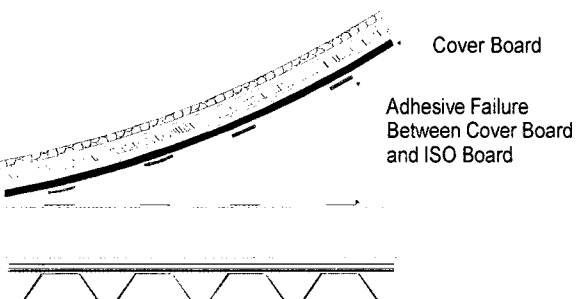
**Table 6.1** Static & Dynamic Failure Investigation Photos and Diagrams: M-1

| Test Protocol | Failure Investigation (M-1)                                                                                                                                                                 |                                                                              |
|---------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Static        | <p>Failure # 1</p>     | <p>Cover Board</p> <p>Adhesive Failure Between Cover Board and ISO Board</p> |
|               | <p>Failure # 2</p>   | <p>Facer Delamination</p>                                                    |
| Dynamic       |                      | <p>Cover Board</p> <p>Adhesive Failure Between Cover Board and ISO Board</p> |

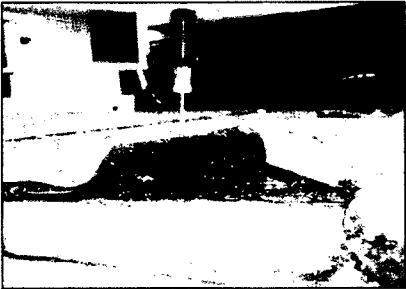
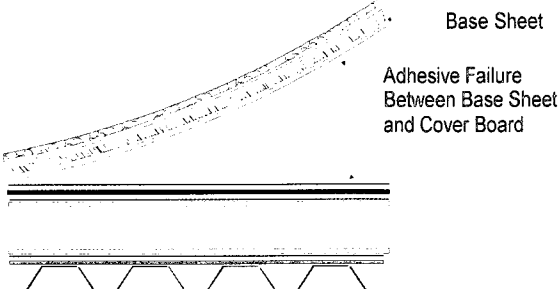
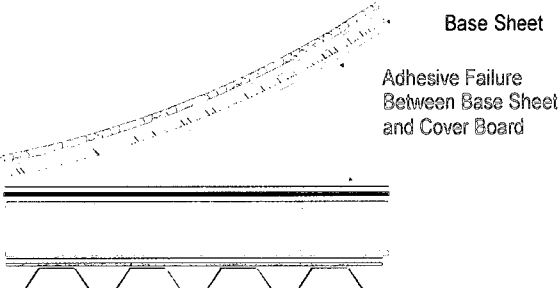
**Table 6.2 Static & Dynamic Failure Investigation Photos and Diagrams: M-2**

| Test Protocol | Failure Investigation (M-2)                                                                           |                                                                                                                                                                   |
|---------------|-------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Static        | <p>Failure # 1</p>   |  <p>Base Sheet</p> <p>Adhesive Failure Between Base Sheet and Cover Board</p>   |
|               | <p>Failure # 2</p>  |  <p>Cover Board</p> <p>Adhesive Failure Between Cover Board and ISO Board</p>  |
| Dynamic       |                    |  <p>Base Sheet</p> <p>Adhesive Failure Between Base Sheet and Cover Board</p> |

**Table 6.3** Static & Dynamic Failure Investigation Photos and Diagrams: M-3

| Test Protocol | Failure Investigation (M-3)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Static        | <p><b>Failure # 1</b></p> <div>  </div> <div>  <p>Base Sheet</p> <p>Adhesive Failure Between Base Sheet and Cover Board</p> </div> <p><b>Failure # 2</b></p> <div>  </div> <div>  <p>Facer Delamination</p> </div> |
| Dynamic       | <div>  </div> <div>  <p>Cover Board</p> <p>Adhesive Failure Between Cover Board and ISO Board</p> </div>                                                                                                                                                                                                                                                                                                                                                                                                                     |

**Table 6.4** Static & Dynamic Failure Investigation Photos and Diagrams: M-4

| Test Protocol | Failure Investigation (M-4)                                                                                                                                                                                                                                                                                                              |
|---------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Static        | <div>  </div> <div>  <p>Base Sheet</p> <p>Adhesive Failure Between Base Sheet and Cover Board</p> </div>     |
| Dynamic       | <div>  </div> <div>  <p>Base Sheet</p> <p>Adhesive Failure Between Base Sheet and Cover Board</p> </div> |

## **6.3 Effect of Number of Cycles on the Wind Uplift Resistance**

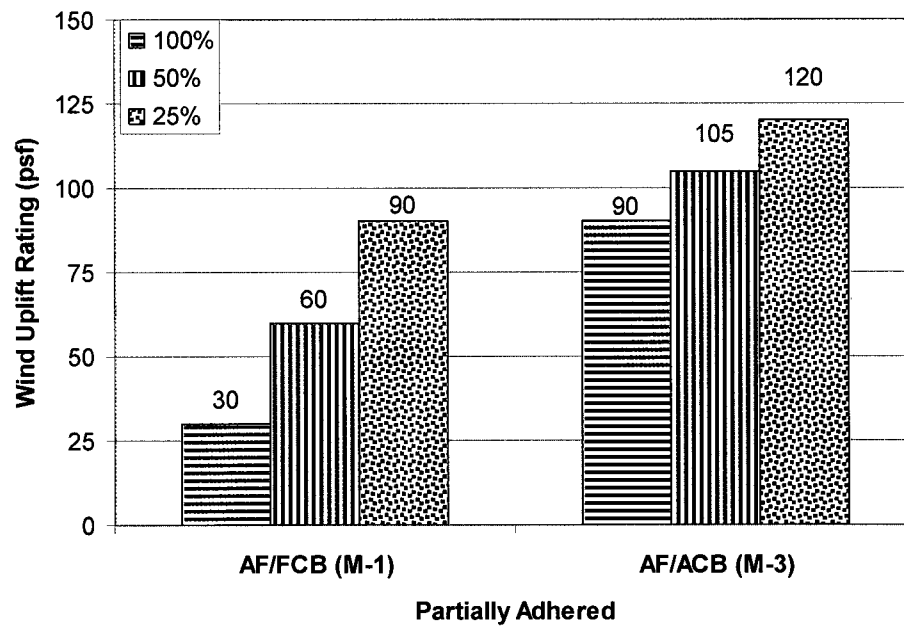
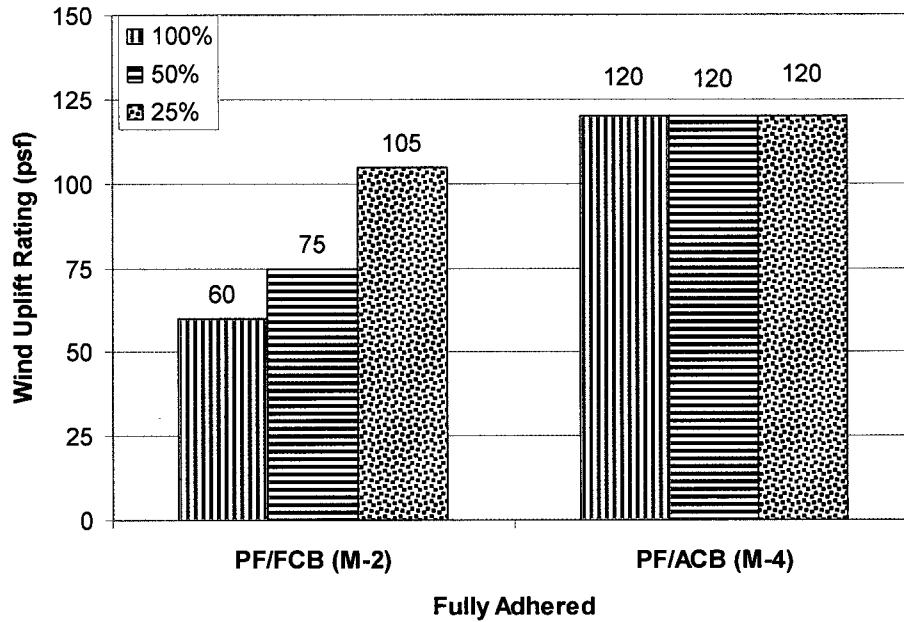
### **6.3.1 General**

Four sets of AARS mock-ups, three per set, were fabricated to study the influence of the number of load cycles on the performance of wind-uplift resistance and to verify whether or not a specific AARS load testing protocol is required. The four sets mock-ups were made from two different types of insulation facer and cover board, and are referred to as AF/FCB (M-1), AF/ACB (M-2), PF/FCB (M-3) and PF/ACB (M-4), in which AF, PF, ACB and FCB stand for the acrylic facer insulation, paper facer insulation, asphaltic core board and fibre cover board respectively. All mock-ups were tested in accordance with CSA 123.21-04 and a 28-day curing time was applied to the mock-ups prior to testing. In order to study the effect of the number of cycles on AARS, the load testing protocol, that consists of a series of load cycles, as illustrated in the Figure 2.8, was applied to the mock-ups with reduction in the total number of cycles on each sequence by about 50% and 75%. For example, the “N1- Level A” of the Figure 2.8, originally had 400 cycles, they were reduced to 200 cycles and 100 cycles, 50% and 25% of the CSA 123.21-04 load cycles, respectively. As previously mentioned, each set consists of three full-scale mock-ups. Each of the mock-ups was tested using the 100%, 50% and 25% of the CSA 123.21-04 load cycle. Section 6.3.2 and Section 6.3.3 summarize the test results and failure modes of the tested mock-ups.

### 6.3.2 Wind Uplift Resistances at 25%, 50% and 100% of CSA Load Cycle

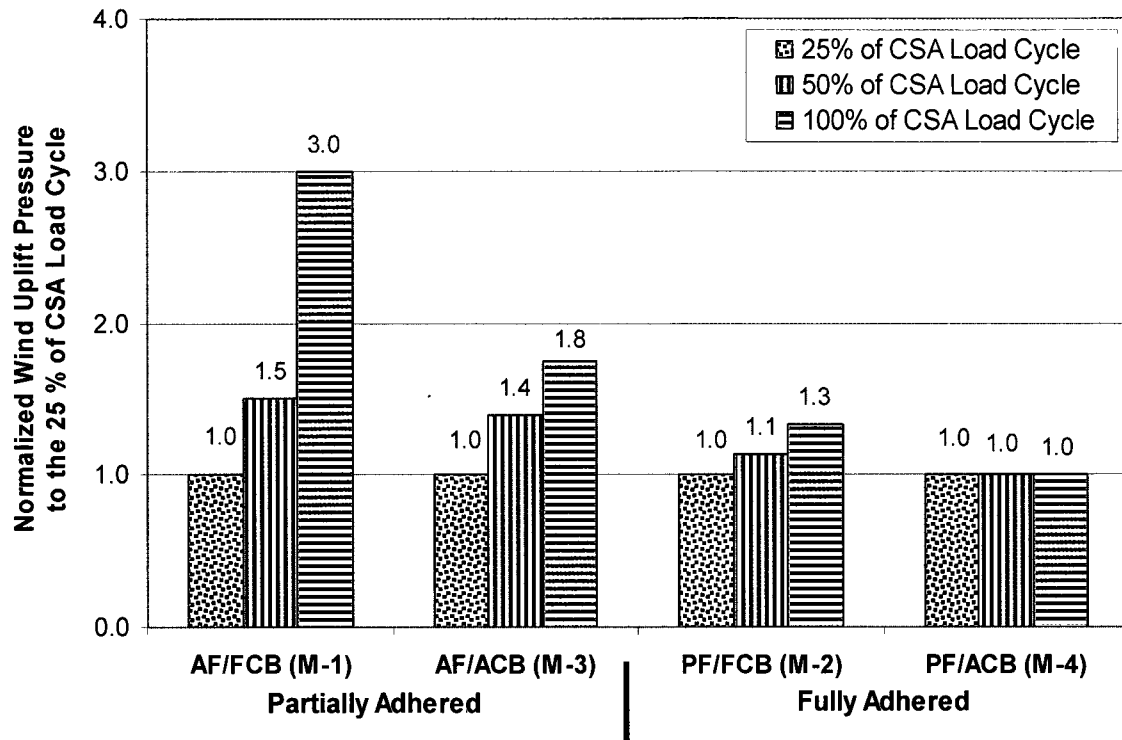
For the purpose of data analysis, the four sets mock-up mentioned above were classified into two groups, fully adhered and partially adhered. The fully adhered set consisted of AF/ACB (M-2) and PF/ACB (M-4), while the partially-adhered set consisted of AF/FCB (M-1) and PF/FCB (M-3) mock-ups. Further information about this classification is mentioned in the Chapter 3. The wind-uplift resistance performance of the fully adhered set is illustrated on the top bar-chart of Figure 6.4. The test results were compared with the performance tested under the 100% CSA load cycles. It shows that the wind-uplift resistance performance was improved when the smaller number of cycles was applied. This means that the number of cycles does influence the wind uplift resistance performance, hence it is necessary to determine the right number of cycles for testing of AARS. A similar tendency was observed for the partially adhered as shown in the bottom bar-chart of Figure 6.4. The M-4 (PF/ACB) however, showed no effects when the number of cycles was reduced. This was because the PF/ACB (M-4) mock-ups passed all levels of the CSA load cycles, and therefore should be excluded from the comparison.

Figure 6.4 also illustrates that the roof component variations significantly influence the wind uplift rating performances. The test results indicate that the use of paper facer insulation with either fibre or asphaltic core board resulted in superior wind-uplift resistance in comparison to the use of acrylic facer insulation. This suggests that combinations of materials used as substrates in mock-up roof components played an important role in increasing the wind-uplift resistance rating.



**Figure 6.4** Wind-Uplift Resistances at the 25%, 50% and 100% of the CSA Load Cycle.

The obtained wind-uplift resistance performance at 25% cycles was divided by the value obtained at 25%, 50% and 100% cycles. For example, the wind-uplift resistances for the 25%, 50% and 100% cycles of the PF/FCB (M-3) were 5.75 kPa (120 psf), 5.02 kPa (105 psf) and 4.30 (90 psf), respectively. The normalized readings are, therefore, 1.0, 1.1 and 1.3, respectively. Following a similar procedure, the normalized factors for AF/FCB (M-1), AF/ACB (M-2) and PF/ACB (M-4) are also calculated and summarized in Figure 6.5. The normalization factors illustrate the effect of reduction of the number of cycles on fatigue of AARS, and increase wind-uplift resistance capacity. As mentioned earlier in Chapter 2, fatigue in material science can be defined as the progressive and localized structural damage that occurs when a material is subjected to cyclic loading (Wikipedia, 2009). If assumption is made that 100% of CSA load cycles could produce full fatigue damage on AARS. Then the applied amount of fatigue on AARS can be assumed to proportionally less for a reduced number of cycles. As the amount of cycles was reduced, the wind-uplift resistance performance increased. Figure 6.5 shows that the average increment of the wind uplift resistance performance was about 2 times. This illustrates the number of load cycles applied plays an important role in the wind-uplift resistance evaluation. There is a need to develop an appropriate AARS load cycle as a load testing protocol for the wind-uplift resistance evaluation rather than simply applying the percentage number of reduction from the CSA load cycle. The appropriate AARS load cycle, was developed by considering the effect of wind-induced pressure fluctuations on rigid roof and was presented in the Chapter 5.

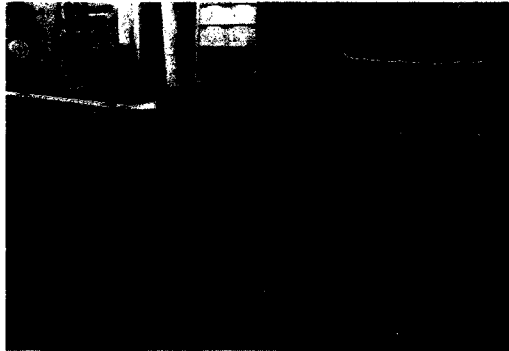


**Figure 6.5** Normalized Fatigue Damage Scale

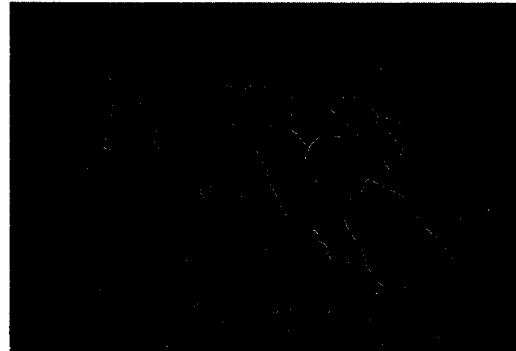
### 6.3.3 Failure Modes at 25%, 50% and 100% of the CSA Load Cycle

This section provides failure mode information for the mock-ups that were tested using 25% and 50% of CSA load cycles. The failure modes were also compared with the mock-ups that were tested using 100% CSA load cycles. Interestingly, it was observed that the type of failure for the mock-ups tested with 25%, 50% and 100% CSA load cycles were all similar. For the partially adhered set, it was the fibre cover board that failed, as shown in Figure 6.6. The type of failure for fully adhered roofs was found to be at the facer insulation, regardless of the type of facer insulation used, as shown in the Figure 6.5. It was noted that no failures were observed during the test for PF/FCB (M-3) under 25% of CSA load cycle and

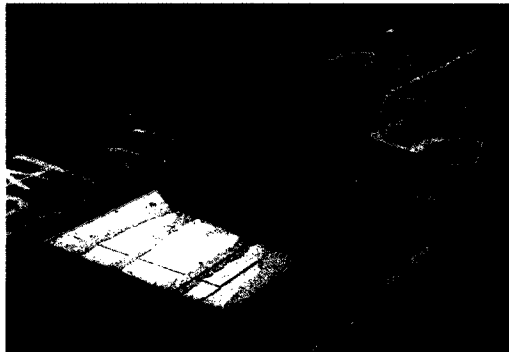
PF/ACB (M-4) under 25% and 50% of CSA load cycle, therefore it was excluded from the following comparison.



25% and 50% of CSA Load Cycle (M-1)



100% of CSA Load Cycles (M-1)



50% of CSA Load Cycle (M-3)

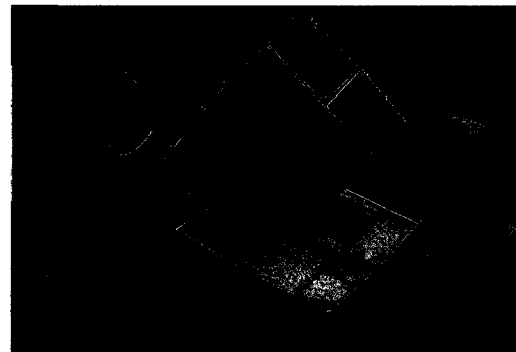


100% of CSA Load Cycle (M-3)

**Figure 6.6** Failure Modes for Partially- Adhered Group



25% and 50% of CSA Load Cycle (M-2)



100% of CSA Load Cycle (M-2)

**Figure 6.7** Failure Mode for Fully- Adhered Group

## **6.4 Comparison of the Wind Uplift Resistance: Flexible Vs Rigid**

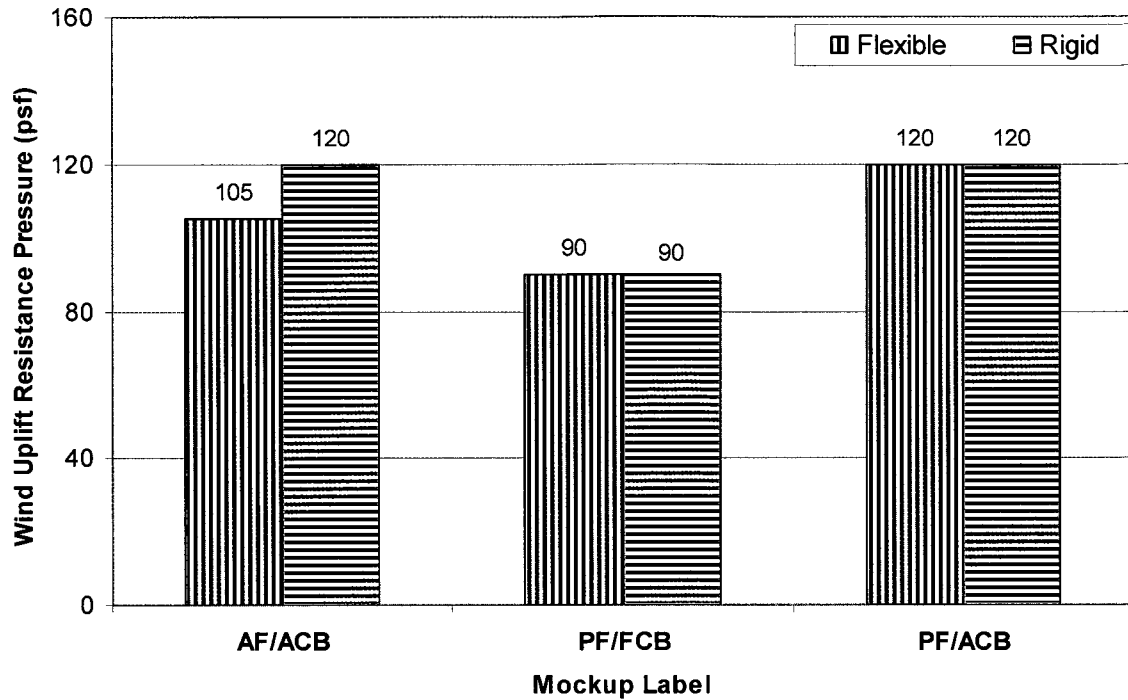
### **6.4.1 General**

Four additional mock-ups were constructed and were tested using the newly developed and CSA load cycles. The purpose of the exercise is to investigate whether the AARS mock-ups tested using the two load cycles would provide similar wind uplift performances. Two out of four mock-ups were labelled as AF/ACB and other two were labelled as PF/FCB and PF/ACB, respectively. The labels describe the component variation used for the AARS mock-ups. The developed load cycle by the present study (Figure 5.7) is hereafter referred as load cycle for rigid roofs, while the CSA load cycle is referred as load cycle for flexible roofs. The PF/FCB and PF/ACB mock-ups were tested using the load cycle for rigid roofs. The PF/FCB and PF/ACB test results were then compared with the PF/FCB and PF/ACB test results that were previously tested using the load cycle for flexible roofs described in Section 6.3. The other two AF/ACB mock-ups were tested using the load cycles for rigid and flexible roofs. Section 6.4.2 and Section 6.4.3 outlines respectively, the wind-uplift resistance ratings and the failure modes obtained by these two different load cycles.

### **6.4.2 Comparison of Wind-uplift Resistance Performances**

Figure 6.8 compares the wind-uplift performance ratings obtained by applying the two load cycles for rigid and flexible roofs. The ordinates represent the rating achieved, while the abscissa gives the mock-up code label. Test results indicate that the mock-ups generally had similar wind-uplift resistances regardless of the

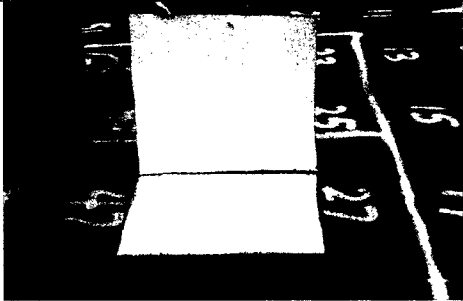
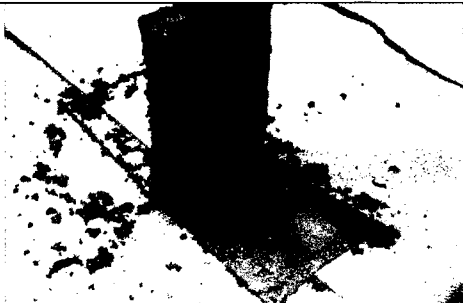
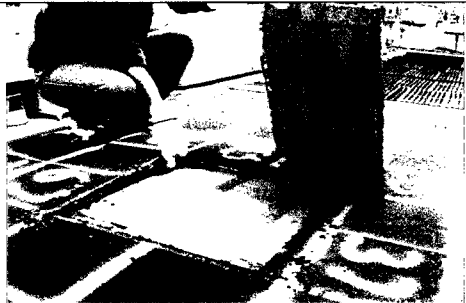
load cycles applied. The AF/ACB mock-up tested using the load cycles for flexible roofs gave a lower resistance rating compared to the case of the load cycle for rigid roofs. However, in general the AF/ACB mock-up wind-uplift rating can be considered similar to that tested using the load cycle for rigid roof. This was because the wind-uplift resistance rating is considered still within the tolerance range as only one level difference between them. It also explains the fact that the use of the load cycle for rigid roofs did not change the ratings of the mock-up compared to the case where the load cycle for flexible roofs was applied. Although the total numbers of cycles for rigid roofs at each level is lower than that for flexible roofs, the numbers of cycles applied at each sequence can be higher than the load cycle for flexible roof. This can clearly be observed by comparing Figure 2.8 with Figure 5.7. The difference in the numbers of cycles applied at each sequence provides a different fatigue response to the tested mock-ups. However, by applying the appropriate load cycles to a tested mock-up, one can produce a reliable response comparable to field data. This was because the load cycle was designed to account for fatigue effects due to wind-induced pressure fluctuations on roofs coupled with the influence of the roof system response. The load cycle for flexible roofs was designed to be used to evaluate flexible roofing systems such MARS and the load cycle for rigid roofs was designed to evaluate the roofing systems that exhibit a rigid system response such as AARS (Chapter 5).



**Figure 6.8** Wind-uplift Resistance Rating of the AARS Mock-up Tested using the Load Cycle for Rigid and Flexible Roofs

#### 6.4.3 Comparison of Failure Modes

Figure 6.9 shows a comparison of the failure mode of the mock-ups tested. Generally, the failure mode can be either delamination of the insulation facer or failure of the fibre cover board. These two failure modes were also observed in the previous mock-up tests, described in Section 6.2 through 6.4. However, out of the four mock-ups tested, the comparison of failure modes was made only on PF/FCB mock-ups because other mock-ups, either one or both, did not failed and completed all five levels (Figure 2.8 or Figure 5.7) of testing. In other words, other failure modes from AF/ACB and PF/ACB were not available for comparison. The condition is marked as “No Failure” in the Figure 6.9.

| Mock-up Label | Load Cycle - Flexible Roof                                                        | Load Cycle - Rigid Roof                                                            |
|---------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| AF/ACB        |  | No Failure                                                                         |
| PF/FCB        |  |  |
| PF/ACB        | No Failure                                                                        |                                                                                    |

**Figure 6.9** Failure Modes Performance of the AARS Mock-up Tested using the Load Cycle for Rigid and Flexible Roofs

## 6.5 Concluding Remarks

Chapter 6 provided information that was used for the development of a full-scale dynamic test method for the evaluation of AARS wind uplift resistance. The chapter is summarized as follows:

- When compared to the dynamic test protocol that simulated the fatigue effects on systems, the static test protocol overestimated the wind-uplift resistance performance, because it did not consider wind-induced pressure fluctuations on roofs. Fluctuations produced lower failure pressures but same mode at failure.

- The effect of the number of gusts fluctuations on AARS was evaluated by applying to AARS assembly, a reduced number of the CSA load cycles, down to 25 % and 50% of the number specified. The test results were then compared with those tested with the full CSA load cycles. By comparing these test results, it was found that the number of load cycles, due to wind-induced pressure fluctuations on roofs, would significantly influence the AARS wind-uplift resistance. This fact indicated that a proper set of load cycles in dynamic loading tests was required for the evaluation of AARS wind uplift resistance. A proper set means a load cycle that accounts for wind induced pressure fluctuations of AARS. This was developed as shown in Chapter 5.
- The effect of component variability was studied by using two types of insulation facers and two types of cover boards that are commonly used in the AARS assembly. The test results showed that a proper selection of the roof components could significantly affect the AARS performance against wind uplift. In addition, the test results also indicated that a new evaluation would be required if one or more components were added to or substituted for in the existing AARS assembly.
- Based on the present research, the weakest link of the AARS assembly was found to be either the insulation or the cover board components. The failure at the insulation component was mostly found when asphaltic core board was used, while the failure at the cover board was found if fibre-cover board was used.

- No adhesive failure was observed when the 28- day curing time was used. It appears that 28 days was an appropriate curing time for the AARS mock-ups used in this experimental study.
- Wind uplift performance of newly developed load cycles for rigid roof and the load cycle for flexible roof (CSA 123.21-04 load cycle) were compared. The test results indicated that the use of the load cycle for rigid roofs did not change the wind-uplift resistance rating resulted from the use of the load cycles for flexible roofs. Also, the failure modes were found to be similar. The study concluded that the newly developed load cycle for rigid roofs is more practical to use for the wind uplift resistance evaluation of AARS because it was faster and provided similar wind uplift ratings in comparison with the CSA 123.21-04 load cycles. A similar phenomena was also noticed when the CSA 123.21-04 load cycle was developed and compared to ETAG-006 test method from Europe.

## **Chapter 7. Correlation between Pullout, Peel and Wind Uplift Tests**

### **7.1 Introduction**

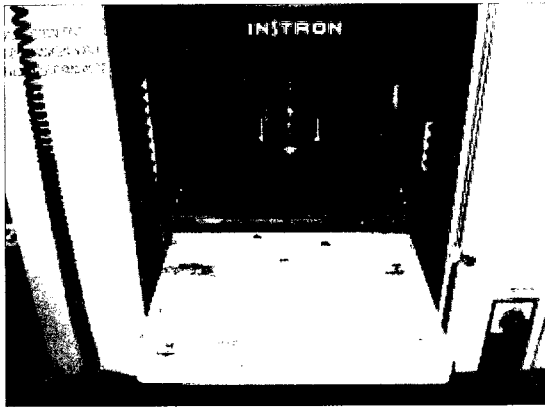
As presented in the Chapter 1, the research described is a part of a project which is developing wind uplift testing methods and design guidelines for the Adhesive Applied Roofing Systems (AARS). The main purpose of the AARS project is to establish a standard testing procedure that can be used for the evaluation of the wind uplift resistance. Two investigation techniques were selected for this purpose, specifically involved experimental study and numerical study. As for the experimental study, the test specimens, called the mock-ups in this project, were divided into two groups, small scale and large scale. Two types of evaluation method were established for small scale samples, the pullout test and peel test. For large scale samples, the wind uplift test evaluation method for AARS was developed. This chapter reports on the performance test results of all three test methods so that the results can be compared. The relative performance of the test results in terms of uplift resistance and failure modes are compared to find how they complement each other. Sections 7.2 to 7.4 provide a summary of the three testing methods. In addition, a possible relationship that can be utilised in relating the three testing methods is outlined in Section 7.5.

## 7.2 Pullout Test

The pullout test method was developed specifically to quantify the resistance of AARS against tensile loading. The pullout test method was performed by applying a static tensile force normal to an AARS small-scale specimen using an Instron testing machine. Prior to the development of the pullout test method, testing parameters such as sample size, pullout rate, the test set-up and the appropriate apparatus were comprehensively studied. Further information on the development of the pullout test method can be obtained elsewhere (Current, 2009). Current (2009) concluded that the pullout test should follow the following procedure,

- A small scale test specimen should be prepared with a minimum size of 305 mm x 457.2 mm (12 in x 18 in)
- Tensile loading should be applied normal to the test specimen with a pulling rate of 6.35 mm (0.25 inches) per min.
- At the end of the test, the maximum sustained load by the specimen and the failure mode can be documented, preferably with some photos.

Figure 7.1 illustrates the experimental setup for this testing method. A plywood plate is attached to connect the specimen to the Instron testing frame. The alignment was checked prior to the placement of the steel bars to hold down the specimen. Once the specimen was properly seated, the steel plate mounted on Instron crosshead was attached to the specimen. The test was performed to the specimen by applying tensile load with a pulling rate of 6.35 mm (0.25 in) per min until failure takes place. After the test finished, the maximum load and the failure mode are recorded.



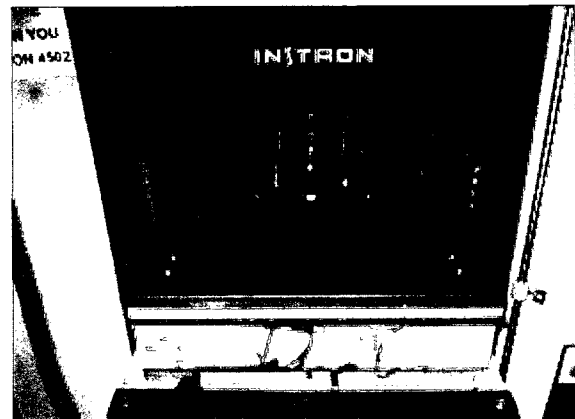
Step 1: Attachment of stress plate & platform



Step 2: Installation of specimen in frame & alignment check



Step 3: Attaching stress plate to stress plate mounting platform



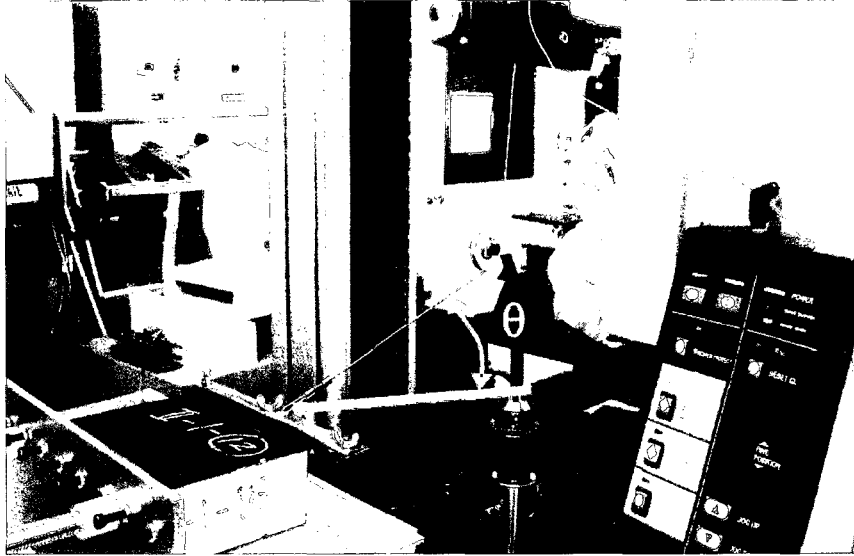
Step 4: Attaching male and female components of stress plate housing

**Figure 7.1** Typical Pullout Test Setup (Current, 2009)

### **7.3 Peel Test**

The peel test method was aimed at evaluating resistance of AARS under shear loading. The test provides information in terms of the peel resistance of AARS when one of the AARS components is peeled off due to wind induced suction. Similar to the pullout test, testing parameters such as the determination of a proper specimen size, the critical peel angle and position of peel as well as the design of the testing apparatus, were studied prior to the development of peel test method. Further information on the development of the peel test method can be obtained in Wu (2008). Wu (2008) concluded that the following procedure should be followed in order to perform the peel test.

- Test specimen should be prepared with a minimum size of 152 mm x 152 mm (6 in x 6 in).
- Peel test should be performed by using the developed peel test apparatus along with the Instron testing machine as shown in Figure 7.2.
- Peel force should be applied at the initial angle of 15-degree (Figure 7.2) along the edge of the specimen.
- At the end of the test the maximum sustained load and the failure mode are to be documented preferably with some photos.



**Figure 7.2 Typical Peel Test Setup (Wu, 2008)**

Figure 7.2 shows test setup for a peel test specimen consisting of insulation and a cover board placed on the peel test apparatus. A gripper was attached to one edge of the cover board, and peel force was applied by using the Instron testing machine. The tensile force was applied at the initial angle of 15-degree. The test was stopped at the failure of the specimen, and the maximum sustained load and the failure modes were recorded.

#### **7.4 Pullout, Peel and Wind Uplift Tests: Performance Comparison**

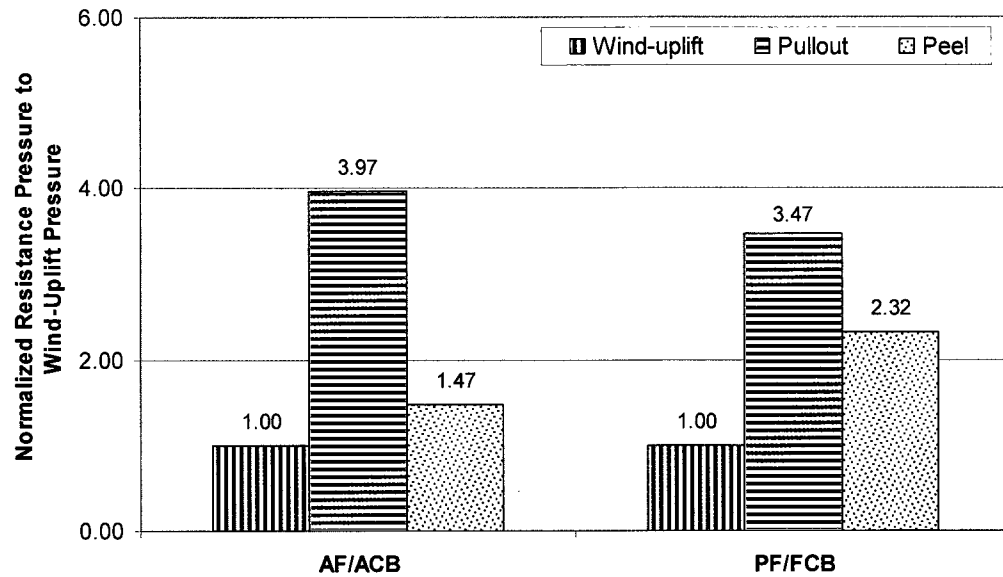
A comparison of the three testing methods with regard to wind uplift resistance and the corresponding failure mode is presented in this section. For comparison purposes, the maximum sustained load of the peel test was divided into two component vectors, components parallel and perpendicular to the surface plane of the specimen. The normal component to the surface plane was considered for

comparison with the pullout test and wind uplift test results. Table 7.1 compares the uplift resistance values obtained from all three tests. To further discuss the uplift resistance for wind uplift, pullout and peel testing, normalized uplift resistance ratios were calculated using the results presented in Table 7.1. For example, a ratio of 3.97 for AF/ACB pullout data was computed by dividing the AF/ACB pullout uplift pressure data (11.41 kPa) with the AF/ACB wind uplift pressure data (2.87 kPa). Following a similar procedure the other ratio for PF/FCB was also established. Figure 7.3 compares the outcome of three testing methods for specimens AF/ACB and PF/FCB. The values are normalized to the wind uplift test results.

**Table 7.1 Uplift Resistance Performance Summary**

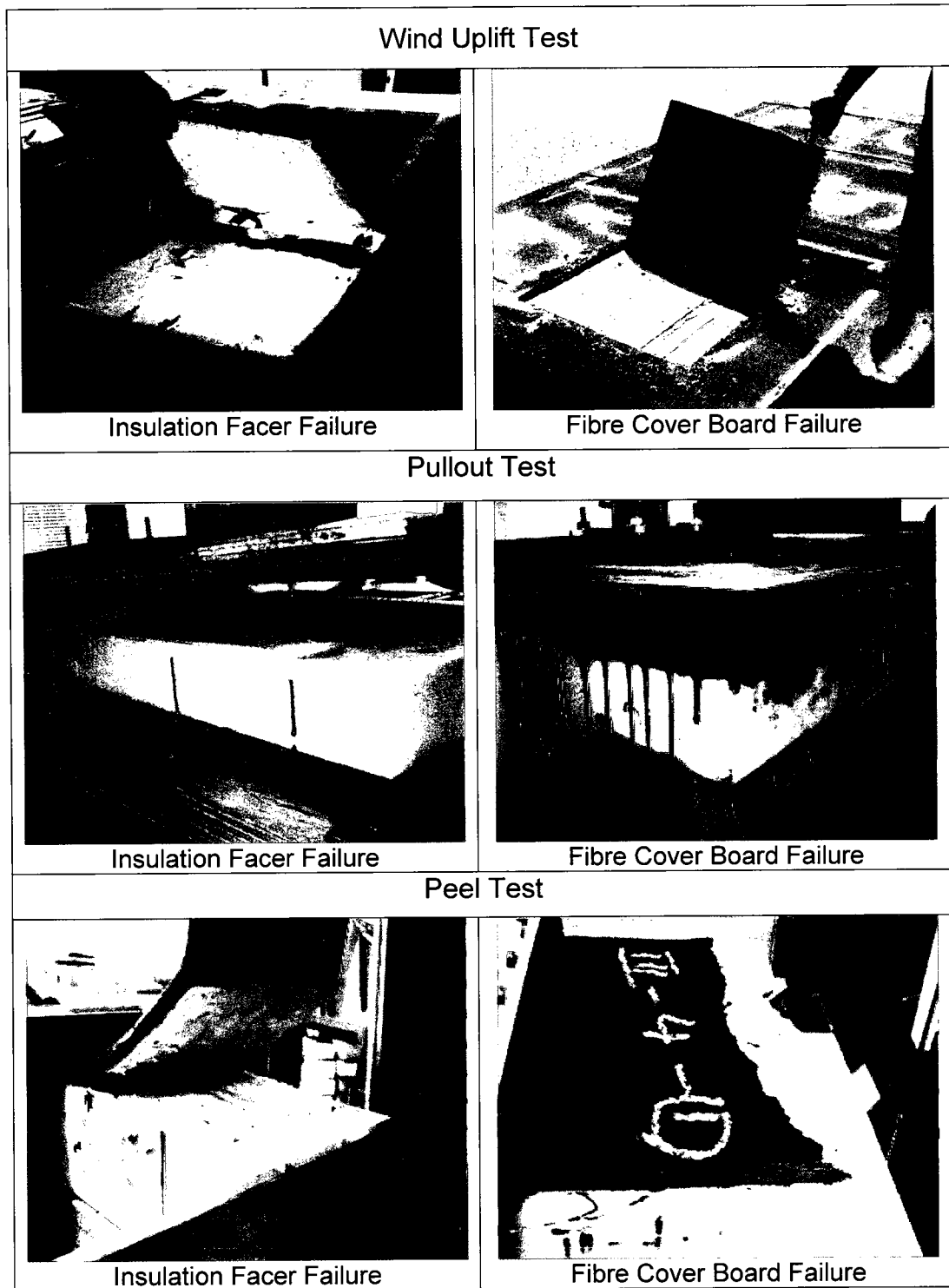
| <b>Mock-ups<br/>Components</b> | <b>Wind Uplift<br/>(kPa/psf)</b> | <b>Pullout<br/>(kPa/psf)</b> | <b>Peel<br/>(kPa/psf)</b> |
|--------------------------------|----------------------------------|------------------------------|---------------------------|
| <b>AF/ACB</b>                  | 2.87/60                          | 11.41/238.3                  | 4.21/87.92                |
| <b>PF/FCB</b>                  | 4.31/90                          | 14.96/312.5                  | 10.01/209.06              |

Figure 7.3 clearly shows that the wind uplift tests gave much lower results. The peel test results are found to be 1.5 to 2 times greater and the pull-out tests resulted in 3.5 to 4 times greater results compared to the wind uplift tests. A possible interpretation of this discrepancy is discussed in Section 7.5.



