GEORGEAU CONSTRUCTION RESEARCH CENTER

Title: **Means and Methods for Improving Structural Integrity of Roof Systems**

PI(s): **Upul Attanayake, Ph.D., P.E.**
Kanchani Basnayake, M.Sc.

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ABSTRACT

Roof covering failure is one of the most prominent failures observed during post hurricane and tornado disaster investigations. Roof covering failure allows water penetration leading to significant damages/losses to buildings' interiors; in most cases this leads to structural failure. The damages caused by such disasters are significant. Understanding the impact of such disasters on human lives, nature, and economies, Mr. Phil Georgeau provided funding to establish the Georgeau Construction Research Center (GCRC) at Western Michigan University to study the means and methods of improving the resilience of structures, including roofing systems. The research team was initially tasked to evaluate the means of improving the performance of flat roof systems by using adhesives and fasteners (a hybrid system). However, the team was more interested in learning state-of-the-art and practice to identify the knowledge gap and research needs for improving structural system resilience under damaging wind loads; of primary interest is the flat roof system. Hence, a thorough review of literature and industry practice was performed to document roofing systems, load path within the roof system and from roof to the building structural system, typical failures observed during past events, roofing construction industry practices/ experience/ perspective, recommendations for improving building envelope integrity and performance, available innovative materials and methods, construction quality assurance methods, maintenance requirements, etc. As a result, this report presents a comprehensive plan of research needs that highlights testing of components and assemblies of roofing systems, simulation needs for evaluating design loads by incorporating structural system response, and performance evaluation as part of construction quality control and asset management. This plan can be used for developing future research projects and implementation plans for project deliverables.

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1 INTRODUCTION

1.1 OVERVIEW

The Federal Emergency Management Agency (FEMA) Mitigation Assessment Teams (MATs) evaluate the performance of buildings subjected to natural and man-made hazards (FEMA 2016). In March 2005, FEMA published a summary report on building performance during the 2004 hurricane season (FEMA 2005). The report indicated that roof covering failure was one of the most consistent structural deficiencies observed during field investigations. Another critical aspect documented in FEMA (2005) is the damages to many critical and essential facilities including shelters, fire departments, hospitals, police stations, emergency operation centers, etc., during high winds due to the poor performance of building envelopes. The primary reasons for such failures is the lack of continuous load path to transfer a wind load from the roof system to the foundation. Following Hurricane Katrina, in 2006, FEMA published a report on building performance. Even though Katrina's wind speed is at/or below the design speeds, among other failure modes, roof decking blow-off was common.

Roof covering types (tiles, asphalt shingles, metal panels, membrane systems, etc.) have shown distinctly low performance levels. As an example, FEMA (2012) presents the observed failure of commercial and industrial buildings during the 2011 tornado outbreak in Alabama, Georgia, Mississippi, Tennessee, and Missouri (Figure 1-1). Failure of the roof deck-to-joist connections as well as the roof-to-wall panel connections was common. Such failures led to the collapse of walls leading to significant damages to buildings' interiors and occupants. Even though welds and screws were designed to carry codified wind loads, during hurricanes and tornadoes, large concentrated forces developed at these connections have ripped off the covering. In addition, cyclic loads acting on the roof can cause the screw holes to get larger making the failure imminent. Hence, there is an interest to use adhesives to enhance structural integrity of roof systems. However, there is a significant resistance to such applications, but the interest among the adhesive manufacturers and contractors is growing. As an example, a white paper was published by Fiberlite (2012) entitled "Roofing – Screw it or Glue it?" The paper discusses the most common reason for roof failures as blisters, open laps, splitting, punctures, penetrations, wrinkles, flashing, surfacing, fasteners, and abuse and neglect. Further, it provides a few case studies on the performance of roofs during Hurricane Katrina. One of the recommendations in the white paper is to "keep the edge and /or perimeter solid and intact to restrict air infiltration into the roof envelope by sealing the deck and wall interfaces." Even though the focus of the article by Fiberlite (2012) is on flat roof systems, some of the recommendations are equally applicable to the steep sloped roof systems. However, the most recent design of steep sloped roofs allows air flow through the attic, that could completely change the wind loads acting on the roofing system.

(a) Failed puddle welds that connected the metal roof deck to the top chord of the joist (red arrows) (FEMA 2012)

(b) Roof system purlins intact with metal roof clips released (red arrows) (FEMA 2012)

Figure 1-1. Roof system failure during the 2011 tornado outbreak

Roof covering failure allows water penetration leading to significant damages/losses to buildings' interiors; in most cases this leads to structural failure (FEMA 2012; FEMA 2005). The social and economic impacts of such disasters are significant. As an example, the damages during 2004 hurricane season required assisting more than 548,000 citizens utilizing the disaster recovery centers located in Florida, approving more than $605 million as public assistance and individual assistance disaster aid, and cleaning 53 million cubic yards of debris (FEMA 2005). Therefore, it is necessary to document the following: roof systems commonly used in hurricane prone and high wind areas, load path within the roof system and from roof to the building structural system, typical failures observed during past events, roofing construction industry practices/ experience/ perspective, recommendations for improving building envelope integrity and performance, available innovative materials and methods, construction quality assurance methods, maintenance requirements, etc. This process helps to identify the knowledge gap and research needs for improving structural resilience under damaging wind loads.

1.2 PROJECT OBJECTIVES AND SCOPE

The primary goal is to develop a research agenda that allows utilizing the research facilities currently being developed by the Center and identifying the expertise and additional resources needed for evaluating various roof systems and materials or mechanisms for improving structural/load path integrity to improve structural resilience under damaging wind loads.

The following are the objectives of this study:

1. Document roof structural systems and load paths.
2. Document means and methods for improving structural performance of roofs.
3. Develop an education and research agenda with short- and longer-term goals.

1.3 REPORT ORGANIZATION

The report is organized into five chapters:

- Chapter 1 includes an overview and project goals and objectives.
- Chapter 2 includes roofing system types, design, and performance; standards and specifications as well as the experimental, analytical, and numerical procedures used for calculating design loads; and roofing system performance evaluation methods.
- Chapter 3 includes a summary of the inputs collected from adhesive manufacturers, product manufacturers, roofing contractors, and consultants through a survey questionnaire.
- Chapter 4 presents a comprehensive plan of research needs that highlights testing of components and assemblies of roofing systems, simulation needs for evaluating design loads by incorporating structural system response, and performance evaluation as part of construction quality control and asset management.
- Chapter 5 includes the reference list.

The following appendices are included in the report.

- Appendix A: Abbreviations
- Appendix B: Recommendations for Improving Building Envelope Integrity and Performance During High Wind Events
- Appendix C: Survey Questionnaire
- Appendix D: Project Specification Standards
- Appendix E: Product Performance Evaluation Standards

2 STATE-OF-THE-ART AND PRACTICE

2.1 OBJECTIVE AND APPROACH

Figure 2-1 illustrates the major topics (roofing system types, design, and performance) and the sub-topics covered in this chapter. Roofing system types and associated components are discussed. Standards and specifications used for the design of roofing systems as well as the experimental, analytical, and numerical procedures used for calculating design loads are discussed. Roofing system performance is evaluated using laboratory and field tests, numerical and experimental simulations, and by visual inspection supported with limited application of non-destructive testing methods. As an example, wind uplift tests are conducted to evaluate the performance of roofing systems under laboratory conditions while insurance agencies and government agencies conduct visual inspection to assess post-disaster damages. The tools (if any) used for such inspection and the findings documented in post-disaster reconnaissance reports are documented in this chapter. The manuals, guides, specifications, post disaster reconnaissance reports published by agencies such as the Federal Emergency Management Agency (FEMA), product manufacturer technical datasheets, and national and international scholarly articles are used as the primary sources of information.

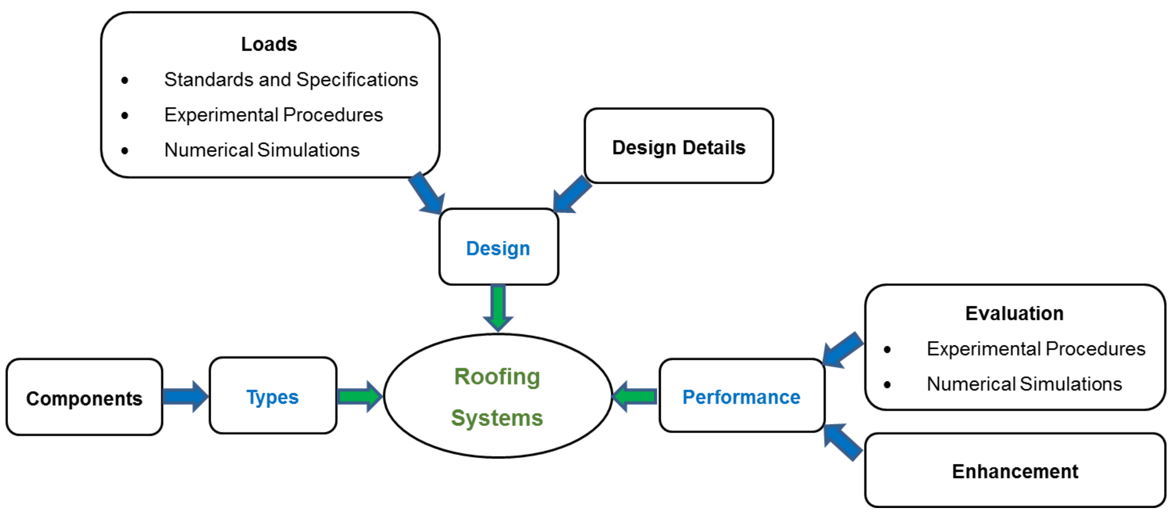


Figure 2-1. An illustration of major and sub-topics covered in Chapter 2

2.2 ROOFING SYSTEMS

A roofing system protects an interior of a building from different climatic conditions such as rain, snow, and wind. It also helps to regulate the interior condition of the building. According to the National Roofing Contractors Association (NRCA), two roofing system categories are defined based on the pitch: steep slope roofs (pitch > 14^0) and flat roofs (pitch ≤ 14^0). The steep slope roofs are further classified into four groups based on the orientation of the roof pitch. They are gabled roofs, hipped roofs, mansard roofs, and shed roofs. The steep slope roofs are used abundantly in residential construction while the flat roofs are mostly used in commercial buildings.

A typical roofing system consists of one or more of these components: roof covering (waterproof membranes, shingles, tiles etc.), insulation, membranes (single ply membranes, Spray Polyurethane Foam (SPF) membranes, etc.), air barriers, vapor barriers, and vapor retarders. According to the Handbook of Accepted Roofing Knowledge by NRCA (1983), the deck is not a part of a roofing system. A roofing assembly is formed when a roofing system is integrated with a deck (metal, concrete, or wooden deck) to safely transfer the loads to the supporting structure. Steel and concrete are favored as roof decks in commercial buildings. Lightweight, strength, and economy make steel the deck of choice for longer spans. The wooden deck, which is often supported over a roof truss, is a popular choice in residential construction. Irrespective of the roof angle and the exposure conditions, the roof covering forms the surface layer and the roof deck forms the support in a roofing system. The arrangement of the interior layers depends on the roof angle and the climatic exposure conditions.