**Figure 7.3** Uplift Resistance Performance Comparison

The failure modes were similar for all three test results. The primary failure mode occurred at the facer insulation and fibre cover board. Other failure modes were also observed such as insulation foam failure and adhesive failure. Figure 7.4 shows photos for the common failure modes from the wind uplift, pullout, and peel tests. Based on this study, it was determined that the weakest link for the AARS is either the insulation board or/and the fibre cover board. Regardless of the method of testing used as is evident in Figure 7.4. Facer insulation failure occurred in most of the AARS configurations, while the fibre cover board became the weakest link if it was used. Further information the AARS failure mode investigations can be found in technical reports by Current et al (2007), Murty et al (2008), Murty et al (2009) and Weihong et al (2009).



**Figure 7.4** Weakest Links for the Wind Uplift Test, Pullout Test and Peel Test

## **7.5 Future Direction: Bringing the Three Tests Together**

This section addresses a possible development of a relationship among the three test methods (wind uplift, pullout and peel tests). The intention is to develop a technical sound procedure and at the same time an economically viable one when a new component is substituted or introduced into previously tested AARS assemblies in order to establish a wind uplift rating. The hypothesis, *“Higher peel and pullout resistance will result in higher wind uplift resistance”*, is proposed in order to develop a procedure that takes of previously tested AARS assemblies.

The following scenarios describe the hypothesis where it might be possible to avoid conducting a wind uplift test when a new component of the AARS assembly is substituted. Scenario 1 provides a hypothesis case where wind uplift test may be avoided and Scenario 2 for a case where a wind uplift test is required.

### Scenario 1

A proponent is testing two AARS assemblies labelled as Assembly A and Assembly B, respectively. The difference between the Assembly A and Assembly B is the insulation board used, Assembly A uses paper facer insulation, while Assembly B applies acrylic facer insulation. All other roofing components and application methodologies remain the same. Assembly A is tested and has the pullout, peel and wind uplift ratings, while Assembly B is tested and has only the pullout and peel ratings. The ratings are presented below,

| Test Rating              |   |                                  |
|--------------------------|---|----------------------------------|
| Assembly A               |   | Assembly B                       |
| Pullout <sub>A</sub>     | < | Pullout <sub>B</sub>             |
| Peel <sub>A</sub>        | < | Peel <sub>B</sub>                |
| Wind uplift <sub>A</sub> |   | ?<br>(Wind uplift <sub>A</sub> ) |

The Pullout<sub>B</sub> and Peel<sub>B</sub> ratings are higher than Pullout<sub>A</sub> and Peel<sub>A</sub>, therefore the wind uplift resistance rating of Assembly B can be concluded identical as to that of the Assembly A wind uplift resistance rating.

### Scenario 2

Assemblies I and II differ only in the use of cover board. Assembly I utilizes fibre cover board, while Assembly II uses asphaltic core board. The test results are presented below,

| Test Rating              |   |                                     |
|--------------------------|---|-------------------------------------|
| Assembly I               |   | Assembly II                         |
| Pullout <sub>I</sub>     | > | Pullout <sub>II</sub>               |
| Peel <sub>I</sub>        | < | Peel <sub>II</sub>                  |
| Wind uplift <sub>I</sub> |   | ?<br>(Wind uplift test is required) |

For this case, the proponent is required to perform the wind uplift test in order to establish the wind uplift resistance rating of the Assembly II. This is because the Pullout<sub>I</sub> rating is higher than the Pullout<sub>II</sub> rating. The wind uplift resistance rating may be considered to be similar to the wind uplift rating of Assembly I only if the pullout and peel ratings of Assembly II are larger than the pullout and peel ratings of Assembly I.

According to the hypothesis, the wind uplift rating obtained cannot be higher than the wind uplift rating of the previously tested assembly. To establish higher wind uplift rating, another wind uplift testing has to be performed. Nevertheless, before this method can be implemented, further research investigations are needed. The research investigation to validate this method is currently in progress.

## **7.6 Concluding Remarks**

This chapter compared the wind uplift resistance and common failure modes resulting from the wind uplift, pullout and peel tests. Based on the present research, regardless of the test method used, the weakest link of the AARS assembly was found to be either the insulation or the cover board components. The failure at the insulation component was mostly found when asphaltic core board was used, while the failure at the cover board was found if the fibre-cover board was used. In terms of uplift resistance performance, the wind uplift test was found to give a much lower uplift resistance rating in comparison to the pull-out or peel tests. This difference can be attributed to the fact that the wind uplift test was performed under dynamic loading conditions that account for the effect of fatigue due to wind pressure fluctuations on roofs, while the other two testing methods were performed under static loading. In addition, a hypothesis was proposed and an attempt was made to correlate the three test methods that were developed as part of the AARS project. The main focus of this exercise was to develop an alternative approach for full scale testing when one component is changed in a previously tested assembly. If proven, this hypothesis will be implemented in practise.

## **Chapter 8. Development of a Finite Element Model**

### **8.1 Introduction**

Developments in roofing technology and products are currently allowing roofing manufactures to continuously develop different types of AARS. The introduction of new components and application techniques could result in different levels of wind uplift resistance performance. The finite element (FE) method has proven to be a viable numerical approach for analysing engineered structures. The FE method can perform robust engineering analysis using virtual (numerical) models in a relatively short time compared to experimental testing. The FE model can also help in reducing the cost of specimen fabrication for testing. In addition to these general advantages of numerical model in the case of the AARS testing, a specific curing time is required prior to the testing. For example a-28 day curing time was used in present study. With this experimental limitation in mind, finite element analysis was chosen as a numerical method for studying the influence of some parameters that include adhesive application technique, adhesive thickness and the type of insulation joints. The aforementioned parameters were selected by considering the crucial parameters that could impact the wind uplift resistance performance of AARS. As illustrated in the Chapter 3, AARS assemblies were prepared with different construction techniques representing the different type of roofing components used from one roofing manufacture to another. The study herein was intended to provide additional information to roof designers when different construction techniques for AARS are utilised. Prior to studying the above

mentioned parameters, a FE model that could be used as a representation of AARS configuration was required. A simplified three dimensional finite element (3D FE) model for AARS was developed using commercially available finite element software called ABAQUS. To benchmark the model, an experimental study was also conducted. Prior to validating of the 3D FE model with the experimental results, a mesh sensitivity study was performed. This chapter provides information on the 3D FE model development. The first step toward development of the 3D FE model was a literature review and is presented in the following section.

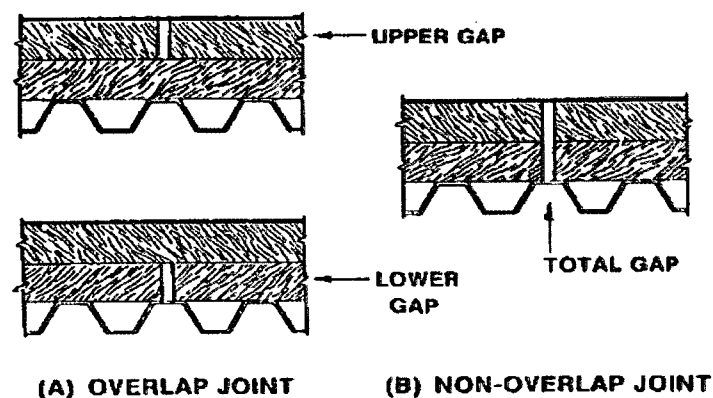
## **8.2 Literature Review on Numerical Modeling of Roofing Systems**

A limited number of studies were found in the literatures that apply numerical modeling to roofing systems performance evaluation. In particular, no research work was available modelling the wind uplift performance of AARS. Thus, the literature presented herein is not directly related to AARS. Nevertheless, the analyses of the review facilitated understanding of the impact of several numerical and modelling issues such as the specification of the bonding conditions and mesh size requirements.

Koike et al. (1978) studied the effect of fatigue rupture of roof substrates that contribute to the membrane failure of roofing systems. The research reported that substrates such as rigid plastic foam and concrete planks were susceptible to a large joint movement which can lead to membrane failure. The ability of the EPDM membrane to withstand the substrate movements was investigated. The differential equations based on elastic theory were used to illustrate the effects of strain

induced on the membranes. It showed that the differential equations can be used to investigate the strain performance of a fully bonded membrane and a loosely laid membrane.

Lewis (1980) performed research using finite element analysis to investigate the effect of thermally induced stress on membranes due to the gap produced by the insulation panel. The membrane was placed on a Fiberglas insulation board that lays over a metal deck. Double layered insulation panels were used for the study. Three different cases of gap size were considered (Figure 8.1). It was concluded that failure of the overlapped insulation panels, when double layer insulation panels were used, could cause at least a 14 percent increase in membrane stresses. In addition, the higher modulus of elasticity and thicker layer of insulation could adversely affect the level of the membrane stress.

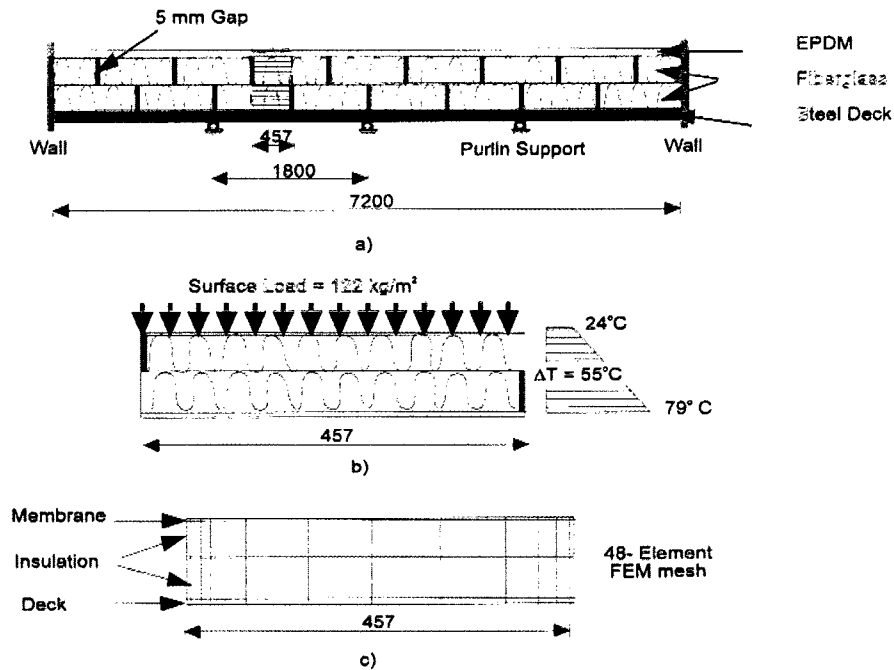


**Figure 8.1** Different Type of Gaps Considered in the Models (Lewis, 1980)

Rossiter and Batts (1985) investigated the effect of thermal gradients on the stress in roof membranes using the MacNeal-Schwendler Corporation Finite Element software. Two roofing systems were modeled using two-dimensional linear elastic finite element models. The models comprised a membrane, Fibreglas insulation and a steel deck (Figure 8.2a). The first model assumed that the membrane was fully-adhered and in the second model, the membrane was assumed to be loose-laid and subjected to a load of  $122 \text{ kg/m}^2$ . Both roofing systems were exposed to a temperature differential of  $55^\circ\text{C}$  as shown in Figure 8.2b. Several assumptions were made such as the membrane was assumed to be stress-free at  $24^\circ\text{C}$ , the adhesive layer was not included in the model and the loose-laid membrane was only constrained at the edges. A typical example of the meshed model is shown in Figure 8.2c. Table 8.1 shows the mechanical properties used for the FE model simulation. From the FE modeling simulations, it was found that the maximum stress from the adhered membrane model (1<sup>st</sup> model) was about 20% of the membrane ultimate tensile stress capacity, while the loose-laid membrane has about 12% of its maximum capacity.

**Table 8.1** Mechanical Properties for the Models (Rossiter and Batts, 1985)

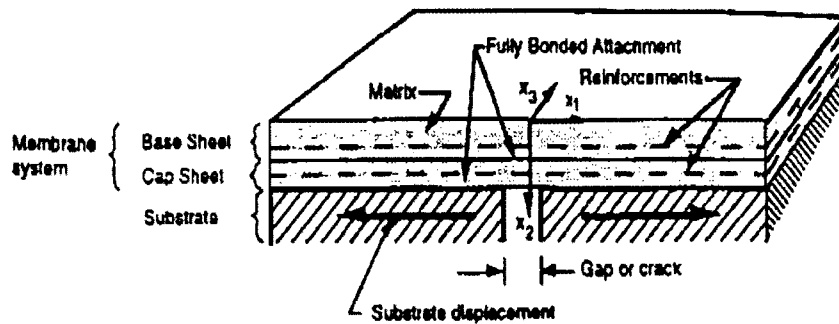
| Material              | Thickness (mm) | Modulus of Elasticity (MPa) | Coefficient of Linear Thermal Expansion ( $\text{mm}/^\circ\text{C}$ ) | Poisson Ratio |
|-----------------------|----------------|-----------------------------|------------------------------------------------------------------------|---------------|
| EPDM                  | 1.5            | 2                           | $660 \times 10^{-6}$                                                   | 0.45          |
| Fibreglass Insulation | 48             | $1.4 \times 10^2$           | $13 \times 10^{-6}$                                                    | 0.3           |
| Steel Deck            | 9.9            | $2 \times 10^5$             | $12 \times 10^{-6}$                                                    | 0.3           |



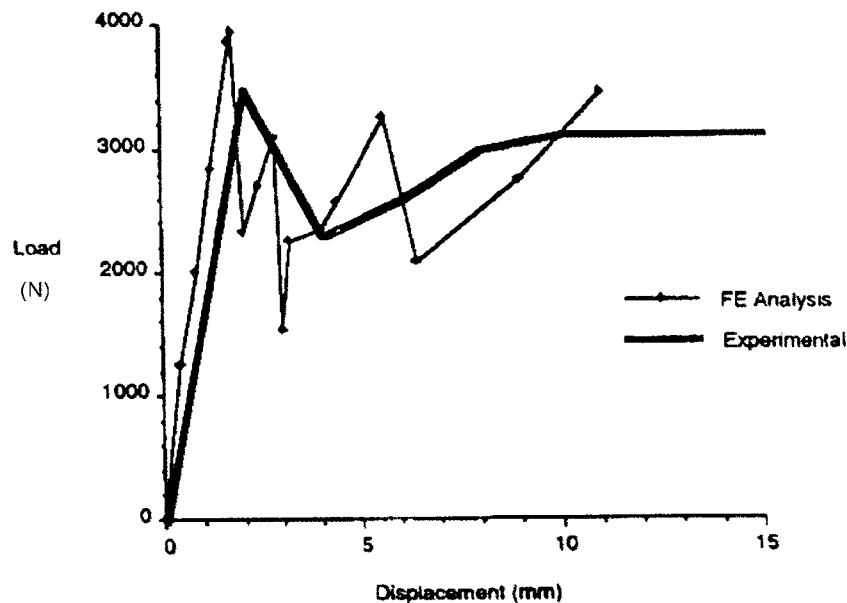
**Figure 8.2** a) Roof Model, b) Loading Mechanism and c) Meshed Model (Rossiter and Batts, 1985)

Broadland et al. (1991) also performed a finite element analysis to study the fully-adhered membrane response to the differential deformation (Figure 8.3) in between adjacent substrates. The differential deformation could be caused by seasonal temperature change and aging. A finite element software called REMA (Reinforced Membrane Analysis) was used for the simulation. The REMA model is capable of modeling a fully-adhered roofing membrane. The model consisted of three parts representing the membranes and rigid substrate (Reinforced Fiberglass) as shown in Figure 8.3. The membrane has two layers called the base sheet and the cap sheet. The cap sheet contained a polyester scrim that was bonded to the top of the base sheet and base sheet was bonded to the substrate. A gap was introduced at the centre of the substrate by specifying the displacement and the analysis was performed at a temperature of  $-5^\circ\text{C}$ . The thickness of the cap sheet,

the base sheet and the substrate was 3.5 mm (0.14 in), 2 mm (0.08 in) and 0.5 mm (0.02 in), respectively. In addition to the FE-model, an experiment was also performed to benchmark the model. It was found that the results from the FE model simulation over-predicted the results obtained from the experimental program (Figure 8.4). However, the model was able to illustrate the sequences of membrane component failure.



**Figure 8.3** In Plane Bending of Membrane System  
Broadland et al. (1991)



**Figure 8.4** FE-Model vs Experimental Results  
Broadland et al, (1991)

Finite element models have been used by several researchers (Easter 1990; Zarghamee 1990; Gerhardt and Kramer 1992; Prevatt 1998) to study the behaviour of mechanically attached flexible roofing systems. The impact of table testing size on the wind uplift performance of membrane roofing systems was investigated by Baskaran and Borujerdi (2001). Later on, the research was enhanced by Baskaran and Molleti (2005) to include the effect of wider membranes and to establish the correction factors for the determination of wind uplift resistance of membrane roofing systems. The correction factors were established by comparing the FE models and experimental results. This work was incorporated in the CSA 123.21-04.

Shi et al (2006), Shi and Burnett (2008) established a closed form solution formula to predict the height of the membrane ballooning (blistering) in wall systems. The application of the closed form solution (Shi et al 2006) for predicting membrane deflection on roof was verified by Baskaran et al (2009). It was found that the closed form solution can be used to predict membrane deflection on roofs only for membrane sizes smaller than 1.83 m (6 ft) by 1.83 m (6 ft).

Sun and Bienkiewicz (1991) investigated the pressure distribution underneath roofing paver systems. The model utilized Darcy's law to model the flow beneath and between pavers. The modelling simulation results were verified by the experimental data. It was found that both model and experimental results were in good agreement. Damatty et al 2003 developed FE model of metal roofs to study the effect of uplift pressure. The study concluded that the model can be used to

investigate the structural behaviour of the metal roofs under the effect of uplift pressures.

The limitations of the existing numerical studies can be summarized as follows:

- Numerical simulations were focused only on the membrane. No further simulation was given for the other roofing components.
- Studies were carried out based on either one or two-dimensional finite element analysis.
- Effect of time and temperature were not considered.
- Numerical simulation was performed based on a linear elastic analysis.
- Only limited numerical simulations were verified with experimental data.
- Modeling was focused on predicting the membrane strain.
- Adhesive application was not included during the numerical simulation.

### **8.3 Three Dimensional Finite Element (3D FE) Model Development**

#### **8.3.1 Modeling Background**

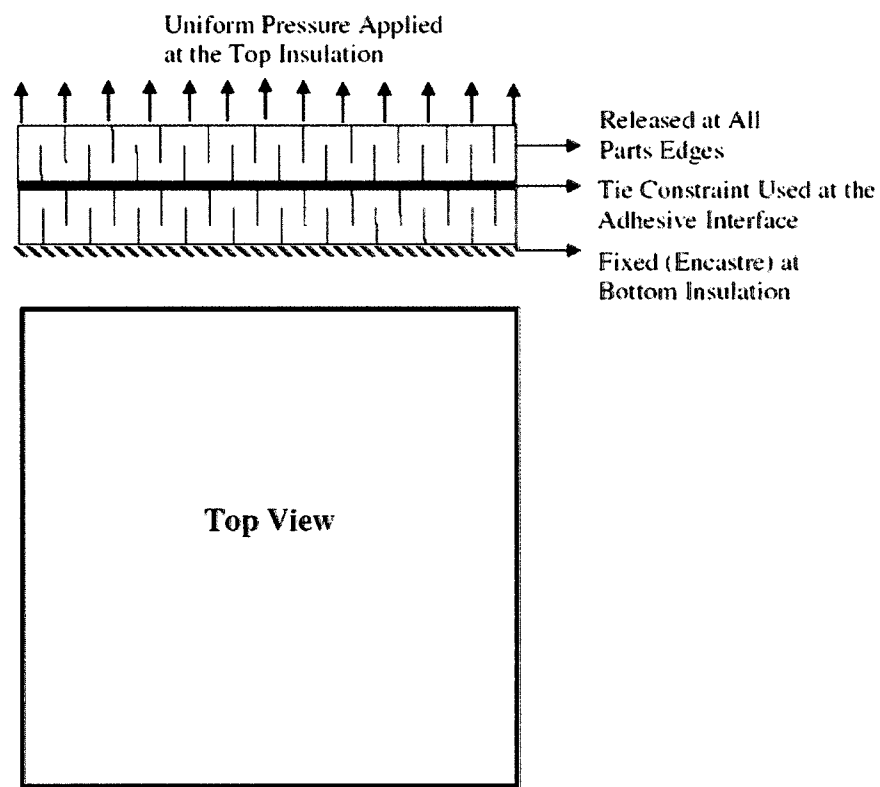
From the full scale experimental investigations (Chapter 6), it was shown that the most common failures occurred at the insulation level, either at the insulation itself or at the adhesive interface (Baskaran et al 2007). Therefore, the present 3D FE model focused on modelling the insulation interfaces. In other words, the three-dimensional finite element (3D FE) model presented herein will work only with the assumption that the weakest link of the AARS structure exists either at the insulation itself or at the insulation-adhesive interface. The numerical analysis performed herein uses ABAQUS, commercially available finite element software,

and the analysis was based on the three-dimensional linear elastic analysis. Modelling information such as modelling details and modelling outputs are outlined in Section 8.4.2 and Section 8.4.3, respectively.

### 8.3.2 Model Details

The model consists of three parts: the bottom insulation, the adhesive and the top insulation. The three parts were modelled as three-dimensional, eight-node, continuum elements (C3D8I) having the same length and width of 305 mm x 305 mm (12 in x 12 in), but different thickness, 51 mm (2 in) and 2 mm (0.08 in) for the two insulation layers and the adhesive, respectively. The three parts were assumed to be solid. Figure 8.5 illustrates the details of the model as well as the boundary conditions. Table 8.2 shows the mechanical properties used for the FE modelling. The mechanical properties of the adhesive and insulation layers were extracted from the data by Henry (2006) and Baskaran & Borujerdi (2001), respectively. The loads were applied to the model at the top insulation surface as a uniform pressure distribution in four different steps, 1.5 kPa (0.20 psi), 4 kPa (0.58 psi), 5.1 kPa (0.74 psi) and 7.2 kPa (1.04 psi). Tie constraint was selected for the model. The tie constraint was chosen because it is suitable for simulating composite material by allowing two surfaces to connect together at a node. This type of constraint allows the model to behave like one composite sandwich material that has different mechanical properties on each part. Two tie constraints were used on the model. The first tie constraint was applied to simulate connection between top layer of adhesive and bottom layer of top insulation, while the second tie constraint was between bottom layer of adhesive and top layer of bottom

insulation. The boundary condition was applied to the bottom surface of the model by using the “Encastre” option in ABAQUS. This option represents a situation in which no movements are allowed in any directions at the nodes, while the edges of the model were released, as shown in Figure 8.5. The adhesive and insulation components were modeled as homogenous isotropic elastic materials with the adhesive area fully in contact with the two insulation surfaces.

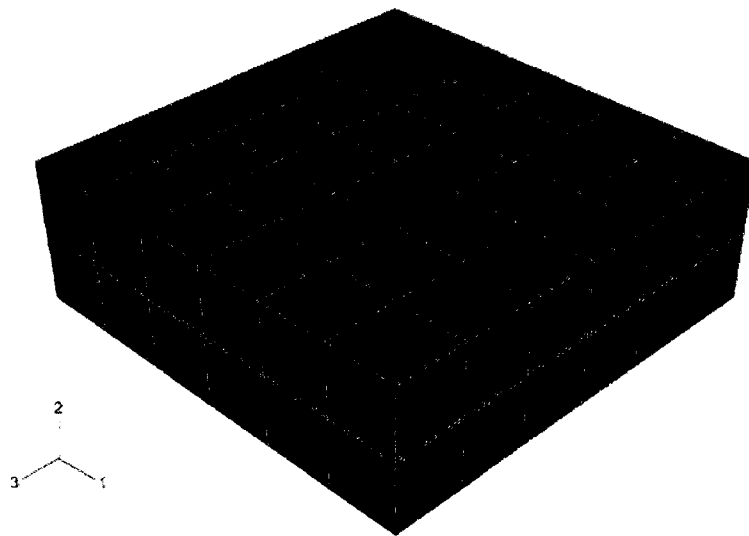


**Figure 8.5** Boundary Conditions Used for the Present Model Development

**Table 8.2** Model Properties Used for the Present Model Development

| Material   | Young's Modulus<br>$E$ (MPa) | Poisson's Ratio<br>$\nu$ |
|------------|------------------------------|--------------------------|
| Adhesive   | 0.724                        | 0.33                     |
| Insulation | 138                          | 0.30                     |

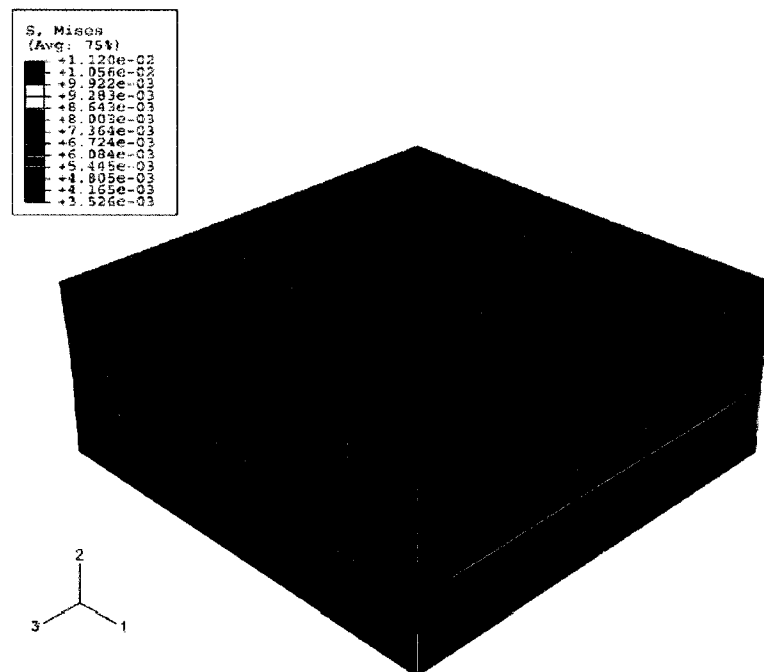
Figure 8.6 shows the undeformed shape of the 3D FE Model. The 3D FE model has a total of 108 elements and 654 nodes. A curvature control deviation factor of 0.1 was selected as the default ABAQUS option to perform the static analysis provided in the ABAQUS software. The curvature control deviation factor is a factor that measures how much element edges deviate from the original geometry. During the simulation, input file processor memory of 256 Mb and ABAQUS standard memory of moderate were used to provide enough memory for the analysis. The AARS uplift performances are indicated in terms of their stresses corresponding to the four different steps load. The stresses resulting from the 3D FE model were obtained at the nodes. An example of model input file is described in Appendix E.



**Figure 8.6** Undeformed Shape of the 3D Model with the 108 Elements

### 8.3.3 Model Outputs

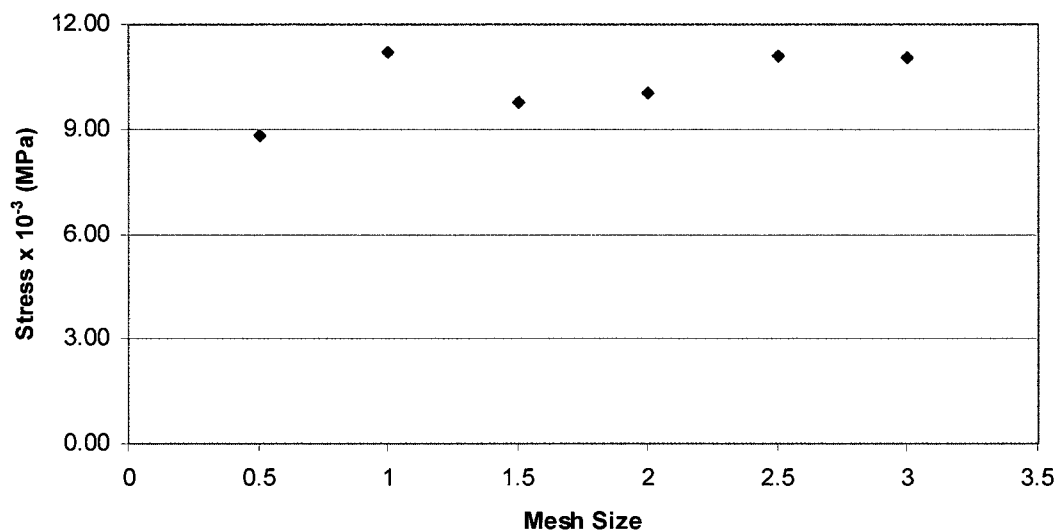
Figure 8.7 shows the stress contours of the deformed shape. The highest stress concentration is located at the top four corners of the bottom insulation part. This indicates that the four corners were the first to fail rather than any other locations. The lowest stresses were mostly located along the adhesive part as illustrated in Figure 8.7. In addition, the stress contour diagram (Figure 8.7) shows an overview of how the stresses are distributed throughout the FE-model parts. By observing the stress contour diagram, the roof designers are assisted in the design and selection process for the roof components. For example, reinforcement methods such as using different type of insulation with higher mechanical properties can be used at the four corners, where the highest stress concentration takes place to strengthen the roof assembly.



**Figure 8.7** Deformed 3D Model Shape with Stress Distribution

## 8.4 Mesh Sensitivity Study

Mesh sensitivity was studied for the developed 3D FE model to verify if the result obtained from the finite element simulation was independent of the mesh size. Changing the mesh size results in a change in the number of elements for the model. For the purpose of this verification, the number of elements was varied from between a half to three times from the original mesh. The other parameters remained constant. Figure 8.8 shows the simulation results for different mesh sizes under a load of 669 N (150 lbf). The mesh independency of the FE model was achieved with mesh size of 33.5 mm (1.32 in) as a result of using an increased number of elements of 2.5 times. A criterion of mesh independency of less than 5% was used in the present study. Therefore the mesh size of 33.5 mm (1.32 in) is used for further FE simulations.



**Figure 8.8** Computed Stresses with Different Mesh Sizes for the FE Model

## **8.5 Experimental Study for 3D FE Model Benchmarking**

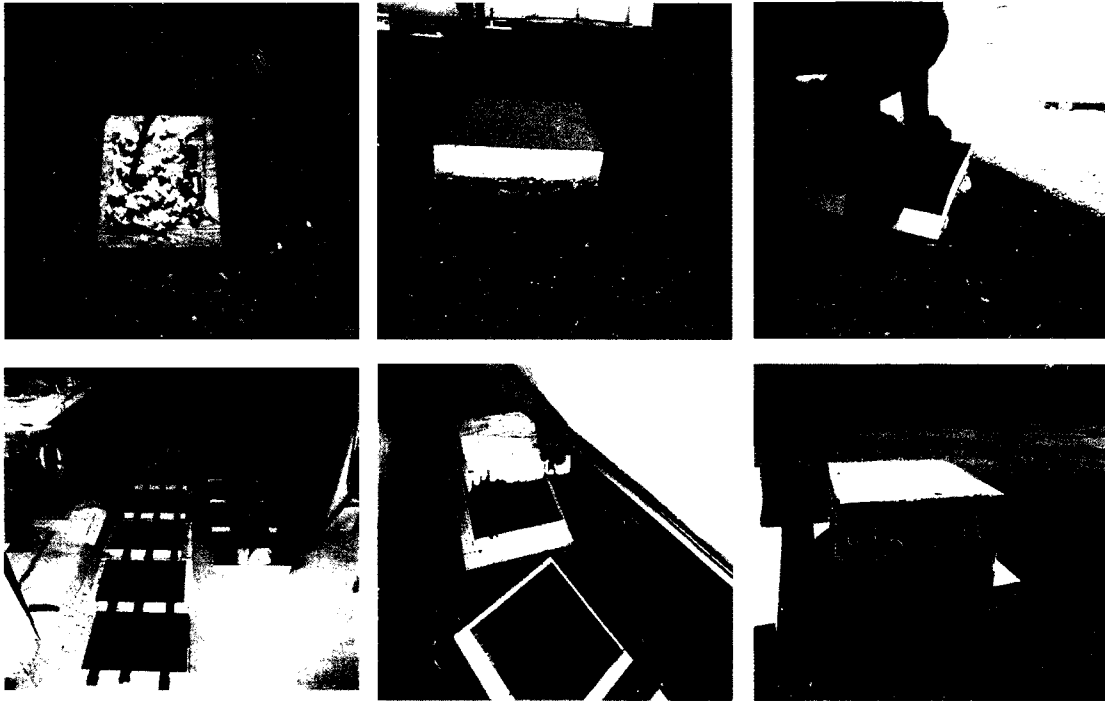
### **8.5.1 General**

In order to benchmark the FE-model, selected experiments were conducted by fabricating the test specimens that have similar components to those of the FE-model. Each specimen comprised three components; top insulation, adhesive and bottom insulation. Six test specimens were fabricated for this purpose. The test results were then compared with the FE-model results. Section 8.5.2 through Section 8.5.4 present the sample preparation, test setup and test results.

### **8.5.2 Preparation of Test Specimens**

Figure 8.9 shows, step by step, how the test specimens were prepared. Two plywood plates were used as dummy sections and attached to the test specimen at the top and bottom insulation layers using adhesive. The plywood dummy plates were used to attach the test specimen to top and bottom testing frame of an Instron machine. Insulation board 51 mm (2 inches) thick and 1.22 m (48 inches) by 1.22 m (48 inches) in dimension was cut to 305 mm (12 inches) by 305 mm (12 inches) as the bottom and top insulation components. A plywood plate of 330 mm x 330 mm (13 inches x 13 inches) was glued to the bottom insulation. The top insulation was also glued to a plywood plate that has the same size of 305 mm x 305 mm (12 inches x 12 inches). Steel bars were placed on them to ensure better cohesion between the plywood plates and the top and bottom insulations as shown in the bottom left side of Figure 8.9. On the following day, the adhesive was applied to the bottom and top insulation components to complete fabrication of the test specimens. The photo on the bottom right corner of Figure 8.9 shows a test

specimen ready for testing. The test specimens were cured for 28 days prior to testing.

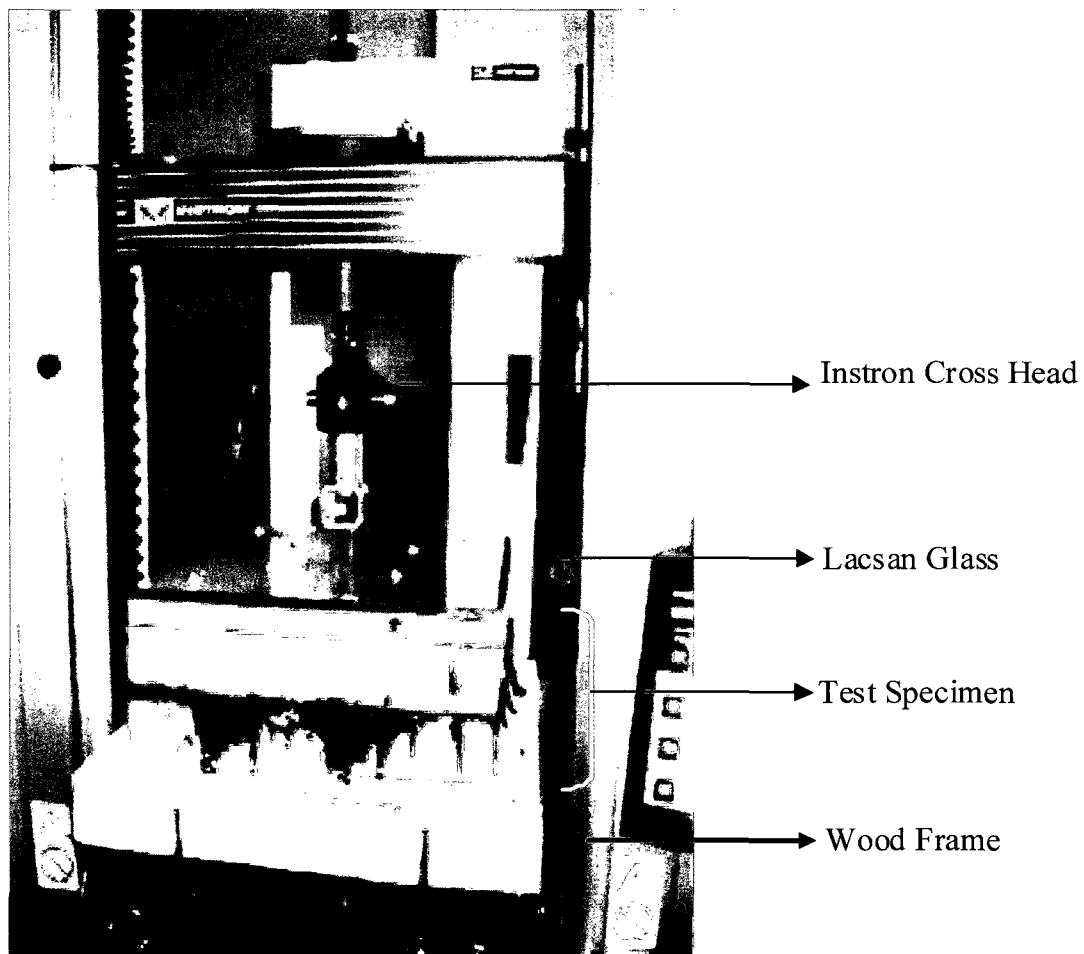


**Figure 8.9** Specimen Preparation for the FE Model Benchmarking

### 8.5.3 Experimental Setup

In order to attach the specimens to the Instron machine, a wood frame was made and placed on the table of the Instron machine as shown in Figure 8.10. The cured test specimen was then placed on the wood frame and screwed to it. In addition a plate made from Plexiglas was used to connect the test specimens to the Instron cross head and to transfer the load to the specimens. The test specimens were then screwed to the plate. The Instron cross head is located at the middle of the Instron testing frame as shown in Figure 8.10. The cross head has a load cell installed to measure the loads applied to the test specimen. The tests were

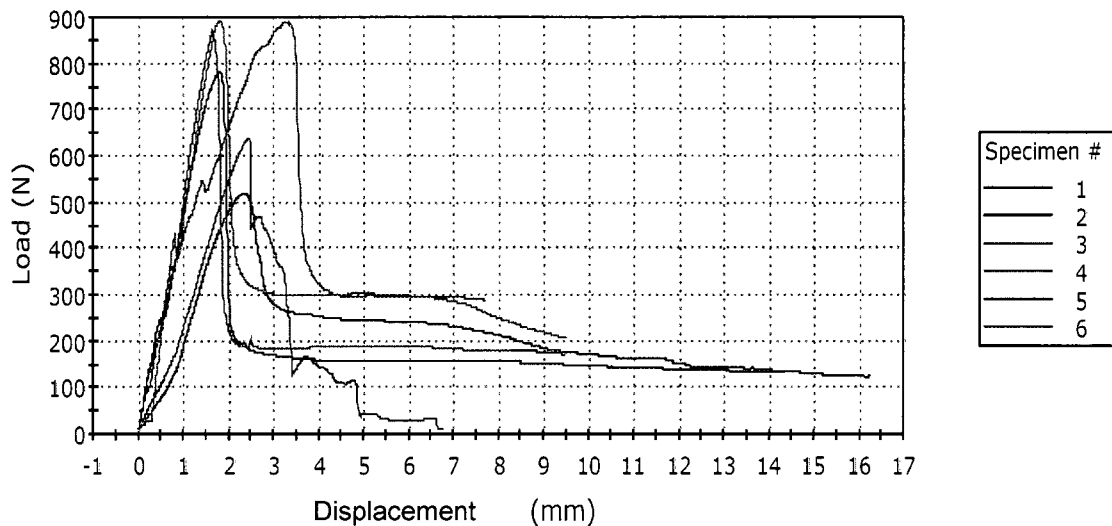
performed using an Instron testing machine type 5566 and the specimen was applied tension force at a rate of 5 mm/min. Figure 8.10 shows the setup used for the FE model benchmarking. The test setup performed herein was slightly different from the pullout test setup proposed by Current (2009) which was under development at the time the present test was conducted.



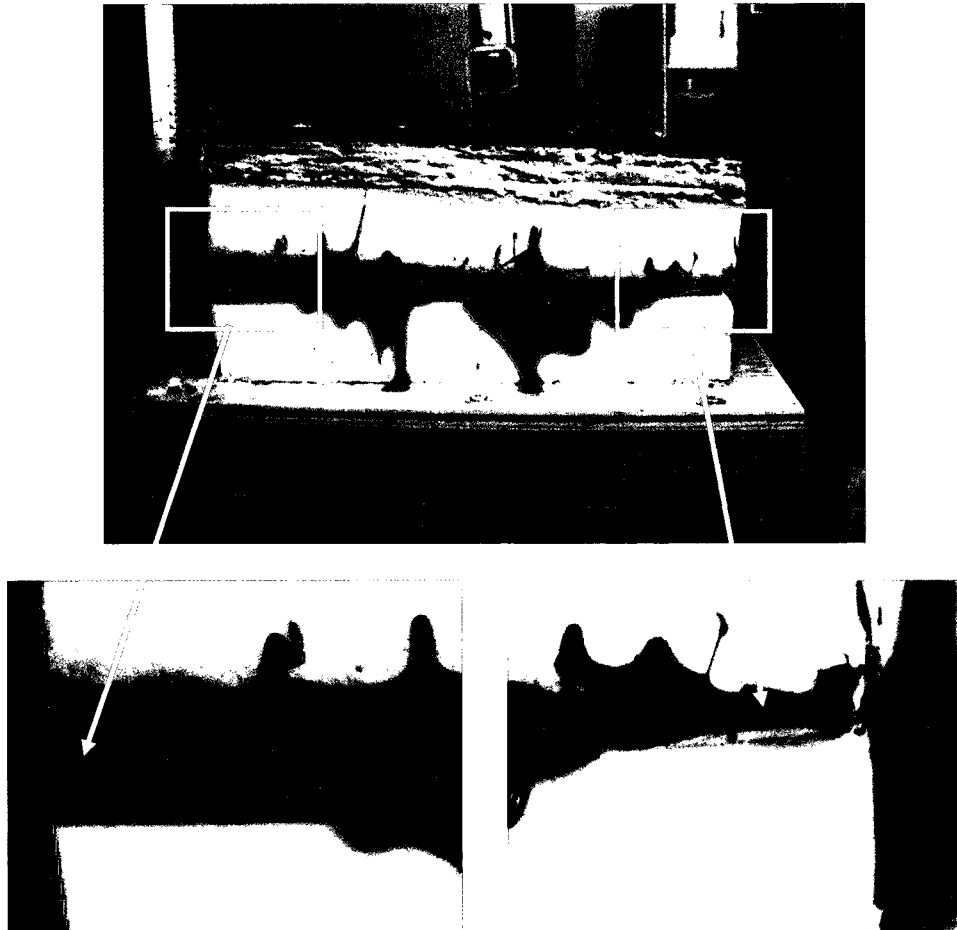
**Figure 8.10** Test Setup for the FE Model Benchmarking

#### 8.5.4 Test Results

Figure 8.11 shows the results of the six specimens tested. The displacement in millimetres (mm) is shown in the abscissa while the magnitude of the load achieved expressed in Newtons (N) is given in the ordinate. The highest and lowest loads achieved through the test were about 890 N (200 lbf) and 520 N (117 lbf), respectively. The average load of the six tested specimens was 669 N (150.4 lbf), while the average maximum displacements was found to be 2.22 mm (0.09 in). Figure 8.12 shows a typical failure mode of the six specimens. The failure of the test specimen started as a delamination of the bottom insulation at the four corners of the top facer, then the failure continued until the bottom insulation separated from the top insulation part. The two bottom photos in Figure 8.12 depict a typical top facer delamination of the bottom insulation.



**Figure 8.11** Load vs Displacement for the Six Specimens Tested



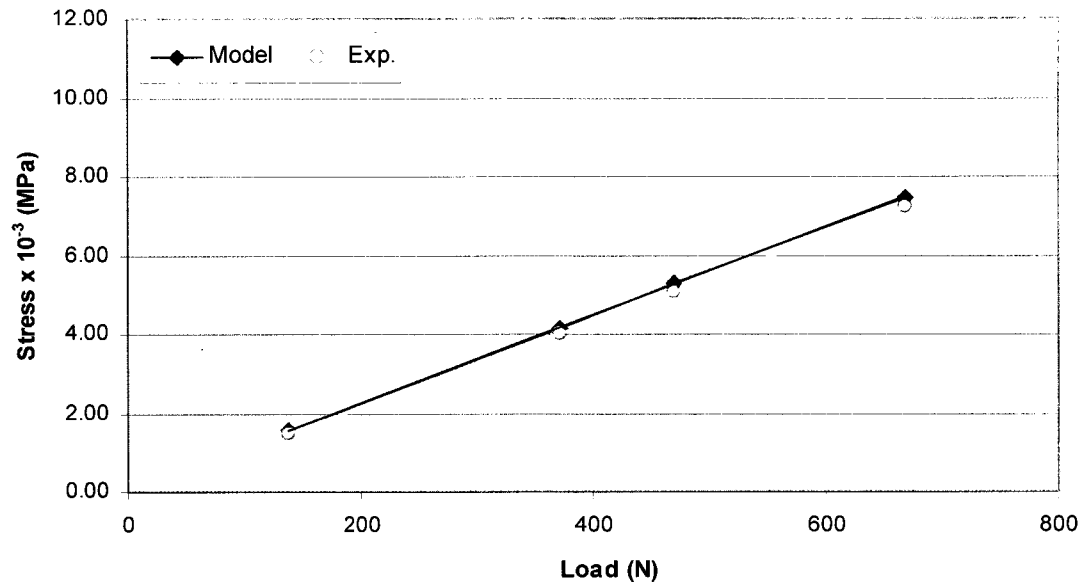
**Figure 8.12** Typical Failure Mode of the Experimental Specimen

## 8.6 3D FE Model and Experimental Study: Performance Comparison

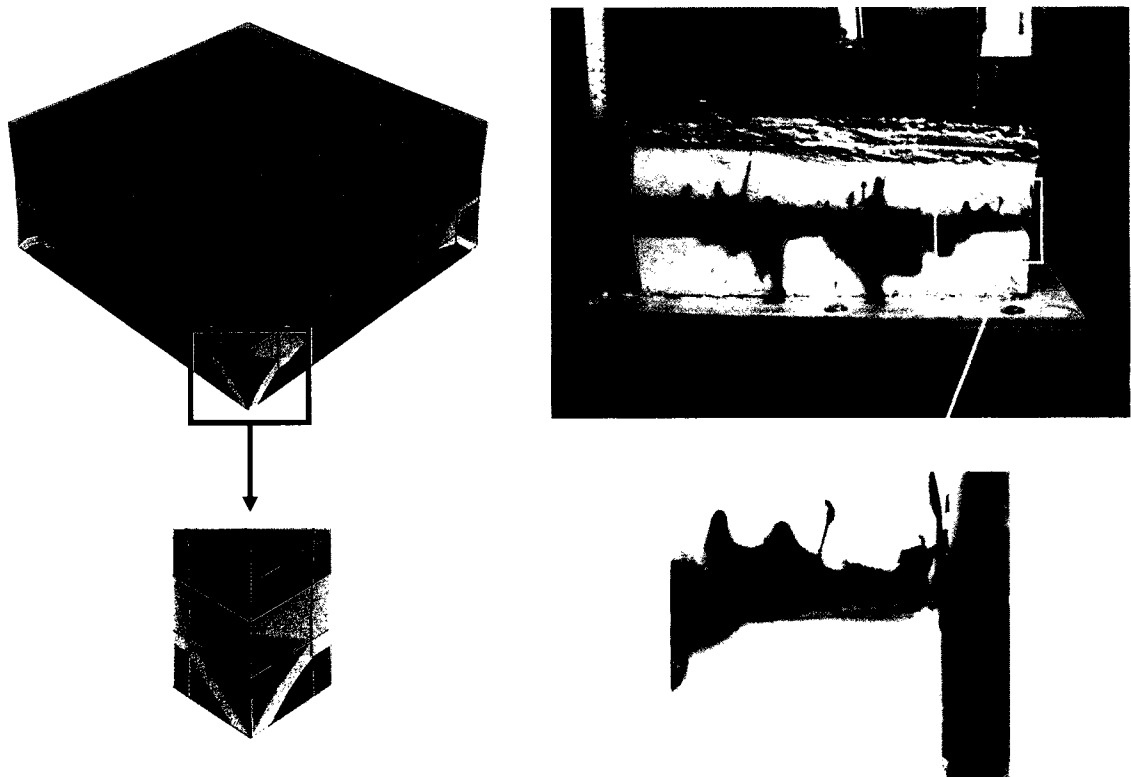
This section compares the performance of the 3D FE model with the experimental data. They are compared in terms of both the uplift resistance capacity and the resulted failure mode. The uplift capacity performance is indicated in terms of the normal stresses. The maximum stresses obtained from the model were 2.02 kPa (0.3 psi), 5.40 kPa (0.78 psi), 6.89 kPa (1 psi) and 9.73 kPa (1.41 psi) for the input loads of 138 N (31.02 lbf), 372 N (83.63 lbf), 470 N (105.66 lbf) and 670 N (150.62 lbf), respectively. The uplift capacity performance is indicated in terms of normal stresses. However, for the purpose of comparison the average normal stresses at the failure surface were used. The average maximum normal stress for the benchmark experiment was calculated by dividing the average maximum load from the six specimens by the surface area of the specimen (7.2 kPa/1.04 psi). To plot a linear “Stress vs Load” curve for the benchmark experiment, three data points of the average loads were selected from the average test data prior to maximum load. Adopting the same procedure for calculating the average maximum normal stress, three other average normal stresses, 1.48 kPa (0.21 psi), 4 kPa (0.58 psi) and 5 kPa (0.73 psi), were calculated.

A comparison of the average normal stresses of the model to the experimental data is shown in Figure 8.13. The results show that the model was able to simulate the test data performance. This was true for the failure mode as evidenced in Figure 8.13 and Figure 8.14. A typical stress distribution contour from the model in Figure 8.14 (left side) shows that the maximum stresses are concentrated at the corners of the insulation part while in the test specimen, the

failures occur at the corners of the insulation facer (Right side). This aspect illustrates that the model predicts the test failure performances well. However, the model overestimated the maximum capacity of the test samples. This might be caused by the stress distribution complexities at the interface of test specimen. These complexities depend mainly on adhesive application and its performance. For example, during the failure mode investigation, it was noticed that the adhesive surface at the interface of the insulations did not have the same thickness and the presence of adhesive bubbles were observed. These phenomena can reduce the performance capacity of the test specimens due to the fact that the insulation surfaces were not 100 % covered by the adhesives, despite the fact that the precautions were taken during test specimen preparation. Nevertheless, the current study does not intend to predict the capacity at the maximum load but rather focuses on investigating the performance *trend* of the specimen in the elastic stage. For this reason, in the following chapter, the FE model was subjected only 50% of its maximum load capacity to study the effects of adhesive application technique, adhesive thickness and the type of joint in the insulation on the wind uplift resistance performance.



**Figure 8.13** Experiment Vs FE Model: Stress Comparison



**Figure 8.14** Experiment Vs FE Model: Failure Mode Comparison

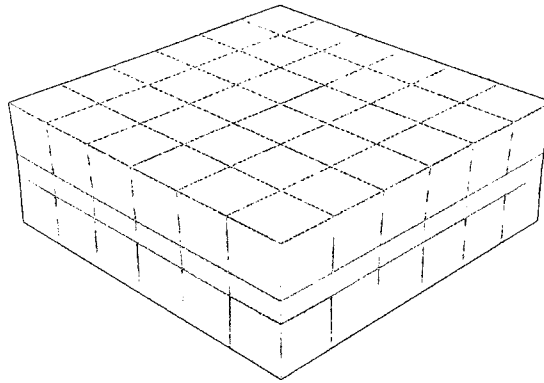
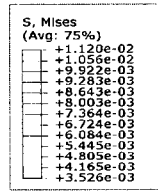
## 8.7 Investigation of Changing Boundary Conditions in the 3DFE Model

Another model was created to investigate the possibility of the changing boundary conditions of the top surface insulation and whether it could create a significant difference in terms of maximum stress compared with the previously developed 3DFE model. As illustrated in Section 8.3, the developed 3DFE model used three parts namely, top insulation, adhesive and bottom insulation. The top surface of insulation of the previously developed 3D FE model was assumed to be free to move to any direction, only the bottom surface of the insulation was fixed. Under this boundary condition, the bottom surface of insulation remained plane during loading, while the top surface of insulation was not. This caused unsymmetrical stress distributions in the model between top and bottom parts of the insulation.

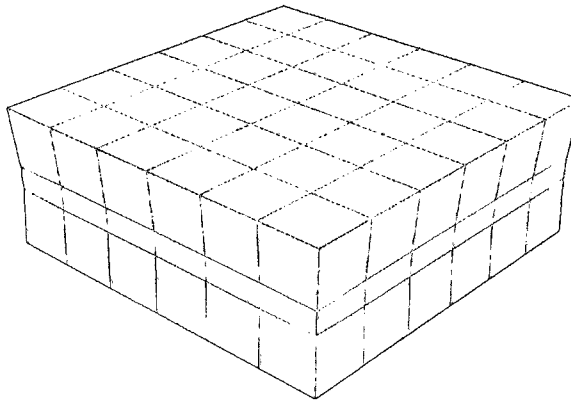
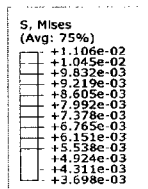
In order to generate symmetrical stress distributions, the top surface boundary condition was modified by constraining the node movements on the top surface insulation at the X and Z directions. Other modelling details and boundary conditions were unchanged from the previously developed 3DFE model. By applying this modification, a symmetrical stress distribution contour was obtained, as shown in Figure 8.15.

Figure 8.15 shows that the location for *higher stress* contour distribution was same as the previously developed 3DFE model. However, in general, different stress distribution contour are generated by the two models. In terms of maximum stress, however, there is a difference for less than 1.5% [ $((1.12 \text{ E-02} - 1.106 \text{ E-02}) / 1.12 \text{ E-02}) \times 100\%$ ] and this difference is considered small. Hence, the previously developed 3DFE model could be maintained and used for further analysis. It is also noted that the objective of the 3DFE model simulation for present study was to *provide general information* to roof designers as to whether different AARS

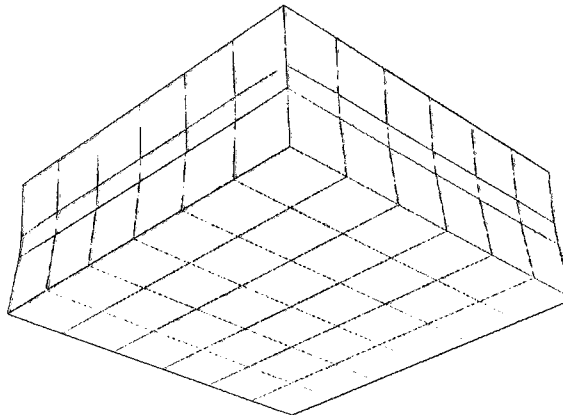
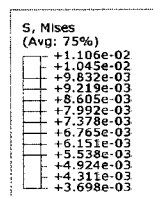
parameters discussed in Chapter 9 significantly affected uplift performance of AARS. It was not intended to quantify the maximum stress capacity of AARS. By maintaining similar modelling details of the 3DFE model and changing only the variable of interest, different AARS parameters were later investigated. However, it is emphasized that the interpretation of the FE simulation results from the present study are subjected to assumptions made herein.



Previously Developed 3DFE Model Distribution Stress Contour



Modified 3DFE Model Distribution Stress Contour: *Top View*



Modified 3DFE Model Distribution Stress Contour: *Bottom View*

Figure 8.15 Modified Stress Distribution Contours of 3DFE Model

## **8.8 Concluding Remarks**

In this chapter, a three-dimensional finite element (3D FE) model was developed and a benchmark experiment was also carried out for the comparison. Prior to comparison, a mesh sensitivity study was conducted on the 3D FE model. The sensitivity study concluded that a maximum mesh size of 33.5 mm (1.32 in) eliminated the effects of mesh size and element numbers on the model. In addition, comparison of the results of the model and benchmark experiment showed that the model gave slightly higher stress values in comparison to the stress values obtained from the experiment. The model, however, was able to well simulate the failure mode of the benchmark experiment. It was also noted that the interpretations of the FE simulation results are subjected to all modeling details and assumptions used in the present study.

## **Chapter 9. Parametric Investigations using the Developed 3D FE Model**

### **9.1 Introduction**

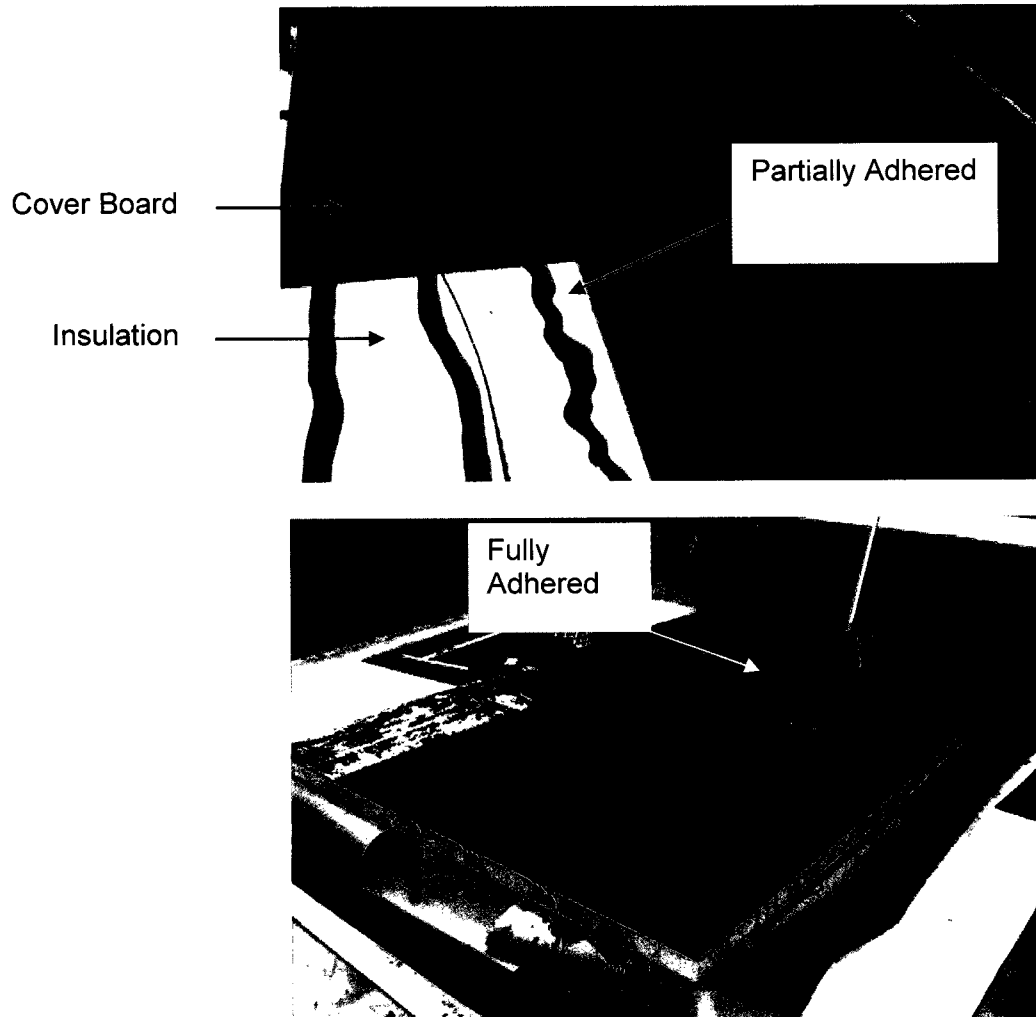
This chapter describes the use of the developed 3D FE model to perform parametric study on the; a) effects of the adhesive application method, b) effects of the adhesive thickness and c) effects of the type of insulation joint on the uplift resistance performance of AARS. The effects considered were based on input received from the industrial partners who indicated that they were the most common failure factors. The parametric study was focused on improving the practical design aspects of AARS by studying the parameters that would have the greatest impact on wind uplift resistance.

In order to perform the parametric study, the developed 3D FE model was modified to incorporate differences in adhesive application method, adhesive thickness, and the type of insulation joints. This chapter outlines the modifications made and presents the results. Section 9.2 and Section 9.3 describe the FE models which simulate the effects of the adhesive application method and adhesive thickness, respectively, while Section 9.4 explains the variation of insulation joints. Each section describes the practical background of the model, the modification made, and the results.

## **9.2 Effect of Adhesive Application Method**

### **9.2.1 Modelling Background**

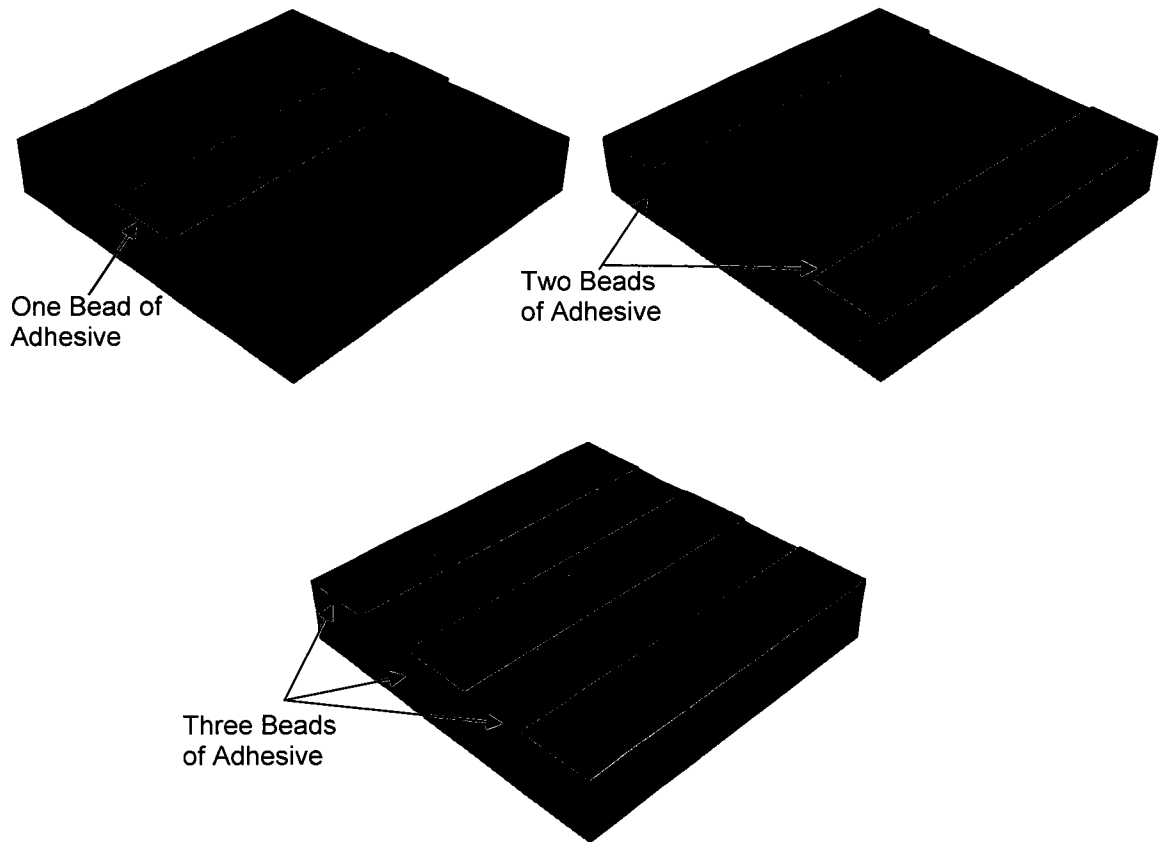
Adhesive application methods play an important role in the determination of the AARS wind uplift resistance since the AARS roof components are integrated using adhesives. The method of adhesive application is different from one roofing manufacturer to another. This is because each roofing manufacturer uses a different combination of roofing materials that require different adhesive application method. The use of a certain method of adhesive application is determined based on the bonding performance achieved, in terms of strength and curing time, between the adhesive and the roofing components. This is usually obtained through testing. Two adhesive application methods are commonly used for AARS are shown in Figure 9.1. One is called the partially adhered (Chapter 3). It applies adhesives in beads between the AARS roof components. Another is called the “fully adhered”, where the surface of the AARS roof components is completely covered with the adhesive. The choice of one of these application methods is specified by the roofing manufacturer. The choice has a significant influence on the resulting stress distribution and the wind-induced behaviour of the AARS.



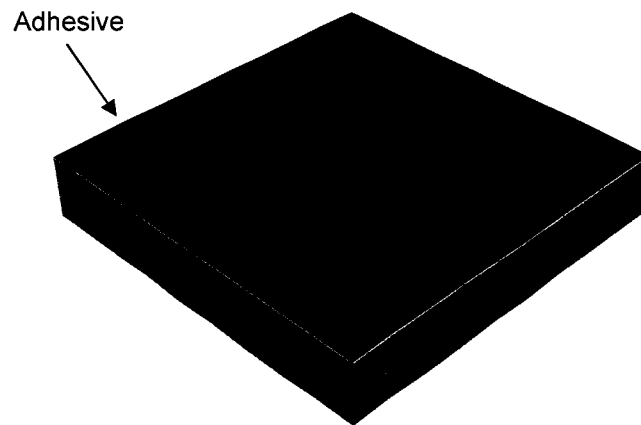
**Figure 9.1** Common Adhesive Application Methods in AARS

### 9.2.2 Model Details

Using the 3D FE model developed, three modifications were created for the partially adhered method. One, two and three beading applications representing approximately 21%, 42% and 62% of the contact areas, respectively, were modelled. The three models utilized the same boundary conditions and mechanical properties as in the previous model. The same size of the component parts and element types (C3D8I) were also used. The modifications were in terms of the adhesive bead width. A beading width of 63.5 mm (2.5 in) was used instead of 305 mm (12 in) while the length and thickness remained the same. Figure 9.2 illustrates the geometry before deformation took place. The mesh size of 33.5 mm (1.32 in) was used for the FE simulation. Tie constraints were used to connect the top and bottom surfaces between the insulation parts and adhesive layer. A 3D FE linear elastic analysis was conducted for the four models, namely the new three models plus the previous model. Each analysis consisted of four loading steps with the increment on each step being 50% lower than the previous model simulation in Chapter 8. This condition ensured that the stresses remained in the elastic range.



a) Partially Adhered Method With one, Two and Three Beads

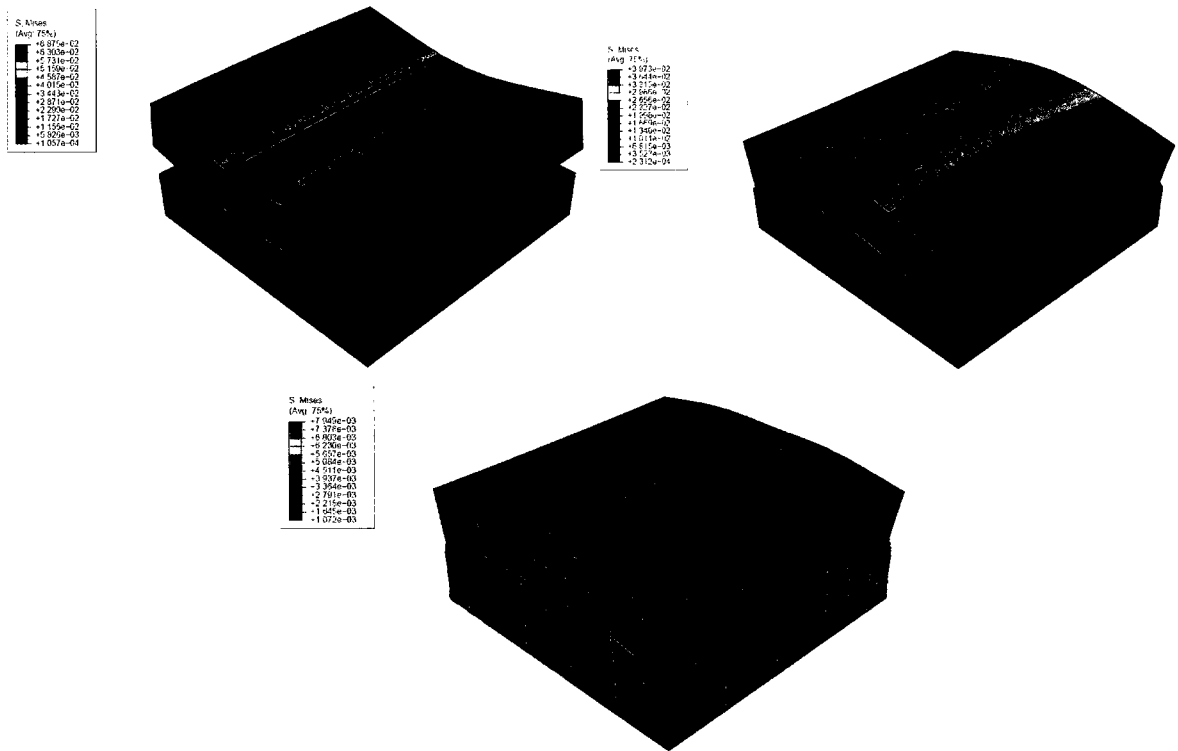


b) Fully Adhered Method

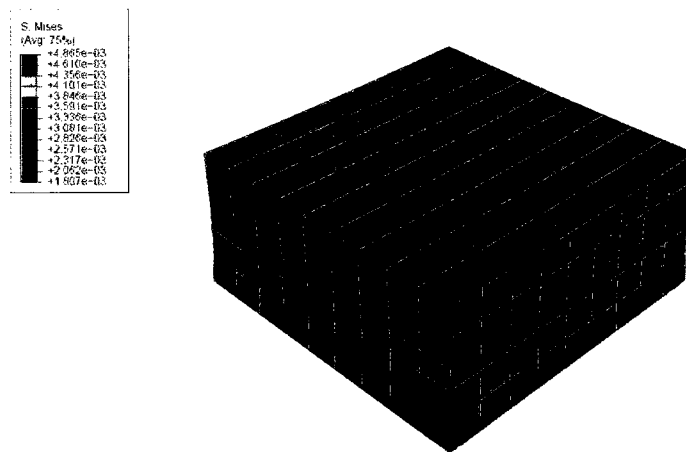
**Figure 9.2** Adhesive Techniques Considered for the Analysis

### 9.2.3 Model Outputs

Figure 9.3 shows typical stress distribution contour diagrams for the models that correspond to an input load of 335 N (75.3 lbf). The stress distribution contour diagram can provide useful information by identifying the location of the highest stress concentration on the section. The highest stress concentration for the partially adhered model with one and two bead cases was found at the middle along the beading strip lines and at the edges, respectively, as shown in Figure 9.3. For the three-bead adhesive application, the high stress concentrations were identified at the corners of the bottom insulation as illustrated in Figure 9.3. Failure can initiate from this location where the stress concentrations are high. The results can be used by roof designers to strengthen the structure at these locations so that the uplift resistance can be increased. This can be done by reinforcing the material or using different type of material that has better performance. Analysis of this nature can also be used to approximately estimate the reduction in performance due to different adhesive application methods.



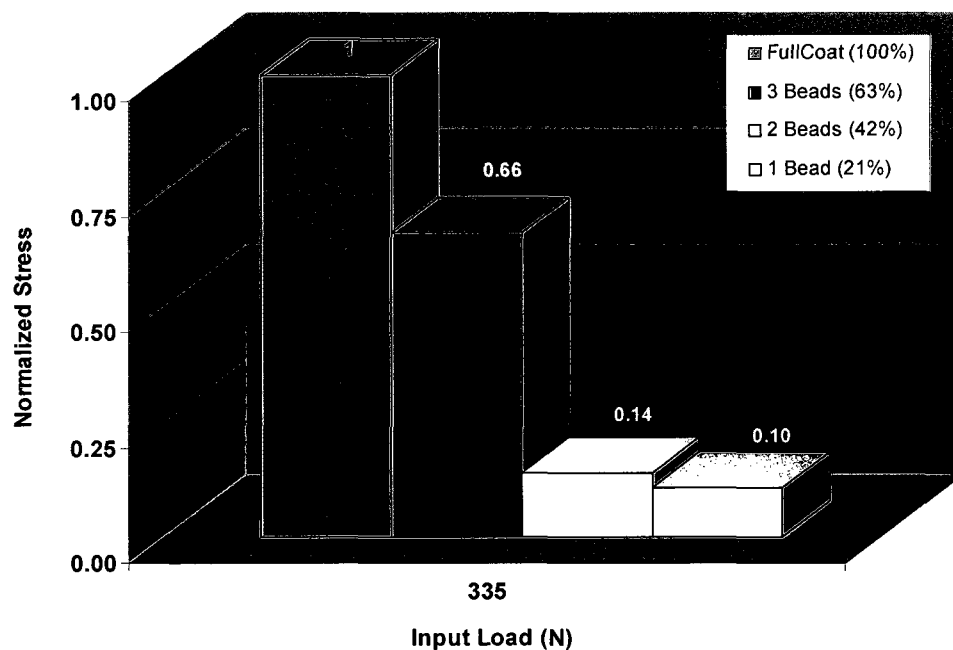
a) Partially Adhered Method With One, Two and Three Beads



b) Fully Adhered Method

**Figure 9.3** Stress Contour Diagrams: Model Output

Figure 9.4 shows the system performance for the four different cases of adhesive application, namely 100%, 63%, 42% and 21% of the surface area covered by the adhesive. The resulted stresses were normalized to the result of the fully adhered case and plotted as the ordinate of Figure 9.4 while the abscissa shows the performance in terms of 335 N load input. Similar normalized stresses were also calculated using different input loads and yielded same ratio. The figure shows that the system performance decreases nonlinearly as the adhesive contact area reduced. The difference of performance reduction between partially adhered with one and two bead applications is 30 to 40%. The system performance of the partially adhered with three beads application decreased significantly by a factor of about 4 to 5 compared to one or two bead applications. These situations occurred because of the stress distribution phenomena that were caused by the system response due to the adhesive beading arrangements.



**Figure 9.4** Stress Reduction Due to the Different of Adhesive Application Methods

### **9.3 Effect of Adhesive Thickness**

#### **9.3.1 Modeling Background**

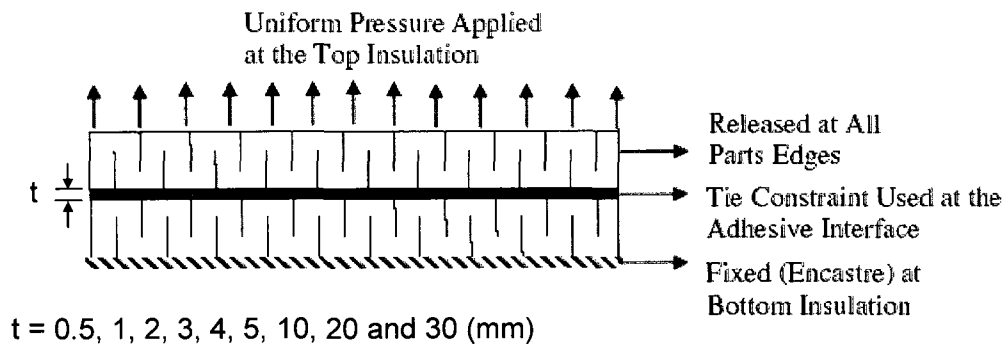
This section describes the effect of adhesive thickness on the uplift resistance performance of AARS. Due to the difference in adhesive application methods, complexities of the roof components (surface shape and porosity in absorbing the adhesive), quality of the roofing applicator (roofer), and environmental conditions, it is rather difficult to maintain the consistency of the adhesive thickness. As a result, the actual adhesive thickness after adhesive completely cured can differ from one surface to another. This situation could influence the AARS wind uplift resistance performance and consequently could adversely affect the ratings from one roofing manufacturer to another. A question arises on how significant is the effect due to this variation. It is difficult to quantify this through experimental investigation since there is currently no method available to measure the thickness of the cured adhesive. Figure 9.5 illustrates a typical example of adhesive application. It was estimated that the cured adhesive thickness was about 1 mm (0.04 in) to 3 mm (0.12 in). However, the difference of uplift resistance performance caused by this difference in adhesive thickness was not known. One way to deal with this issue is to use FE model. An adhesive type, for which the mechanical properties are known, was used for the FE simulation. The details of the model and simulation outputs are described in Section 9.3.2 and Section 9.3.3, respectively.



**Figure 9.5** Variation in the Application of the Adhesive Thickness

### 9.3.2 Model Details

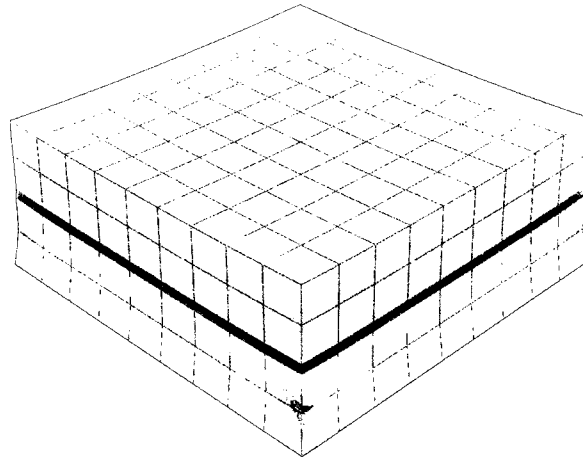
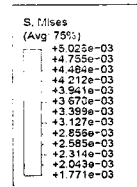
To study the effect of adhesive thickness to the AARS uplift resistance performance, eight additional 3D FE models were developed. The previously developed 3D FE model utilized an adhesive thickness of 2 mm (0.08 in) covering 100% of the surface. Nine different thicknesses from 0.5 mm (0.02 in) to 30 mm (1.18 in) were modelled for the simulations. All other variables such as the boundary conditions, material properties, the type of analysis, load input, the type of element, and mesh size, remained the same. Figure 9.6 illustrates the modeling input information for the finite element model simulation.