2.3 STEEP SLOPED ROOF SYSTEMS

Shingled roofs (with asphalt shingles, concrete tiles, slate shingles, clay tiles or wooden shingles), thatched roofs and metal roofs are examples for steep sloped roofs (Figure 2-2).

Clay-tiled roof **Asphalt-shingled roof** **Thatched roof** **Metal roofs**

Figure 2-2. Types of steep sloped roofs (Turner Roofing Company Inc. 2018)

2.3.1 Components of a Steep Sloped Roof Assembly

Figure 2-3 illustrates an exploded view of a typical steep sloped roof assembly.

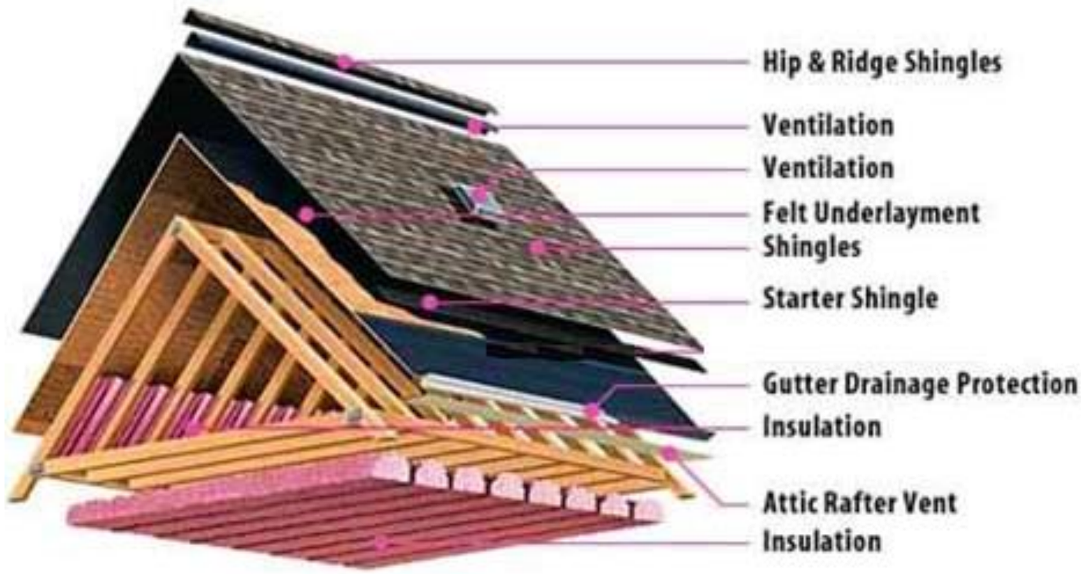


Figure 2-3. A typical steep sloped roof assembly (OldProRoofing 2014)

2.3.1.1 Roof Covering

Asphalt shingles, clay tiles, concrete tiles, slate shingles, metal shingles and wooden shingles are the popular choices as roof coverings in steep sloped roofs. Shingles are made of asphalt, metal, plastic, wood, slate, flagstone, and composite materials. Shingles are produced in a single layer or in two or more layers. For example, asphalt shingles have a base layer and a surface layer. The base layer is made with asphalt and fillers, and gives strength to the shingle. The Surface layer is mostly composed of mineral granules and provides necessary protection. Tiles are made of local materials such as clay and slate or modern materials such as concrete and plastic. Material and testing standards published by the American Society for Testing and Materials (ASTM), Factory Mutual (FM), and Underwriters Laboratory (UL) define the suitability of shingles and tiles for roofing application. Natural thatching, such as reed and palm, and synthetic thatching are used as roof coverings in thatched roofs.

2.3.1.2 Underlayment and Sheathing

An underlayment is provided over a roof deck as the second barrier against moisture intrusion through unsealed locations on the roof and in situations where shingles tear off due to undesirable weather conditions. A majority of the underlayments are asphalt based products such as saturated felts, synthetic underlayments and rubberized asphalt underlayments. Asphalt saturated felts, one of the oldest underlayments used in the industry, are the weakest waterproofing material among the three types. Synthetic underlayments are of an asphalt saturated fiberglass material with relatively better wearing resistance. Because of their ability to be used with waterproofing products, they are more popular than the asphalt saturated felts. On the other hand, the rubberized underlayment contains asphalt and rubber polymers thereby making it both waterproof and expensive. Selection of the type of underlayment depends on the expected weather in the region, slope of the roof and the specific location of the roof. For instance, waterproof underlayments are used at roof eaves, valleys, and at the joints with chimneys and skylights (Long roofing 2017). In certain scenarios, sheathings are applied in addition to the underlayment laid over the deck, but this is not mandatory. Oriented Strand Board (OSB) and plywood are the most commonly used roof sheathings.

2.3.1.3 Insulation

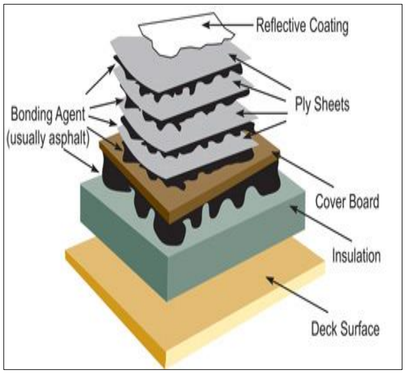
The insulation materials used in steep sloped roofs are similar to those discussed under flat roof systems. The location of the insulation layer can be at the ceiling level (as shown in Figure 2-3) or between the rafters.

2.4 FLAT ROOF SYSTEMS

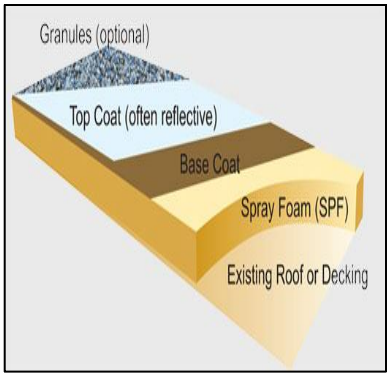
Built-up roofs (BURs), spray polyurethane foam (SPF) roofs, single ply membrane roofs, and metal panel roofs are the prominent flat roof systems. Figure 2-4 shows the roof systems and their components.

BURs are commonly known as "tar and gravel" roofs and have been in the US for over 100 years. Alternating layers of ply sheets (often referred as roofing felts) and bitumen add strength to the BUR systems. The bitumen can be asphalt, coal tar or a cold applied adhesive, and it acts as the bonding agent that binds the ply sheets together. Reflective coatings, aggregates, glass fiber or mineral surfaced cap sheets, aluminum coatings, elastomeric coatings or hot asphalt mopping are a few surfacing types used in BURs (NRCA n.d.).

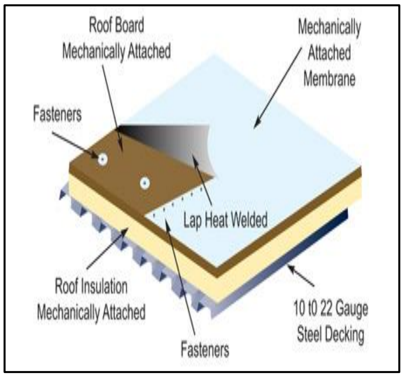
In SPF roof systems, the foam is sprayed over the roof deck up to a desired thickness. The thickness of the foam determines the drainage and the thermal resistance of the roof. The foam is composed of two components: isocyanate and polyol. The two components are heated, proportioned at a 1:1 ratio, mixed together and sprayed over the deck using a spray gun. Later, a protective coating of acrylic, butyl rubber, silicon or elastomers is applied over the foam. In certain cases, mineral granules or sand is incorporated into a surface coating (NRCA n.d.).



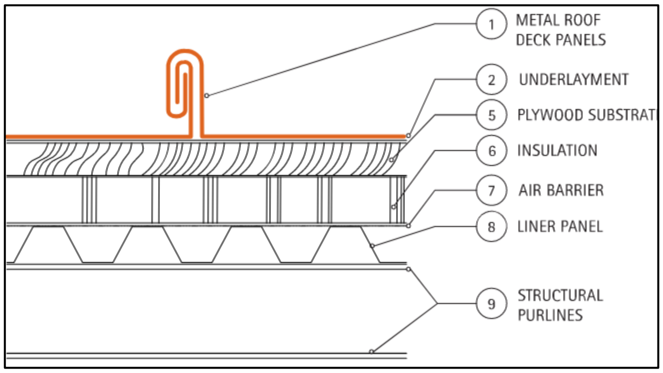
Built-up roof (Roofing Southwest n.d.)



Spray polyurethane foam roof (Roofing Southwest n.d.)



Single ply membrane roof (Roofing Southwest n.d.)



Metal panel roof (Copper Development Association Inc. n.d.)

Figure 2-4. Flat roof types and their components

In single ply membrane roofs, factory manufactured single ply sheet membranes are either mechanically attached or adhered onto the roof deck over an insulation layer. These single ply membranes can be thermoset or thermoplastic. Thermoplastic membranes (thermoplastic polyolefin (TPO) and poly vinyl chloride (PVC)) and thermoset membranes (ethylene propylene diene monomer (EPDM)) are the main two types of single ply membranes used in roofing. The installation of a surfacing layer over the single ply membrane is optional (NRCA n.d.).

The metal roof systems consist of structural metal panels due to their inherent hydrostatic nature. The panels are installed over continuous or closely spaced supports such as purlins. If spaced supports are used, underlayments are often installed under the metal panels. Installation of vapor retarders, air barriers, and insulation as needed help to prevent the moisture condensation problems that occur within metal panel systems (NRCA n.d.).

2.4.1 Components of a Flat Roof Assembly

Figure 2-5 illustrates a typical section of a flat roof assembly.

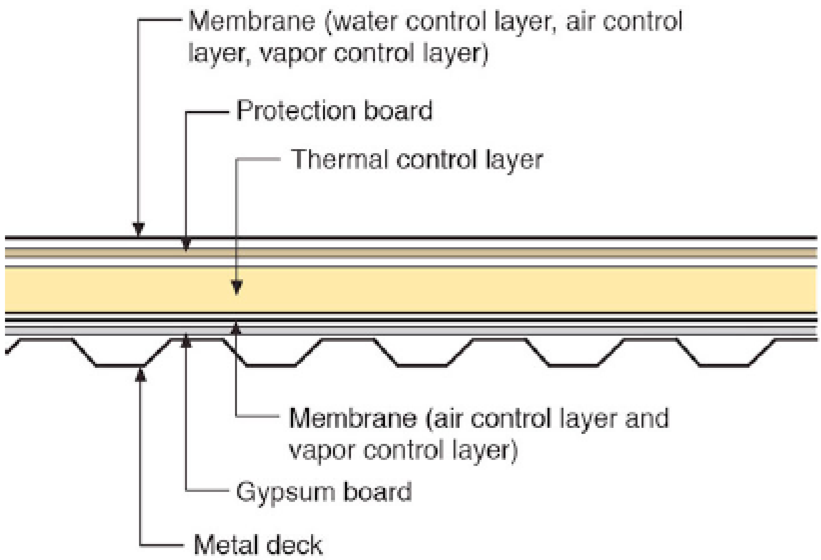


Figure 2-5. Typical section of a flat roofing assembly (Lstiburek 2016)

2.4.1.1 Roof Covering

Mostly in flat roofs, except in metal roof systems, the roof covering is a waterproof membrane with adequate physical resistance, thermal resistance, wearing resistance, and durability. Occasionally, this membrane is paved with a loose ballast to hold down the membrane. In non-metal roof systems, surfacing techniques such as aggregate surfacing with bitumen and protective coatings are applied over the roof covering to improve its durability and wearing resistance. Use of a vegetative surface cover has been the latest trend to minimize the heat island effect and to improve energy efficiency and aesthetics.

2.4.1.2 Vapor Control Layer

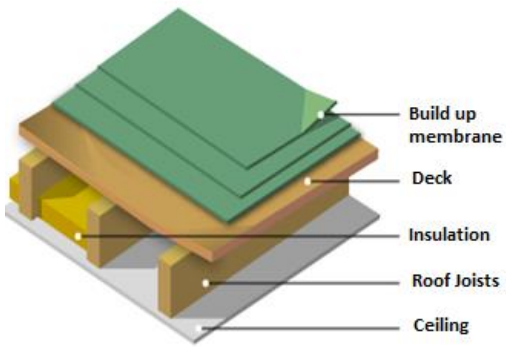
Vapor control layers are typically vapor barriers or vapor retarders: a vapor barrier prevents the migration of water vapor while a vapor retarder slows down the migration of water vapor. In practice, it is hard to find a vapor barrier. Based on the climate of a region, water can migrate from the exterior of the building to the interior or vice versa. Therefore, the exact location of the vapor barrier/retarder in a roofing assembly is determined based on the climatic conditions. As an example, under cold climatic conditions, a vapor barrier is placed at the bottom of the assembly while it is placed at the top of the assembly in hot climatic conditions (Pierson 2016). Two of the most popular vapor retarders are polyethylene plastic sheets and two-ply fiberglass felts adhered with hot asphalt. In addition, any material with a permeability rating of 1.0 or less in accordance to ASTM E1745 is suitable as a vapor retarder (Pierson 2016).

2.4.1.3 Air Control Layer/Air Barrier

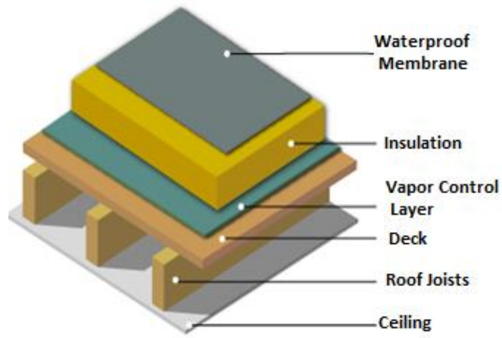
The purpose of an air control layer or an air barrier is to control the airflow within a roof system; as a result, the vapor movement is controlled. An air barrier needs to be continuous, durable, strong, and air impermeable. The other benefits of an air barrier are improved energy efficiency, increased comfort, odor control, and noise control (Straube 2011).

2.4.1.4 Thermal Control Layer/Insulation

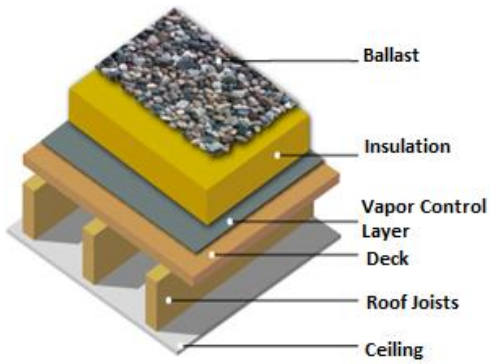
Insulation is often referred to as the thermal control layer. R-value, which represents the capacity of a material to resist heat flow, is the primary factor used to select a material for a specific application. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 outlines required R-values and the amount of insulation required to achieve certain R-values based on the building location (Blum 2007). The insulation layer needs to meet the design requirements for tensile strength, compressive strength, flexural strength, fire resistance, corrosion resistance, and moisture resistance. Polyisocyanurate (Poly iso) boards are the most popular insulation used in commercial roofing applications, along with polystyrene foam, perlite, and wood fiberboard (Singh et al. 2005). The compatibility of the insulation layer provided in a roof with the other layers is important, especially in an adhesive applied roofing system. Based on the location of the insulation layer, flat roofs are termed as warm roofs (insulation above the roof deck), cold roofs (insulation below the roof deck), and inverted warm roofs (insulation above all the other layers) as in Figure 2-6 (Greenspec n.d.).



Warm roof



Cold roof



Inverted warm roof

Figure 2-6. Warm roof, cold roof, and inverted warm roof (Greenspec n.d.)

2.4.2 Historical Background and Evolution of the Flat Roof Systems

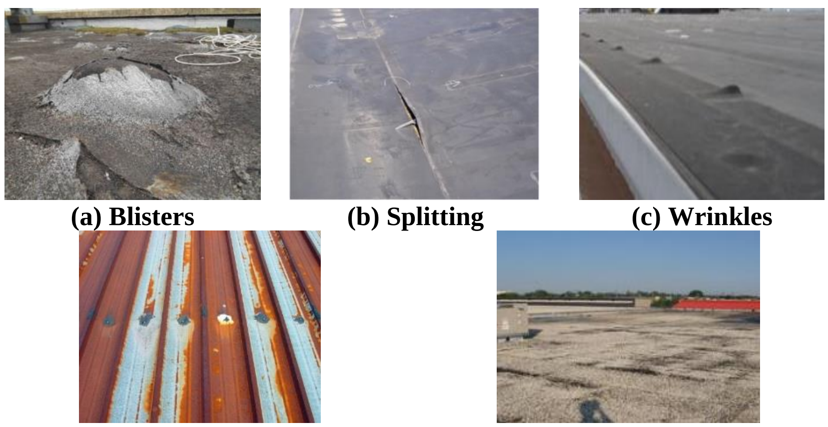
By 1990, BUR had been dominating the flat roof market for over 140 years. However, BUR's market share reduced from one third to 15% from the 1990s to 2005. Instead, single ply roof systems and modified bituminous membrane roof systems increased their market dominance to nearly 70% in 1990 from being at less than 10% in 1980. According to a RSI (Roofing Siding Insulation) survey, by the year of 2005, modified bituminous and cold applied bitumen roof systems held one third of the market share, EPDM roof systems held 30%, metal roofs held 10% and PVC and TPO membranes held about 20% of the flat roof system market. The emergence of new, high strength and lightweight roofing materials, rise of concerns about the environmental pollution, safety and energy costs, and ease of prefabrication with less labor intensive installation, led to BURs decrease in popularity o during the 1990s (Griffin and Fricklas 2006).

2.5 PERFORMANCE OF ROOFING AND STRUCTURAL SYSTEMS

Roofing failure damages the building interior and potentially lead to complete structural failure. Based on the severity of the failures, roof failures can be categorized as performance failures and structural failures. Roofing failures that have an impact on the aesthetic appearance and hinder the functioning of the roof are known as performance failures. On the other hand, structural failures are due to overloading or lack of capacity resulting from degradation of the components, connections, and primary/secondary members in the load path, or a combination thereof.

2.5.1 Performance Failures

Membrane failures (blisters, splitting, wrinkles, and punctures), fastener failure, surfacing failure, flashing failure, and ponding are a few common performance failures of flat roofs (Payne 2012). Figure 2-7 shows a few examples of flat roof performance failures. Although some of these performance failures seem superficial, if not attended and repaired, they could lead to further deterioration and severe damages.



(a) Blisters **(b) Splitting** **(c) Wrinkles**

(d) Fastener failure **(e) Surface failure**

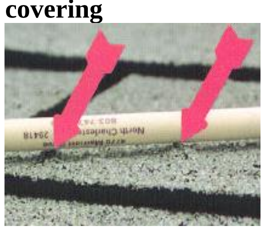
Figure 2-7. A few examples of flat roof performance failures (Payne 2012)

The most commonly observed performance failures of steep slope roofing are in the roof coverings. A majority of performance failures are due to weathering and aging of the roofing components as shown in Figure 2-8(a). The brittling and shrinkage of roof covering, patterned cracks, loss of mineral granules, and algae growth are few examples. Shingle splitting, as shown in Figure 2-8(b), occurs in asphalt shingles due to thermal expansion and contraction. Diagonal tearing in asphalt shingles, as shown in Figure 2-8(c), is observed due to underlying deck movement or severe foundation settlement. Blisters, shown in Figure 2-8(d), are a result of heating up and vaporizing of the volatiles in asphalt shingles (Marshall et al. n.d.). Figure 2-8(e) shows buckled shingles. This is a result of having wrinkled underlayment, lack of roof ventilation, roof deck movement, lack of spacers between roof deck boards, or a combination thereof (Roofmax n.d.).

(a) Weathered roof covering

(b) Splitting

(c) Diagonal tearing



(d) Blisters

(e) Buckling

Figure 2-8. Failures of steep sloped roof systems (Haag Engineering n.d.)

2.5.2 Structural Failures

The interaction of wind with a typical structure causes positive pressure on the surfaces (walls and roof) on windward side and negative pressure (suction) on the leeward surfaces as well as on the surfaces that are parallel to the wind direction. Figure 2-9 shows the loads acting on a flat roof structure. Wind uplift of a roof occurs when the negative pressure of passing wind pulls the assembly (Payne 2012).

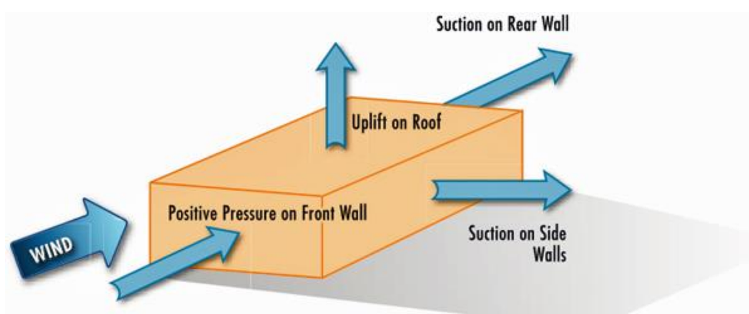


Figure 2-9. Wind flow around a typical flat roof building (FEMA 2007)

A wind flowing over and around a building causes the wind flow separation at locations such as corners of roofs and walls, ridges, hips, and overhangs. This flow separation creates small vortices that cause much higher pressures in localized areas. These flow separation regions generally occur along the edges and the perimeter of the roof as shown in Figure 2-10. Therefore, the design wind pressures used in the production of roof cladding can be nearly three times higher than the pressure used for designing structural framing of the building (FEMA 2009). As detailed later in the report, failures are mostly initiated at these locations.