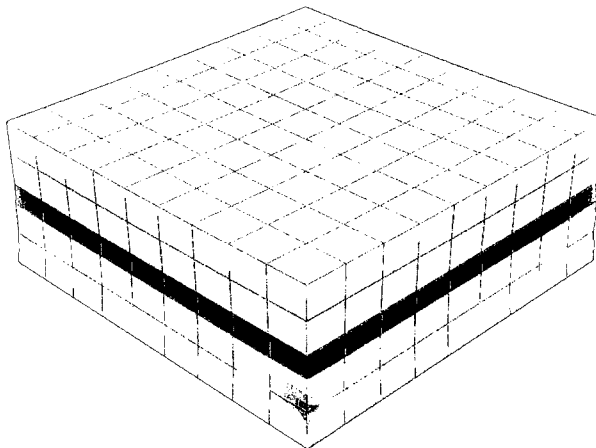
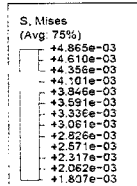
**Figure 9.6 Modeling Detail: Adhesive Thickness Investigation**

### 9.3.3 Model Outputs

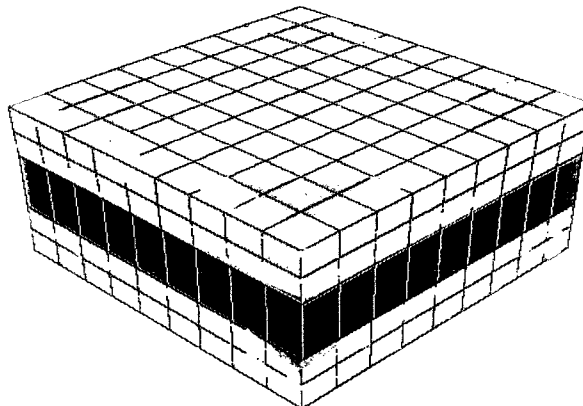
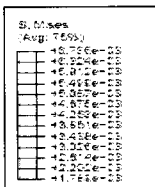
Figure 9.7 describes the typical stress contours for models using adhesive thicknesses of 0.5 mm (0.02 in), 2 mm (0.08 in) and 30 mm (1.18 in), respectively. The simulation results from this exercise indicate that there are no significant differences in stress level between the 0.5 mm (0.02 in) to 10 mm (0.39 in) adhesive thicknesses as shown in Figure 9.8. A significant difference in the level of stress was noticed in the case of adhesive thicknesses ranging between 10 mm (0.39 in) and 30 mm (1.18 in). This also means that the variations of the uplift resistance capacity for the adhesive thickness less than 10 mm (0.39 in) are not significant hence the current adhesive thickness can still be maintained and used in the field application.



a) 0.5 mm ( 0.02 in) Adhesive Thickness

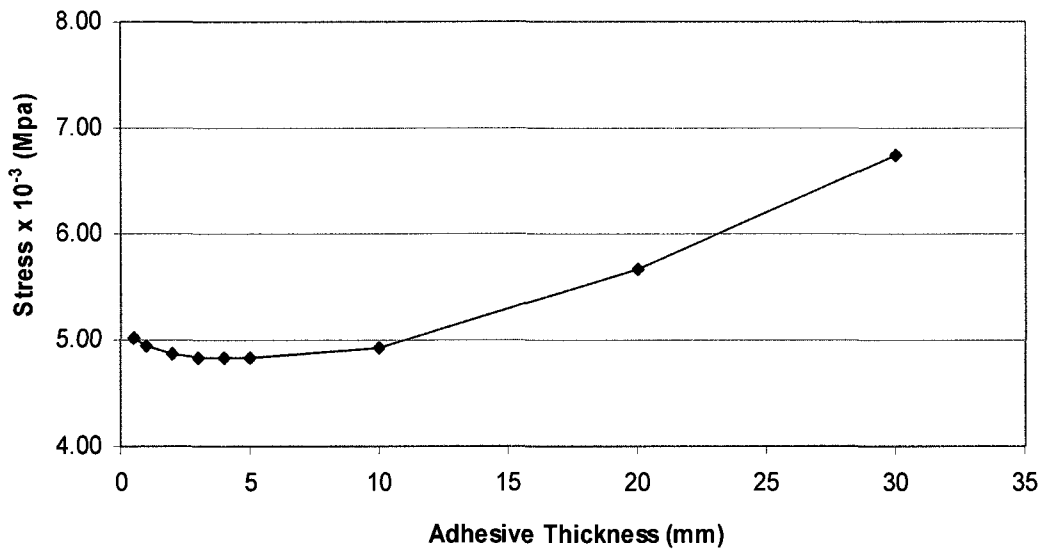


b) 2 mm (0.08 in) Adhesive Thickness



c) 30 mm (1.18 in) Adhesive Thickness

**Figure 9.7** Typical Stresses Contours Due to the Different Adhesive Thickness



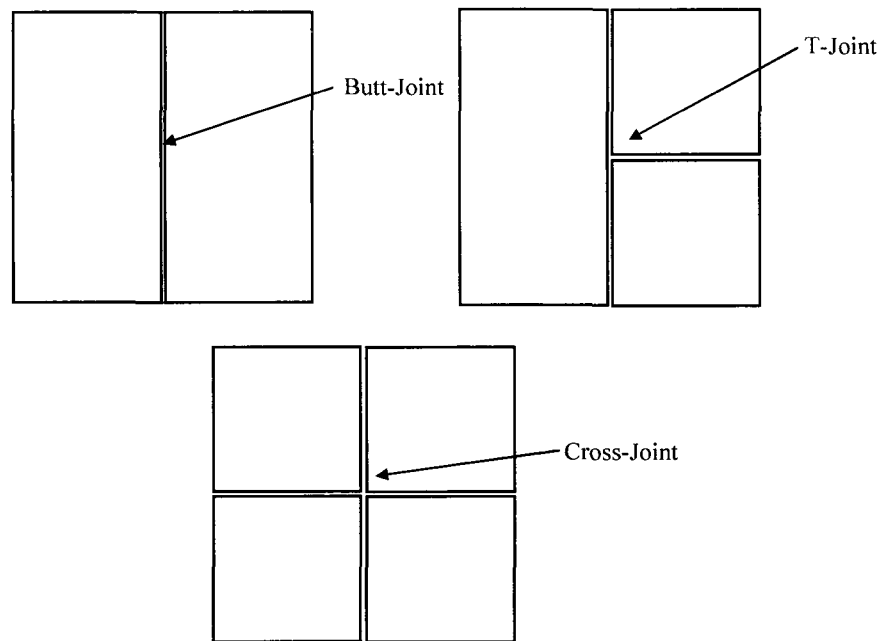
**Figure 9.8** The Effect of Adhesive Thickness on the Highest Stress

It must be noted, in relation to the interpretation of these test results, that this analysis was performed using only one type of adhesive. Since the Young's Modulus ( $E$ ) and Poisson's ratio ( $\nu$ ) can be different from one manufacturer to another, the nominal stress value obtained from the model simulation can vary. Therefore it is important to emphasize that the study here does not attempt to evaluate nominal stress value of the specific adhesive properties but to have general information on how significant adhesive thickness could affect the uplift capacity performance of AARS and to find out whether or not the current adhesive thickness used in the field can still be maintained.

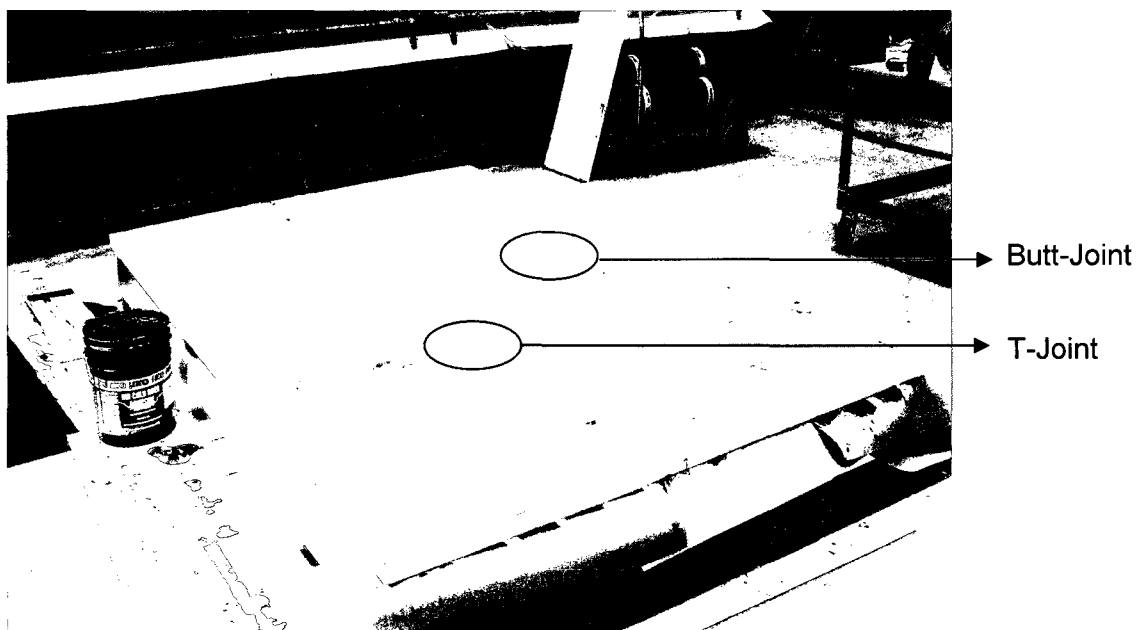
## **9.4 Effect of Insulation Joints**

### **9.4.1 Modeling Background**

This section discusses the influence of insulation joints on the AARS uplift resistance performance. Joints in the insulation components cannot be avoided on AARS application due to the sizes of insulation boards, which are smaller than the size of the roof. Common sizes of insulation board and their types are listed in the Chapter 3. The type of insulation joints can be categorized into three types: Butt joint, T joint and Cross joint as shown in Figure 9.9. A photograph of typical insulation joints of AARS is given in Figure 9.10. Similar joint types can also occur in the cover board components. The present study only considers the insulation joints because experimental failures of the system were mostly observed at the insulation component, and no mechanical property data are readily available for the cover board. The focus of the study was not intended to quantify the nominal uplift capacity of the insulation components but to obtain a general idea of significance of the joint type on the AARS uplift resistance. Section 9.4.2 and Section 9.4.3 describe the detail of the model and simulation results, respectively.



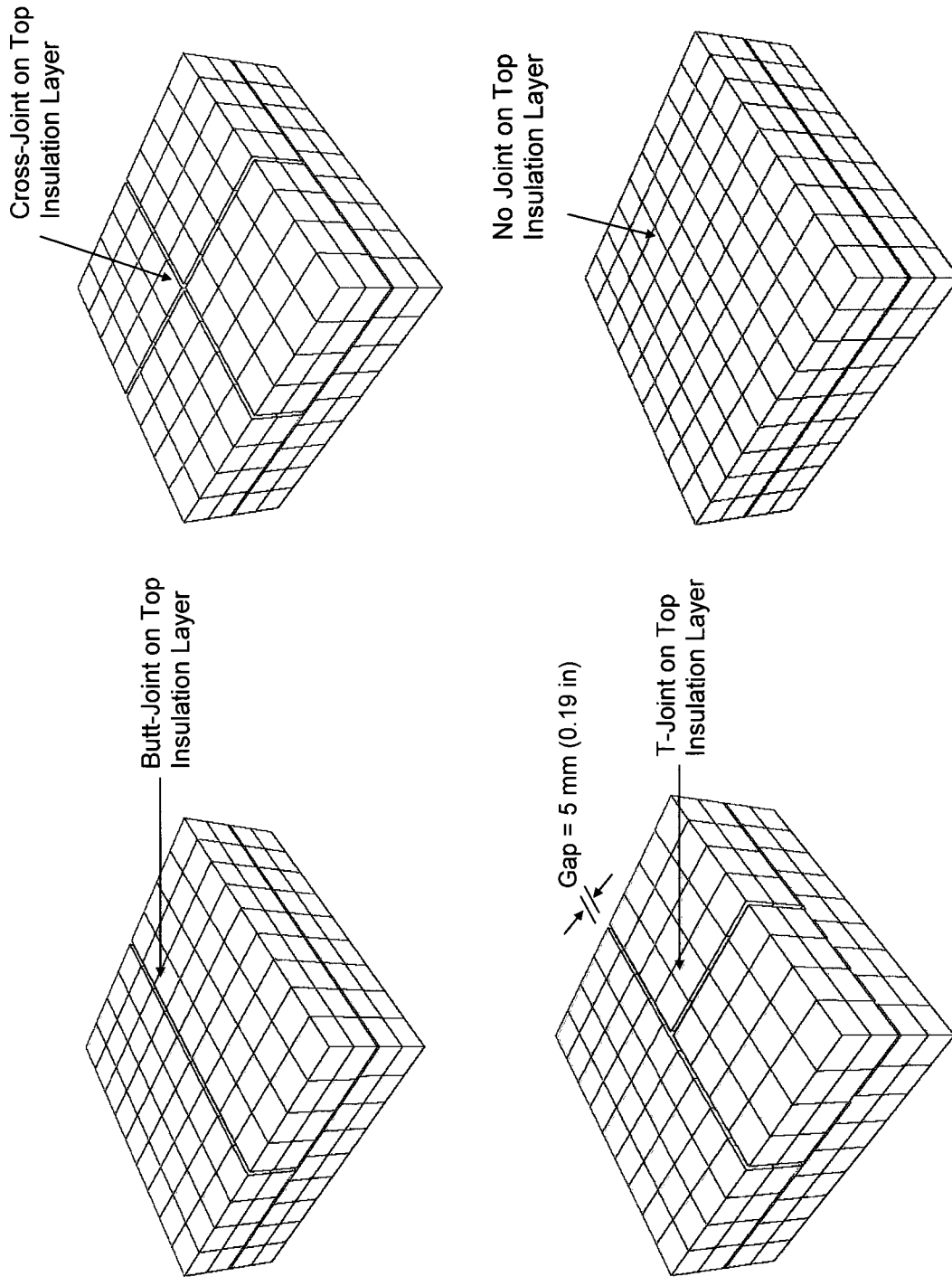
**Figure 9.9** Type of Insulation Joints Considered for the FE Simulations



**Figure 9.10** Typical Use of the Insulation Joints

#### 9.4.2 Model Details

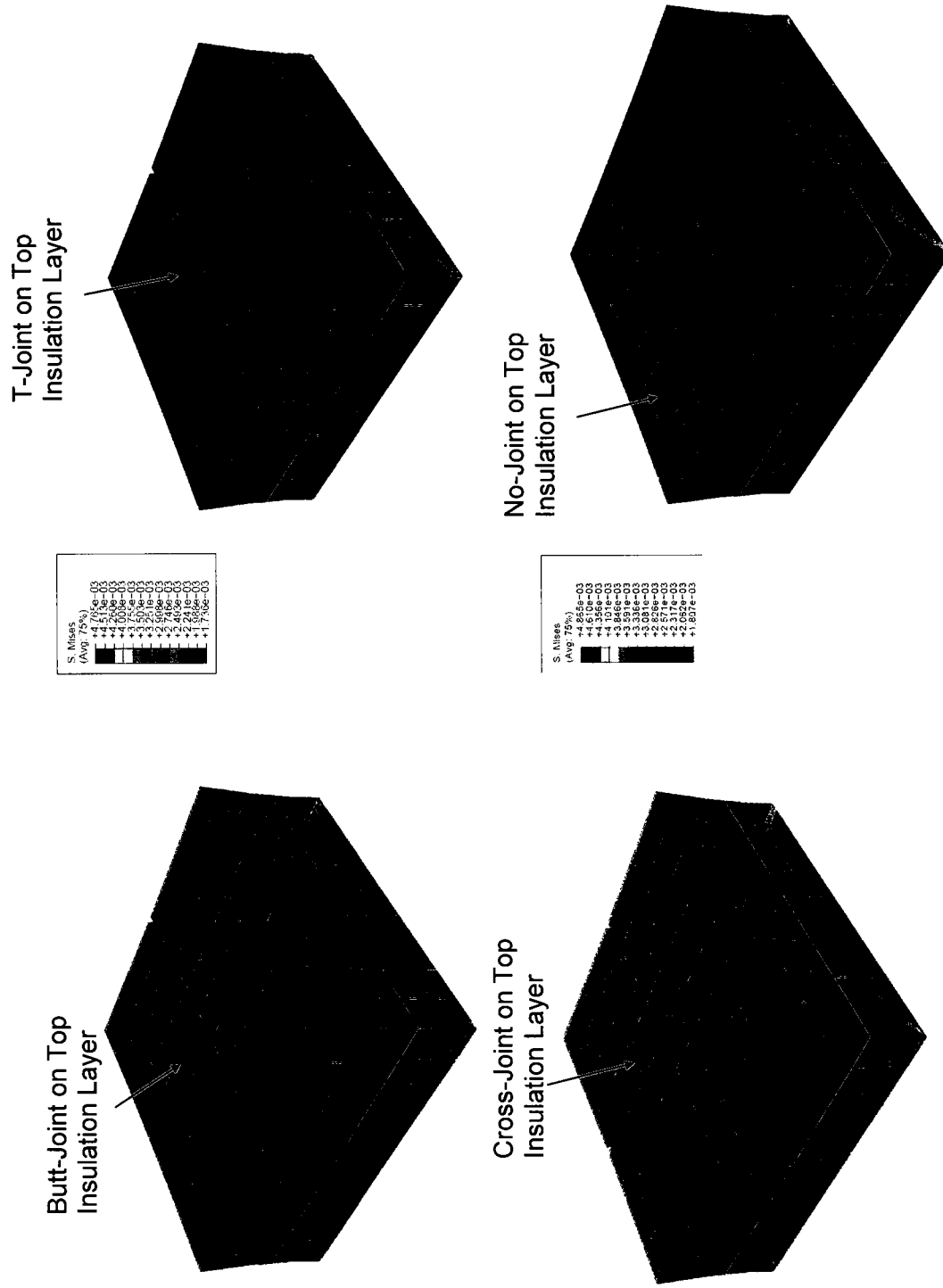
The 3D FE model was modified to accommodate three different insulation joint types. This modification was made on the top insulation layer of the model, while the bottom insulation was left unchanged. The top insulation was modelled as a smaller size board to incorporate the different joints and was fully bonded to the bottom insulation. However, the overall size of the top insulation was maintained same as before (305 mm x 305 mm (12 in x 12 in)). A 5 mm (0.19 in) gap was given between the board segments of the top insulation throughout the simulation. Figure 9.11 shows the three 3D FE models considered for the present study. Other modelling parameters such as the mechanical properties, load input, boundary conditions, element type and mesh size were maintained the same as Chapter 8. The tie constraint was used to connect the nodes of the top and bottom surfaces of the insulation layers with the adhesive layer.



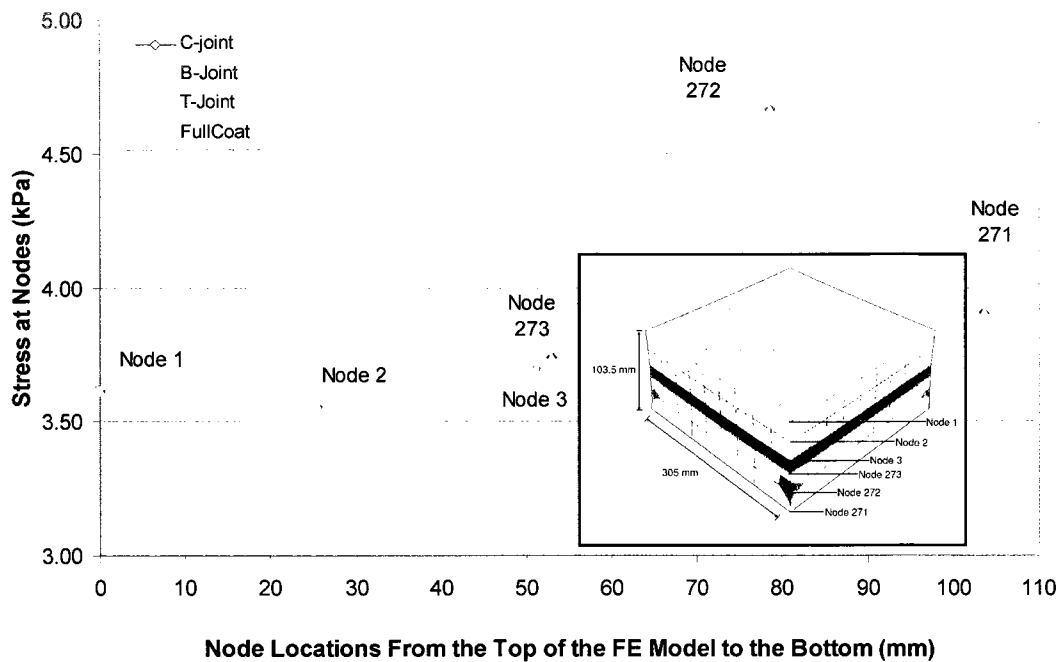
**Figure 9.11** Types of Joints adopted for the 3D FE model

### 9.4.3 Model Outputs

Figure 9.12 shows the calculated stress distribution contours from the FE simulations. In general, the introduction of joints on the top insulation does not change the location of the highest stresses. This may be because the insulation surface area removed is too small in comparison to overall surface area of the insulation so it does not provide significant effect to the maximum uplift strength capacity. This may be different for the air leakage and moisture transfer performance since more gaps could lead toward more air leakage and moisture transfer. Although the maximum stress does not seem to be significantly influenced by the type of insulation joints, the stresses on the model show different stress distributions. Figure 9.13 shows the stress distribution pattern at the corner of the model taken from the nodes of 1, 2, 3, 271, 272 and 273. The X-axis locates the position of the nodes from the top to the bottom of the FE model while the Y-axis gives the stress at nodes (kPa). Figure 9.13 indicates that the use of different type of insulation joints influences the stress distribution of the model.



**Figure 9.12** Stresses Contour Diagrams for the three Types of Joints Considered



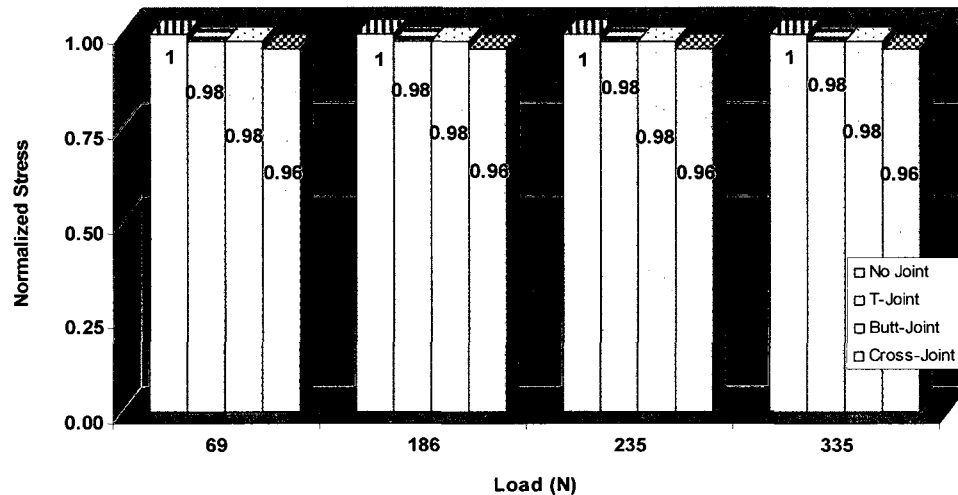
**Figure 9.13** Stress Distribution at Node 1, 2, 3, 273, 272 and 271

The 3D FE model simulation was performed using four different input loads and the results are given in terms of the maximum normal stress for each input load. Table 9.1 summarizes the resulted maximum normal stresses. The maximum normal stresses are used as an indicator of the model capacity to resist uplift load for various types of insulation joints, compared with a model without insulation joints. The insulation without joint in this study was used as reference for measuring the full uplift resistance capacity. Table 9.1 shows the maximum stresses obtained from the FE simulation. In order to understand the significance of the types of insulation joints on the uplift resistance capacity, the maximum stresses in Table 9.1 were normalized to the uplift resistance capacity in which no joints were assumed. Figure 9.14 shows the results of normalized stresses. The abscissa describes the input loads, while the ordinate gives the normalized stresses of the

Butt-Joint, T-Joint and Cross-Joint. For example, at the 69 N (15.5 lbf) input load, the normalized stress of the model for the Butt-joint, T-Joint and Cross-joint was about 0.98, 0.98 and 0.96, respectively. It indicates that at the 69 N (15.5 lbf) input load the model uplift resistance capacity for the Butt-joint, T-Joint and Cross-joint was decreased about 2 %, 2 % and 4 %, respectively, of the model without joint. The FE simulation results illustrate that although there are reduction of maximum uplift resistance capacity by introducing the joints on the top insulation part, this reduction is always less than 5% and not significant.

**Table 9.1** FE Model Maximum Stresses

| Load (N) | Type of Joints (MPa) |           |           |             |
|----------|----------------------|-----------|-----------|-------------|
|          | No-Joint             | T-Joint   | B-Joint   | Cross-Joint |
| 69       | 1.014E-03            | 9.927E-04 | 9.926E-04 | 9.721E-04   |
| 186      | 2.703E-03            | 2.647E-03 | 2.647E-03 | 2.592E-03   |
| 235      | 3.446E-03            | 3.375E-03 | 3.375E-03 | 3.305E-03   |
| 335      | 4.865E-03            | 4.765E-03 | 4.765E-03 | 4.666E-03   |



**Figure 9.14** Stress Reduction Due to the Different of Joint Types

## **9.5 Concluding Remarks**

Parametric investigations regarding the effects of, adhesive application, adhesive thickness and the type of joints for insulation on the AARS uplift resistance capacity were discussed in this chapter. It was concluded that the method of adhesive application both in terms of its contact area and adhesive thickness has a significant influence on the uplift resistance capacity of AARS. The greater the glued area was, the better the performance, particularly when the area coverage exceeds a half of the contact area. In terms of the effect of adhesive thickness, research indicated that the variation of AARS uplift resistance capacity was not significant if the adhesive thickness was less than 10 mm (0.39 in). Regarding the insulation joints, it was found that the type of joints would not have much influence on the AARS uplift performance. Hence, the current practice for adhesive thickness and the type of insulation joints can be maintained and used in the field application.

## **Chapter 10      Conclusions and Recommendations**

### **10.1 Conclusions**

A comprehensive study for establishing a test method to quantify the wind uplift performance of Adhesive Applied Roofing Systems (AARS) was presented in this dissertation. The research was specifically intended to develop a full scale laboratory testing procedure to evaluate the wind uplift resistance performance of rigid roofing systems such as AARS and to contribute to the development of design guidelines. Based on the research performed, enhancements were proposed to the current CSA 123.21-04 standard. The following conclusions can be given:

1. Examination of the pressure fluctuations using probability distribution and spectral analysis concluded that rigid and flexible roofs exhibited different system responses under wind action. The probability distribution of pressure fluctuations showed that the variation of pressure fluctuations on flexible roofs was higher than that of the rigid roof models, while spectral analysis of the wind-induced pressure fluctuations indicated that the frequency for rigid roof models, in which strong energy variation occurs, was higher than that of the flexible roof. The frequency of wind-induced pressure fluctuations for rigid roofs was less than 4 Hz. In order to better incorporate the effect of wind-induced pressure fluctuations, the study concluded that each type of roofing system required a different set of load cycles.
2. A new load cycle for the wind uplift resistance evaluation of rigid systems such as AARS was developed. The developed load cycle consists of two groups of

varying amplitude cycles. The effect of wind-induced suction over rigid roof assembly was accounted in Group 1, while the effect of exterior wind fluctuations combined with a constant interior pressure on a building was characterized using Group 2. A time period of 8 seconds was selected to complete one cycle. A cycle consists of two phases, loading and unloading. Each phase has 2 seconds or longer duration. The duration of 2 seconds was longer than the time period observed during spectral analysis of wind-induced pressure for rigid roofs. Therefore, the time period selected for the newly developed load cycle was longer compared to the time period observed during wind tunnel testing of rigid roof.

3. To further study wind uplift performance of AARS, experimental investigations were carried out by performing tests under static and dynamic loading conditions on 30 full-scale AARS mock-ups. The dynamic loadings included the application of the newly developed load cycles and the existing CSA 123.21-04 load cycle. The critical results from the tests are outlined below:
  - The static test protocol yielded a higher wind uplift resistance performance in comparison to the dynamic test protocol. This was because the static testing protocol did not consider the wind-induced pressure fluctuations on roofs that create the fatigue effects on roofing systems. The test also illustrated that the majority of the failure modes were found to be similar irrespective of the testing protocols used.
  - The effect of the number of load cycles on AARS was evaluated by simply reducing the CSA 123.21-04 load cycles by 50% and 75% load cycles. Test

results showed that by reducing the number of load cycles increased the AARS wind uplift resistance. This was because the reduction on the number of load cycles reduced the effect of fatigue on AARS. Therefore, it was evident that a suitable load cycle testing protocol to quantify AARS wind uplift resistance rating was needed. For this, a new load cycle for rigid roof evaluation was developed as shown in Chapter 5.

- Wind uplift resistance performance was significantly influenced by the variation of the roofing components and the type of adhesive used. Therefore, proper selection of AARS components is necessary to have desired wind uplift resistance rating particularly in terms of bonding performance.
- The weakest link of the AARS was generally found to be the insulation board and the failure location could be either in the insulation foam or delamination of the facers.
- Wind uplift performances of AARS tested using the load cycle for rigid roofs and the load cycle for flexible roofs were compared. The test results indicated that the use of the load cycle for rigid roofs did not change the wind-uplift resistance rating resulted from the use of the load cycle for flexible roof. Also, the failure modes were found to be similar. The study concluded that the dynamic load cycle for rigid roofs is more appropriate for the wind uplift resistance evaluation of AARS because it allows faster testing and provides similar wind uplift rating in comparison with the load cycle for flexible roofs (CSA 123.21-04 load cycles). Similar phenomena were also noticed when the load cycle for flexible roofs (CSA 123.21-04 load cycle)

was developed and compared to ETAG-006 test method which is practised in Europe.

4. Performance comparison in terms of uplift resistance and failure mode between the wind uplift, pullout and peel tests showed that the wind uplift test was found to give much lower uplift resistance ratings when compared to the pullout or peel tests. This was because the wind uplift test was performed under the dynamic loading condition that accounted the effect of fatigue, while the other two testing methods applied static loadings. In terms of failure mode, the weakest link of the AARS assembly was found to be either the insulation or the cover board components. The failure of the insulation component was mostly found when asphaltic core board was used, while the failure at the cover board was found if a fibre-cover board was used. In addition, if a component is substituted or added, a method was proposed on how to take the advantage of the data from a previously tested AARS assembly. However, further research is needed before the proposed method can be implemented.
5. A simplified three dimensional finite element (3D FE) model of AARS was developed and benchmarked with experimental data. It was proven that the simplified model could be used to predict AARS uplift performance if the weakest link of the AARS lies in insulation and its adhesive interface. Prior to the 3D FE model validation, a mesh sensitivity study was performed. By using enhanced 3D FE model, effects of variations in the: adhesive application method, adhesive thickness and types of insulation joints were studied. It was concluded that there was no significant variation in terms of the uplift resistance

capacity when the adhesive thickness less than 10 mm was used. Similarly the effect of insulation joints with 5 mm gap does not significantly influence the uplift resistance performance. Hence the current practise and procedure for AARS can still be maintained and used.

## **10.2 Recommendations for Future Work**

This dissertation successfully developed a full scale testing procedure to evaluate the wind uplift resistance performance of rigid systems such as the AARS. However, improvements to the developed testing procedure are possible to provide more reliable wind uplift resistance data. The following summarizes some options for future research in this area.

In Chapter 4, the wind tunnel data comparison between flexible roofs and rigid roofs was performed for different model scales and wind tunnel testing facilities. This could affect the results. Future research using the same model configurations for flexible and rigid roofs tested using the same wind tunnel facility is necessary to review the results.

The method of identifying the failure and stopping the tests presented herein relied solely on the estimation of the testing operator, which was based on percentage of blister or delamination identified area on the surface of the test mock-up. Another possible method of failure identification that could improve the estimation of surface blister or delamination area such as the use of computer imaging technique, would be useful. For instance, using a surface scanning device one can measure the percentage of blister.

The developed testing procedure evaluated a roof with uniform pressure distribution over the roof surface. Since the roof surface consists of three zones, depending on the design pressures, incorporating pressure variations with respect to roof surface into the developed testing procedure can avoid multiple full-scale wind uplift testing, for instance, when two types or more of roof combinations are used.

A hypothesis was proposed when correlating the three different test methods (wind uplift, pullout and peel tests). However, this proposed procedure requires further research to verify whether or not it can be implemented.

The 3D FE simulations performed in this study excluded the effect of wind-induced pressure fluctuations on roof. Future research that incorporates dynamic load cycles on the system can enhance the current 3D FE simulations.

The 3D FE simulations were performed only using the size of 305 mm x 305 mm (12 in x 12 in), further 3D FE simulations using, for instance, a full-scale AARS mock-up size and validating these results with the experimental data can be used in the system evaluation.

The 3D FE simulation in this study only utilized three parts of the roof assembly; namely, the top insulation, the adhesive layer and the bottom insulation. Future research can be carried out to incorporate other AARS roof components in the 3D FE model, especially the cover board component since, it is a possible failure plane noticed during experimental investigation.

## References

- Abaqus (2007). " User's manual, v 6.7.-1." *Hibbitt, Karlsson and Sorensen, inc.*, Pawtucket, RI.
- Amzallag, C., Gerey, J.P., Robert, J.L., Bahuaudl, J. (1994). "Standardization of the rain flow counting method for fatigue analysis." *J. Fatigue*, Butterworth-Heinemann Ltd, 16, 287-293.
- ASCE 7 (2005)." Minimum Design Loads for Buildings and Other Structures." *American Society of Civil Engineer (ASCE)*, Reston, VA.
- ASTM D6164 (2005)." Standard specification for styrene butadiene styrene (sbs) modified bituminous sheet materials using polyester reinforcements." *American Society for Testing Material (ASTM) International*, West Conshohocken, PA.
- ASTM E1049-85 (2005)." Standard practices for cycle counting in fatigue analysis." *ASTM International*, West Conshohocken, PA.
- ASTM C1289 (2008)." Standard specification for faced rigid cellular polyisocyanurate thermal insulation board." *ASTM International*, West Conshohocken, PA.
- ASTM A653 / A653M (2009)." Standard specification for steel sheet, zinc-coated (galvanized) or zinc-iron alloy-coated (gal annealed) by the hot-dip process." *ASTM International*, West Conshohocken, PA.
- ASTM A792 / A792M (2009)." Standard specification for steel sheet, 55 % aluminum-zinc alloy-coated by the hot-dip process." *ASTM International*, West Conshohocken, PA.
- ASTM D6506 (2009)." Standard specification for asphalt based protection for below-grade waterproofing." *ASTM International*, West Conshohocken, PA.
- Baskaran, A. (1986)." Wind load on flat roofs with parapet." MEng. thesis, (Building), Centre for Building Studies, Concordia University, Montreal, QC.
- Baskaran, B.A., Dutt, O., Paroli, R.M (1994). "Investigating roofing systems' ability to withstand dynamic wind effects, New Roofing Study Under Dynamic Wind Effects." *Building Performance News*, National Research Council of Canada (NRCC), 24, 1, Ottawa, ON, Canada.
- Baskaran, A. and Dutt, O. (1995). "Application of lab procedures for the dynamic evaluation of roofing systems. Part 1: review of existing standards." IRC Internal Report No. 692, NRCC, Ottawa, ON. Canada.

- Baskaran, B.A. (1996).” Effects of dynamic wind loads on roofing systems – New Research Investigates the Effects of Dynamic Wind Loads on Roofing Systems.”, *Interface, J. of Roof Consultant Institute (RCI)* 14 (10), 5-8.
- Baskaran, A, Savage, M.G., Alfawakhiri, F and Cooper, K (1996).” Pressure distribution data measured during the october 1995 wind tunnel tests on a mechanically attached epdm single ply roofing systems.” Internal Report LTR A 004, *Institute for Aerospace Research (IAR)*, NRCC, 1-203, Ottawa, ON, Canada.
- Baskaran, A., Chen, Y , Savage, M (1997), “Development of a wind load cycle for testing commercial building envelopes, *Proc., Struct. Congress XV*, ASCE, Portland, Oregon, 1, 6-10.
- Baskaran, A., Chen, Y., Vilaipornsawai, A (1999).” A new dynamic wind load cycle to evaluate flexible membrane roofs.” *J. Testing and Evaluation*, 27 (4), 249-265.
- Baskaran, A., Lei, W. and Richardson C. (1999).” Dynamic evaluation of thermoplastic roofing systems for wind performance.” *J. Arch. Eng.*, ASCE, 5 (5), 16-24.
- Baskaran, A. and Borujerdi, J. (2001).” Application of numerical models to determine wind uplift ratings of roofs.” *J. Wind and Struct.*, 4(3), 213-226.
- Baskaran, A., Savage, M.G. (2003).” Wind pressure measurements on full scale flat roofs.” *Interface J. of RCI*, 21 (4), 17-21
- Baskaran, A. and Molleti, S. (2005).” Application of numerical models to determine wind uplift ratings of roofs – Part II, *J. Wind and Struct.*, 8(3), 213-233.
- Baskaran, B. A., **Murty, B.**, and Tanaka, H. (2007).” Pilot study on wind uplift resistance of adhesive applied low slope roofing systems.” *J. ASTM International*, 4 (10), 32-46.
- Baskaran, B. A., **Murty, B.**, and Wu, J (2009).” Calculating roof membrane deformation under simulated moderate wind uplift pressures.” *J. Eng. Struct.*, 31 (3), 642-650.
- Baskaran, B.A., Current, J., **Murty, B.**, Tanaka, H., and Wu, J. (2010), “Fastener free low slope roofing systems can it resist wind uplifts,” *Proc. the 25th RC) Inter. Convention Trade Show*; RCI, Orlando, FL.
- Banks D. (2000).” The suction induced by conical vortices on low-rise buildings with flat roofs.” Ph.D. Thesis, Dep. of Civil Eng., Colorado State University, Fort Collins, CO.

- Banks, D., Meroney, R.N., Sarkar p.P., Zhao, Z., Wu, F. (2000). "Flow visualization of conical vortices on flat roofs with simultaneous surface pressure measurement." *J. Wind Eng. and Ind. Aero.*, 84, 65-85.
- Blackmore, P.A (1988). "Load reduction on flat roofs-the effect of edge profile." *J. Wind Eng. and Indust. Aero.*, 29, 89-98.
- Brodland, G.W., Dell, M.J., Gailey, C., and Burnett, E.F.P (1991). "Finite element modeling of reinforced bitumen membranes." *Proc. 3<sup>rd</sup> Int. Symp. on Roofing Technology*, Montreal, QC, 21-25.
- Byrne, S.M. (1976). "Dynamic-load testing of sheet metal roofing." *Proc. Metal Structures Conference*, Adelaide, Aus., 46-50.
- CAN/UL C S706 (2002). "Standard for wood fibre thermal insulation for buildings." *Underwriters Laboratories (UL) of Canada*, Toronto, ON.
- CAN/ULC S126M (2003). "Standard method of test for fire spread under roof-deck assemblies." *Underwriters Laboratories (UL) of Canada*, Toronto, ON.
- CAN/ULC S 704 (2003). "Standard for thermal insulation, polyurethane and polyisocyanurate boards faced." *Underwriters Laboratories (UL) of Canada*, Toronto, ON.
- CSA A123.21-04. (2004). "Standard test method for the dynamic wind uplift resistance of mechanically attached membrane-roofing systems." *Canadian Standards Association (CSA)*, Toronto, ON.
- Chen, Y. and Baskaran, B.A. (1997). "Development of load sequence using pressure records measured from wind tunnel studies for mechanically attached single-ply PVC and EPDM roofs, Internal report No. IR743, *Institute for Research in Construction*, NRCC, Ottawa, ON.
- Cook, N.J., Keevil, A.P. and Sfobart, R.K. (1988), BRERWULF- The big bad wolf, *J. Wind Eng. and Ind. Aero.*, 29, 99-107.
- Compaq Visual FORTRAN Version 6.6 (2001), Compaq Computer Corporation.
- Current, J, **Murty, B.**, Wu, J., Baskaran, A., Tanaka, H (2007). "Wind uplift resistance data for adhesive applied roofing systems - Part 1." Internal report No.IR-876, *Institute for Research in Construction*, NRCC, Ottawa, ON.
- Current, J (2009). "Development of a pullout test method for adhesive applied roofing systems." MAsc. Thesis, Dept. Civil Eng., University of Ottawa, Ottawa, ON.

- Dalgliesh, W.A. (1970). "Treatment of peak gusts on cladding." *J. Struct. Eng.*, ASCE, 97 (1), 2170-2187.
- Damatty El.,A.A., Rahman, M., Ragheb, O (2003). "Component testing and finite element modeling of standing seam roofs." *J. Thin-Wall Struct.*, 41, 1053-1072.
- Downing, S. D., Socie, D. F (1982). "Simple rainflow counting algorithms." *Int. J. Fatigue*, Jan. ed., 31-40.
- Davenport, A.G. (1961). "The application of statistical concepts to the wind loading of structures." *Proc. Inst. Civil Engineers*, ASCE, Reston, VA, 449-472.
- Easter, M.R. (1990), "Finite element analysis of roofing systems," *Roofing Research and Standards Development*, ASTM International, Philadelphia, 2, 138-151.
- ETAG (2006). "Guideline for European technical approval of mechanically fastened flexible roof waterproofing membranes." EOTA, Kunstlaan 40 Avenue des Arts, B-1040, Brussels.
- Factory Mutual Research, (1986). "Approval standard: class I roof covers (4470)." *FM*, Norwood, Massachusetts.
- Factory Mutual Research, (2004). "Approval standard: class I roof covers (4474)." *FM*, Norwood, Massachusetts.
- Factory Mutual Research (1992), "In search of excellence: FRMC improves roof tests", *The Roofing Industry Educational Institute*, Norwood, Massachusetts, 5-7
- Henry Company Canada Inc. (2006). "Young's modulus and Poisson's ratio for Bakor mba gold and Bakor thermostick 880-33." Test report, July 6<sup>th</sup>, BAKOR inc. Toronto, ON.
- Holmes, J. D. ( 2001). "Wind loading for structures, *Spon Press*, 29 West 35<sup>th</sup> Street, New York, NY.
- IKO-TDS# 130059 (2006). "Armourgard Vapour Retardant – 68." Technical Data Sheet, *IKO Industries Ltd.*, Toronto, ON.
- Irwin, P.A (2008). "Bluff body aerodynamic in wind engineering." *J. Wind Eng. and Ind. Aero.*, 96, 701-712.
- Jancauskas, E.D.J., Mahendran, M. and Walker, G.R., (1994). "Computer simulation of the fatigue behavior of roof cladding during the passage of a tropical cyclone." *J. Wind Eng. and Ind. Aero.*, 51, 215-227.