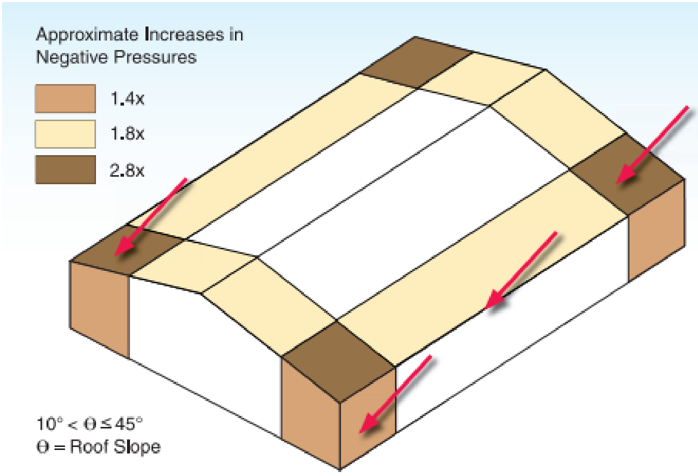


Figure 2-10. High wind pressure zones on a roof (FEMA 2009)

After every major event, FEMA conducts investigations, primarily visual inspections, and develops assessment reports. Each of the mitigation assessment reports submitted by FEMA after hurricane events provides recommendations for improvements to the current design practice. The observations and recommendations provided in these reports have resulted in modifications and additions to the existing design codes and standards, installation techniques, construction practices, and maintenance practices. The goal of developing such recommendations is to prevent the occurrence of similar failures during future events. Hence, the existing national and regional building design codes and standards were updated by incorporating modified design details of structural members and connections, providing clear definitions and details to establish structural load paths, updating wind maps, etc.

FEMA P-55 presents two diagrams, as shown in Figure 2-11 and Figure 2-12, illustrating a timeline of the significant coastal flood and wind events that occurred during the period from 1900 to 2010, along with important milestones for changes to regulations, building codes, and construction practices (FEMA 2011).

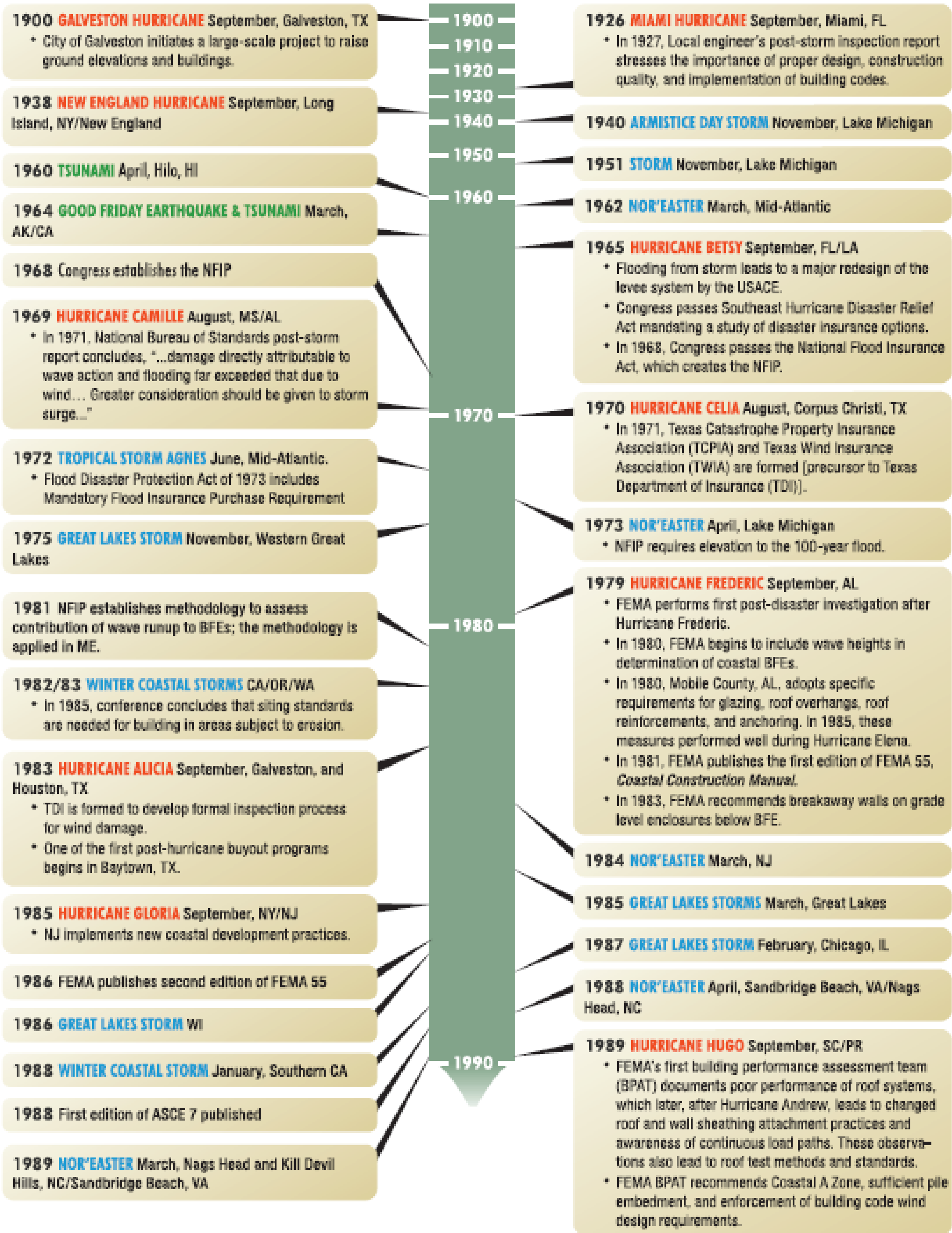


Figure 2-11. 1900 to 1990 timeline of significant coastal flood and wind events and important milestones for changes to regulations, building codes, and construction practices (FEMA 2011)

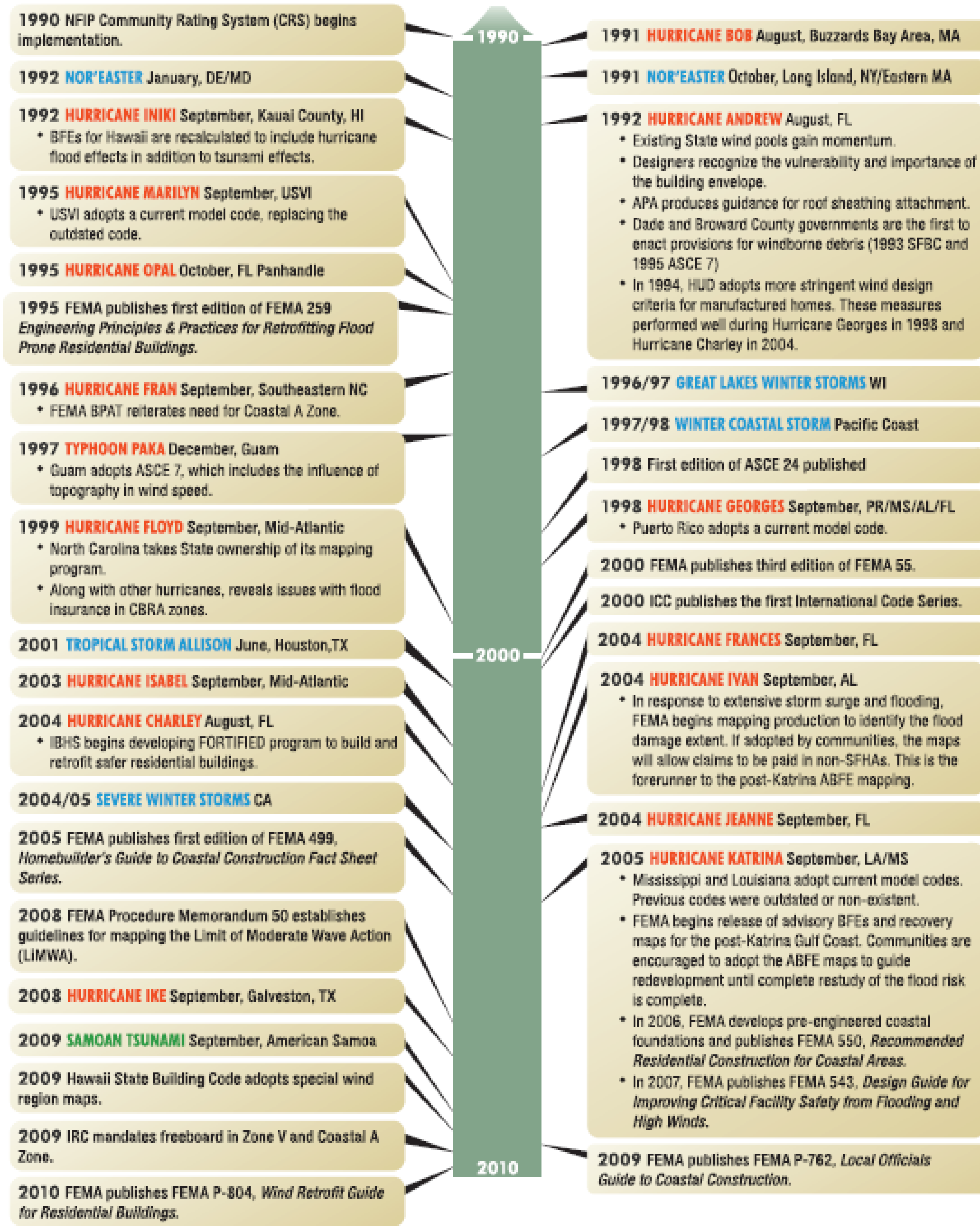


Figure 2-12. 1990 to 2000 timeline of significant coastal flood and wind events and important milestones for changes to regulations, building codes, and construction practices (FEMA 2011)

Figure 2-11 and Figure 2-12 show the evolution of design and construction guidelines and specifications following historical events. In 1980, the Mobile County, Al, adopted specific requirements for glazing, roof covering, roof reinforcements, and anchoring after Hurricane Frederic in 1979. Later in 1985, Hurricane Elena proved the performance improvements due to adopting new roofing requirements. Following 1989's Hurricane Hugo, the Building Performance Assessment Team (BPAT) formed by FEMA documented poor roof system performance. However, until after observing the damages due to 1992's Hurricane Andrew, the importance of maintaining integrity of a building envelope and continuous load paths was not highlighted. Following Hurricane Andrew, wall and roof sheathing attachment practices and foundation requirements were changed. During the same period, APA published the guidance for roof sheathing attachment. Based on the observations and lessons learned during past events, the following publications resulted:

- FEMA 55 - Coastal Construction Manual, first edition in 1981, second edition in 1986, and third edition in 2000
- The first edition of ASCE 7, 1988
- FEMA 499 - Homebuilder's Guide to Coastal Construction Fact Sheet Series, 2005, (comprises 37 technical data sheets specializing in areas such as planning, foundations, load paths, wall systems, openings, roofing systems, and roof repairs)
- FEMA 550 - Recommended Residential Construction for Coastal Areas, 2006
- FEMA 543 - Design Guide for Improving Critical Facilities Safety from Flooding and High Winds, 2007
- FEMA P-804 - Wind Retrofit Guide for Residential Buildings, 2010

In addition to the publications listed in Figure 2-11 and Figure 2-12, the following new publications and the new editions have resulted from the lessons learned from past events:

- SSTD 10-99 Hurricane Resistant Construction Standard (provides design and construction details for ensuring structural integrity of single and family dwellings within the limitations in building geometry, materials and climate)

- ICC 600-2014: Standard for Residential Construction in High-Wind Regions (is based on SSTD 10 and material standards, to provide wind resistant design and construction details for masonry, concrete, wood framed or cold formed steel residential buildings in regions with wind speeds of 120 to 180 mph.)