- Gerhardt, H.J. and Kramer, C. (1986). "Wind Induced Loading Cycle and Fatigue Testing of Lightweight Roofing Fixations." *J. Wind Eng. and Ind. Aero.*, 23, 237-247.
- Gerhardt, H.J. and Gerbatsch, R.W. (1989). "Wind loads on single-ply membranes." *The Construction Specified*, Nov. ed., 60-71.
- Gerhardt, H.J. and Kramer, C. (1988). "Wind loading and fatigue behavior of fixings and bondings of roof coverings." *J. Wind Eng. and Ind. Aero.*, 29, 109-118.
- Gerhardt, H.J. and Kramer, C. (1991). "Effect of building geometry on wind Loading, *Proc. of the 8<sup>th</sup> Inter. Conf. on Wind Engineering*, London, ON
- Gerhardt, H.J. and Kramer, C. (1992). "Wind safety of single-ply roofs under time varying wind load", *J. Wind Eng. and Ind. Aero.*, 41-44, 1513-1524
- Glinka, G. , Kam, J. C. P. (1987). "Rainflow counting algorithm for very long stress histories." *Int. J. Fatigue*, 3, 223-228.
- Ginger, J.D., Reardon, G.F., Whitbread, B.J (2000). "Wind load effects and equivalent pressures on low-rise house roofs." *J. Eng. Struct.*, 22, 638-646.
- Ginger, J.D., Letchford, C.W (1999). "Net pressure on a low-rise full scale building." *J. Wind Eng. and Ind. Aero.*, 83, 239-250.
- Gioffre, M., Gusella, V., Grigoriu, M. (2000). "Simulation of non-gaussian field applied to wind pressure fluctuations." *J. Probabilistic Eng. Mech.*, 15, 339-345.
- Gullo, I., Muscolino, G., Vasta, M. (1998). "Non-gaussian probability density function of SDOF linear structures under wind actions." *J. Wind Eng. and Ind. Aero.*, 74-76, 1123-1134
- Kawai, H., Nishimura, G (1996). "Characteristic of fluctuating suctions and vortices on a flat roof in oblique flow." *J. Wind Eng. and Ind. Aero.*, 60, 147-173
- Kawai, H (1997). "Structure of conical vortices related with suction fluctuation on flat roof in oblique smooth and turbulent flows." *J. Wind Eng. and Ind. Aero.*, 69-71, 579-588.
- Kawai, H (2002). "Local peak pressure and conical vortex on building." *J. Wind Eng. and Ind. Aero.*, 90, 251-263.
- Kind, R.J (1986). "Worst suctions near edges of flat rooftops on low rise building." *J. Wind Eng. and Ind. Aero.*, 25, 31-47.

- Koike, M., Tanaka, K and Tomita, T (1978). "Strains in multi-ply membranes caused by joint movement in substrate." *Report of Research Laboratory of Engineering Materials*, Tokyo, 3, 145-177
- Kumar, S.K (1997). "Simulation of fluctuating wind pressures on low building roofs, PhD thesis." (Building), Centre for Building Studies, Concordia University, Montreal, QC.
- Laaly, H.O (1991). "The science and technology of traditional and modern roofing systems." *Laaly Scientific Publishing*, Los Angeles, CA.
- Lam, K.M and To, A.P (1995). "Generation of wind loads on a horizontal grandstand roof of large aspect ratio." *J. Wind Eng. and Ind. Aero.*, 54/55, 345-357.
- Lawson, T.V. (1980). "Wind effect on buildings: *J. Applied Science*, 1, 1-318.
- Lewis, J.E. (1980). "Preliminary stress evaluation of the effects of gaps between roof insulation panels." *J. Thermal Insulation*, 4, 3-36.
- Letchford, C.W. and Norville, H.S. (1993). "Wind induced pressure loading cycles for wall cladding during hurricanes." *Glass Research and Testing Laboratory*, Texas Tech University, Lubbock, Texas.
- Liu, K. K. Y.; Paroli, R. M.; Smith, T. L. (2000). "Blistering in SBS polymer modified bituminous roofs, *Construction Technology Update*, NRCC, Ottawa, ON.
- Lin, J.X., Surry, D., Tieleman, H.W. (1995). "The distribution of pressure near roof corners of flat roof low buildings." *J. Wind Eng. and Ind. Aero.*, 56, 235-265.
- Lythe, G., Surry, D (1983). "Wind loading of flat roofs with and without parapet." *J. Wind Eng. and Ind. Aero.*, 11, 75-94.
- Mahendran, M. (1990). "Fatigue behaviour of corrugated roofing under cyclic wind loading." *Civil Engineering Transaction*, the Institution Engineer, Australia, 32 (4), 219-226.
- Mahendran, M. (1993). "Fatigue behaviour of light gauge steel roof claddings under simulated cyclonic wind forces." *Technical Report No. 39, Cyclone Structural Testing Station*, James Cook University of North Queensland.
- Mahendran, M. (1994). "Effect of overload cycles on thin steel roof claddings during cyclone winds." *J. Testing and Evaluation*, ASTM, 22 (5), 453-459.
- Mathwork inc (2004). "Matlab, the language of technical computing." version 7.0.1., Math Software Co., USA.

- Morgan, J.W. and Beck, V.R. (1997). "Failure of sheet metal roofing under repeated wind loading." *Civil Engineering Transactions*, the Institution of Engineers, Australia, 19, 1-5.
- Murty, B.**, Current, J., Wu, J., Baskaran, A.; Tanaka, H (2008). "Wind uplift resistance data for adhesive applied roofing systems - Part 2." Internal report # IR-877, IRC, NRCC, Ottawa, ON.
- Murty, B.**, Baskaran, A. and Tanaka, H.,(2008). "Numerical modeling of adhesive applied low slope roofing systems for wind uplift resistance evaluation – a pilot study", *Proc. of the AEI 8<sup>th</sup> National Conference on Building Integration Solutions*, ASCE, Denver, CO.
- Murty, B.**, Current, J., Davelay, C., Baskaran, A., Tanaka, H (2009). "Wind uplift resistance data for adhesive applied roofing systems - Part 3." Internal report # IR-878, IRC, NRCC, Ottawa, ON.
- National Research Council Canada (2005). "National building code of Canada user's guide -structural commentaries." NRCC, Ottawa, Canada
- NT BUILD 307 (1986). "Roof coverings: wind load resistance (NT BUILD 307)." Nordtest, Finland.
- NBI 160 (1990), Roof coverings-dynamic wind load resistance." Norwegian Building Research Institute, Finland.
- Paulsen, E.M. (1989). "NBI Roof wind uplift strength test facility and load programs, *Proc. of the Roof Wind Uplift Testing Workshop*, Oak Ridge, Tennessee, 46-51.
- Prevatt, David. O (1998). "Wind uplift behaviour of mechanically-attached single-ply roof membrane systems." Ph.D Thesis, Clemson University, Clemson, SC.
- Prevatt, D.O, Schiff, S.D., Starn, J.S., Kulkarni, A.S (2008). "Wind uplift behaviour of mechanically attached single-ply roofing systems: the need for correction factors in standardized tests." *J. Struct. Eng.*, ASCE, 134(3), 489-498.
- Richards, P.J., Hoxey, R.P (2008). "Wind load on the roof of a 6 m cube." *J. Wind Eng. and Ind. Aero.*, 96, 984-993.
- Rychlik, I (1987). "A new definition of the rain flow cycle counting method." *Int. J. Fatigue*, 2, 119-121.
- Rossiter, W.J., Jr. and Batts, M.E. (1985). "Finite-element analysis of temperature induced stresses in single-ply roofing membranes, *Durability of Building Materials*, 2, 195-208.

- Sadek, F. and Simiu, E. (2002).” Peak non-gaussian wind effect for database-assisted low-rise building design.” *J. Eng. Mechanic*, 128(5), 530-539.
- Savage, M.G, Baskaran, A., Cooper, K.R and Lei, W., (1996).” Pressure distribution data measured during the november 1994 wind tunnel tests on a mechanically attached, pvc single-ply roofing system.” *IAR Report LTR-A-003*, NRCC, Ottawa,ON.
- SBCCI (1994).” SSTD 12 - Test standard for determining impact resistance from wind-borne debries.” p 12-94.
- Shi X, Liang J, Burnett E (2006).” Mechanics and test study of two-dimensional flexible membranes.” *J. Arch. Eng.*, ASCE, 12 (2), 93-99.
- Shi X, Liang J, Burnett E (2008).” Mechanics and test study of flexible membranes ballooning in three dimensions.” *J. Building and Environment*, 43, 1871-1881.
- Singh, S.N., Nturu-Karamagi, M., Ritche, M (2005).” Optimizing polyiso blowing agents.” *API05 Huntsman Construction Paper*, Huntsman Advanced Technology Center, Woodlands, TX.
- Singh, S.N, Fife, J.S. , Dubs, S., Coleman, P.D (2006).” Effect of formulation parameters on performance of polyisocyanurate laminate boardstock insulation, *API06 Huntsman Construction Paper*, Huntsman Advanced Technology Center, Woodlands, TX.
- Simiu, E and Scanlan, R.H (1986).” Wind effects on structures: An introduction to wind engineering.” *John Willey & Sons*, NY, 1-589.
- Smith, P.J (1992).” Testing methods for roof systems, *ASCE symposium on the Hurricanes*, ASCE, Reston, VA, 46-51.
- Smith, T. L (1996).” High-wind performance of mechanically-attached single-ply roof systems.” *Proc. of Roof Magazine*, 26,18-22.
- Smith, T. L (2009).”Wind safety of the building envelope, whole building design guide (WBDG).” *National Institute of Building Science*, Washington, DC
- Soprema-TDS# 061101CAN2E (2008).” SOPRAVAP’R, Technical data sheet, *Soprema Industries*, Drummondville, QC.
- Stathopoulos, T. (1980).” PDF of wind pressures on low-rise buildings, *J. Struct. Division*, ASCE, 106, 973-990.
- Stathopoulos, T., Mohammadian, A.R (1986).” Wind load on low building with mono-sloped roofs.” *J. Wind Eng. and Ind. Aero.*, 23,81-97.

- Stathopoulos, T., Marathe, R., Wu, H (1999).” Mean wind pressures on flat roof corners affected by parapets:field and wind tunnel studies.” *J. Eng. Struct.*, 21, 629-638.
- Stathopoulos, T (2008).” Pressure time histories from rigid wind tunnel models.” Technical Report, *Centre for Building Studies*, Concordia University. Montreal, QC.
- Sun, Y., and Bienkiewicz, B. (1991).” Numerical simulation of pressure distributions underneath roofing paver systems.” *J. Wind Eng. and Ind. Aero.*, 46 &47, 517-526.
- TR 440 (1991).” Guidelines for testing and evaluation of products for cyclone prone areas.” *Experimental Building Station (EBS)*, Sydney, Australia.
- UEAtc (1991), “Supplementary guide for the assessment of mechanically fastened roof water-proofing.” MOAT Number 55, *UEAtc*, Paris
- Uematsu, Y., Yamada, M., Sasaki, A (1996).” Wind-induced dynamic response and resultant load estimation for a flat long-span roof.” *J. Wind Eng. and Ind. Aero.*, 65, 155-166.
- Uematsu Y. and Isyumov N. (1999).” Review wind pressure acting on low-rise buildings.” *J. Wind Eng. and Ind. Aero.*, 82, 1-25.
- Uematsu, Y., Watanabe, K., Sasaki, A., Yamada, M., Hongo, T (1999).” Wind-induced dynamic response and resultant load estimation of a circular flat roof, closed-type wind tunnel at Kajima Technical Research Institute.” *J. Wind Eng. and Ind. Aero.*, 83, 251}261.
- Underwriters Laboratories Inc. (2006).” UL standard for safety tests for uplift resistance of roof assemblies, *Underwriter Laboratory of Canada*, Toronto, Canada.
- Xu, Y.L. (1993).” Wind-induced fatigue loading on roof cladding of low-rise buildings.” Cyclone Testing Station, James Cook University of North Queensland.
- Xu, Y.L., Mehta, K.C. and Reardon, G.F (1995).” Fatigue of metal roof cladding subject to wind loading, part 1: fatigue-related characteristics of roof pressures.” Proc. of 9<sup>th</sup> ICWE, New Delhi. India., 1067-1078.
- Weihong, L., **Murty, B.**, Current, J., Baskaran, A., Tanaka, H (2009).” Wind uplift resistance data for adhesive applied roofing systems - Part 4.” Internal report, IRC, NRCC, Ottawa, ON.

Wikipedia (2009). "Fatigue (Material)." [http://en.wikipedia.org/wiki/Fatigue\\_\(material\)](http://en.wikipedia.org/wiki/Fatigue_(material)).

Wu, J (2008)." Development of a peel test procedure for adhesive applied roof systems." MAsc. Thesis, Dept. of Civil Eng., University of Ottawa, Ottawa, ON.

Zarghamee, M. S. (1990)."Wind effects on single-ply roofing systems." J. Struct. Eng., 116(1), 177-187.

## Appendix A: Program for Power Spectra Density Computation

A program using Matlab Version 7.0.1 (Matwork inc 2004) was used to calculate the power spectra density of coefficient pressures-time signals that was obtained from the wind tunnel tests of rigid model and flexible model. The following is the Matlab programs used for the calculation.

```
=====
%%This program calculates the Power Spectral Density (PSD) of time
%%coefficient pressure-time signal allocated in a file with 8 columns.
%%The first column contains the times while the remaining 7 columns are
%%the coefficient pressure measurements in 7 taps.
%%
%%Note: that during the reading process, the array is transposed in
%%order to follow standard procedures

%Input: User is prompted to choose a file containing the time pressure
%signals
%Output: The PSD of pressure signal

[fname,pname] = uigetfile('Y:\wt750\*.','Pick Corrected Pressure Data
file');

Data=textread(fname, '%f', 'delimiter', ',');          %Read file

%%Constants values for the specific file format-----
ncols=8;
nrows=size(Data,1)/ncols;
spRate=418.75;          %Sampling Frequency
%%-----
Data=(reshape(Data, ncols, nrows));          %Reshape data file. Each ROW
                                           %contains the pressure signal
                                           %of a specific tap.

for i=1:7
    Variance(i)=(std(Data(i+1,:)))^2;
    [PSD_Cp(i,:), f]=pburg(Data(i+1,:), 10, 1024, spRate); %PSD using
                                                           %Burg method
    PSD_Cp_norm(i,:)=f'.*PSD_Cp(i,:)/Variance(i);

    %Create figure
    figurei = figure('Position', [60 300 800 420], 'Name', ['PSD ',
num2str(i)]);
    %Create axes
    axesi = axes('Layer','top', 'XScale','log','XMinorTick','on',
'Parent',figurei);
    title(axesi, 'Power Spectral Densities');
    %    xlim([0 spRate/2])

```

```
    xlabel(axesi,'Frequency (Hz)');  
    ylabel(axesi,'Normalized PSD');  
    box(axesi,'off');  
    hold(axesi,'all');  
    %Create waterfall  
    semilogx(f, PSD_Cp_norm(i,:), 'Parent', axesi)  
    grid on  
end
```

## Appendix B: Rain Flow Counting Program for Predicting Wind Induced Fatigue Loading on Roofs

The Rain Flow Counting (RFC) method for predicting wind induced fatigue loading on roofs was rewritten from its original version using Compaq Visual FORTRAN Version 6.6 (2001). The input of the program is coefficient pressures data obtained from the wind tunnel test using rigid models. The program computes the number of cycles occurred and calculates the maximum number of cycle under same group conditions. The output of the program is given in term of 10 by 10 matrixes. The program is described as follows,

```

c=====c
c          VARIABLE DECLARATIONS
c
c  character*12 ifile      ! filename
c  integer inputun /7/    ! input file unit number
c  integer grpun  /8/     ! graphics file unit number
c  integer legendun /9/   ! plot legend unit number
c  integer np /30000/     ! number of samples in the time series
c  integer npks          ! number of peaks (after filtering)
c  integer nrange        ! total number of ranges in the series
c  real max              ! |maximum| value in the time series
c  integer*2 nch /7/     ! number of channels in file (8 max.)
c  integer*2 st_len,l1
c  integer*2 len,l1
c  integer*2 ch1,ch2,ch3,ch4,ch5,ch6,ch7,dumch
c  character*10 grpfile1,grpfile2,grpfile3,grpfile8 ! filenames
c  character*10 grpfile4,grpfile5,grpfile6,grpfile7
c  character*10 legend1,legend2,legend3,legend4,legend5
c  character*10 legend6,legend7,legend8
c  real a,b,c,d,e,f,g,h
c  real acount,bcount,ccount,dcount,ecount,fcount,gcount,hcount
c
c  arrays containing time series and count results
c
c  dimension a(30000),b(30000),c(30000),d(30000)
c  dimension e(30000),f(30000),g(30000),h(30000)
c  dimension acount(30000,2),bcount(30000,2),ccount(30000,2)
c  dimension dcount(30000,2),ecount(30000,2),fcount(30000,2)
c  dimension gcount(30000,2),hcount(30000,2)
c  character*31 fname
c
c=====c
c          MAIN PROGRAM
c
c
c  nar=iargc()

```

```

c  if ((nar.eq.0).or.(nar.gt.1)) goto 1030
c  call igetarg(1,ifile,12) ! check for correct number of arguments
c      ! and get input file name
c      WRITE(*,('Input File Name: ', $))
c      read(*, '(a12)') ifile
c
c=====c
c  This section is specific to the original project for which
c  the program was written. It gets the first tap number from
c  the file name and names the output files.
c
c  l1=st_len(ifile)
c  l1=len(ifile)
c  ch1=-1
c  dumch=0
c
c  single digit first no
c
c  if((l1.eq.6).or.(l1.eq.10).or.(l1.eq.7).or.(l1.eq.11)) then
c      read(ifile(5:5), '(i1)') ch1
c  else if((l1.eq.8).or.(l1.eq.12))then
c      read(ifile(5:6), '(i2)') ch1
c  end if
c  ch2=ch1+1
c  ch3=ch1+2
c  ch4=ch1+3
c  ch5=ch1+4
c  ch6=ch1+5
c  ch7=ch1+6
c  ch8=ch1+7
c  grpfile1(1:4)=ifile(1:4)
c  grpfile2(1:4)=ifile(1:4)
c  grpfile3(1:4)=ifile(1:4)
c  grpfile4(1:4)=ifile(1:4)
c  grpfile5(1:4)=ifile(1:4)
c  grpfile6(1:4)=ifile(1:4)
c  grpfile7(1:4)=ifile(1:4)
c  grpfile8(1:4)=ifile(1:4)
c  if (ch1.eq.1) then
c      write(grpfile1(5:5), '(i1)') dumch
c      write(grpfile2(5:5), '(i1)') dumch
c      write(grpfile3(5:5), '(i1)') dumch
c      write(grpfile4(5:5), '(i1)') dumch
c      write(grpfile5(5:5), '(i1)') dumch
c      write(grpfile6(5:5), '(i1)') dumch
c      write(grpfile7(5:5), '(i1)') dumch
c      write(grpfile1(6:6), '(i1)') ch1
c      write(grpfile2(6:6), '(i1)') ch2
c      write(grpfile3(6:6), '(i1)') ch3
c      write(grpfile4(6:6), '(i1)') ch4
c      write(grpfile5(6:6), '(i1)') ch5
c      write(grpfile6(6:6), '(i1)') ch6
c      write(grpfile7(6:6), '(i1)') ch7
c  else if (ch1.eq.8) then
c      write(grpfile1(5:5), '(i1)') dumch
c      write(grpfile2(5:5), '(i1)') dumch

```

```

write(grpfile1(6:6),'(i1)') ch1
write(grpfile2(6:6),'(i1)') ch2
write(grpfile3(5:6),'(i2)') ch3
write(grpfile4(5:6),'(i2)') ch4
write(grpfile5(5:6),'(i2)') ch5
write(grpfile6(5:6),'(i2)') ch6
write(grpfile7(5:6),'(i2)') ch7
else
write(grpfile1(5:6),'(i2)') ch1
write(grpfile2(5:6),'(i2)') ch2
write(grpfile3(5:6),'(i2)') ch3
write(grpfile4(5:6),'(i2)') ch4
write(grpfile5(5:6),'(i2)') ch5
write(grpfile6(5:6),'(i2)') ch6
write(grpfile7(5:6),'(i2)') ch7
write(grpfile8(5:6),'(i2)') ch8
end if
legend1(1:6)=grpfile1(1:6)
legend2(1:6)=grpfile2(1:6)
legend3(1:6)=grpfile3(1:6)
legend4(1:6)=grpfile4(1:6)
legend5(1:6)=grpfile5(1:6)
legend6(1:6)=grpfile6(1:6)
legend7(1:6)=grpfile7(1:6)
legend8(1:6)=grpfile8(1:6)
legend1(7:10)='.lab'
legend2(7:10)='.lab'
legend3(7:10)='.lab'
legend4(7:10)='.lab'
legend5(7:10)='.lab'
legend6(7:10)='.lab'
legend7(7:10)='.lab'
legend8(7:10)='.lab'
grpfile1(7:10)='.grp'
grpfile2(7:10)='.grp'
grpfile3(7:10)='.grp'
grpfile4(7:10)='.grp'
grpfile5(7:10)='.grp'
grpfile6(7:10)='.grp'
grpfile7(7:10)='.grp'
grpfile8(7:10)='.grp'
c
c=====
c
c  fname(1:19)='/data1/dpm/bas/all/' ! directory containing time series
c  fname(20:31)=ifile
c  open(unit=inputun,file=ifile,status='old',err=1000)
c  rewind (unit=inputun)
c
c  n=0
c  do i=1,np
c    n=n+1
c    read(inputun,10,end=100) a(i),b(i),c(i),d(i),e(i),f(i)
c      * ,g(i),h(i)
C 10  format(6x,8(2x,e10.4))
10  format(6x,8(1x,e11.4))

```

```

end do
write(*,*) a(5),b(5),c(5),d(5),e(5),f(5),g(5),h(5)
100 max=0.
npks=0
nrange=0      ! initialize count variables
n=n-1
do i=1,nch
  if (i.eq.1) then
    open(unit=grpun,file=grpfile1,status='new',err=2000)
    rewind(unit=grpun)
    open(unit=legendun,file=legend1,status='new',err=2000)
    rewind(unit=legendun)
    call maxsrt(a,n,np,max)
    call peaks(a,n,np,npks,max)
    call raincut(a,acount,npks,np,nrange)
    call group(acount,grpun,legendun,legend1,nrange,max,np)
    close (unit=grpun)
    close (unit=legendun)
  else if (i.eq.2) then
    open(unit=grpun,file=grpfile2,status='new',err=2000)
    rewind(unit=grpun)
    open(unit=legendun,file=legend2,status='new',err=2000)
    rewind(unit=legendun)
    call maxsrt(b,n,np,max)
    call peaks(b,n,np,npks,max)
    call raincut(b,bcount,npks,np,nrange)
    call group(bcount,grpun,legendun,legend2,nrange,max,np)
    close (unit=grpun)
    close (unit=legendun)
  else if (i.eq.3) then
    open(unit=grpun,file=grpfile3,status='new',err=2000)
    rewind(unit=grpun)
    open(unit=legendun,file=legend3,status='new',err=2000)
    rewind(unit=legendun)
    call maxsrt(c,n,np,max)
    call peaks(c,n,np,npks,max)
    call raincut(c,ccount,npks,np,nrange)
    call group(ccount,grpun,legendun,legend3,nrange,max,np)
    close (unit=grpun)
    close (unit=legendun)
  else if (i.eq.4) then
    open(unit=grpun,file=grpfile4,status='new',err=2000)
    rewind(unit=grpun)
    open(unit=legendun,file=legend4,status='new',err=2000)
    rewind(unit=legendun)
    call maxsrt(d,n,np,max)
    call peaks(d,n,np,npks,max)
    call raincut(d,dcount,npks,np,nrange)
    call group(dcount,grpun,legendun,legend4,nrange,max,np)
    close (unit=grpun)
    close (unit=legendun)
  else if (i.eq.5) then
    open(unit=grpun,file=grpfile5,status='new',err=2000)
    rewind(unit=grpun)
    open(unit=legendun,file=legend5,status='new',err=2000)

```

```

        rewind(unit=legendun)
        call maxsrt(e,n,np,max)
        call peaks(e,n,np,npks,max)
        call raincut(e,ecount,npks,np,nrange)
        call group(ecount,grpun,legendun,legend5,nrange,max,np)
        close (unit=grpun)
        close (unit=legendun)
    else if (i.eq.6) then
        open(unit=grpun,file=grpfile6,status='new',err=2000)
        rewind(unit=grpun)
        open(unit=legendun,file=legend6,status='new',err=2000)
        rewind(unit=legendun)
        call maxsrt(f,n,np,max)
        call peaks(f,n,np,npks,max)
        call raincut(f,fcount,npks,np,nrange)
        call group(fcount,grpun,legendun,legend6,nrange,max,np)
        close (unit=grpun)
        close (unit=legendun)
    else if (i.eq.7) then
        open(unit=grpun,file=grpfile7,status='new',err=2000)
        rewind(unit=grpun)
        open(unit=legendun,file=legend7,status='new',err=2000)
        rewind(unit=legendun)
        call maxsrt(g,n,np,max)
        call peaks(g,n,np,npks,max)
        call raincut(g,gcount,npks,np,nrange)
        call group(gcount,grpun,legendun,legend7,nrange,max,np)
        close (unit=grpun)
        close (unit=legendun)
    else if (i.eq.8) then
        open(unit=grpun,file=grpfile8,status='new',err=2000)
        rewind(unit=grpun)
        open(unit=legendun,file=legend8,status='new',err=2000)
        rewind(unit=legendun)
        call maxsrt(h,n,np,max)
        call peaks(h,n,np,npks,max)
        call raincut(h,hcount,npks,np,nrange)
        call group(hcount,grpun,legendun,legend8,nrange,max,np)
        close (unit=grpun)
        close (unit=legendun)
    end if
    max=0.
    nrange=0
    npks=0
end do
stop
1000 write(6,1010)
1010 format('===Error opening data file===')
stop
c
1030 write(6,200)
200  format('Run rain with input file name',
+      ' on command line.')
stop
2000 write(6,201)
201  format('===Error opening graphics data files===',/,

```

```

+ '===Make sure old files are deleted===')
end
c
c=====c
subroutine maxsrt(a,n,np,max)
c
c Sorts raw time series to start with the |maximum| value. Returns
c the sorted time series in the original array.
c
integer i          ! counter
integer n          ! no. of points in time series
integer np         ! physical size of the array
integer nmax       ! address of |maximum value|
real a            ! time series
real b            ! reorganized series
real max          ! maximum or minimum value
real amax         ! maximum absolute value
dimension a(np)
dimension b(np)
c
amax=abs(a(1))
max=a(1)
nmax=1
do 12 i=2,n
  if (abs(a(i)).gt.amax) then
    amax=abs(a(i))
    max=a(i)      ! find address and |max|
    nmax=i
  end if
12 end do
c
do 13 i=1,n-nmax+1
  b(i)=a(nmax+i-1)      ! read last part of series into b
13 end do
c
do 14 i=1,nmax
  b(n-nmax+i+1)=a(i)    ! read first part of series into b
14 end do
c
do 15 i=1,n+1
  a(i)=b(i)  ! output into original array
15 end do
c
return
end
c
c=====c
subroutine peaks(a,n,np,npks,max)
c
c Subroutine called by rain.
c
c Sorts a raw time series into peaks and valleys and records the total
c number for further reference. The sorted series is returned in the
c original array.
c      VARIABLE DECLARATION
c

```

```

c   integer np      ! physical size of array containing time series
integer n          ! actual number of points in original series
integer npks       ! number of peaks and valleys after filtering
integer slope      ! 1=positive slope, -1=negative slope
integer i          ! counter
real filt          ! filtering value
real old           ! last peak or valley
real now           ! point being considered as a peak or valley
real next          ! current point for comparison to now
real max           ! max or min of the time series
real a,b
dimension a(np),b(np)

c
c   filt=.05*(abs(max))
filt=1.04169
i=1
old=a(i)           ! input the first value and write to file
b(i)=a(i)
npks=1             ! first peak or valley

c
10  i=i+1
    now=a(i)       ! input first point for consideration and
    if (now.eq.old) goto 10
    if (old.gt.now) then ! set slope
        slope=-1
    else
        slope=1
    endif

c
20  continue
    i=i+1
    if (i.gt.n+1) go to 1000 ! input next point and compare to
    next=a(i) ! reference point
    if (next.eq.now) go to 20
    if (next.lt.now) go to 30
    if (next.gt.now) go to 40

c
30  continue
    if (slope.eq.-1) then ! if the slope is the same as before,
        now=next ! set the current point to the
        go to 20 ! reference pt.
    endif

c
    if ((now-next).lt.filt) then ! if the step is too small, keep
        go to 20 ! reference pt. and get the next pt.
    end if

c
    npks=npks+1 ! the step is large enough so now
    b(npks)=now ! is a peak or valley
    old=now
    now=next
    slope=-1
    go to 20

c
40  continue
    if (slope.eq.1) then ! if the slope is the same as before,

```

```

        now=next          ! set the current point to the
        go to 20          ! reference point.
    endif
c
    if ((next-now).lt.filt) then ! if the step is too small, keep the
        go to 20          ! reference point and get the next pt.
    end if
c
    npks=npks+1           ! the step is large enough so now
    b(npks)=now           ! is a peak or valley.
    old=now
    now=next
    slope=1
    go to 20
c
1000 npks=npks+1
    b(npks)=next
c
    do j=1,npks
        a(j)=b(j)
    end do
    do j=npks+1,n+1
        a(j)=0.
    end do
    return                ! end of file reached
end
c
=====c
    subroutine raincut(a,acount,npks,np,nrange)
c
c    Rainflow counting subroutine. Fuchs and Stephens (1980)
c
    integer nrange ! total number of ranges after counting
    integer npks  ! total number of peaks and valleys
    real a,c
    real acount
    dimension c(10000)
    dimension acount(np,2)
    dimension a(np)
    real range
    real mean
c
    i=0
    j=0
    nrange=0
100 i=i+1
    j=j+1
c
    c(i)=a(j) ! read from file
c
300 if (i.lt.3) goto 100 ! if less than three points, read more
c
    if (abs(c(i)-c(i-1)).lt.abs(c(i-1)-c(i-2))) goto 100
c
c    if current cycle is greater than the previous, count the previous as one
c    cycle

```

```

c
  range=abs(c(i-1)-c(i-2)) ! calculate range and mean and ouput to file
  mean=(c(i-1)+c(i-2))/2
  nrange=nrange+1          ! update range counter
  acount(nrange,1)=range
  acount(nrange,2)=mean
c
  i=i-2
  c(i)=c(i+2)
  if (i.ne.1) goto 300
c
  1000 return
  end
c
c=====C
  subroutine group(acount,grpun,legendun,legend,nrange,max,np)
c
c  Groups the results from the count into the appropriate bins in the
c  histogram.
c  Bin size = .1*|Cp|max
c
  integer grpun,legendun
  integer nrange
  integer np
  character*10 legend
  real acount
  real max
  real zero,one,two
  real three,four,five
  real six,seven,eight
  real nine,ten
  real range,mean
  real scale
  dimension acount(np,2)
c
c  scale=abs(max)
c  scale=5.8
c  scale = 4.66
c
  zero=0.
  one=.1
  two=.2
  three=.3
  four=.4
  five=.5
  six=.6
  seven=.7
  eight=.8
  nine=.9
c
c set initial to zero
  n00=0
  n01=0
  n02=0
  n03=0
  n04=0

```

n05=0  
n06=0  
n07=0  
n08=0  
n09=0  
n10=0  
n11=0  
n12=0  
n13=0  
n14=0  
n15=0  
n16=0  
n17=0  
n18=0  
n19=0  
n20=0  
n21=0  
n22=0  
n23=0  
n24=0  
n25=0  
n26=0  
n27=0  
n28=0  
n29=0  
n30=0  
n31=0  
n32=0  
n33=0  
n34=0  
n35=0  
n36=0  
n37=0  
n38=0  
n39=0  
n40=0  
n41=0  
n42=0  
n43=0  
n44=0  
n45=0  
n46=0  
n47=0  
n48=0  
n49=0  
n50=0  
n51=0  
n52=0  
n53=0  
n54=0  
n55=0  
n56=0  
n57=0  
n58=0  
n59=0  
n60=0

```

n61=0
n62=0
n63=0
n64=0
n65=0
n66=0
n67=0
n68=0
n69=0
n70=0
n71=0
n72=0
n73=0
n74=0
n75=0
n76=0
n77=0
n78=0
n79=0
n80=0
n81=0
n82=0
n83=0
n84=0
n85=0
n86=0
n87=0
n88=0
n89=0
n90=0
n91=0
n92=0
n93=0
n94=0
n95=0
n96=0
n97=0
n98=0
n99=0

```

```

do i=1,nrange
  range=acount(i,1)
  mean=acount(i,2)
  range=abs(range)/scale
  mean=abs(mean)/scale
  if (range.gt.zero.and.range.lt.one) then
    if (mean.gt.zero.and.mean.lt.one) then
      n00=n00+1
    else if (mean.ge.one.and.mean.lt.two) then
      n01=n01+1
    else if (mean.ge.two.and.mean.lt.three) then
      n02=n02+1
    else if (mean.ge.three.and.mean.lt.four) then
      n03=n03+1
    else if (mean.ge.four.and.mean.lt.five) then
      n04=n04+1

```

```

else if (mean.ge.five.and.mean.lt.six) then
  n05=n05+1
else if (mean.ge.six.and.mean.lt.seven) then
  n06=n06+1
else if (mean.ge.seven.and.mean.lt.eight) then
  n07=n07+1
else if (mean.ge.eight.and.mean.lt.nine) then
  n08=n08+1
else
  n09=n09+1
end if
else if (range.ge.one.and.range.lt.two) then
  if (mean.gt.zero.and.mean.lt.one) then
    n10=n10+1
  else if (mean.ge.one.and.mean.lt.two) then
    n11=n11+1
  else if (mean.ge.two.and.mean.lt.three) then
    n12=n12+1
  else if (mean.ge.three.and.mean.lt.four) then
    n13=n13+1
  else if (mean.ge.four.and.mean.lt.five) then
    n14=n14+1
  else if (mean.ge.five.and.mean.lt.six) then
    n15=n15+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n16=n16+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n17=n17+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n18=n18+1
  else
    n19=n19+1
  end if
else if (range.ge.two.and.range.lt.three) then
  if (mean.gt.zero.and.mean.lt.one) then
    n20=n20+1
  else if (mean.ge.one.and.mean.lt.two) then
    n21=n21+1
  else if (mean.ge.two.and.mean.lt.three) then
    n22=n22+1
  else if (mean.ge.three.and.mean.lt.four) then
    n23=n23+1
  else if (mean.ge.four.and.mean.lt.five) then
    n24=n24+1
  else if (mean.ge.five.and.mean.lt.six) then
    n25=n25+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n26=n26+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n27=n27+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n28=n28+1
  else
    n29=n29+1
  end if
else if (range.ge.three.and.range.lt.four) then

```

```

if (mean.gt.zero.and.mean.lt.one) then
  n30=n30+1
else if (mean.ge.one.and.mean.lt.two) then
  n31=n31+1
else if (mean.ge.two.and.mean.lt.three) then
  n32=n32+1
else if (mean.ge.three.and.mean.lt.four) then
  n33=n33+1
else if (mean.ge.four.and.mean.lt.five) then
  n34=n34+1
else if (mean.ge.five.and.mean.lt.six) then
  n35=n35+1
else if (mean.ge.six.and.mean.lt.seven) then
  n36=n36+1
else if (mean.ge.seven.and.mean.lt.eight) then
  n37=n37+1
else if (mean.ge.eight.and.mean.lt.nine) then
  n38=n38+1
else
  n39=n39+1
end if
else if (range.ge.four.and.range.lt.five) then
  if (mean.gt.zero.and.mean.lt.one) then
    n40=n40+1
  else if (mean.ge.one.and.mean.lt.two) then
    n41=n41+1
  else if (mean.ge.two.and.mean.lt.three) then
    n42=n42+1
  else if (mean.ge.three.and.mean.lt.four) then
    n43=n43+1
  else if (mean.ge.four.and.mean.lt.five) then
    n44=n44+1
  else if (mean.ge.five.and.mean.lt.six) then
    n45=n45+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n46=n46+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n47=n47+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n48=n48+1
  else
    n49=n49+1
  end if
else if (range.ge.five.and.range.lt.six) then
  if (mean.gt.zero.and.mean.lt.one) then
    n50=n50+1
  else if (mean.ge.one.and.mean.lt.two) then
    n51=n51+1
  else if (mean.ge.two.and.mean.lt.three) then
    n52=n52+1
  else if (mean.ge.three.and.mean.lt.four) then
    n53=n53+1
  else if (mean.ge.four.and.mean.lt.five) then
    n54=n54+1
  else if (mean.ge.five.and.mean.lt.six) then
    n55=n55+1

```

```

else if (mean.ge.six.and.mean.lt.seven) then
  n56=n56+1
else if (mean.ge.seven.and.mean.lt.eight) then
  n57=n57+1
else if (mean.ge.eight.and.mean.lt.nine) then
  n58=n58+1
else
  n59=n59+1
end if
else if (range.ge.six.and.range.lt.seven) then
  if (mean.gt.zero.and.mean.lt.one) then
    n60=n60+1
  else if (mean.ge.one.and.mean.lt.two) then
    n61=n61+1
  else if (mean.ge.two.and.mean.lt.three) then
    n62=n62+1
  else if (mean.ge.three.and.mean.lt.four) then
    n63=n63+1
  else if (mean.ge.four.and.mean.lt.five) then
    n64=n64+1
  else if (mean.ge.five.and.mean.lt.six) then
    n65=n65+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n66=n66+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n67=n67+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n68=n68+1
  else
    n69=n69+1
  end if
else if (range.ge.seven.and.range.lt.eight) then
  if (mean.gt.zero.and.mean.lt.one) then
    n70=n70+1
  else if (mean.ge.one.and.mean.lt.two) then
    n71=n71+1
  else if (mean.ge.two.and.mean.lt.three) then
    n72=n72+1
  else if (mean.ge.three.and.mean.lt.four) then
    n73=n73+1
  else if (mean.ge.four.and.mean.lt.five) then
    n74=n74+1
  else if (mean.ge.five.and.mean.lt.six) then
    n75=n75+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n76=n76+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n77=n77+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n78=n78+1
  else
    n79=n79+1
  end if
else if (range.ge.eight.and.range.lt.nine) then
  if (mean.gt.zero.and.mean.lt.one) then
    n80=n80+1

```

```

else if (mean.ge.one.and.mean.lt.two) then
  n81=n81+1
else if (mean.ge.two.and.mean.lt.three) then
  n82=n82+1
else if (mean.ge.three.and.mean.lt.four) then
  n83=n83+1
else if (mean.ge.four.and.mean.lt.five) then
  n84=n84+1
else if (mean.ge.five.and.mean.lt.six) then
  n85=n85+1
else if (mean.ge.six.and.mean.lt.seven) then
  n86=n86+1
else if (mean.ge.seven.and.mean.lt.eight) then
  n87=n87+1
else if (mean.ge.eight.and.mean.lt.nine) then
  n88=n88+1
else
  n89=n89+1
end if
else
  if (mean.gt.zero.and.mean.lt.one) then
    n90=n90+1
  else if (mean.ge.one.and.mean.lt.two) then
    n91=n91+1
  else if (mean.ge.two.and.mean.lt.three) then
    n92=n92+1
  else if (mean.ge.three.and.mean.lt.four) then
    n93=n93+1
  else if (mean.ge.four.and.mean.lt.five) then
    n94=n94+1
  else if (mean.ge.five.and.mean.lt.six) then
    n95=n95+1
  else if (mean.ge.six.and.mean.lt.seven) then
    n96=n96+1
  else if (mean.ge.seven.and.mean.lt.eight) then
    n97=n97+1
  else if (mean.ge.eight.and.mean.lt.nine) then
    n98=n98+1
  else
    n99=n99+1
  end if
end if
end do
one=.05
two=.15
three=.25
four=.35
five=.45
six=.55
seven=.65
eight=.75
nine=.85
ten=.95
write(grpun,") " mean .0-.1 .1-.2 .2-.3 .3-.4 .4-.5 .5-.6 .6-.7 .7..
&-.8 .8-.9 .9-1."
write(grpun,200) " .9-1.",n90,n91,n92,n93,n94,n95,n96,n97,n98,n99

```

```

write(grpun,200) " .8-.9",n80,n81,n82,n83,n84,n85,n86,n87,n88,n89
write(grpun,200) " .7-.8",n70,n71,n72,n73,n74,n75,n76,n77,n78,n79
write(grpun,200) " .6-.7",n60,n61,n62,n63,n64,n65,n66,n67,n68,n69
write(grpun,200) " .5-.6",n50,n51,n52,n53,n54,n55,n56,n57,n58,n59
write(grpun,200) " .4-.5",n40,n41,n42,n43,n44,n45,n46,n47,n48,n49
write(grpun,200) " .3-.4",n30,n31,n32,n33,n34,n35,n36,n37,n38,n39
write(grpun,200) " .2-.3",n20,n21,n22,n22,n24,n25,n26,n27,n28,n29
write(grpun,200) " .1-.2",n10,n11,n12,n13,n14,n15,n16,n17,n18,n19
write(grpun,200) " .0-.1",n00,n01,n02,n03,n04,n05,n06,n07,n08,n09
C    write(grpun,200) ten,ten,n99
200  format(A,10(2x,i4))
      write(legendun,201) legend,nrange,max
C 201  format('0.05 0.95 8 90.0 0 11',3x,a6,3x,i4,3x,f5.2)
201  format(a6,3x,i4,3x,f5.2)
1000 return
      end
C=====C

```

## Appendix C: FORTRAN Programs for Computing the Eight Pressure Zones

The following is the two FORTRAN programs used to compute the eight pressure zones for the development of dynamic load cycles for AARS. The 1<sup>st</sup> FORTRAN program helps for combining the RFC 10 by 10 matrixes data output prior to data sorting. The out put from the 1<sup>st</sup> FORTRAN program is used as an input for the 2<sup>nd</sup> FORTRAN program to compute the eight pressure zones. The two FORTRAN programs are outlined below.