- 2014 ICC/NSSA Standard for the Design and Construction of Storm Shelters

- FEMA P-55, Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas, 4th Edition, 2011

Roof covering damage is commonly observed in both low slope and steep sloped roofs after high wind events. According to FEMA (2009), roof covering damage ranges from a loss of a few shingles to loss of a large number of coverings and underlayment. Use of roof covering that does not meet the specified regional requirements (as an example, the class of asphalt shingles for a specified design wind speed) and failure to follow the installation guidelines for high wind regions were two major reasons for roof covering damages in newer buildings. Roof covering damages in older buildings were mainly age related - weathering of roof coverings and limitations in the codes and standards that were in effect at the time of original construction.

Figure 2-13 illustrates few steep sloped roof covering failures due to poor or incorrect installation. Figure 2-13(a) shows a house in Mississippi that lost several shingles during Hurricane Katrina in 2005. Incorrect application of the shingle starter course was identified as the cause for this failure (FEMA 2005). Figure 2-13(b) shows unlatching of concealed clips from the metal panels of a roof in Galveston Island, Texas, during Hurricane Ike in 2008. Upon inspection, it was found that the first row of clips indicated by the red line in Figure 2-13(b) was installed several inches from the roof eave whereas it should have been within a few inches from the roof eave (FEMA 2009). In most of the mortar set tiled-roofs, use of lesser amounts of mortar paddies and incorrect placement on the roof reduced the tiles' uplift resistance during high winds.

Similarly, in foam-set tiled roofs, inadequate size of foam paddies, installation of foam paddies at incorrect locations on the roof, and use of screws instead of the foam (as instructed in manufacturer's guidelines) resulted in tile damages during high winds (FEMA 2005). Figure 2-13(c) illustrates the failure of clay tiles in a foam-set tiled roof due to an inadequate foam contact area at the head and tail of a tile during Hurricane Charley in 2004. Figure 2-13(d) illustrates the uplift of ridge tiles due to poor attachment during Hurricane Katrina in 2005. The wind turbulence is very high in areas behind parapet walls and causes the ridge tiles behind the parapet to uplift (FEMA 2006).

(a) Loss of shingles during Hurricane Katrina, 2005 (FEMA 2006)

(b) Concealed clips unlatched from the metal panels during Hurricane Ike, 2008 (FEMA 2009)

(c) Loss of clay tiles during Hurricane Charley, 2004 (FEMA 2005)

(d) Uplift of ridge tiles during Hurricane Katrina, 2005 (FEMA 2006)

Figure 2-13. Roof covering damages due to incorrect or poor installation practices

The roof covering damage in a flat roof includes roof membrane peeling, punctures, tearing, and blow off. In most cases, roof membrane blow off occurs as a result of lifting and peeling off of the edge flashing or coping. Blow off may also be due to lifting of the gutter which, in turn, causes the lifting of the edge flashing as shown in Figure 2-14(a) (Smith 2017). This problem applies not to flat roofs but also to steep sloped roofs, such as shingled roofs; the shingles can undergo a progressive failure when the edge flashing fails as illustrated in Figure 2-14(b).

(a) Lifting and peeling off of build-up membrane (Smith 2017)

(b) Failure of shingles during Hurricane Charley, 2004 (FEMA 2005)

Figure 2-14. Progressive failure of roof covering due to edge or coping failure

Figure 2-15(a) shows an improper installation of an edge flashing in a modified bitumen membrane roof. In this case, the edge flashing is installed underneath the membrane whereas it should have been installed over the membrane. Wind can easily penetrate through an unsealed location such as the opening shown in Figure 2-15(a) and lift up the roof membrane (Smith 2017). Figure 2-15(b) shows the traditional metal edge or coping attachment installed on a roof using concealed cleats. Here, the vertical flange of the metal edge or cope is lifted up and deformed under wind loads. Generally, this causes the edge or cope failure to continue and causes the membrane to lift and peel off (FEMA 2005).

(a) Improper installation of an edge flashing

(b) Disengagement of the flashing from the cleat and lift up of the vertical flange

Figure 2-15. Failure of edge flashing (Smith 2017)

As shown in Figure 2-16, uplift of the roof gutters could potentially lift the edge or cope flashing that extends down into the gutter. Lifting of the edge or cope flashing leads to the progressive peel off and failure of roof membrane. Since gutters are usually designed to resist only the gravity loads, special attachments with adequate wind uplift resistance need to be used (Smith 2017). Lack of testing and design standards for gutters further contributed to the lifting and peeling of roof membranes during hurricanes (FEMA 2006).

Figure 2-16. Roof gutter with hanger bracket attachment (Smith 2017)

Roofing designs without key components or details required for wind uplift resistance could easily trigger failures. One such example is the omission of an air barrier on mechanically attached roofing systems in high wind regions. Typically, an air barrier is installed in between a rigid insulation and a porous deck. Otherwise, air passage through the deck causes membrane fluttering that leads to partial or complete disengagement of the membrane (Figure 2-17). The EPDM roof membrane failure of the Louisiana Superdome under high winds of Hurricane Katrina is an example of this phenomenon (Progar 2005).

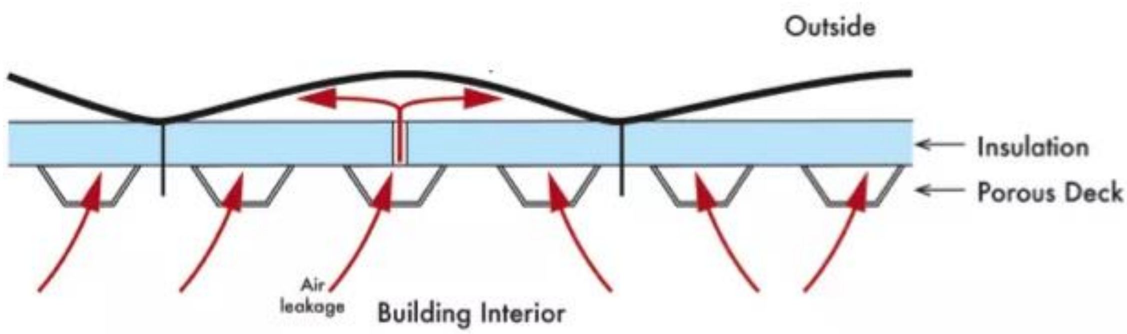


Figure 2-17. Membrane fluttering due to lack of an air barrier (Building Science Corporation 2016)

The locations of high-pressure zones, discussed in section 2.6.2, are evident from the roof covering damages observed after hurricanes. Figure 2-18(a) shows the roof covering damage in an apartment complex in Ocean Springs, Mississippi, during Hurricane Katrina. Figure 2-18(b) shows the detachment of a cementitious wood-fiber deck panel in a school in Biloxi, Mississippi, due to an inadequate attachment to the support structure. These type of old wood-fiber deck panels were unable to withstand the increased uplift loads at the roof edge (an indication of the need for roofing system load capacity assessment). The damages at roof corners, edges, and ridges were commonly observed (FEMA 2006).

(a) Roof covering damage **(b) BUR panel blow off at a roof corner**

Figure 2-18. Roof damages indicating high-pressure zones during Hurricane Katrina (FEMA 2006)

Indirect cause of roof structure failure during high winds is the internal pressurization of the building due to failure of windows or doors located along the wind paths (FEMA 2005). Figure 2-19 (a) shows the failure of a complete roof structure of a masonry residential building in Punta Gorda, Florida, during Hurricane Charley in 2004. The failure of doors and windows led to the internal pressurization of the building, which led to the roof structure blow off. Similarly, Figure 2-19 (b) shows the failure of plywood sheathing in a wood framed residential building in Ocean Springs, Mississippi, during Hurricane Katrina in 2005. Initially, the gable end wall of the building failed leading to the pressurization of the attic. As a result, the roof sheathing (indicated by red arrows) blew off. In both cases, the ‘enclosed’ and maybe the ‘partially enclosed’ design criteria was violated with the failure of the openings in the structure.

(a) Failure of a wood roof structure in a masonry building (FEMA 2005)

(b) Failure of plywood sheathing in a wood framed building (FEMA 2006)

Figure 2-19. Failure of roof structures due to internal pressurization of buildings

Progressive failure of structures due to lack of continuous load paths in structural systems was observed. As discussed in section 2.5.2., a structure needs to be constructed with members and connections of adequate resistance along the load path to safely transfer the loads to the foundation. Improperly designed, undersized, unprotected or improperly attached metal straps, anchors or mechanical fasteners at connections of a load path result in roof and/or structure failure. Figure 2-20 shows the failure of connections along the load path during Hurricane Iniki in 1992. Figure 2-20(a) shows a failure at the roof to wall connection that occurred because the toenailing of the roof rafters to wall system could not withstand the wind load. Figure 2-20(b) shows the failure of a metal fastener strip under wind uplift forces.

(a) Failure of roof rafter to wall connection due to uplift forces

(b) Failure of an undersized and improperly attached metal fastener

Figure 2-20. Failure of connections located along the load path (FEMA 1993)

Upon the failure of a connection or a member in the load path, structural performance is controlled by the ability of remaining members in the load path to withstand the loading that was not typically considered during design. Members in the alternate load path also factor into this situation. Several partial or complete structure failures due to a lack of continuous load paths have been reported. Figure 2-21(a) shows a failure of an exterior wall of a two-story light framed wood building during Hurricane Iniki in 1992. Once the roof system of the building failed due to wind overload, the capacity of the exterior walls to withstand the direct wind pressure was reduced and resulted in wall failure. Figure 2-21(b) shows a failure of a wood framed exterior wall and roof trusses during Hurricane Iniki. Once the roof sheathing was damaged, the truss system became unstable. The connections between the roof trusses and wall system had insufficient load capacity to maintain the load path that led to the failure of the system (FEMA 1993).

(a) Failure of exterior walls **(b) Failure of truss and exterior wall connection**

Figure 2-21. Structural failure due to lack of a continuous load path (FEMA 1993)

The performance of roofing systems during high wind events differ from each other. Even though the factors such as quality of materials and construction techniques definitely affect the performance, in general the following conclusions were drawn on the performance of different roofing systems.

Aggregate-ballast paved roofing systems perform well in high winds. However, if the aggregate-ballast is not properly designed and attached, it can blow off and damage the adjacent buildings upon impact. Figure 2-22(a) and Figure 2-22(b) show this phenomenon where the roofing membrane and glass on the façade of a building were damaged due to aggregate impact under high winds.