### 1<sup>st</sup> FORTRAN Program: Combining

```

!*****!
! PROGRAM: FormatFile
!
! PURPOSE: Entry point for the console application.
!
!*****!
      program CombineFile

      implicit none

      ! Variables
      character*120 ifile, ifilestart      ! filename
      character*120 outfile
      character*100 ifilenum
      character*512 linestring

      integer inputun /7/      ! input file unit number
      integer grpun  /8/      ! graphics file unit number
      integer legendun /9/      ! plot legend unit number
      integer np /30000/      ! number of samples in the time series
      integer npks      ! number of peaks (after filtering)
      integer nrange      ! total number of ranges in the series
      real max      ! [maximum] value in the time series
      integer*2 nch /7/      ! number of channels in file (8 max.)
C   integer*2 st_len,l1
      integer*2 len,l1
      integer*2 ch1,ch2,ch3,ch4,ch5,ch6,ch7,dumch
      character*10 grpfile1,grpfile2,grpfile3,grpfile8 ! filenames
      character*10 grpfile4,grpfile5,grpfile6,grpfile7
      character*10 legend1,legend2,legend3,legend4,legend5
      character*10 legend6,legend7,legend8
      real a,b,c,d,e,f,g,h,hh
      real acount,bcount,ccount,dcount,ecount,fcount,gcount,hcount

C
C   arrays containing time series and count results
C

```

```

dimension a(30000),b(30000),c(30000),d(30000)
dimension e(30000),f(30000),g(30000),h(30000),hh(30000)
dimension acount(30000,2),bcount(30000,2),ccount(30000,2)
dimension dcount(30000,2),ecount(30000,2),fcount(30000,2)
dimension gcount(30000,2),hcount(30000,2)
character*31 fname
integer i, n,j

c
c=====c
c          MAIN PROGRAM
c
c          n=0

c          ! Body of FormatFile

c          WRITE(*,('Starting characters of input file: ",$'))
c          read(*, '(a12)') ifilestart

c          WRITE(*,('Output File Name: ",$'))
c          read(*, '(a12)') outfile
c          open(8,file=outfile,status='REPLACE',err=1000)
c          WRITE(full_name_of_input_file,*)dir_input_file,"\",name_of_input_file

c          do i=1,15
c              write(ifilenum,*)i
c              ifilenum=ADJUSTL(ifilenum)
c              WRITE(ifile,*)trim(ifilestart),trim(ifilenum),".grp"

c              open(1,file=ifile,status='old',err=1000)
c              do j=1,11
c                  read(1,'(A)',end=100)linestring
c                  write(8,'(A)')trim(linestring)
c              end do
c              close(1)
c              if(i.eq.15) then
c                  open(1,file=ifile,status='old',err=1000)
c                  do j=1,11
c                      read(1,'(A)',end=100)linestring
c                      write(8,'(A)')trim(linestring)
c                  end do
c                  close(1)
c              end if
c          end do

c          100          max=0.

c          open(unit=inputun,file="G1S20107.TSF",status='old',err=1000)c
c          rewind (unit=inputunc)
c          open(unit=8,file="test.dat",status='new',err=1000)
c
c          do i=1,np
c              n=n+1
c              read(inputun,*,end=100) a(i),b(i),c(i),d(i),e(i),f(i)
c              *      ,g(i),h(i)

```

```

c      write(8,20) a(i),b(i),c(i),d(i),e(i),f(i)
c      *      ,g(i),h(i)
c
c      read(inputun,10,end=100) a(i),b(i),c(i),d(i),e(i),f(i)
c      *      ,g(i),h(i)
C 10    format(6x,8(2x,e10.4))
c 10    format(f6.3,7(1x,e11.4))
c 20    format(f6.3,7(1x,d11.4))
c
c      end do
c
1000    max=1
        close(8)
        end program CombineFile

```

## 2<sup>nd</sup> FORTRAN Program: Sorting and Computing

```

        program sorting_1

c      read in the cycle numbers from .grp file for the corner region (tap 1,
c      2, 3, 4, 8, 9, 11, 15, 16, 17, 18, 22, 23, 24 and 25. Find the maximum
c      number for each mean and range.
c      n12, n:number of cycles; 1:mean; 2:range.
c      the load sequence can be divided into 8 sections
c 1      0 - 0.25: n11,n12,n13,n21
c 2      0 - 0.50: n14,n15,n16,n17,n18,n22,n23,n24,n25,n26,n31,n32,n33,n34,n42
c 3      0 - 0.75: n19,n27,n28,n29,n35,n36,n37,n38,n39,n43,n44,n45,n46,n47,n54,
c              n55
c 4      0 - 1.00: n48,n49,n56,n57,n58,n59,n65,n66,n67,n68,n69,n78,n79
c 5      0.25 - 0.50: n41,n51
c 6      0.25 - 0.75: n52,n53,n61,n62,n63
c 7      0.25 - 1.00: n54,n64,n73,n74,n75,n76,n77,n85,n86,n87,n88,n89,n97,n98,
c              n99
c 8      0.50 - 1.00: n71,n72,n81,n82,n83,n84,n91,n92,n93,n94,n95,n96
        character*120 outfile, outfile2

        dimension n(10, 10, 16)
c              | | |
c              mean range tap

        dimension max_num(10,10), n_load(8)

        WRITE(*,('Start of File Name: ',*))
        read(*,'(a12)') outfile
        write(outfile2,*)trim(outfile),'.tap'

        open(10, file=outfile2)
        do 10 i=1,10
        do 10 j=1,10
            max_num(i,j) = 0
        do 10 k=1,16
            n(i,j,k)=0

```

```

10      continue

      do 20 k=1,16
      read(10,*)
      do 20 i=10,1, -1
c       write(*,*) 'j=', j, 'k=', k
      read(10,100) (n(i,j,k),j=1,10)
c       write(*,*) 'nijk=', (n(i,j,k),i=1,10)
100     format(6x,10(2x,i4))
20      continue
c       write(*,*) (n(i,1,1),i=1,10)

      do 30 i=1,10
      do 30 j=1,10

      do 30 k=1,16

c       i,j of max_num exchanged to get N_mean_range instead of N_range_mean
      if(abs(n(i,j,k)).ge.max_num(j,i)) then
         max_num(j,i) = abs(n(i,j,k))
      endif
30      continue
      do 35 i=1,10
      write(*,'(10i5)') (max_num(i,j),j=1,10)
35      continue
      sum=0.
      sum_load=0.
c       do 11 i=1,10
c       do 11 j=1,10
c       sum = sum +max_num(i,j)
c11      continue
c       write(*,*) 'sum=', sum

      n_load(1) = max_num(1,1)+max_num(1,2)+max_num(1,3)+max_num(2,1)

      n_load(2)=max_num(1,4)+max_num(1,5)+max_num(1,6)+max_num(1,7)+
&   max_num(1,8)+max_num(2,2)+max_num(2,3)+max_num(2,4)+
&   max_num(2,5)+max_num(2,6)+max_num(3,1)+max_num(3,2)+max_num(3,3)+
&   max_num(3,4)+max_num(4,2)

      n_load(3)=max_num(1,9)+max_num(2,7)+max_num(2,8)+max_num(2,9)+
&   max_num(3,5)+max_num(3,6)+max_num(3,7)+max_num(3,8)+
&   max_num(3,9)+max_num(4,3)+max_num(4,4)+max_num(4,5)+
&   max_num(4,6)+max_num(4,7)+max_num(5,5)+max_num(1,10)+
&   max_num(2,10)

      n_load(4)=max_num(4,8)+max_num(4,9)+max_num(5,6)+max_num(5,7)+
&   max_num(5,8)+max_num(5,9)+max_num(6,5)+max_num(6,6)+
&   max_num(6,7)+max_num(6,8)+max_num(6,9)+max_num(7,8)+max_num(7,9)
&   +max_num(3,10)+max_num(4,10)+max_num(5,10)+max_num(6,10)
&   +max_num(7,10)+max_num(8,10)

      n_load(5)=max_num(4,1)+max_num(5,1)

      n_load(6)=max_num(5,2)+max_num(5,3)+max_num(6,1)+max_num(6,2)+

```

```

& max_num(6,3)
  n_load(7)=max_num(5,4)+max_num(6,4)+max_num(7,3)+max_num(7,4)+
& max_num(7,5)+max_num(7,6)+max_num(7,7)+max_num(8,5)+
& max_num(8,6)+max_num(8,7)+max_num(8,8)+max_num(8,9)+max_num(9,7)+
& max_num(9,8)+max_num(9,9)+max_num(9,10)+max_num(10,9)
& +max_num(10,10)

  n_load(8)=max_num(7,1)+max_num(7,2)+max_num(8,1)+max_num(8,2)+
& max_num(8,3)+max_num(8,4)+max_num(9,1)+max_num(9,2)+
& max_num(9,3)+max_num(9,4)+max_num(9,5)+max_num(9,6)
& +max_num(10,1)+max_num(10,2)+max_num(10,3)+max_num(10,4)
& +max_num(10,5)+max_num(10,6)+max_num(10,7)+max_num(10,8)

  write(*,*) n_load
c    do 12 i=1,8
c      sum_load=sum_load+n_load(i)
c12   continue
c     write(*,*) 'sum_load=',sum_load
      open(11,file='load_seq.dat')
      write(11,*) 'max_num(10,10)='
      do 14 i=1,10
14    write(11, '(10i5)') (max_num(i,j),j=1,10)
      write(11,*) 'load sequence for the ',trim(outfile),' region,'
      write(11,*) '0.00-0.25 ', n_load(1)
      write(11,*) '0.00-0.50 ', n_load(2)
      write(11,*) '0.00-0.75 ', n_load(3)
      write(11,*) '0.00-1.00 ', n_load(4)
      write(11,*) '0.25-0.50 ', n_load(5)
      write(11,*) '0.25-0.75 ', n_load(6)
      write(11,*) '0.25-1.00 ', n_load(7)
      write(11,*) '0.50-1.00 ', n_load(8)
      stop
      end

```

## **Appendix D: Test Setup, Failure Criteria, Failure Mode Investigation and the Proposed Full Scale Dynamic Testing Procedure for AARS Wind Uplift Resistance Performance Evaluation**

### **D.1 Test Setup**

#### Mock-up Handlings

This section explains mock-up handling information prior to its testing. Once the mock-ups were ready for the testing, they were transported from the conditioning area to the DRF and were then installed into the testing table. The conditioning area means the area in which the testing mock-ups were kept after mock-up fabrication to allow adhesives to cure at room temperature with a specific time period. Information for the mock-up curing time will be further discussed in Chapter 6. A forklift was used to transport the testing mock-up from the conditioning area to the DRF. Placement of the mock-ups into the testing table was aided by a crane and a small portable hydraulic jack as shown in Figure. A four-by-eight plywood of one inch thickness was placed on top of the portable hydraulic jack to create wider surface so that the mock-up can temporarily be placed at rest prior to the final adjustment on the testing table. In addition, dummies were fabricated on both sides of the table. The dummy size was 1.98 m x 1.52 m (6.5 ft x 5 ft). It is a half size of the testing mock-up in terms of both length and width. The dummy sections consisted of a wood frame, plywood sheeting and membranes (Figure E1). Pressure taps were installed on both dummies at the locations close to the edge of the testing table to measure the surface pressure during testing. The top surface of the active mock-up model is marked and divided into ninth equal segments to help the testing operator for identifying the failure criteria (Figure E2). Figure E3 shows typical condition of the testing mock-up prior to testing.

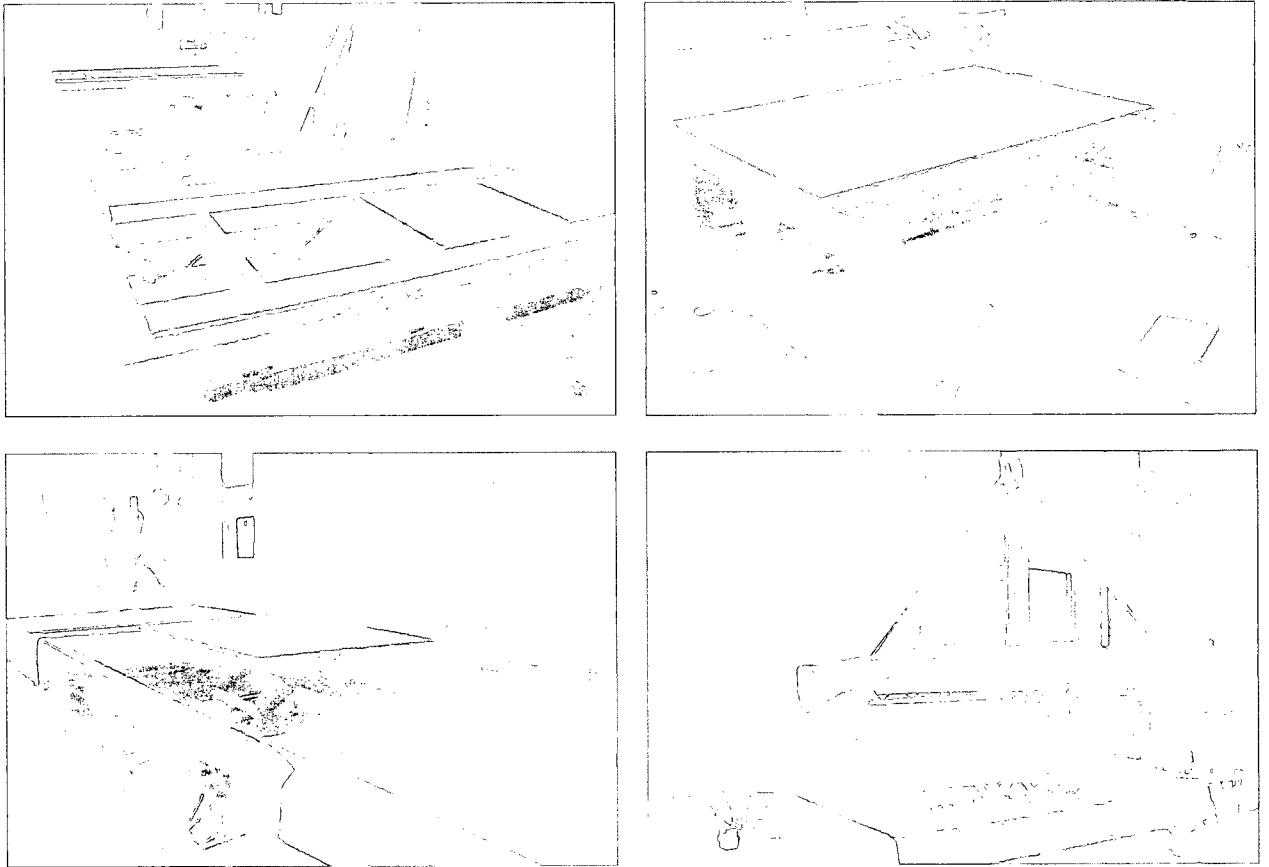


Figure D1. Mock-up Handling

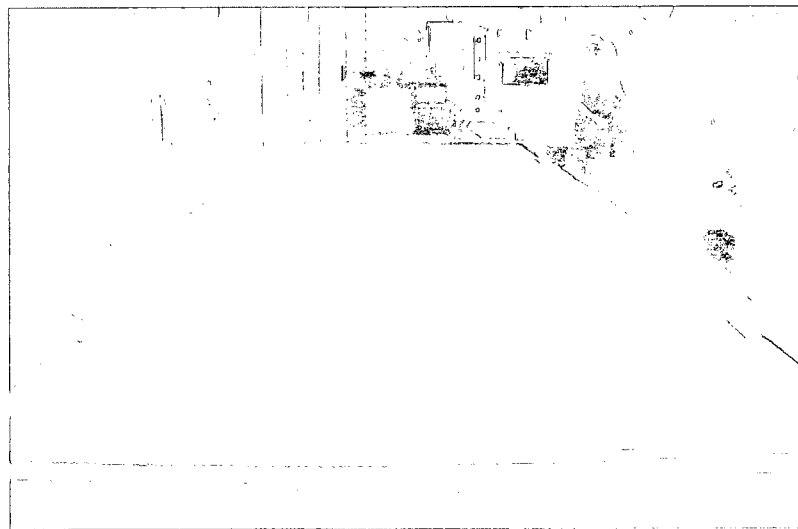


Figure D2 Testing Mock-up after being divided into Nine Equal Sections



**Figure D3 Mock-up Layout on the DRF Table Prior to Testing**

#### Mock-up Edge Treatments

In parallel to the above mentioned mock-up handling, edge treatment was carried out on mock-ups prior to testing. The edge treatments were performed to reduce air leakage during testing. This treatment is necessary unless otherwise if too much air leakages exist during testing, the pressure cannot develop inside the chamber hence the test cannot be completed. The edge treatment was performed as shown in Figure D4. The diagram on the bottom left side of Figure D4 shows the edge treatment between the dummy section and the testing mock-up, while the edge treatment between the testing mock-up and the testing table is illustrated in a diagram located on bottom right side of Figure D4. The edge treatment between the testing mock-up and the testing table was performed by ensuring the six inch overhangs on the vapour barrier, the base sheet membrane and the cap sheet membrane extended over the testing table frame. Similar concept was also applied for the edge treatment between the testing mock-up and the dummy section, however to have similar level high between the dummy section and the testing mock-up, wood planks and ply wood were used. The two wood planks were attached to the steel joists and then the plywood was screwed to the wood planks to level the dummy section up to the testing mock-up (Figure D4).



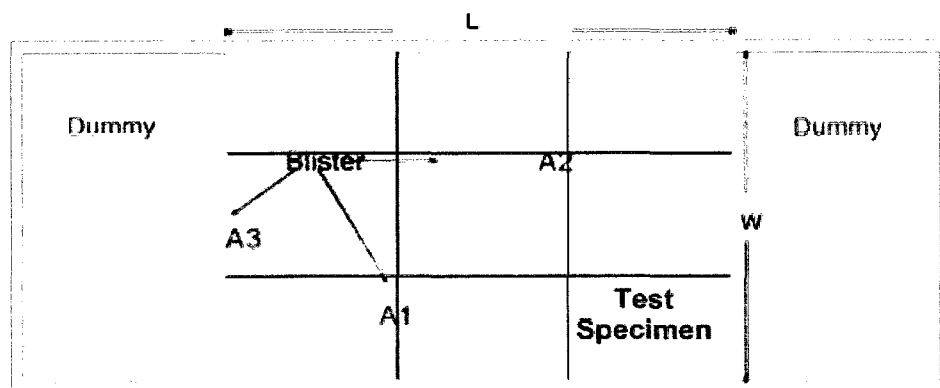
**Figure D4. Mock-up Edges Treatment- Photo and Diagram**

## **D2. Determination of Failure Criteria**

The determination of failure for AARS mock-ups was a challenge because of the fact that the failure is mostly a progressing process and did not follow a certain pattern or did not happen at a discrete location. Hence it is difficult to draw a clear line when should be defined as a failure. In order to maintain a consistency of the failure determination, a failure criterion was developed and used in this study. The failure criterion was determined based on the observation of the testing operator by estimating the percentage of the blistering area to the total mock-up surface area. Figure D5 describes how the failure criterion of the AARS was determined. As mentioned previously, nine equal segments were created on the mock-up surface, before testing, by using coloured markers to better estimate the percentage of the blistered areas, so that later, if the total blistering was observed to be equal to about the size of one segment, it was measured about 10 % of the total surface area ( $A$ ). For example, let us consider that three blisters occur and their areas are labelled as  $A_1$ ,  $A_2$ , and  $A_3$ . The summation of the blistering area is then  $(A_1+A_2+A_3)$ . When the ratio of  $(A_1+A_2+A_3)$  to  $A$  equals to or exceeds 10 %, then the corresponding pressure level is classified as “sustained wind uplift rating.” The sustained pressure is recorded and the test is continued. The system is considered that it reached a failure and the test is stopped when  $(A_1+A_2+A_3)$  over  $A$  exceeds 20 %. It is noted that the number of blister occurrences on a mock-up did not affect the failure criteria; rather, the summation of the blistered area was critical. This means that the number of blisters can vary among the mock-ups. However, to increase the accuracy for predicting the percentage of blister that mainly depends on the testing operator observations, the size of equal segments was later determined as to it should be less than 2% of  $A$ . In lieu of the above mentioned failure criterion, the test would also be stopped when either one or a combination of the following conditions were observed during testing:

- Test specimen (mock-up) sustains or exceeds the desired test pressure target as dictated by the client.
- One component of the test specimen (mock-up) becomes detached from the other.

- Test specimen (mock-up) exhibits air intrusion, such as delamination or detachment, observed on the surface layer equal to or more than 20% of the specimen's total surface area.
- Test specimen (mock-up) exhibits seam failures, openings or ruptures such that pressure is no longer sustainable
- Any deck failures.



L = Test specimen length

W = Test specimen width

A = Total test specimen surface area

A1, A2, A3 and etc = Area of delamination or detachment identified on the specimen.

Failure Criteria Determination:

$$A = W \times L$$

Sustained if

$$\Sigma A1 + A2 + A3 + \dots \leq 10 \% \text{ of } A$$

$$A = W \times L$$

Failed if

$$\Sigma A1 + A2 + A3 + \dots \geq 20 \% \text{ of } A$$

Note:

To visually quantify the area of delamination or detachment, the top surface area of the specimen should be marked with the grids of equal area.

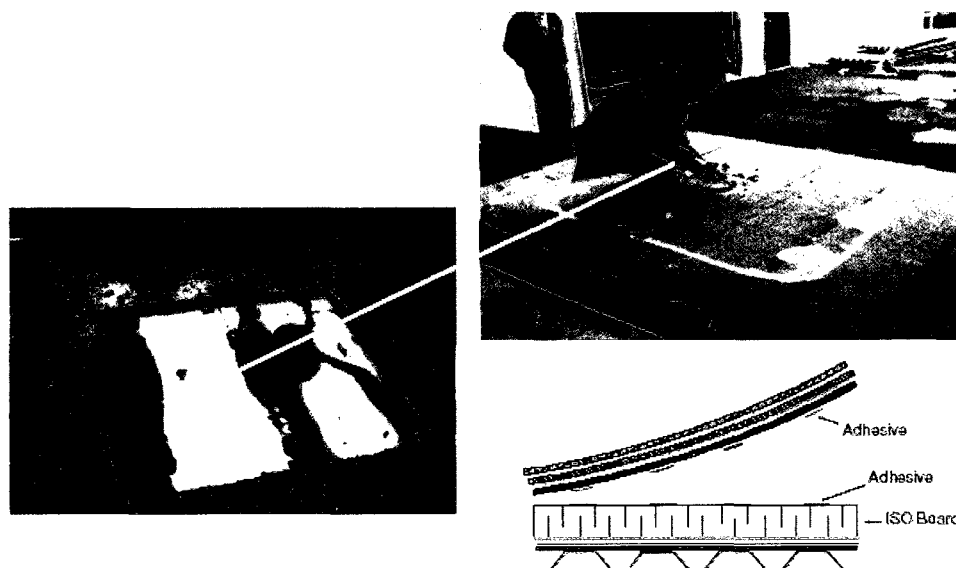
Area of each grid should be less than 2% of A.

**Figure D5. Failure Criteria Used During Testing**

### D3. Failure Mode Investigation and Classifications

#### Failure Mode Investigation

Once testing mock-ups reached the failure state, the test was stopped and the testing chamber was opened. Then top-surface of the testing mock-ups was marked by using a colour marker for the failure mode investigation. The test cuts were made at the observed failure location to identify the weakest link of the tested mock-up. Figure D6 depicts an example of typical failure mode investigation after the test. For the particular case shown in Figure D6, the failure mode was determined as an adhesive failure between the cover board and the insulation. The diagram at the right bottom of Figure D6 shows the complete cross-section view of the testing mock-up components as well as the failure mode. In addition, a deeper cut up to the steel deck was some time also made to verify the integration of other roof components. If other failure is also found, it was mentioned as failure mode # 2. Note that by doing so, it does not mean that failure # 1 had taken place before failure #2. In other words, it only shows that the sequence of the failure investigation. Hence, the second failure should be also recoded and presented in the test report. Similar procedure would also be followed if there are more failures such as # 3 and # 4.



**Figure D6.** Typical Failure Investigation

#### **D4. Standard Test Method for the Dynamic Wind Uplift Resistance of Adhesive Applied Roofing Systems (AARS)**

One of the main objectives of this dissertation is to draft a laboratory testing procedure for AARS. The CSA 123.21-04 standard has been modified to include a laboratory test method for the wind uplift resistance evaluation of AARS. The modification draft of the CSA 123.21-04 standard test method is presented in this section. Wind tunnel data analysis and experimental results obtained in this thesis as well as input received from participating industrial partners formed the basis for this standard development. The draft is written following the format requirement of the CSA standards. The format includes the scope, reference publication, definitions, significant of test, test precautions, test apparatus, test specimen and preparation, dynamic load sequences and test report preparation. The draft's has also been submitted to Canadian standard development organization for further reviews and undergoes consensus process. Upon completion, this standard method will serve as a regulatory guide for Canadian roofing community to evaluate the wind uplift resistance performance of AARS.

##### *Scope*

###### **7.1.1**

This test method determines the wind uplift resistance of:

- Method 1: Mechanically attached membrane-roofing systems
- Method 2: Adhesive applied membrane-roofing systems

when subjected to dynamic wind load cycles. The roofing system consists of a deck and roofing membrane. It should include components such as air/vapour barriers or retarders, insulation, cover board, etc. It is subjected to a dynamic load sequence that has been developed based on wind pressure records, simulating the effects of wind on membrane roof assemblies.

###### **7.1.2**

Method 1: Testing under this test method is limited to mechanically attached, reinforced membrane systems having a fastener row separation not greater than 2896 mm (114 in) and fastener in-line spacing not greater than 610 mm (24 in).

Method 2: Testing in accordance with this test method shall be limited to roof components bonded in place using cold adhesives, without the use of mechanical fasteners or ballast as a means of resisting wind uplift.

### 7.1.3

The values given in SI (metric) units are the standard. The values given in parentheses are for information only.

### 7.1.4

In CSA Standards, “shall” is used to express a requirement, i.e., a provision that the user is obliged to satisfy in order to comply with the standard; “should” is used to express a recommendation or that which is advised but not required; and “may” is used to express an option or that which is permissible within the limits of the standards. Notes accompanying Sections do not include requirements or alternative requirements; the purpose of a note accompanying a Section is to separate from the text explanatory or informative materials. Notes to tables and figures are considered part of the table or figure and may be written as requirements. Legends to equations and figures are considered requirements.

### *Reference Publication*

This Standard refers to the following publication. Where such reference is made it shall be to the edition listed below.

ANSI (American National Standards Institute)/SPRI  
ANSI/SPRI FX-1-2001

Standard Field Test Procedure for Determining the Withdrawal Resistance of  
Roofing Fasteners

ASTM (American Society for Testing and Materials)

D 1621-00  
Standard Test Method for Compressive Properties of Rigid Cellular Plastics

E 631-93a (1998)  
Standard Terminology of Building Construction

### *Definitions*

*Note: For definitions of general terms relating to building construction used in this standard, see ASTM E 631.*

The following definitions apply in this Standard:

Base pressure — calculated as a percentage of the test pressure, as described in Section 8.2.

Gust cycle — time duration for each wind gust, as described in Clause 8.3.

Loading sequence — a set of load fluctuation (wind gusts) with specified load-amplitude pressure levels, as described in Clause 7.8.2.

Mechanically attached membrane-roofing systems — systems in which the membrane is intermittently attached to the deck, as described in Clause 7.7.3.

Adhesive applied membrane-roofing systems — systems in which the components are bonded using cold adhesives, as described in Clause 7.7.3.

Specimen — the entire assembled unit subjected to testing, as described in Clause 7.7

Test pressure — the applied pressure used to test the roof assembly, as described in Clause 7.8.1.

### *Significant of Test*

#### 7.4.1

The wind-induced forces on a roof and the responses of the roof system are time- and space-dependent, and thus are dynamic in nature. Design wind pressure varies with building location, height, roof slope, and other parameters. Using the local building code or wind standard or internet ([www.sigders.ca](http://www.sigders.ca)) based tool Wind-RCI, one can calculate the design pressure for roof assemblies.

#### 7.4.2

Wind-induced loads on the membrane reach the structural supporting system through two load paths, the pneumatic load path and the structural load path, as described below:

Method 1: In the structural load path, the pressure fluctuations are slower than the membrane response time, and the loads are transmitted directly through the attachments, such as fasteners.

Method 2: In the pneumatic load path, the wind pressure fluctuations are faster than the membrane response time. Thus, the load is shared among the layers (membrane, cover board, insulation, and deck) by the difference in pressure across them.

To simulate the wind-induced effects on a roof, a time-dependent (dynamic) load sequence is imposed on the roof system. The procedure applied for the development of the dynamic load cycle is summarized in Annex D-A.

### *Test Precaution*

#### 7.5.1

This test procedure does not purport to address all the safety concerns associated with its use. It is the responsibility of the user of this test procedure to establish appropriate safety and health practices and to determine the applicability of requirements prior to use.

#### 7.5.2

During the test, all testing agency representative and observers adjacent to the test chamber shall wear all necessary safety clothing and equipment.

#### 7.5.3

Any relevant material safety data sheet (MSDS) shall be kept in place during the period of installation and testing.

### *Test Apparatus*

#### 7.6.1

The apparatus shall be shown in Figure E8. The test apparatus shall consist of a pressure chamber. Its interior dimensions shall be  $6100 \pm 50$  mm ( $240 \pm 2$  in) long and  $2200 \pm 50$  mm ( $87 \pm 2$  in) wide. The structural stiffness of the test apparatus shall withstand a minimum of 20-kPa (400 psf) suction pressure. The test apparatus shall consist of a movable top chamber  $800 \pm 50$  mm ( $31 \pm 2$  in) high, mounted on a height-adjustable bottom frame that is fixed to the floor and on which the test specimen shall be installed. The height of the bottom frame shall be adjustable to accommodate roof assemblies with a different thickness. The roof deck shall be installed on structural purlins with spacing based on the structural span requirements. The roofing specimen is installed between the top chamber and the bottom frame. Air leakage shall be minimized to facilitate the control of test pressure that is applied over the assembly.

#### 7.6.2

The top chamber shall incorporate a minimum of six viewing windows of size  $1860 \text{ mm}^2$  ( $288 \text{ in}^2$ .) and a gust simulator. The gust simulator shall consist of a flap valve connected to a stepping motor through a timing belt arrangement. The top chamber shall be connected to a suction box having fans capable of producing a minimum suction of 10 kPa (200 psf) over the roof assembly.

#### 7.6.3

Method 1: The membrane shall be applied so as to have at least two full membrane widths in the test chamber, resulting in a minimum of three seams.

Method 2: Length of the test specimen should be minimum 10' (3040 mm) while accommodating a minimum of 2 structural spans. The width of the specimen should have a minimum of 2 component joints. Primary insulation layer is limited to a maximum size of 4' x 4' (1220mm x 1220mm).

#### 7.6.4

A pressure-measuring apparatus, capable of measuring the test pressure differential within a tolerance of 0.05 % full-scale pressure or  $\pm 10$  Pa ( $\pm 0.2$  psf), whichever is smaller, shall be used. A pressure sensor shall be installed at each of the following three locations:

- (a) on the inside of the chamber, to indicate the reference pressure;
- (b) on the top of the membrane, to measure the simulated pressure; and
- (c) on the top of the insulation, to measure the pressure below the membrane, (only for Method 1).

#### 7.6.5

A force-measuring apparatus capable of measuring the induced forces within a tolerance of 0.05 % of full-scale load or  $\pm 20$  N ( $\pm 4.5$  lbf), whichever is smaller, shall be used. A minimum of one sensor shall be installed at the middle fastener row to measure the induced forces (only for Method 1).

### *Test Specimen and Installation*

#### 7.7.1 Installation

The different components of the roofing system shall be installed and cured according to the manufacture, proponent, or client. When insulated roof systems are tested, the top surface of the insulation boards shall be flush with the top edges of the bottom frame.

#### 7.7.2 Application of Components

Method 1: Depending on the fastener row spacing and fastener spacing of the roofing membrane, the testing table width can require the application of correction factors. Correction factor values and applications are shown in Figure D10.

Method 2: The components shall be applied in such a way as to have at least two joints in the test chamber, resulting in a minimum of three individual segments. Where membrane application dictates a multi-ply membrane, the joints shall be staggered from each layer in accordance with the manufacturer's instructions.

#### 7.7.3 Component Attachment

Method 1 - Mechanically attached membrane-roofing systems: Attachment devices shall include mechanical fasteners and/or plates and mechanical fasteners and/or bars. After attachment, the roof surface shall be impermeable to water. Membrane types shall include, but shall not be limited to, those made from single- or multi-ply bituminous or non-bituminous materials (Appendix D-B1).

Method 2- Adhesive applied membrane-roofing systems: Cold adhesive shall be used to bond all layers of the roof assembly. After bonded, the roof surface shall be impermeable to water. Membrane layers shall include single or multiply modified bituminous membranes (Appendix D-B2).

#### 7.7.4 Seams

Seams shall have an overlap as specified by the manufacture, proponent, or client.

#### 7.7.5 Preparation

The removable top frame shall be placed over the installed specimen, ensuring that the top frame is tightly fixed to the bottom frame during the test. Gaskets or C-clamps may be used to reduce air leakage.

Method 1: Slippage of the membrane during the test shall be limited to a total of 12 mm (0.5 in) in any one direction.

Method 2: Delaminations along the edges of the test specimen shall be prevented.

#### 7.7.6 Conditioning Time

After installation, the membrane system shall be allowed to cure at ambient temperature ( $23 \pm 5^{\circ}\text{C}$  or  $73 \pm 9^{\circ}\text{F}$ ) before proceeding with the test. Conditioning time shall be in accordance with the manufacture, proponent, or client, and it shall be reported in the test report.

#### 7.6.7 Static Air Leakage Test

To ensure proper curing of the seams, the manufacture, proponent, and client may request an initial air leakage test before starting. The air leakage measurement shall be performed by applying three static pressure levels of 480, 960, and 1440 Pa  $\pm$  0.05% (10, 20, and 30 psf  $\pm$  0.05%) and maintaining each pressure for  $60 \pm 3$  s.

### *Dynamic Load Sequence*

#### 7.8.1 Calculation of test pressure

The test pressure used in the testing shall be determined according to building code requirements for a specific building, or it shall be a pressure specified by the proponent, whichever is greater. Using this value, the percentages of design wind pressure shown in Figure D11 can be converted into test pressures.

#### 7.8.2 Calculation of base pressure

For Group 1 loading sequences, the base pressure shall be equal to the atmospheric pressure. For Group 2 loading sequences, the base pressure shall be as shown Figure D11.

#### 7.8.3 Requirement of gust cycle

As shown in Figure D12, test pressures shall be applied and maintained for no less than 2 s. The pressure shall then be released, with the system remaining at base pressure for at least 2 s. The total duration of the load cycle, including time to reach the required pressure, shall not exceed 8 s.

#### 7.8.4 Testing Procedure

To evaluate a roof assembly for a specific wind resistance, all the gusts corresponding to Level A of Figure D11 shall be applied. To evaluate the ultimate strength of the roofing system, testing shall start at Level A and shall be continuous when moving from one level to another. To obtain a rating, all specified numbers of gusts in each level shall be completed.

##### *Termination of the Test*

The test shall be carried out until the cycles selected by manufacturer, proponent, or client are completed, or until any of the following types of damage is noticed:

##### Method 1:

- (a) any one fastener disengages from the deck;
- (b) any one fastener plate disengages from the fastener;
- (c) any one seam/membrane ruptures, tears, or delaminates;
- (d) any one seam/membrane develops holes; or
- (e) any deck fails.

##### Method 2:

- a) Test specimen sustains or exceeds the desired test pressure target as dictated by the client;
- b) One component of the test specimen becomes detached from the other;
- c) Test specimen exhibits air intrusion, (delamination/detachment), observed on the surface layer.
- d) Test specimen exhibits seam failures, openings or ruptures such that pressure is no longer sustainable; or
- e) Any deck fails.

##### *Test Report*

Note: A sample report is provided in Appendix D-C

#### 10.1

The test report shall contain the date of test and report, the name of the author of the report, and the names and addresses of both the testing agency that conducted the tests and the Manufacture/Proponent/Client.

#### 10.2

Wind uplift resistance of the tested specimen shall be calculated by dividing the sustained test pressure using a minimum safety factor of 1.5.

#### 10.3

The report shall contain a description of the roof assembly test specimen, including the manufacturer of all components, a description of all components, and the method of test specimen construction (including the number of fasteners and or

spacing, type of deck used, insulation type and thickness, description of the air, and vapour barriers/retarders used).

#### 10.4

The results of the tested specimens shall be reported, with each specimen being properly identified. A separate drawing for each specimen shall not be required if all the differences between them are noted and provided. A copy of the published application instructions provided by the manufacture shall be attached.

#### 10.5

The following information shall be reported:

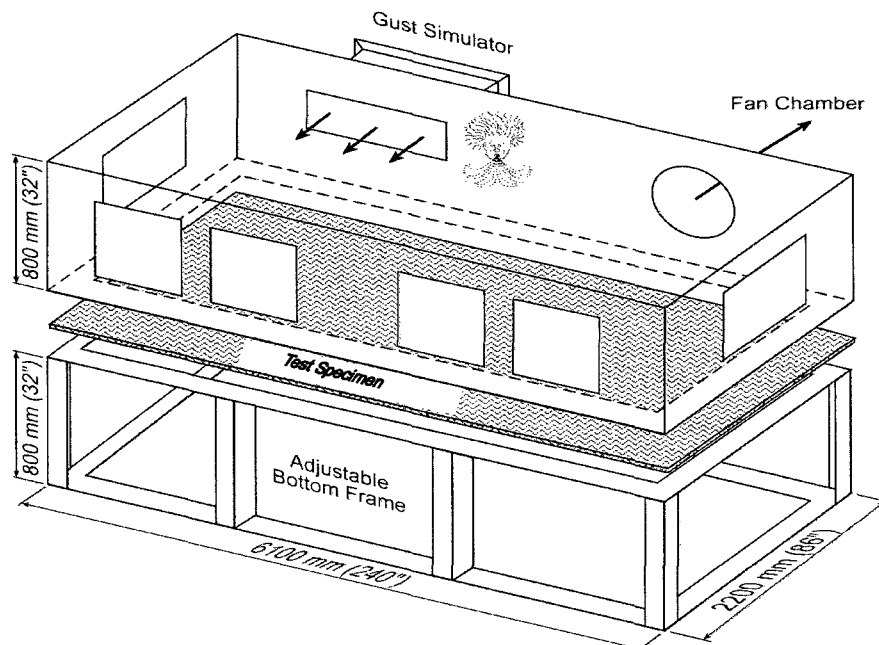
- time lapsed between system construction and testing;
- total time taken for the test, if failure was not observed by the end of the dynamic pressure interval;
- curing temperature;
- temperature at the beginning and at the end of the test; and
- dynamic pressures interval and load amplitudes.

#### 10.6

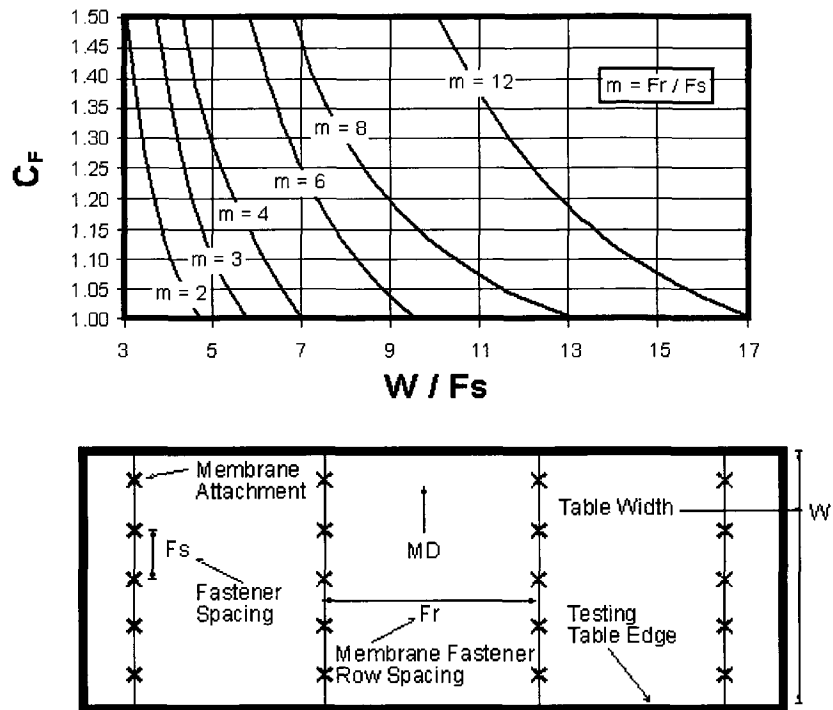
Through post-evaluation, the observed condition of the test specimen at each dynamic pressure interval and after the testing shall be reported. The report shall include details of any damage and/or the mode of failure.

#### 10.7

Any differences of the test specimen from the manufacturer's specifications shall be reported.



**Figure D8.** Test Apparatus and Test Specimen Arrangement



Example for the usage of Correction Factor

Scenario 1:

A proponent is testing a flexible roof membrane with fastener row spacing of 72" (1829mm) and fastener spacing of 12" (305mm) using a table width of 108" (2743mm); then

X – axis value =  $108/12 = 9$

M – value of the curve =  $72/12 = 6$

For these values of 9 and 6, Figure D9 gives a correction factor of 1.04.

During the testing, for a measured fastener force of 300lbf (1320N), the design fastener force will be  $300 \times 1.04 = 312 \text{ lbf (1373N)}$ .