(a) Membrane damage (Smith 2017)

(b) Broken glasses in a façade (FEMA 2006)

Figure 2-22. Damages to the adjacent buildings due to aggregate impact

On the other hand, the impact of aggregate blow off to the SPF roofing systems and liquid coated roofing systems is minimum. Further, SPF roofing systems and liquid coated roofing systems have performed well under high wind situations, unless the substrate to which the SPF foam or the liquid is applied is uplifted. BURs and modified bitumen roofing systems without aggregate surfacing have demonstrated relatively better performance, unless the edge flashing or the coping fails. The performance of metal panel roofing systems has been highly variable and heavily dependent on the panel attachment techniques. The fully adhered single ply roofs have proven to be less problematic; however, they are very vulnerable upon projectile impacts (Smith 2017). Therefore, by overcoming these shortcomings of roofing systems through the proper modifications, it is possible to enhance their performance against wind loads.

2.6 DESIGN WIND LOADS AND DETAILS

2.6.1 Determination of Wind Loads

Wind loads typically govern the design of a roof. Individual components as well as the complete roofing system should be designed to provide the necessary capacity against wind loading. After a roof configuration is selected, the design requires accurate quantification of wind load magnitudes and load patterns. Standard guidelines, specifications, and wind tunnel tests are used to calculate wind loads and patterns. As needed, computational fluid dynamic (CFD) simulations can be performed for such purposes.

2.6.1.1 Standard Guidelines and Specifications for Wind Loads

Standard guidelines and specifications are required in designing a structure to satisfy strength and serviceability requirements. ASCE 07 is one such standard widely used in the US to calculate the minimum design loads for buildings and structures. Chapters 26 to 31 of ASCE 07-10 outline several procedures to calculate the design wind loads on the main wind force resisting systems (MWFRS) and on the components and claddings. Directional procedure, envelope procedure, and wind tunnel testing are discussed in ASCE 07-10. Building enclosure, site location, surface roughness of the site, building rigidity, and building height are the primary parameters considered for identifying wind pressure and load patterns (ASCE 2010).

The design wind pressure formula given in ASCE 07 is used to calculate the design wind load of a roof. The other standards used for wind load calculation include Factory Mutual (FM) 1-28, International Building Code (IBC), and local building codes (Florida Building Code (FBC), New York Building Code etc.). However, all these standards adapt the design wind pressure formula given in ASCE 07 as the fundamental basis in their wind load calculation procedures.

2.6.1.2 Determination of Wind Loads Using Wind Tunnel Tests

Wind tunnel tests are used to forecast static and dynamic wind pressure loads on roofing components or a complete structure. The design coefficients specified in current design codes such as ASCE 07-10 are mostly based on wind tunnel testing. Wind tunnel tests are conducted to determine the loads on iconic structures or when such structures are not covered within the scope of existing standards. Further, wind tunnel tests are used to validate results obtained through other techniques such as computational fluid dynamics. Wind tunnel testing requires the technical expertise and considerable resources.

Wind tunnel experiments require modeling the building and the environment to an appropriate scale and subjecting to simulated scaled wind conditions. Instruments installed within the tunnel measure the wind velocities, pressures, forces, and accelerations. In most of the cases, the data obtained are transferred into non-dimensional coefficients such as pressure coefficients, which can be directly used in structural design (Geurts n.d.). Technical guidelines issued by ASCE, the Council on Tall Buildings and Urban Habitat (CTBUH), the Boundary Layer Wind Tunnel Laboratory (BLWTL) in Canada, and the Council on Undergraduate Research (CUR) in the

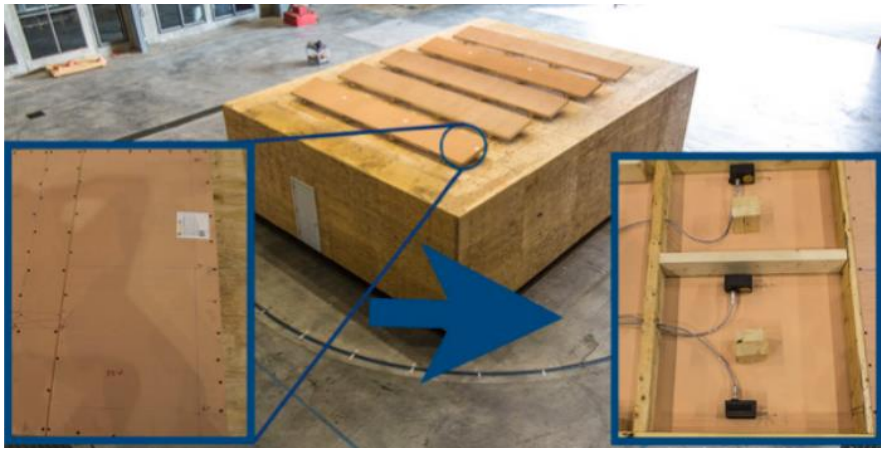
Netherlands outline the procedures of conducting wind tunnel experiments, collecting and analyzing data, and interpretation of results. Chapter 31 of ASCE 07-10 describes the wind tunnel procedure for structures (ASCE 2010).

2.6.1.3 Determination of Wind Loads on Rooftop Structures and Equipment

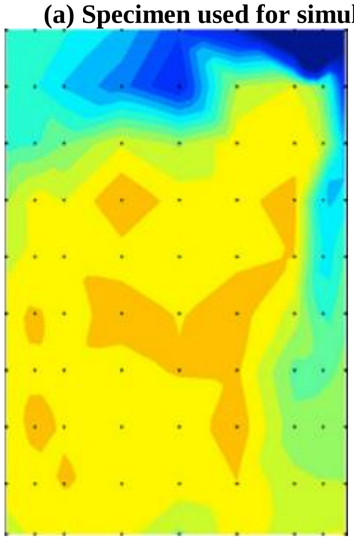
Determination of wind loads on rooftop structures and equipment is equally important as the determination of the loads on the roof and the main structure. Failure cases during high wind events have proven that the failure of rooftop equipment causes significant damages to the roof system and the surrounding structures. Chapter 29 of ASCE 7-10 describes application of the directional procedure to calculate wind pressure on rooftop structures and equipment. Two equations are presented, one for the buildings taller than 60 ft and the other one for buildings less than or equal to 60 ft In addition, an equation to calculate the vertical uplift force on rooftop structures and equipment in buildings of less than 60 ft is given. However, for parapets and roof overhangs, the directional procedure is recommended for buildings of all heights, and the envelope procedure is recommended for low rise buildings. The values for the pressure coefficients used in the wind pressure calculation were derived from the wind tunnel test procedures conducted on scale models (ASCE 2010).

Specific provisions are not included in ASCE 07-10 or prior versions for calculating wind loads on rooftop mounted solar photovoltaic (PV) systems. Alternatively, the available design provisions in ASCE 07-10 to calculate the wind pressure on different roof types can be used. For flat roof mounted PV systems or flush mounted PV systems, the external pressure coefficients for the flat roof itself can be used to calculate the wind pressure. For tilted PV systems with a tilt angle greater than 10 degrees, the equation to calculate the design wind pressure of a mono-slope roof can be used (Banks 2014). However, the accuracy of these approximations is highly doubtful. The PV array is a collection of solar cells. Factors such as the distance to the roof edge, the distance between two adjacent cells, direction of the wind, friction coefficient of the cells etc., influence the wind patterns and the loads; hence, additional research was needed. Based on wind tunnel testing results, the Solar Photovoltaic System Committee of the Structural Engineers Association of California (SEAOC) published a report on the Wind Design for Low Profile Solar Photovoltaic Arrays on Flat Roofs (SEAOC PV2-2012). SEAOC PV2-2012 outlines procedures to calculate wind pressure on flat roof mounted solar PV arrays and guidelines on the wind tunnel testing of roof mounted solar panels (SEAOC, 2012). These findings are modified and incorporated into the new ASCE 07-16 provisions, along with the introduction of the SEAOC PV2-16.

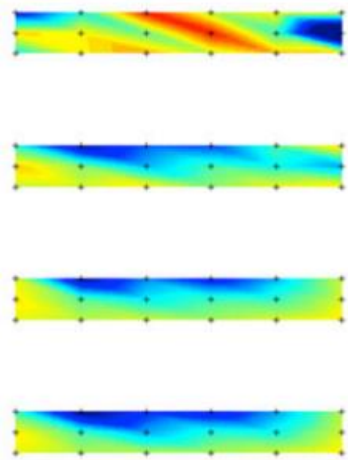
Wind tunnel testing is another popular technique used to determine the wind loads on rooftop structures and equipment. Several wind tunnel test studies have been conducted to identify the behavior of flow patterns around roof-mounted equipment and to obtain the resulting wind loads. Pratt and Kopp (2013) investigated the wind flow around solar PV arrays mounted on a building using wind tunnel testing. It was discovered that a peak uplift on the solar panels mounted at the leading edge of the building occurs due to a building generated vortex interacting with the solar panels. The results indicate that the evaluation of solar panels without incorporating the supporting structure would not have replicated this actual flow pattern around the solar panels (Pratt and Kopp 2013). Erwin et al. (2011) conducted full scale testing of air conditioner (A/C) condensers mounted on a building, using a 6-fan Wall of Wind (WoW) apparatus. The A/C condensers were mounted on an aluminum stand fastened to the roof of the building. Subsequently, the wind was applied perpendicularly to the roof edge. The detachment of the A/C stand from the roof of the building was identified as a possible failure mode (Erwin et al. 2011). This is a good example that shows the initiation of roof failure due to the failure of rooftop attachments. The Insurance Institute for Business and Home Safety (IBHS) conducted full-scale testing to determine wind loads on solar PV arrays on flat roofs in 2014 (Figure 2-23). The results indicated impact of roof top mounted PV arrays on the roof wind load distribution (IBHS 2014).



(a) Specimen used for simulation of wind loads on roofs with solar panels



(b) Pressure distribution on the roof



(c) Net pressure on the solar panels

Figure 2-23. (a) Specimen used for the experiment, (b) roof wind pressure distribution, and (c) wind pressure on solar panels (IBHS 2014)

However, several challenges and limitations were associated with the wind tunnel experiments conducted to evaluate the performance of rooftop equipment. When small scale testing is conducted, it is a challenge to install a sufficient number of pressure taps to capture the pressure distribution. This lack of sufficient data can result in inaccurate pressure averaging over an area, resulting in inaccurate force values (Erwin et al. 2011).

A majority of wind tunnel test procedures included only the rooftop structure or the equipment without incorporating the supporting structure. With such procedures, interaction of the wind with the complete system is not properly captured. Numerical modeling is useful in identifying the wind flow path and patterns around roofing systems and rooftop equipment and in identifying the pressure distribution due to wind flow. The disadvantages of scaled down model testing in wind tunnels can be overcome through numerical modeling. Further, alternative configurations and connection details can be evaluated through numerical simulations. This will help to develop favorable aerodynamic features around the rooftop equipment, thus improving the performance of the entire roof system.

2.6.2 Design Details for a Continuous Load Path

As discussed previously, until after observing the damages due to 1992's Hurricane Andrew, the importance of maintaining integrity of a building envelope and continuous load paths was not highlighted. After learning from past events, details were developed to provide continuous load paths to safely transfer the loads to the ground. Connections between the members along such load paths play a key role and usually are the weakest links in the load path. Figure 2-24 shows typical one-story wood framed building members and connections that are critical to transfer wind pressure loading to the ground.