Scenario 2:

A membrane with fastener row spacing of 120" (2540mm) is tested in the same table with same fastener spacing; then

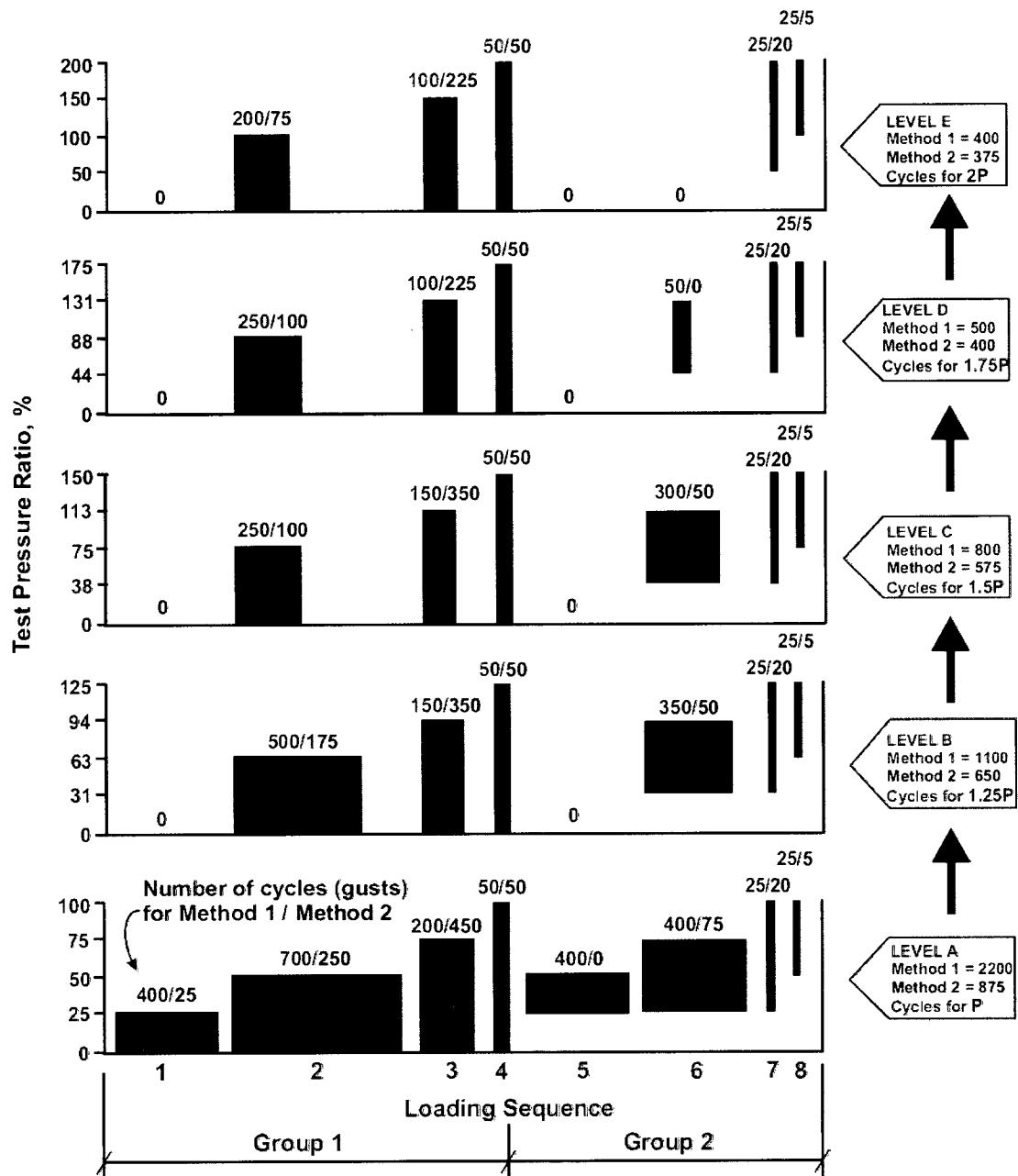
X – axis value =  $108/12 = 9$

M – value of the curve =  $120/12 = 10$

Interpolating the curves for  $m = 8$  and  $10$ , Figure D9 gives a correction factor = 1.40.

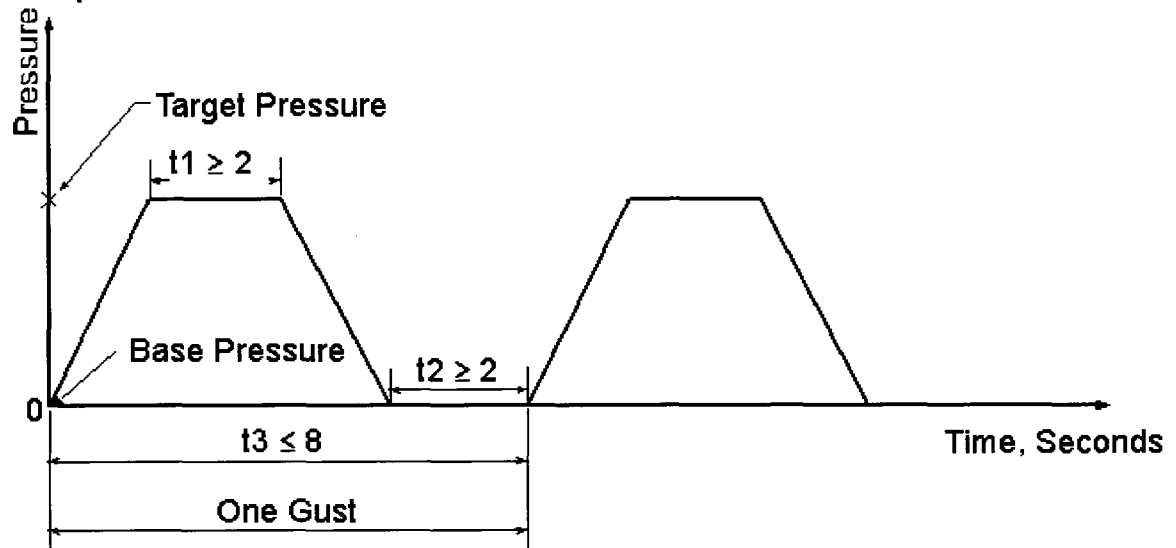
For this scenario, if the measured fastener is 400 lbf (1760), then design fastener force will be  $400 \times 1.4 = 560 \text{ lbf (2464N)}$ .

**Figure D9.**Table Size Correction Factors for Method 1



**Figure D10.** Dynamic Wind Load Cycles for Method 1 / Method 2

Group 1



Group 2

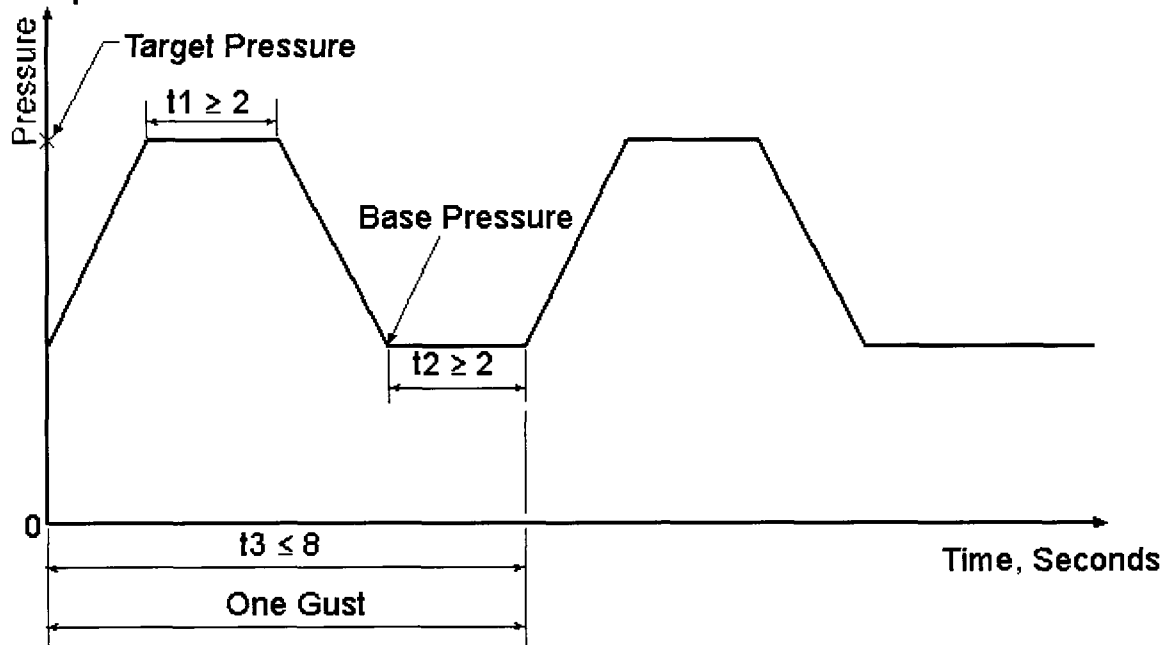


Figure D11. Time Requirement of a Gust

## **Annex D-A: Information on the Development of Dynamic Load Cycles**

The following sentences provide information for the development of dynamic load cycles prescribed in Section D4 of Appendix D. However, it is not a mandatory part of the proposed standard.

### **D-A1**

#### **Method 1**

To develop a dynamic test procedure for Method 1, the National Research Council Canada (NRCC) formed an industry-based consortium during 1994. The consortium is known as the Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS).

#### **Method 2**

To develop a dynamic test procedure for Method 2, the National Research Council Canada (NRCC) formed an industry-based consortium during 2005. The consortium is known as the Adhesive Applied Roofing System (ARRS).

### **D-A2**

The development of a full-scale test procedure requires several levels of generalization of the true wind-induced effect on a roof assembly. Often, these generalizations warrant a compromise between the technically sound approach and the practically acceptable procedure. The study had the advantage of having received input from all parties concerned with roofing, including researchers, manufacturers, roofing associations representing the contractors, and building owners. Six attributes for the development of a dynamic load cycle were selected from the concerns raised by the members and listed, based on priority, as follows:

- mimic as much as possible the true wind effects;
- simulate failure modes similar to those under field conditions;
- be easy to apply in a common laboratory environment;
- account for variation in the roofing components and materials;
- have a reasonable test-processing time of not more than a day, including set-up and testing; and
- be compatible with building codes and wind standards.

### **D-A3**

#### **Method 1**

The load cycle was developed based on wind tunnel studies of full-scale roof assemblies. Under simulated wind flow conditions, roofing systems were tested in the 9 m by 9 m NRC wind tunnel. The roofing systems were 3 m by 3 m in size and used full-scale roofing components. The influences of all four roofing components (deck, underlayment, insulation, and membrane) were considered. Two series of wind tunnel investigations, one in November 1994 and the other in

October 1995, 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 monomer (EPDM) membrane. The roof region was divided as “perimeter”, “field”, and pressure time histories were measured. For PVC, there were 30 different test configurations, whereas in the case of EPDM, 48 configurations were tested.

#### Method 2

The load cycle was developed based on wind tunnel studies using rigid models that were tested under simulated wind flow conditions. The models were configured to consider different; building height, building aspect ratio and wind speed. Model measurements in an atmospheric boundary layer wind tunnel were made for simulated open country terrain. Three geometries (Aspect ratios ( $L/W$ ) equal to 1, 0.5 and 2) were tested for two different wind directions, 0 and 45 degrees: at three different full-scale equivalent heights, namely 20', 40' and 60'. In total there are 18 model configurations were tested.

#### D-A4

A computer program was developed to count the occurrences of a pressure amplitude level from the pressure time histories. A rain flow counting (RFC) method was applied to compute the number of cycles. To develop a laboratory procedure for certifying full-scale roofing assemblies, the above data were reorganised into different pressure zones with their respective number of cycles. Eight pressure zones were selected under two groups. Group #1 represents wind-induced suction over a roof assembly. It consists of four sequences, where the pressure level alternates between zero and a fixed pressure. Group 2 represents the effects of exterior wind fluctuations combined with a constant interior pressure on a building. In Group 2, a constant minimum static pressure is applied to the roof system, and the gusts are applied above this constant static pressure. The roof membrane is lifted by static pressure; thus, Group 2 mimics membrane tension effects that are aimed to simulate fatigue on a roof system.

#### D-A5

By applying the developed load cycles, the researches have tested a wide range of systems with different roof covering materials, including PVC, thermoplastic poly olefins (TPO), modified bitumen (Mod Bit), EPDM. The failure mechanism and failure load compare favourably with the UEAtc test procedure that calls for a large number of low-intensity cycles. In addition, the failure modes produced by the both load cycles methods are also similar to the failure modes observed during field investigations. Technical details on the development of the standards for the Method 1 and Method 2 are documented in Baskaran et. al (1999) and Baskaran et al (2009), respectively.

## **Annex D-B: Typical Example of Membrane-Roofing Systems**

This Appendix shows typical examples of membrane-roofing systems. However, it is not a mandatory part of the proposed standard presented in Section D4 of Appendix D.

### **D-B1**

#### **Typical Mechanically Attached Membrane Roofing Systems- Method 1**

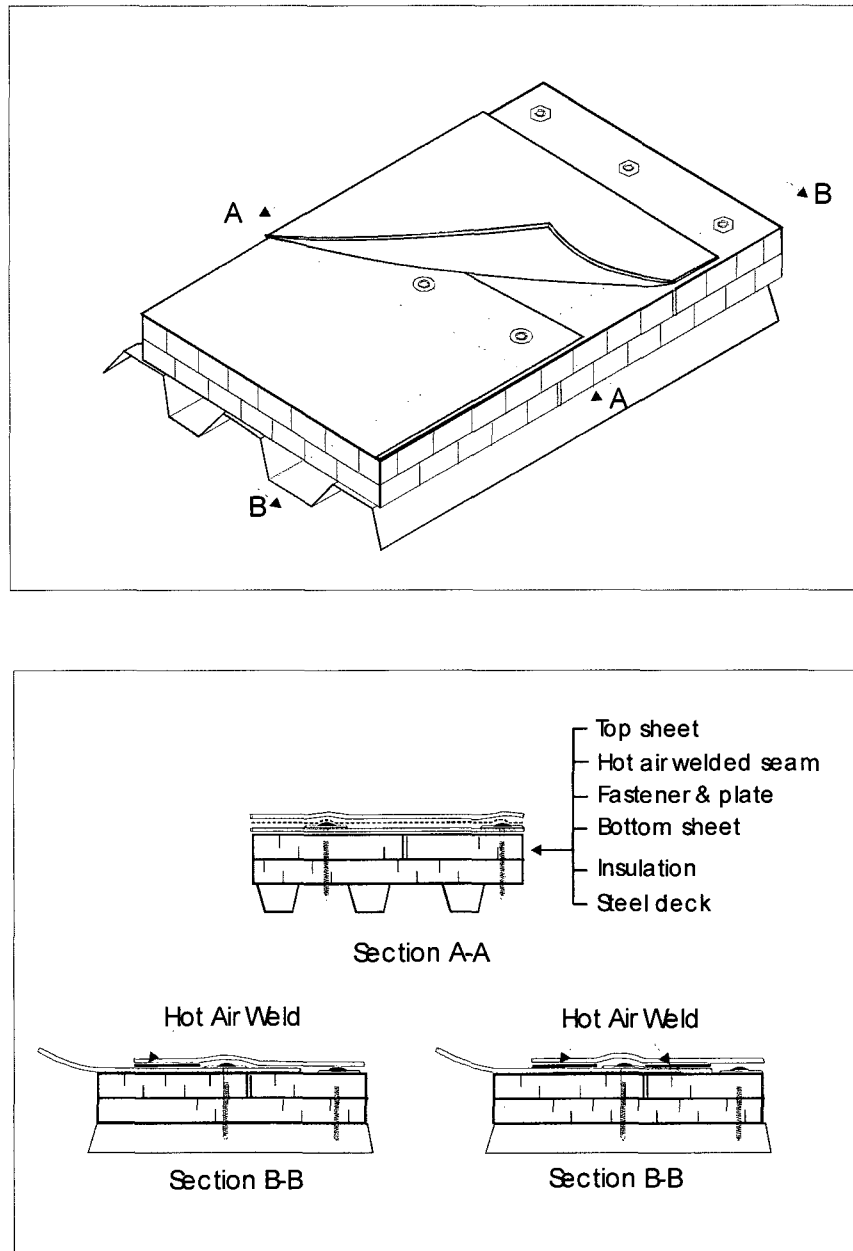


Figure D-B1a. Thermoplastic System

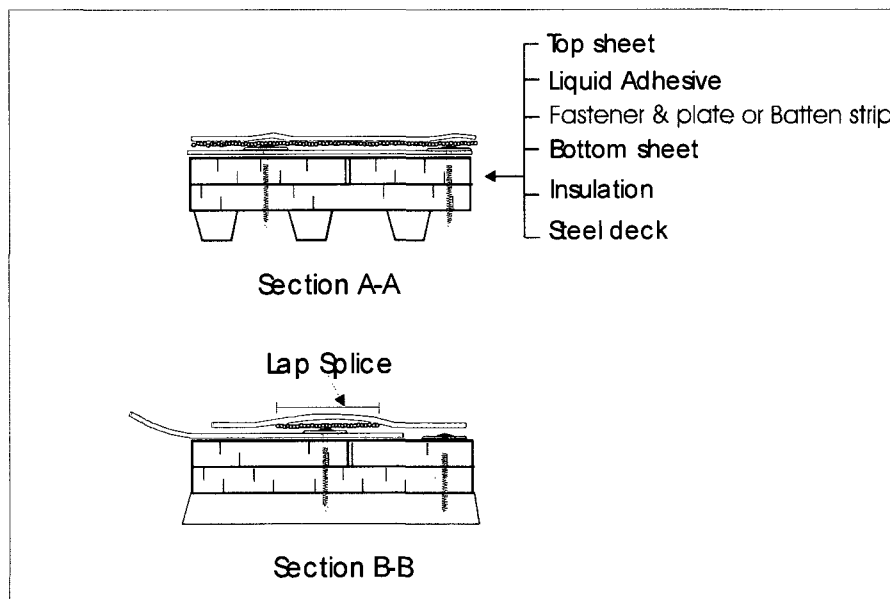
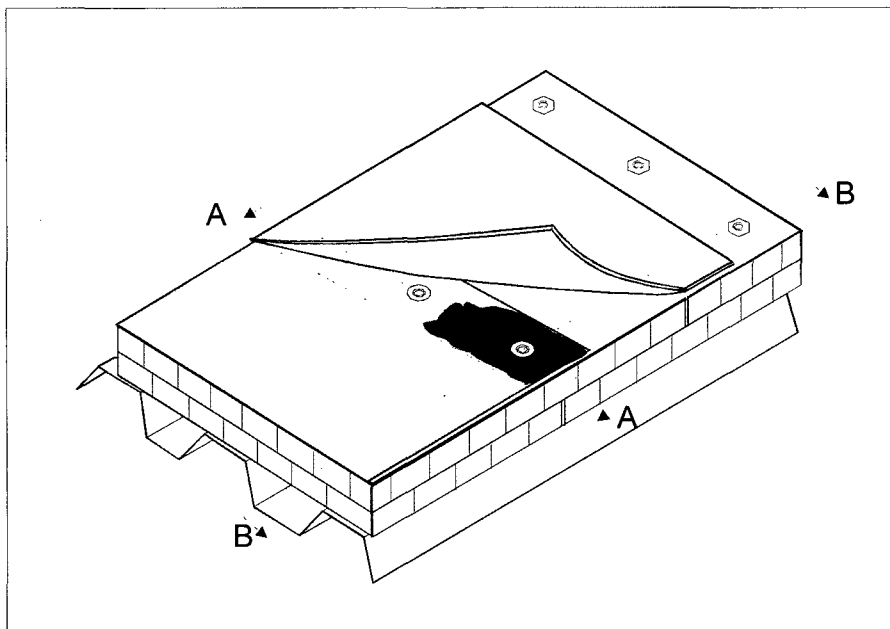


Figure D-B1b. Thermoset System with Liquid Adhesive

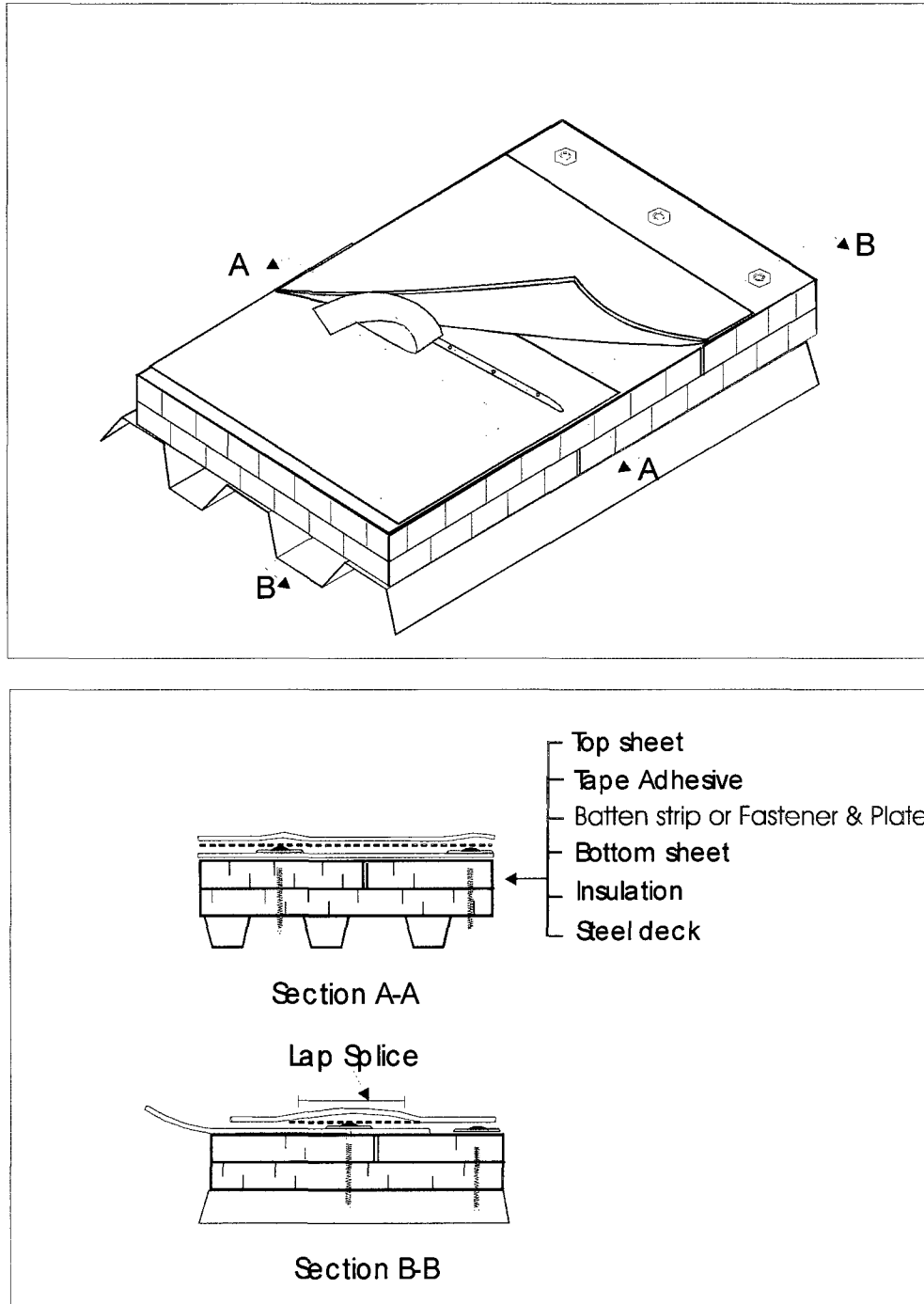


Figure D-B1c. Thermoset System with Tape Adhesives

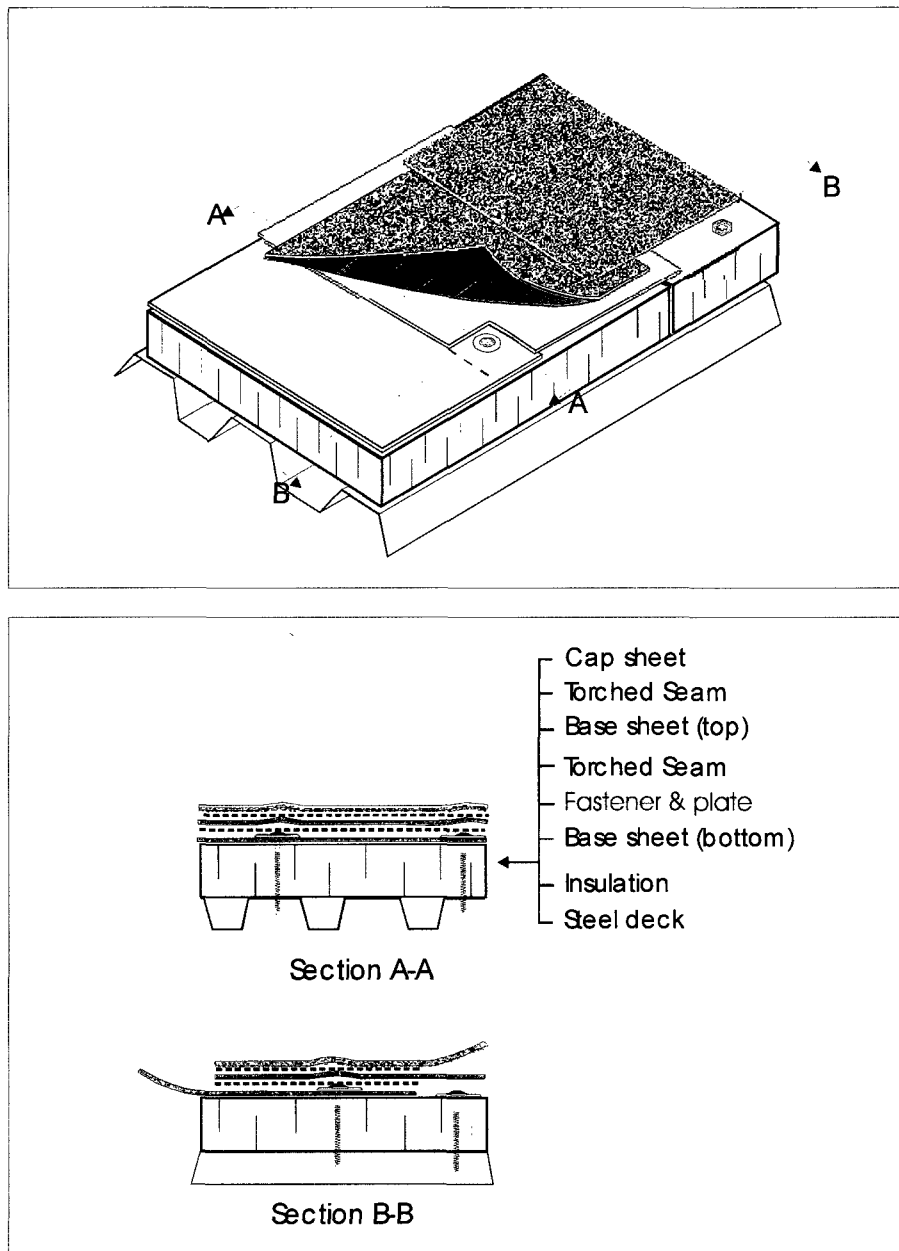


Figure D-B1d. Modified Bituminous System

*Note: Two ply torch applications are shown above. It can be single ply with either cold adhesive or with hot asphalt application.*

## D-B2

### Typical Adhesive Applied Membrane Roofing Systems- Method 2

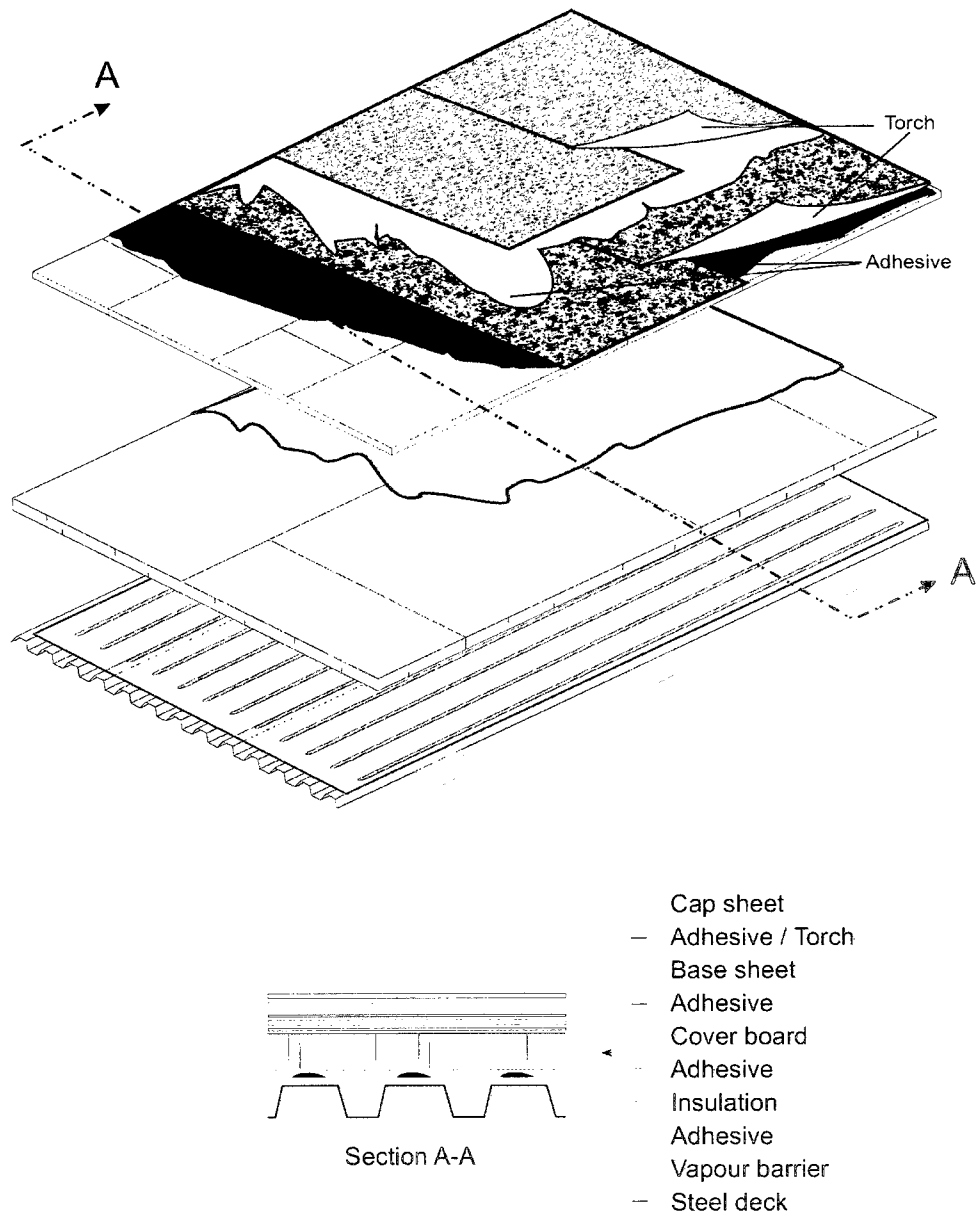


Figure D-B2a. Variation in Membrane Application (Adhesive or Torch)

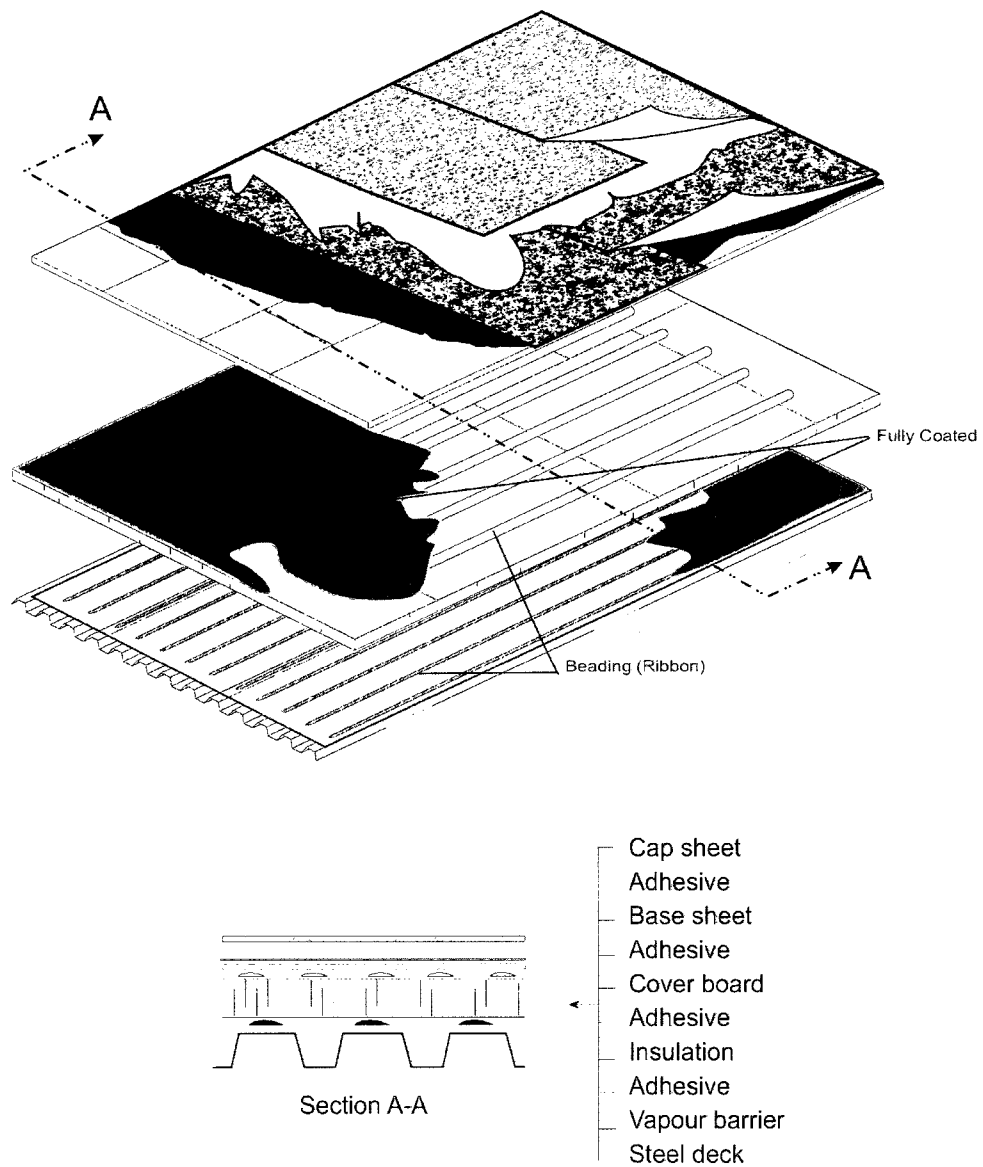


Figure D-B2b. Variation in Component Integration (Fully Coated or Beading)

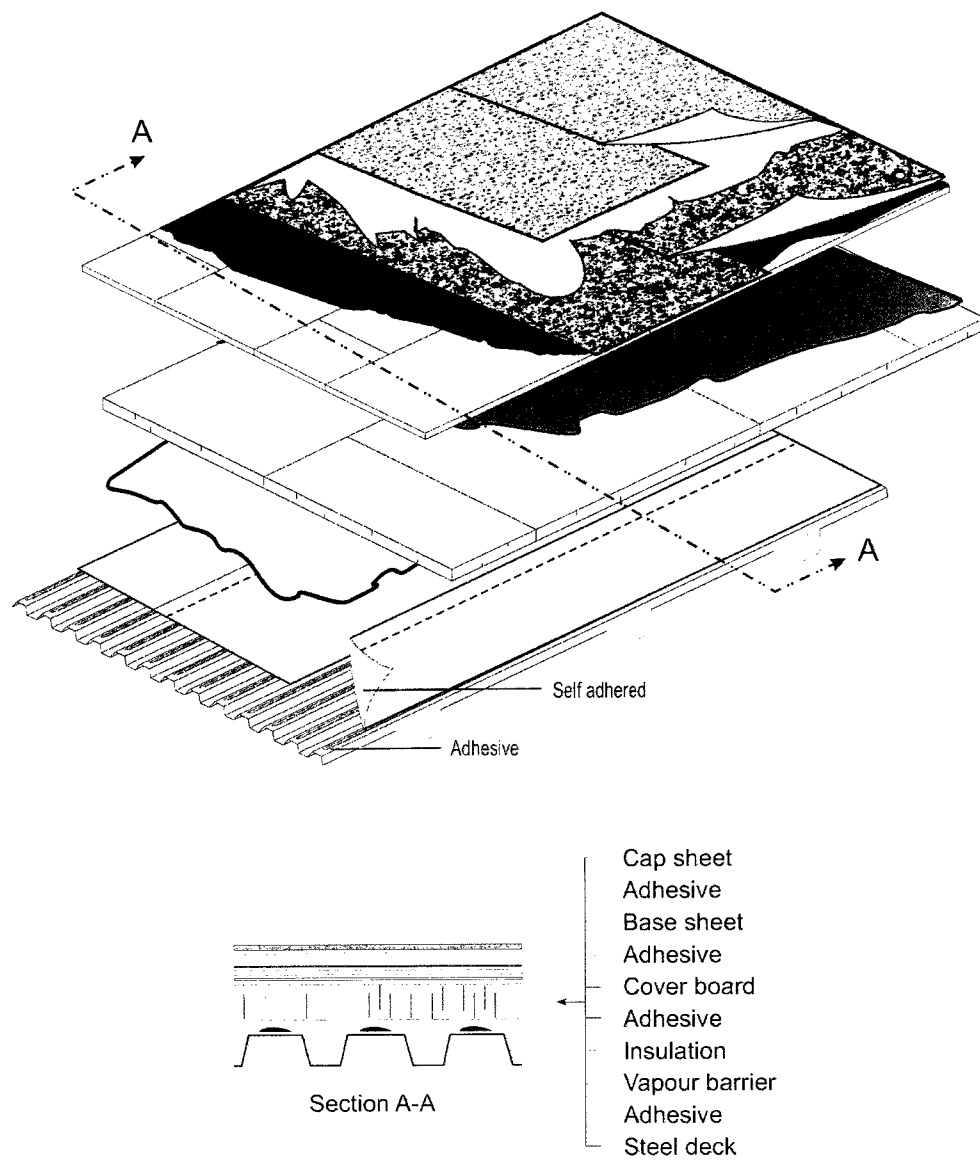


Figure D-B2c. Variation in Barrier Installation (Adhesive or Self Adhered)

## **Annex D-C: Typical Test Report Example**

The following pages provide sample data sheets and test report forms for the procedures described in the proposed standard prescribed in Appendix D

### **Testing Report**

---

Title:

Standard Test Method for the Dynamic Wind Uplift Resistance of  
Membrane-Roofing Systems

Report No:

XXXX.1

Report Date:

July 2<sup>nd</sup>, 2008

Proponent:

Bestroof Inc  
1111 Roofing Circle  
Moon, Star 4567  
Heaven  
Att: Dr Roof Man

System Installed By:

Mr. Roof Hand

System Tested by:

Mr. Roof Test

Report By:

Mr. Roof Report

Report Approved by:

Mr. Roof Approve

**SAMPLE**

Please note our general conditions below.