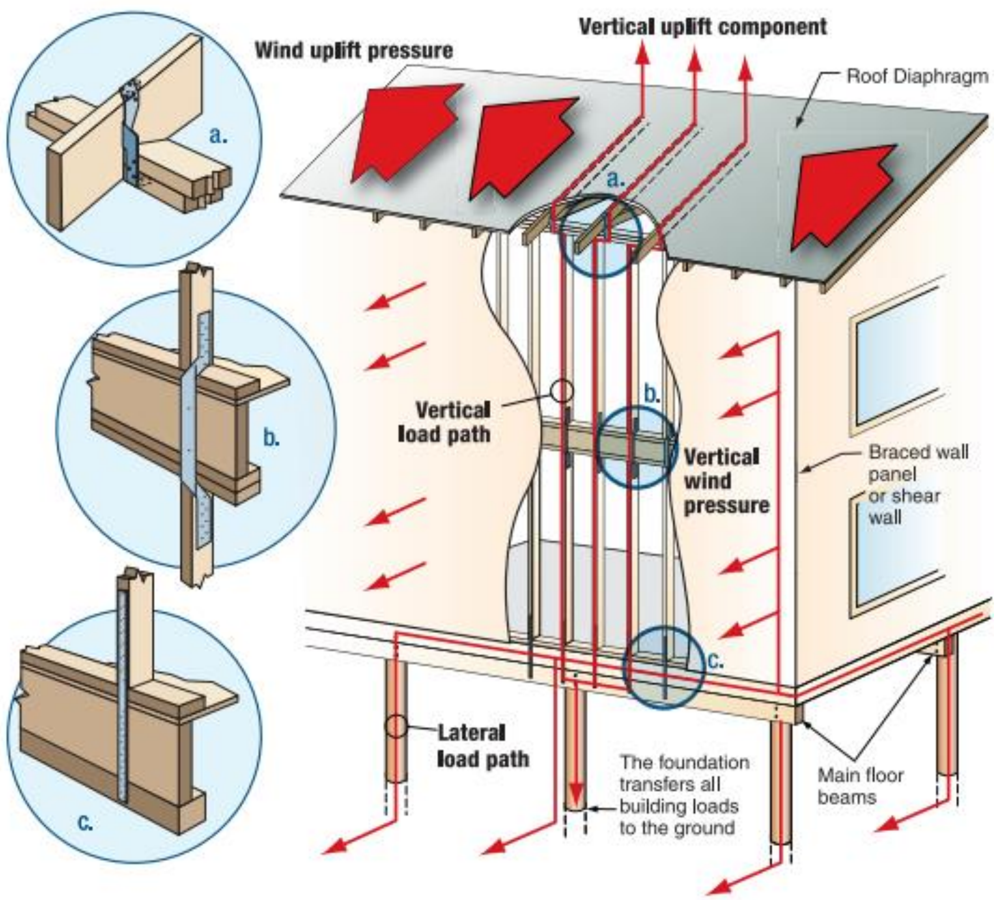


Figure 2-24. Load path of a typical wood frame building (FEMA 2006)

As shown in Figure 2-24, the structural system consists of roof trusses, load bearing walls, shear walls, floor beams, and footings. Four critical locations through which the wind uplift load at the roof level is transferred into the ground are indicated on the figure. At the roof level, the roof coverings are connected to the underlayments through fasteners or adhesives, and underlayments and sheathing are connected to the roof truss through fasteners. Wind uplift force experienced by the roof covering is transferred along these connections onto the roof truss. The ties at the roof to wall connection (at location a) direct the load from the roof truss to the load bearing walls. This load path is continued from the upper wall to the lower walls through the wall stud connection at location b. At location c, the accumulated load is transferred from wall studs to the floor beams and then to the foundation through the brackets or bolts at the connection. It should be noted that this load path of a building varies with the type of construction and building design details. In case of the failure of a member(s) or a connection(s) along a defined load path, the remaining members of the load path have to withstand the load, or an alternate path is generated as a new load path. Because of this reason, the structure needs to be evaluated as a system to identify the critical members and the redundancy in the system.

Appendix B describes the recommendations provided in FEMA P-499 and in the Summary Report on Building Performance - 2004 Hurricane Season (FEMA 2005).

2.7 EXPERIMENTAL EVALUATION OF ROOFING SYSTEM PERFORMANCE

Static and dynamic wind uplift tests are conducted to evaluate the strength and serviceability performance of roofing components and systems as well as to identify the possible failure locations and failure modes under simulated wind loads. According to Baskaran et al. (1999a), static tests tend to yield conservative results while failures under dynamic tests could closely resemble the observed failures in the field. However, the duration of a static test is significantly shorter compared to that of a dynamic test. Most importantly, the actual wind conditions experienced by a roof are dynamic and non-uniform in nature.

Static and dynamic test standards and guidelines are developed by several organizations. Factory Mutual (FM), Underwriters Laboratories (UL), and the American Society for Testing and Materials (ASTM) have published standards and guidelines for static wind uplift tests. The European Organization for Technical Approvals (EOTA), the Norwegian Building Research

Institute (NBI), and the Canadian Standards Association (CSA) have published standard procedures for dynamic wind uplift tests. The performance of individual roofing components is often evaluated under laboratory conditions while the performance of roofing assemblies is evaluated either under laboratory or outdoor conditions. Figure 2-25 illustrates the wind uplift test procedures used under laboratory and outdoor (field) conditions. The test methods are classified under flat roofs and steep sloped roofs. The wind uplift test procedures are discussed in the following sections.

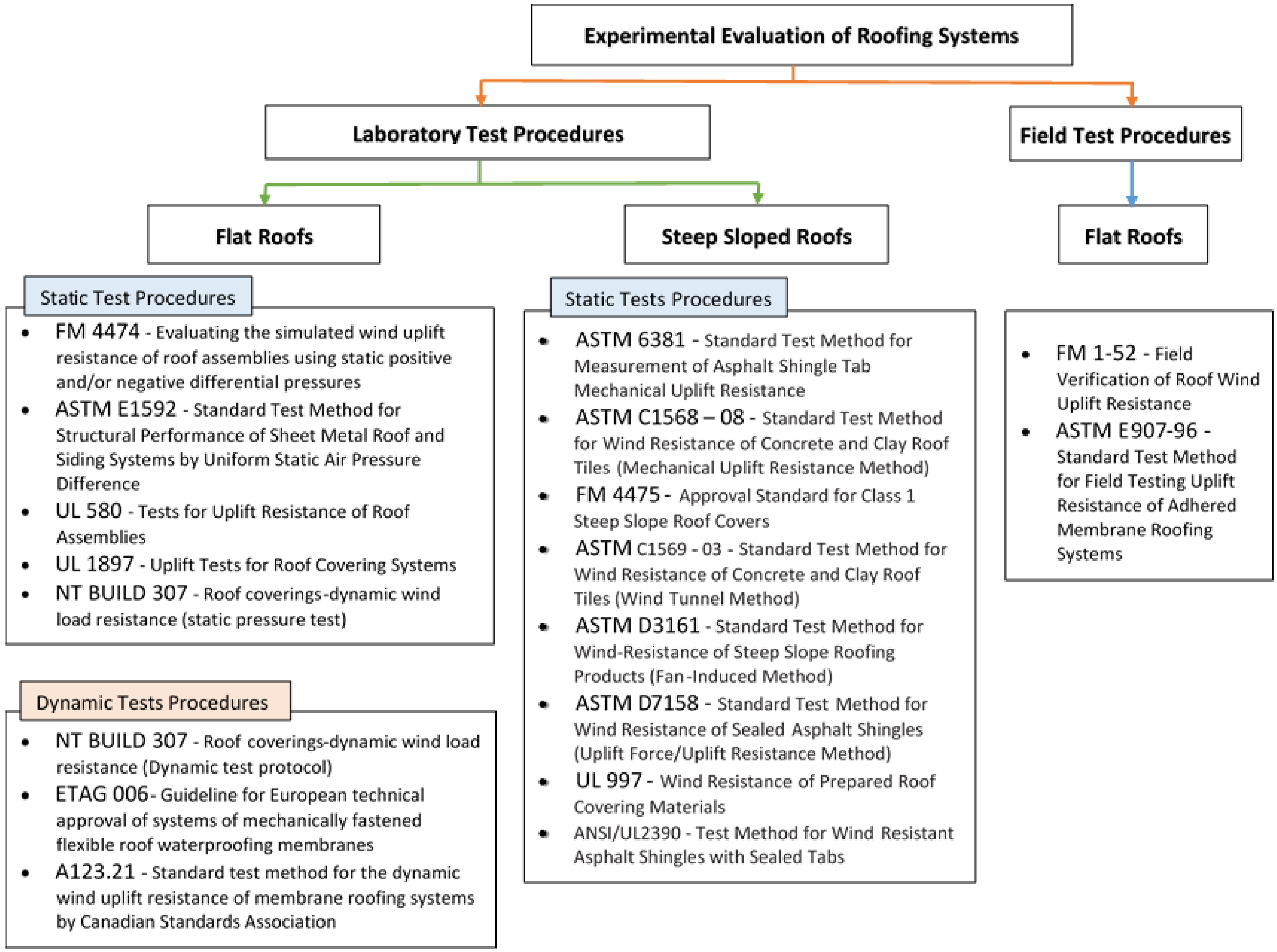


Figure 2-25. A summary of wind uplift test standards

2.7.1 Laboratory Wind Uplift Tests

Standard laboratory tests are conducted to evaluate the suitability of products for specific applications and possible failure mechanisms and locations of roofing assemblies. The findings are used to improve product and roofing assembly performance. FM 4474, ASTM E1592, UL 580, UL 1897, and NT BUILD 307 outline laboratory static wind uplift tests for flat roofs. NT BUILD 307 (by NBI), ETAG 006 (by EOTA), and A123.21 (by CSA) outline laboratory dynamic wind uplift tests for flat roofs. ASTM D3161, UL 997, ASTM D6381, ASTM D7158, UL 2390, ASTM C1568, ASTM C1569, and FM 4475 outline laboratory test procedures to evaluate the wind uplift resistance of steep sloped roofs. An overview of these test methods is presented in the subsequent sections of this report.

Several standard laboratory wind uplift test procedures for flat roofs are available. A typical test set up consists of a pressure chamber and/or a vacuum chamber and a frame to support the test specimen, as shown in Figure 2-26.