- *The indicated test data are valid under test conditions only. A successful application under other than the reported test conditions is not proven with this test report.*

## REPORT ON SPECIMEN

- Wind uplift resistance of the tested specimen: 60 psf (2873 Pa)
- Wind uplift rating pressures interval and load amplitudes:

SYSTEM SUSTAINED: 90 psf (4309 Pa)

SYSTEM FAILED: 105 psf (5027 Pa)

Level = D

Sequence Number = 4

Gust Number = 10

- Failure modes: Method 1: Membrane tearing around fasteners (Figure D-C1)  
Method 2: Insulation facer delamination (Figure D-C2)
- Tested roofing system components: See Table D-C1
- System layout: Method 1: See Figure D-C3  
Method 2: See Figure D-C4
- Curing temperature: 20°C
- Time lapsed between system construction and testing: 13 hours
- Temperature at the beginning and at the end of the test: 20°C
- Total time taken for the test: 9 hours and 33 minutes
- Differences of the test specimen from the proponent's specifications: None

**SAMPLE**

Figure D-C1. Method 1: Failure Mode of Specimen

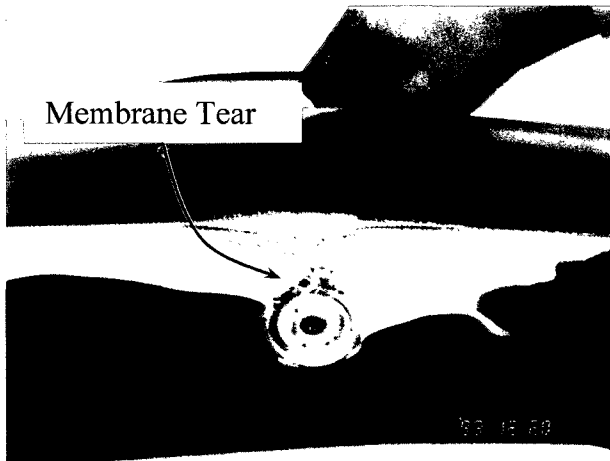
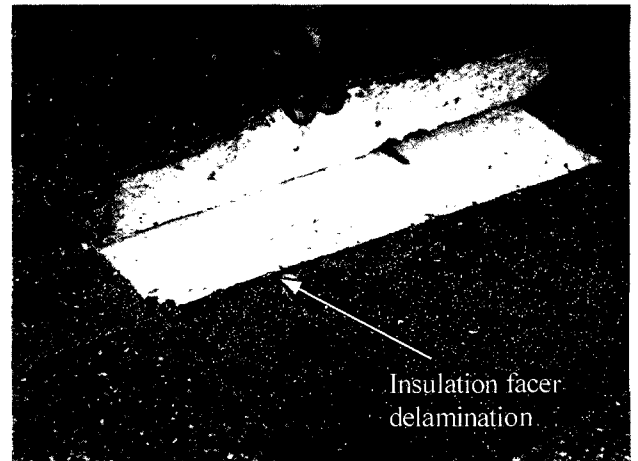


Figure D-C2. Method 2: Failure Mode of Specimen



**Table D-C1. TESTED ROOFING SYSTEM COMPONENTS**

**Structural Deck**

|                                              |                                  |
|----------------------------------------------|----------------------------------|
| Type                                         | Profiled metal sheeting 22-gauge |
| Nominal Thickness                            | 0.030" (0.76 mm)                 |
| Overall Depth                                | 1.5" (38 mm)                     |
| Flute Spacing, c/o                           | 5.9" (150 mm)                    |
| Fastener Pullout as per ANSI/SPRI FX-1-1996* | 470 lbf (2120 N)                 |
| Manufacturer                                 | Strong Steel                     |

**Vapor Barrier/Vapor Retarder (s)**

|             |                |
|-------------|----------------|
| Type        | Vapour Barrier |
| Dimensions  | 36" (1 m) Wide |
| Adhesive    | VB Adhesive    |
| Manufacture | Best Barrier   |

**Thermal Insulation**

|                                            |                                                                                 |
|--------------------------------------------|---------------------------------------------------------------------------------|
| Type                                       | Polyiso                                                                         |
| Dimensions                                 | 2 boards of 4' (1219 mm) by 8'(2438 mm) with a total thickness of 4" (101.5 mm) |
| Attachment (Method 1 / Method 2)           | Mechanically fastened / Adhesive                                                |
| Compressive Strength as per ASTM D1621-94* | 18.8 psi (130 kPa)                                                              |
| Manufacturer                               | ThermaPlus                                                                      |

**Insulation Attachment Details (Method 1 only)**

|                   |                                         |
|-------------------|-----------------------------------------|
| Type              | Mechanical fasteners with plates        |
| Fastener Details  | Assembled 5" (127 mm) screws and plates |
| Plate Details     | 3" (76 mm) plastic lock plate           |
| Fastening Pattern | 4 fasteners per board                   |
| Manufacturer      | West Insulation                         |

**SAMPLE**

**Roof Membrane**

**Method 1**

|                   |                                        |
|-------------------|----------------------------------------|
| Type              | TPO (144" -3657.5 mm wide), Single-ply |
| Nominal Thickness | 45 mil (1.1 mm)                        |

**Method 2**

|                       |                   |
|-----------------------|-------------------|
| Base / Cap sheet type | Base S A / Cap SA |
| Nominal thickness     | 90 mil (2.2 mm)   |
| Method of adhesion    | Torched           |
| Manufacturer          | Best manufacturer |

**Membrane Attachment Details (Method 1 only)**

|                           |                                  |
|---------------------------|----------------------------------|
| Type                      | Mechanical fasteners with plates |
| Fastener                  | 5" (127 mm) Superfast #15        |
| Plate Details             | 3" (76 mm) Dia. metal plate      |
| Fastener Row Spacing, c/o | 130" (3302 mm)                   |
| Fastener Spacing, c/o     | 12" (305 mm)                     |
| Slippage Control          | Yes                              |

**Membrane Seam Details**

**Method 1**

|         |                                                                                                                    |
|---------|--------------------------------------------------------------------------------------------------------------------|
| Type    | Hot air welding                                                                                                    |
| Details | Overlap = 14" (355.6 mm), Type of weld: <b>One Side Weld</b><br>Welding temp: 950°F (510°C) Welding speed: 10'/min |

**Method 2**

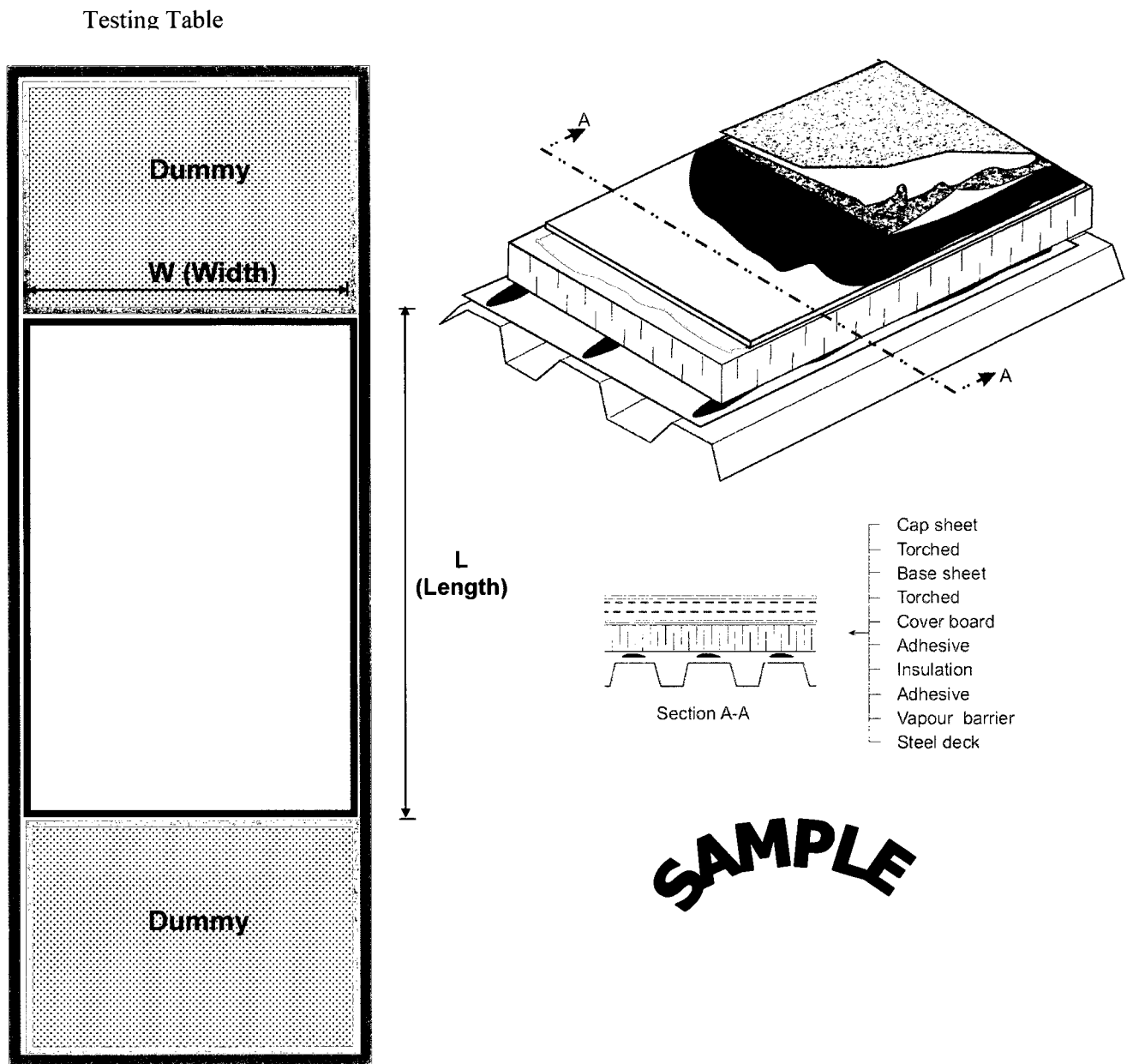
|         |                              |
|---------|------------------------------|
| Type    | Torched                      |
| Details | Overlap = 3-4" (76-101.5 mm) |

The technical drawings illustrate the roof assembly details:

- Plan View (Left):** Shows three sheets of insulation (Sheet 1, Sheet 2, Sheet 3) with dimensions  $S_W = 4\frac{3}{4}"$ ,  $F_S = 12"$ ,  $F_T = 70\frac{1}{2}"$ , and  $236" \times 79"$ . It includes fasteners (P), welds (D), and labels for 'One Side Weld' and 'One Side Hot Air Weld 4-36"'. Dimensions  $3\frac{1}{2}"$ ,  $a$ , and  $b$  are also indicated.
- Section View (Top Right):** A 3D perspective showing the TPO membrane, 2" x 2" Polyiso insulation, and 22 Ga steel deck.
- Section a-a (Middle Right):** A cross-section showing the top sheet, welded portion, fastener & plate, bottom sheet, polyiso insulation, and steel deck. The spacing is 12" o/c.
- Section b-b (Bottom Right):** A cross-section showing the one side hot air weld 4-36" detail.

**SAMPLE**

Figure D-C4: SYSTEM LAYOUT – Method 2



## Appendix E: Typical Example of ABAQUS Input File Used for the FE Simulations

A typical ABAQUS input file for the FE simulations of the simplified AARS model with the fully coated adhesive is presented below. Critical explanations are highlighted in bold.

```

=====
*Heading
** Job name: FE-model-1-1 Model name: Model-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name="Adhesive 25-20"
*Node
1,      152.5,  -1.60000002,      305.
2,    101.666664,  -1.60000002,      305.
3,    50.8333321,  -1.60000002,      305.
4,         0.,  -1.60000002,      305.
5,   -50.8333321,  -1.60000002,      305.
6,   -101.666664,  -1.60000002,      305.
7,     -152.5,  -1.60000002,      305.
8,      152.5,  -1.60000002,    254.166672
9,    101.666664,  -1.60000002,    254.166672
10,   50.8333321,  -1.60000002,    254.166672
11,         0.,  -1.60000002,    254.166672
12,   -50.8333321,  -1.60000002,    254.166672
13,   -101.666664,  -1.60000002,    254.166672
14,     -152.5,  -1.60000002,    254.166672
15,      152.5,  -1.60000002,    203.333328
16,    101.666664,  -1.60000002,    203.333328
17,   50.8333321,  -1.60000002,    203.333328
18,         0.,  -1.60000002,    203.333328
19,   -50.8333321,  -1.60000002,    203.333328
20,   -101.666664,  -1.60000002,    203.333328
21,     -152.5,  -1.60000002,    203.333328
22,      152.5,  -1.60000002,      152.5
23,    101.666664,  -1.60000002,      152.5
24,   50.8333321,  -1.60000002,      152.5
25,         0.,  -1.60000002,      152.5
26,   -50.8333321,  -1.60000002,      152.5
27,   -101.666664,  -1.60000002,      152.5
28,     -152.5,  -1.60000002,      152.5
29,      152.5,  -1.60000002,    101.666664
30,    101.666664,  -1.60000002,    101.666664
31,   50.8333321,  -1.60000002,    101.666664
32,         0.,  -1.60000002,    101.666664
33,   -50.8333321,  -1.60000002,    101.666664
34,   -101.666664,  -1.60000002,    101.666664
35,     -152.5,  -1.60000002,    101.666664
36,      152.5,  -1.60000002,    50.8333321
37,    101.666664,  -1.60000002,    50.8333321

```

|     |              |              |            |
|-----|--------------|--------------|------------|
| 38, | 50.8333321,  | -1.60000002, | 50.8333321 |
| 39, | 0.,          | -1.60000002, | 50.8333321 |
| 40, | -50.8333321, | -1.60000002, | 50.8333321 |
| 41, | -101.666664, | -1.60000002, | 50.8333321 |
| 42, | -152.5,      | -1.60000002, | 50.8333321 |
| 43, | 152.5,       | -1.60000002, | 0.         |
| 44, | 101.666664,  | -1.60000002, | 0.         |
| 45, | 50.8333321,  | -1.60000002, | 0.         |
| 46, | 0.,          | -1.60000002, | 0.         |
| 47, | -50.8333321, | -1.60000002, | 0.         |
| 48, | -101.666664, | -1.60000002, | 0.         |
| 49, | -152.5,      | -1.60000002, | 0.         |
| 50, | 152.5,       | 0.400000006, | 305.       |
| 51, | 101.666664,  | 0.400000006, | 305.       |
| 52, | 50.8333321,  | 0.400000006, | 305.       |
| 53, | 0.,          | 0.400000006, | 305.       |
| 54, | -50.8333321, | 0.400000006, | 305.       |
| 55, | -101.666664, | 0.400000006, | 305.       |
| 56, | -152.5,      | 0.400000006, | 305.       |
| 57, | 152.5,       | 0.400000006, | 254.166672 |
| 58, | 101.666664,  | 0.400000006, | 254.166672 |
| 59, | 50.8333321,  | 0.400000006, | 254.166672 |
| 60, | 0.,          | 0.400000006, | 254.166672 |
| 61, | -50.8333321, | 0.400000006, | 254.166672 |
| 62, | -101.666664, | 0.400000006, | 254.166672 |
| 63, | -152.5,      | 0.400000006, | 254.166672 |
| 64, | 152.5,       | 0.400000006, | 203.333328 |
| 65, | 101.666664,  | 0.400000006, | 203.333328 |
| 66, | 50.8333321,  | 0.400000006, | 203.333328 |
| 67, | 0.,          | 0.400000006, | 203.333328 |
| 68, | -50.8333321, | 0.400000006, | 203.333328 |
| 69, | -101.666664, | 0.400000006, | 203.333328 |
| 70, | -152.5,      | 0.400000006, | 203.333328 |
| 71, | 152.5,       | 0.400000006, | 152.5      |
| 72, | 101.666664,  | 0.400000006, | 152.5      |
| 73, | 50.8333321,  | 0.400000006, | 152.5      |
| 74, | 0.,          | 0.400000006, | 152.5      |
| 75, | -50.8333321, | 0.400000006, | 152.5      |
| 76, | -101.666664, | 0.400000006, | 152.5      |
| 77, | -152.5,      | 0.400000006, | 152.5      |
| 78, | 152.5,       | 0.400000006, | 101.666664 |
| 79, | 101.666664,  | 0.400000006, | 101.666664 |
| 80, | 50.8333321,  | 0.400000006, | 101.666664 |
| 81, | 0.,          | 0.400000006, | 101.666664 |
| 82, | -50.8333321, | 0.400000006, | 101.666664 |
| 83, | -101.666664, | 0.400000006, | 101.666664 |
| 84, | -152.5,      | 0.400000006, | 101.666664 |
| 85, | 152.5,       | 0.400000006, | 50.8333321 |
| 86, | 101.666664,  | 0.400000006, | 50.8333321 |
| 87, | 50.8333321,  | 0.400000006, | 50.8333321 |
| 88, | 0.,          | 0.400000006, | 50.8333321 |
| 89, | -50.8333321, | 0.400000006, | 50.8333321 |
| 90, | -101.666664, | 0.400000006, | 50.8333321 |
| 91, | -152.5,      | 0.400000006, | 50.8333321 |
| 92, | 152.5,       | 0.400000006, | 0.         |
| 93, | 101.666664,  | 0.400000006, | 0.         |
| 94, | 50.8333321,  | 0.400000006, | 0.         |

```

95,          0., 0.400000006, 0.
96, -50.8333321, 0.400000006, 0.
97, -101.666664, 0.400000006, 0.
98, -152.5, 0.400000006, 0.
*Element, type=C3D8R
1, 50, 51, 58, 57, 1, 2, 9, 8
2, 51, 52, 59, 58, 2, 3, 10, 9
3, 52, 53, 60, 59, 3, 4, 11, 10
4, 53, 54, 61, 60, 4, 5, 12, 11
5, 54, 55, 62, 61, 5, 6, 13, 12
6, 55, 56, 63, 62, 6, 7, 14, 13
7, 57, 58, 65, 64, 8, 9, 16, 15
8, 58, 59, 66, 65, 9, 10, 17, 16
9, 59, 60, 67, 66, 10, 11, 18, 17
10, 60, 61, 68, 67, 11, 12, 19, 18
11, 61, 62, 69, 68, 12, 13, 20, 19
12, 62, 63, 70, 69, 13, 14, 21, 20
13, 64, 65, 72, 71, 15, 16, 23, 22
14, 65, 66, 73, 72, 16, 17, 24, 23
15, 66, 67, 74, 73, 17, 18, 25, 24
16, 67, 68, 75, 74, 18, 19, 26, 25
17, 68, 69, 76, 75, 19, 20, 27, 26
18, 69, 70, 77, 76, 20, 21, 28, 27
19, 71, 72, 79, 78, 22, 23, 30, 29
20, 72, 73, 80, 79, 23, 24, 31, 30
21, 73, 74, 81, 80, 24, 25, 32, 31
22, 74, 75, 82, 81, 25, 26, 33, 32
23, 75, 76, 83, 82, 26, 27, 34, 33
24, 76, 77, 84, 83, 27, 28, 35, 34
25, 78, 79, 86, 85, 29, 30, 37, 36
26, 79, 80, 87, 86, 30, 31, 38, 37
27, 80, 81, 88, 87, 31, 32, 39, 38
28, 81, 82, 89, 88, 32, 33, 40, 39
29, 82, 83, 90, 89, 33, 34, 41, 40
30, 83, 84, 91, 90, 34, 35, 42, 41
31, 85, 86, 93, 92, 36, 37, 44, 43
32, 86, 87, 94, 93, 37, 38, 45, 44
33, 87, 88, 95, 94, 38, 39, 46, 45
34, 88, 89, 96, 95, 39, 40, 47, 46
35, 89, 90, 97, 96, 40, 41, 48, 47
36, 90, 91, 98, 97, 41, 42, 49, 48
*Nset, nset=_PickedSet2, internal, generate
1, 98, 1
*Elset, elset=_PickedSet2, internal, generate
1, 36, 1
** Region: (Adhesive25:Picked)
*Elset, elset=_PickedSet2, internal, generate
1, 36, 1
** Section: Adhesive25
*Solid Section, elset=_PickedSet2, material=Adhesive25
1.,
*End Part
**
*Part, name="ISO bottom"
*Node
1, -152.5, -52.5, 305.
2, -152.5, -1.5, 305.

```

|     |              |        |            |
|-----|--------------|--------|------------|
| 3,  | -152.5,      | -52.5, | 254.166672 |
| 4,  | -152.5,      | -1.5,  | 254.166672 |
| 5,  | -152.5,      | -52.5, | 203.333328 |
| 6,  | -152.5,      | -1.5,  | 203.333328 |
| 7,  | -152.5,      | -52.5, | 152.5      |
| 8,  | -152.5,      | -1.5,  | 152.5      |
| 9,  | -152.5,      | -52.5, | 101.666664 |
| 10, | -152.5,      | -1.5,  | 101.666664 |
| 11, | -152.5,      | -52.5, | 50.8333321 |
| 12, | -152.5,      | -1.5,  | 50.8333321 |
| 13, | -152.5,      | -52.5, | 0.         |
| 14, | -152.5,      | -1.5,  | 0.         |
| 15, | -101.666664, | -52.5, | 305.       |
| 16, | -101.666664, | -1.5,  | 305.       |
| 17, | -101.666664, | -52.5, | 254.166672 |
| 18, | -101.666664, | -1.5,  | 254.166672 |
| 19, | -101.666664, | -52.5, | 203.333328 |
| 20, | -101.666664, | -1.5,  | 203.333328 |
| 21, | -101.666664, | -52.5, | 152.5      |
| 22, | -101.666664, | -1.5,  | 152.5      |
| 23, | -101.666664, | -52.5, | 101.666664 |
| 24, | -101.666664, | -1.5,  | 101.666664 |
| 25, | -101.666664, | -52.5, | 50.8333321 |
| 26, | -101.666664, | -1.5,  | 50.8333321 |
| 27, | -101.666664, | -52.5, | 0.         |
| 28, | -101.666664, | -1.5,  | 0.         |
| 29, | -50.8333321, | -52.5, | 305.       |
| 30, | -50.8333321, | -1.5,  | 305.       |
| 31, | -50.8333321, | -52.5, | 254.166672 |
| 32, | -50.8333321, | -1.5,  | 254.166672 |
| 33, | -50.8333321, | -52.5, | 203.333328 |
| 34, | -50.8333321, | -1.5,  | 203.333328 |
| 35, | -50.8333321, | -52.5, | 152.5      |
| 36, | -50.8333321, | -1.5,  | 152.5      |
| 37, | -50.8333321, | -52.5, | 101.666664 |
| 38, | -50.8333321, | -1.5,  | 101.666664 |
| 39, | -50.8333321, | -52.5, | 50.8333321 |
| 40, | -50.8333321, | -1.5,  | 50.8333321 |
| 41, | -50.8333321, | -52.5, | 0.         |
| 42, | -50.8333321, | -1.5,  | 0.         |
| 43, | 0.,          | -52.5, | 305.       |
| 44, | 0.,          | -1.5,  | 305.       |
| 45, | 0.,          | -52.5, | 254.166672 |
| 46, | 0.,          | -1.5,  | 254.166672 |
| 47, | 0.,          | -52.5, | 203.333328 |
| 48, | 0.,          | -1.5,  | 203.333328 |
| 49, | 0.,          | -52.5, | 152.5      |
| 50, | 0.,          | -1.5,  | 152.5      |
| 51, | 0.,          | -52.5, | 101.666664 |
| 52, | 0.,          | -1.5,  | 101.666664 |
| 53, | 0.,          | -52.5, | 50.8333321 |
| 54, | 0.,          | -1.5,  | 50.8333321 |
| 55, | 0.,          | -52.5, | 0.         |
| 56, | 0.,          | -1.5,  | 0.         |
| 57, | 50.8333321,  | -52.5, | 305.       |
| 58, | 50.8333321,  | -1.5,  | 305.       |
| 59, | 50.8333321,  | -52.5, | 254.166672 |

|     |             |        |            |
|-----|-------------|--------|------------|
| 60, | 50.8333321, | -1.5,  | 254.166672 |
| 61, | 50.8333321, | -52.5, | 203.333328 |
| 62, | 50.8333321, | -1.5,  | 203.333328 |
| 63, | 50.8333321, | -52.5, | 152.5      |
| 64, | 50.8333321, | -1.5,  | 152.5      |
| 65, | 50.8333321, | -52.5, | 101.666664 |
| 66, | 50.8333321, | -1.5,  | 101.666664 |
| 67, | 50.8333321, | -52.5, | 50.8333321 |
| 68, | 50.8333321, | -1.5,  | 50.8333321 |
| 69, | 50.8333321, | -52.5, | 0.         |
| 70, | 50.8333321, | -1.5,  | 0.         |
| 71, | 101.666664, | -52.5, | 305.       |
| 72, | 101.666664, | -1.5,  | 305.       |
| 73, | 101.666664, | -52.5, | 254.166672 |
| 74, | 101.666664, | -1.5,  | 254.166672 |
| 75, | 101.666664, | -52.5, | 203.333328 |
| 76, | 101.666664, | -1.5,  | 203.333328 |
| 77, | 101.666664, | -52.5, | 152.5      |
| 78, | 101.666664, | -1.5,  | 152.5      |
| 79, | 101.666664, | -52.5, | 101.666664 |
| 80, | 101.666664, | -1.5,  | 101.666664 |
| 81, | 101.666664, | -52.5, | 50.8333321 |
| 82, | 101.666664, | -1.5,  | 50.8333321 |
| 83, | 101.666664, | -52.5, | 0.         |
| 84, | 101.666664, | -1.5,  | 0.         |
| 85, | 152.5,      | -52.5, | 305.       |
| 86, | 152.5,      | -1.5,  | 305.       |
| 87, | 152.5,      | -52.5, | 254.166672 |
| 88, | 152.5,      | -1.5,  | 254.166672 |
| 89, | 152.5,      | -52.5, | 203.333328 |
| 90, | 152.5,      | -1.5,  | 203.333328 |
| 91, | 152.5,      | -52.5, | 152.5      |
| 92, | 152.5,      | -1.5,  | 152.5      |
| 93, | 152.5,      | -52.5, | 101.666664 |
| 94, | 152.5,      | -1.5,  | 101.666664 |
| 95, | 152.5,      | -52.5, | 50.8333321 |
| 96, | 152.5,      | -1.5,  | 50.8333321 |
| 97, | 152.5,      | -52.5, | 0.         |
| 98, | 152.5,      | -1.5,  | 0.         |

\*Element, type=C3D8I

|     |     |     |     |     |     |     |     |    |
|-----|-----|-----|-----|-----|-----|-----|-----|----|
| 1,  | 15, | 16, | 18, | 17, | 1,  | 2,  | 4,  | 3  |
| 2,  | 17, | 18, | 20, | 19, | 3,  | 4,  | 6,  | 5  |
| 3,  | 19, | 20, | 22, | 21, | 5,  | 6,  | 8,  | 7  |
| 4,  | 21, | 22, | 24, | 23, | 7,  | 8,  | 10, | 9  |
| 5,  | 23, | 24, | 26, | 25, | 9,  | 10, | 12, | 11 |
| 6,  | 25, | 26, | 28, | 27, | 11, | 12, | 14, | 13 |
| 7,  | 29, | 30, | 32, | 31, | 15, | 16, | 18, | 17 |
| 8,  | 31, | 32, | 34, | 33, | 17, | 18, | 20, | 19 |
| 9,  | 33, | 34, | 36, | 35, | 19, | 20, | 22, | 21 |
| 10, | 35, | 36, | 38, | 37, | 21, | 22, | 24, | 23 |
| 11, | 37, | 38, | 40, | 39, | 23, | 24, | 26, | 25 |
| 12, | 39, | 40, | 42, | 41, | 25, | 26, | 28, | 27 |
| 13, | 43, | 44, | 46, | 45, | 29, | 30, | 32, | 31 |
| 14, | 45, | 46, | 48, | 47, | 31, | 32, | 34, | 33 |
| 15, | 47, | 48, | 50, | 49, | 33, | 34, | 36, | 35 |
| 16, | 49, | 50, | 52, | 51, | 35, | 36, | 38, | 37 |
| 17, | 51, | 52, | 54, | 53, | 37, | 38, | 40, | 39 |

```

18, 53, 54, 56, 55, 39, 40, 42, 41
19, 57, 58, 60, 59, 43, 44, 46, 45
20, 59, 60, 62, 61, 45, 46, 48, 47
21, 61, 62, 64, 63, 47, 48, 50, 49
22, 63, 64, 66, 65, 49, 50, 52, 51
23, 65, 66, 68, 67, 51, 52, 54, 53
24, 67, 68, 70, 69, 53, 54, 56, 55
25, 71, 72, 74, 73, 57, 58, 60, 59
26, 73, 74, 76, 75, 59, 60, 62, 61
27, 75, 76, 78, 77, 61, 62, 64, 63
28, 77, 78, 80, 79, 63, 64, 66, 65
29, 79, 80, 82, 81, 65, 66, 68, 67
30, 81, 82, 84, 83, 67, 68, 70, 69
31, 85, 86, 88, 87, 71, 72, 74, 73
32, 87, 88, 90, 89, 73, 74, 76, 75
33, 89, 90, 92, 91, 75, 76, 78, 77
34, 91, 92, 94, 93, 77, 78, 80, 79
35, 93, 94, 96, 95, 79, 80, 82, 81
36, 95, 96, 98, 97, 81, 82, 84, 83
*Nset, nset=_PickedSet2, internal, generate
  1, 98, 1
*Elset, elset=_PickedSet2, internal, generate
  1, 36, 1
** Region: (ISO:Picked)
*Elset, elset=_PickedSet2, internal, generate
  1, 36, 1
** Section: ISO
*Solid Section, elset=_PickedSet2, material=ISO
1.,
*End Part
**
*Part, name="ISO top"
*Node
  1,      152.5,      52.5,      305.
  2,      152.5,      1.5,      305.
  3,      152.5,      52.5,      254.166672
  4,      152.5,      1.5,      254.166672
  5,      152.5,      52.5,      203.333328
  6,      152.5,      1.5,      203.333328
  7,      152.5,      52.5,      152.5
  8,      152.5,      1.5,      152.5
  9,      152.5,      52.5,      101.666664
 10,      152.5,      1.5,      101.666664
 11,      152.5,      52.5,      50.8333321
 12,      152.5,      1.5,      50.8333321
 13,      152.5,      52.5,      0.
 14,      152.5,      1.5,      0.
 15,      101.666664,      52.5,      305.
 16,      101.666664,      1.5,      305.
 17,      101.666664,      52.5,      254.166672
 18,      101.666664,      1.5,      254.166672
 19,      101.666664,      52.5,      203.333328
 20,      101.666664,      1.5,      203.333328
 21,      101.666664,      52.5,      152.5
 22,      101.666664,      1.5,      152.5
 23,      101.666664,      52.5,      101.666664
 24,      101.666664,      1.5,      101.666664

```

|     |              |       |            |
|-----|--------------|-------|------------|
| 25, | 101.666664,  | 52.5, | 50.8333321 |
| 26, | 101.666664,  | 1.5,  | 50.8333321 |
| 27, | 101.666664,  | 52.5, | 0.         |
| 28, | 101.666664,  | 1.5,  | 0.         |
| 29, | 50.8333321,  | 52.5, | 305.       |
| 30, | 50.8333321,  | 1.5,  | 305.       |
| 31, | 50.8333321,  | 52.5, | 254.166672 |
| 32, | 50.8333321,  | 1.5,  | 254.166672 |
| 33, | 50.8333321,  | 52.5, | 203.333328 |
| 34, | 50.8333321,  | 1.5,  | 203.333328 |
| 35, | 50.8333321,  | 52.5, | 152.5      |
| 36, | 50.8333321,  | 1.5,  | 152.5      |
| 37, | 50.8333321,  | 52.5, | 101.666664 |
| 38, | 50.8333321,  | 1.5,  | 101.666664 |
| 39, | 50.8333321,  | 52.5, | 50.8333321 |
| 40, | 50.8333321,  | 1.5,  | 50.8333321 |
| 41, | 50.8333321,  | 52.5, | 0.         |
| 42, | 50.8333321,  | 1.5,  | 0.         |
| 43, | 0.,          | 52.5, | 305.       |
| 44, | 0.,          | 1.5,  | 305.       |
| 45, | 0.,          | 52.5, | 254.166672 |
| 46, | 0.,          | 1.5,  | 254.166672 |
| 47, | 0.,          | 52.5, | 203.333328 |
| 48, | 0.,          | 1.5,  | 203.333328 |
| 49, | 0.,          | 52.5, | 152.5      |
| 50, | 0.,          | 1.5,  | 152.5      |
| 51, | 0.,          | 52.5, | 101.666664 |
| 52, | 0.,          | 1.5,  | 101.666664 |
| 53, | 0.,          | 52.5, | 50.8333321 |
| 54, | 0.,          | 1.5,  | 50.8333321 |
| 55, | 0.,          | 52.5, | 0.         |
| 56, | 0.,          | 1.5,  | 0.         |
| 57, | -50.8333321, | 52.5, | 305.       |
| 58, | -50.8333321, | 1.5,  | 305.       |
| 59, | -50.8333321, | 52.5, | 254.166672 |
| 60, | -50.8333321, | 1.5,  | 254.166672 |
| 61, | -50.8333321, | 52.5, | 203.333328 |
| 62, | -50.8333321, | 1.5,  | 203.333328 |
| 63, | -50.8333321, | 52.5, | 152.5      |
| 64, | -50.8333321, | 1.5,  | 152.5      |
| 65, | -50.8333321, | 52.5, | 101.666664 |
| 66, | -50.8333321, | 1.5,  | 101.666664 |
| 67, | -50.8333321, | 52.5, | 50.8333321 |
| 68, | -50.8333321, | 1.5,  | 50.8333321 |
| 69, | -50.8333321, | 52.5, | 0.         |
| 70, | -50.8333321, | 1.5,  | 0.         |
| 71, | -101.666664, | 52.5, | 305.       |
| 72, | -101.666664, | 1.5,  | 305.       |
| 73, | -101.666664, | 52.5, | 254.166672 |
| 74, | -101.666664, | 1.5,  | 254.166672 |
| 75, | -101.666664, | 52.5, | 203.333328 |
| 76, | -101.666664, | 1.5,  | 203.333328 |
| 77, | -101.666664, | 52.5, | 152.5      |
| 78, | -101.666664, | 1.5,  | 152.5      |
| 79, | -101.666664, | 52.5, | 101.666664 |
| 80, | -101.666664, | 1.5,  | 101.666664 |
| 81, | -101.666664, | 52.5, | 50.8333321 |

```

82, -101.666664, 1.5, 50.8333321
83, -101.666664, 52.5, 0.
84, -101.666664, 1.5, 0.
85, -152.5, 52.5, 305.
86, -152.5, 1.5, 305.
87, -152.5, 52.5, 254.166672
88, -152.5, 1.5, 254.166672
89, -152.5, 52.5, 203.333328
90, -152.5, 1.5, 203.333328
91, -152.5, 52.5, 152.5
92, -152.5, 1.5, 152.5
93, -152.5, 52.5, 101.666664
94, -152.5, 1.5, 101.666664
95, -152.5, 52.5, 50.8333321
96, -152.5, 1.5, 50.8333321
97, -152.5, 52.5, 0.
98, -152.5, 1.5, 0.
*Element, type=C3D8I
1, 15, 16, 18, 17, 1, 2, 4, 3
2, 17, 18, 20, 19, 3, 4, 6, 5
3, 19, 20, 22, 21, 5, 6, 8, 7
4, 21, 22, 24, 23, 7, 8, 10, 9
5, 23, 24, 26, 25, 9, 10, 12, 11
6, 25, 26, 28, 27, 11, 12, 14, 13
7, 29, 30, 32, 31, 15, 16, 18, 17
8, 31, 32, 34, 33, 17, 18, 20, 19
9, 33, 34, 36, 35, 19, 20, 22, 21
10, 35, 36, 38, 37, 21, 22, 24, 23
11, 37, 38, 40, 39, 23, 24, 26, 25
12, 39, 40, 42, 41, 25, 26, 28, 27
13, 43, 44, 46, 45, 29, 30, 32, 31
14, 45, 46, 48, 47, 31, 32, 34, 33
15, 47, 48, 50, 49, 33, 34, 36, 35
16, 49, 50, 52, 51, 35, 36, 38, 37
17, 51, 52, 54, 53, 37, 38, 40, 39
18, 53, 54, 56, 55, 39, 40, 42, 41
19, 57, 58, 60, 59, 43, 44, 46, 45
20, 59, 60, 62, 61, 45, 46, 48, 47
21, 61, 62, 64, 63, 47, 48, 50, 49
22, 63, 64, 66, 65, 49, 50, 52, 51
23, 65, 66, 68, 67, 51, 52, 54, 53
24, 67, 68, 70, 69, 53, 54, 56, 55
25, 71, 72, 74, 73, 57, 58, 60, 59
26, 73, 74, 76, 75, 59, 60, 62, 61
27, 75, 76, 78, 77, 61, 62, 64, 63
28, 77, 78, 80, 79, 63, 64, 66, 65
29, 79, 80, 82, 81, 65, 66, 68, 67
30, 81, 82, 84, 83, 67, 68, 70, 69
31, 85, 86, 88, 87, 71, 72, 74, 73
32, 87, 88, 90, 89, 73, 74, 76, 75
33, 89, 90, 92, 91, 75, 76, 78, 77
34, 91, 92, 94, 93, 77, 78, 80, 79
35, 93, 94, 96, 95, 79, 80, 82, 81
36, 95, 96, 98, 97, 81, 82, 84, 83
*Nset, nset=_PickedSet2, internal, generate
1, 98, 1
*Elset, elset=_PickedSet2, internal, generate

```

```

1, 36, 1
** Region: (ISO:Picked)
*Elset, elset=_PickedSet2, internal, generate
1, 36, 1
** Section: ISO
*Solid Section, elset=_PickedSet2, material=ISO
1.,
*End Part
**
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name="ISO top-1", part="ISO top"
0., -1., 0.
*End Instance
**
*Instance, name="ISO bottom-1", part="ISO bottom"
*End Instance
**
*Instance, name="Adhesive 25-20-1", part="Adhesive 25-20"
0., 0.1, 0.
*End Instance
**
*Nset, nset=_PickedSet71, internal, instance="ISO bottom-1", generate
1, 97, 2
*Elset, elset=_PickedSet71, internal, instance="ISO bottom-1", generate
1, 36, 1
*Elset, elset=__PickedSurf72_S6, internal, instance="ISO top-1", generate
1, 36, 1
*Surface, type=ELEMENT, name=_PickedSurf72, internal
__PickedSurf72_S6, S6
*Elset, elset=_BottomSurAd_S2, internal, instance="Adhesive 25-20-1",
generate
1, 36, 1
*Surface, type=ELEMENT, name=BottomSurAd
_BottomSurAd_S2, S2
*Elset, elset=_adhesivetopsurface_S1, internal, instance="Adhesive 25-20-
1", generate
1, 36, 1
*Surface, type=ELEMENT, name=adhesivetopsurface
_adhesivetopsurface_S1, S1
*Elset, elset=_TopSurBottomISO_S4, internal, instance="ISO bottom-1",
generate
1, 36, 1
*Surface, type=ELEMENT, name=TopSurBottomISO
_TopSurBottomISO_S4, S4
*Elset, elset=_bottomsurfaceisotop_S4, internal, instance="ISO top-1",
generate
1, 36, 1
*Surface, type=ELEMENT, name=bottomsurfaceisotop
_bottomsurfaceisotop_S4, S4
** Constraint: Constraint-1
*Tie, name=Constraint-1, adjust=yes
BottomSurAd, TopSurBottomISO
** Constraint: Constraint-2

```

```

*Tie, name=Constraint-2, adjust=yes
adhesivetopsurface, bottomsurfaceisotop
*End Assembly
**
** MATERIALS
**
*Material, name=Adhesive25
*Elastic
    0.72395, 0.33
*Material, name=Adhesive100
*Elastic
    0.293027, 0.25
*Material, name=ISO
*Elastic
    137.895, 0.3
**
** BOUNDARY CONDITIONS
**
** Name: Fixed Type: Symmetry/Antisymmetry/Encastre
*Boundary
    _PickedSet71, ENCASTRE
** -----
**
** STEP: Step-1
**
*Step, name=Step-1
Load on the top of the ISO top
*Static
    1., 1., 1e-05, 1.
**
** LOADS
**
** Name: Pressure    Type: Pressure
*Dload
    _PickedSurf72, P, -0.0015
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Node Output
    CF, RF, RM, RT, TF, U, UR, UT
    V, VF, VR, VT
*Element Output, directions=YES
    ALPHA, CTSHR, DAMAGEC, DAMAGET, E, EE, ER, ESF1, IE, LE, MISESMAX, NE,
    NFORC, PE, PEEQ, PEEQMAX, PEEQT, PEMAG, PEQC, PS, S, SALPHA, SDEG, SE,
    SEE, SEP, SEPE, SF, SPE, THE, TSHR, VE, VEEQ, VS
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**

```

```

*Output, history, variable=PRESELECT
*End Step
** -----
**
** STEP: Step-2
**
*Step, name=Step-2
*Static
1., 1., 1e-05, 1.
**
** LOADS
**
** Name: Pressure    Type: Pressure
*Dload
_PickedSurf72, P, -0.004
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Node Output
CF, RF, RM, RT, TF, U, UR, UT
V, VF, VR, VT
*Element Output, directions=YES
ALPHA, CTSHR, DAMAGEC, DAMAGET, E, EE, ER, ESF1, IE, LE, MISESMAX, NE,
NFORC, PE, PEEQ, PEEQMAX, PEEQT, PEMAG, PEQC, PS, S, SALPHA, SDEG, SE,
SEE, SEP, SEPE, SF, SPE, THE, TSHR, VE, VEEQ, VS
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** -----
**
** STEP: Step-3
**
*Step, name=Step-3
*Static
1., 1., 1e-05, 1.
**
** LOADS
**
** Name: Pressure    Type: Pressure
*Dload
_PickedSurf72, P, -0.0051
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**

```

```

** FIELD OUTPUT: F-Output-2
**
*Output, field
*Node Output
CF, RF, RM, RT, TF, U, UR, UT
V, VF, VR, VT
*Element Output, directions=YES
ALPHA, CTSHR, DAMAGEC, DAMAGET, E, EE, ER, ESF1, IE, LE, MISESMAX, NE,
NFORC, PE, PEEQ, PEEQMAX, PEEQT, PEMAG, PEQC, PS, S, SALPHA, SDEG, SE,
SEE, SEP, SEPE, SF, SPE, THE, TSHR, VE,VEEQ, VS
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
** -----
**
** STEP: Step-4
**
*Step, name=Step-4
*Static
1., 1., 1e-05, 1.
**
** LOADS
**
** Name: Pressure      Type: Pressure
*Dload
_PickedSurf72, P, -0.0072
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-2
**
*Output, field
*Node Output
CF, RF, RM, RT, TF, U, UR, UT
V, VF, VR, VT
*Element Output, directions=YES
ALPHA, CTSHR, DAMAGEC, DAMAGET, E, EE, ER, ESF1, IE, LE, MISESMAX, NE,
NFORC, PE, PEEQ, PEEQMAX, PEEQT, PEMAG, PEQC, PS, S, SALPHA, SDEG, SE,
SEE, SEP, SEPE, SF, SPE, THE, TSHR, VE,VEEQ, VS
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step

```