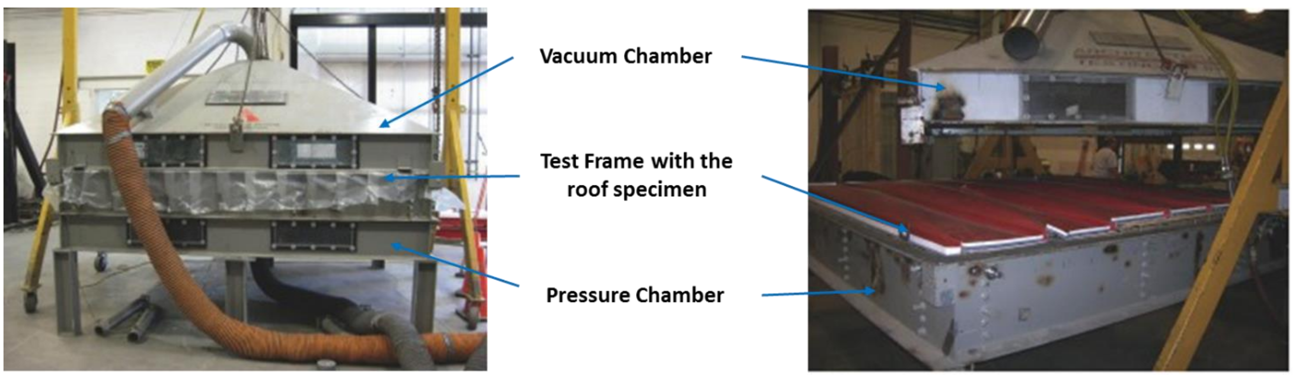


Figure 2-26. A typical wind uplift test setup used for the evaluation of flat roof assemblies (ConstructionMagnet Contributors 2010)

Testing standards use different terms to describe the components of this test setup. For example, the pressure chamber is often referred as the bottom chamber, pressure vessel or positive pressure chamber whereas the vacuum chamber is often referred as the suction chamber or top chamber. The test frame is often referred to as the mounting panel. Throughout this report, bottom chamber, top chamber and test frame are used.

2.7.1.1 FM 4474: Evaluating the Simulated Wind Uplift Resistance of Roof Assemblies Using Static Positive and/or Negative Differential Pressures

FM 4474 was first introduced in 2004 by Factory Mutual (FM) Approval under the certification of the American National Standards Institute (ANSI), and it was reaffirmed in 2011 without any major revisions. This standard describes mainly three-test methods to evaluate the uplift resistance of a complete roof assembly when subjected to positive and/or negative differential pressures. These tests include a pull test using a 2 ft × 2 ft specimen and simulated wind uplift tests using either a 5 ft × 9 ft or a 12 ft × 24 ft test frames. FM 4474 can be used to evaluate different types of roofing assemblies, except the loosely laid ballast roof systems (FM 2011).

For the pull test, a 2 ft × 2 ft sample of the roofing assembly is prepared as per the manufacturer's specifications and cured under laboratory conditions for a period of not more than 28 days. The test sample is then adhered onto a specimen that is representative of the roof deck. Next, a 24 in. × 24 in. × ¾ in. plywood piece is adhered on the top of the test sample with a compatible adhesive. Finally, a test jig with a centrally located eye-bolt is attached onto the plywood. The test jig is a 24 in. × 24 in. metal plate fastened onto the 24 in. × 24 in. × 3⁄4 in. plywood plate. A test specimen configuration is shown in Figure 2-27.

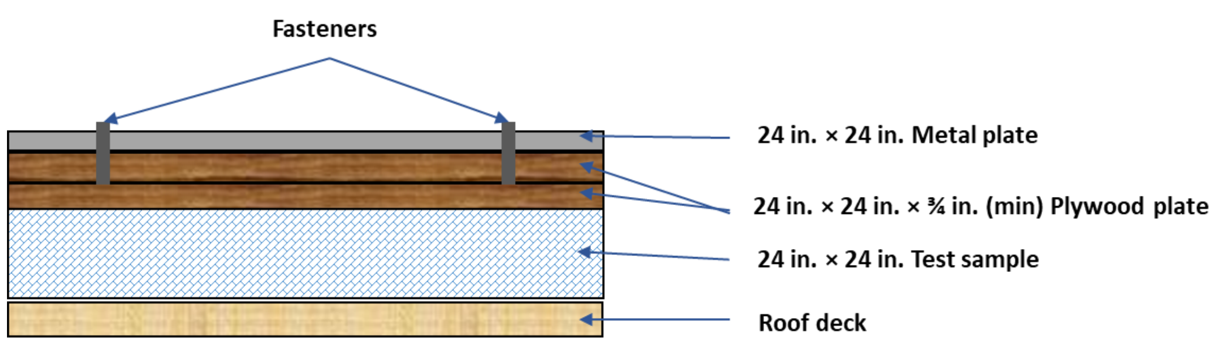


Figure 2-27. Test jig used in a FM 4474-pull test

The use of a 5 ft × 9 ft test frame is limited to certain flat roof types. The specimen is prepared as per manufacturer specifications and mounted on the steel frame. A gasket is used between the specimen and the pressure chamber, and the specimen is clamped to the frame. According to FM 4474, the pressure is applied using only the bottom chamber. An initial uplift pressure of 15 psf is applied to the sample and maintained for 60 seconds during which the sample is visually examined to verify if the conditions of acceptance specified in FM 4474 are satisfied. Upon satisfactory observations, the uplift pressure is applied successively in 15 psf increments. The pressure is increased at a uniform rate of 1.5 psf/sec. At each of the 15 psf pressure increments, the pressure is maintained for 60 seconds, and the sample is visually examined. This process is continued until the sample fails to maintain the conditions of acceptance or the maximum pressure of 90 psf is reached. The Simulated Uplift Resistance Rating is equal to the maximum uplift pressure that the assembly could sustain for a period of 60 seconds prior to failure or the maximum pressure that the apparatus could maintain: 90 psf for the 5 ft × 9 ft frame.

The 12 ft × 24 ft frame is used for evaluating specific roof systems by applying pressure using only the bottom chamber. The specimen mounting procedure as well as the loading cycles are similar to those of a 5 ft × 9 ft frame. However, a maximum pressure for this apparatus is not defined. Hence, the rating is equal to the maximum uplift pressure that the assembly could sustain for a period of 60 seconds prior to failure or the maximum pressure at which the test is terminated. Figure 2-28 shows a 12 ft × 24 ft frame with a specimen.

Figure 2-28. Testing of a Sika Sarnafil Rhinobond roof using a 12 ft × 24 ft frame (Sika n.d.)

In addition to the aforementioned three-test procedures, two-alternate test methods are given in FM 4474 for evaluating roofing systems using the 12 ft × 24 ft test frame. These two methods require applying a suction pressure by placing the top chamber over the test specimen, in addition to the pressure applied using the bottom chamber. For the alternate method 1, 85% of pressure is applied as a vacuum pressure using the top chamber while the remaining 15% of pressure is applied as a positive pressure using the bottom chamber. For the alternate method 2, 100 % of the pressure is applied as a vacuum pressure using the top chamber. The loading pattern used for both methods is similar to the one described above for the 5 ft × 9 ft frame (FM 2011).

2.7.1.2 ASTM E1592: Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Difference

The ASTM E1592, originally introduced in 1995 and reapproved in 2017, describes a test procedure to evaluate the uplift resistance of sheet metal roof systems. This test method is applicable to standing seam, trapezoidal, ribbed or corrugated metal panels with a thickness ranging from 0.012 in. to 0.05 in. with single skin construction or one sheet metal layer of multiple skin construction. The roof specimen is mounted on a test frame, and the frame is placed over a 12 ft × 24 ft pressure chamber, as shown in Figure 2-29. The length and width requirements of the test specimens are provided in the standard. Displacement measuring devices are mounted on the test specimen to measure the maximum mid span deflection. As a reference, a displacement measuring device is mounted near the edge of the specimen and at one structural rib that is not influenced by the attachments to the test chamber. Additional dial gauges are mounted as needed.

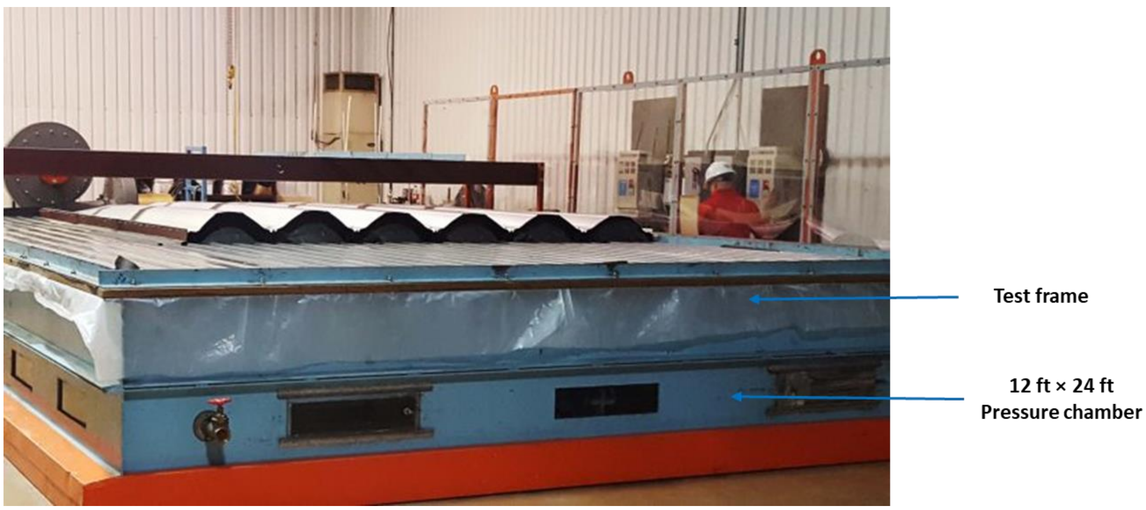
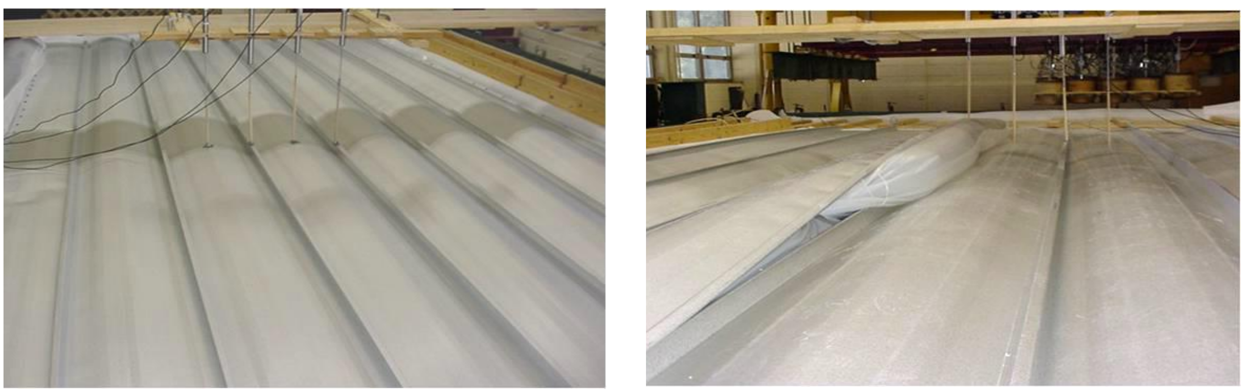


Figure 2-29. Test setup as per ASTM E1592 (Allen 2016)

The initial pressure applied on the specimen is equal to at least four times but not more than ten times the dead weight of the specimen. The displacements recorded at this initial pressure are taken as the references. After that the pressure is increased to one third of the anticipated failure pressure (first increment of load), unless the manufacturer specifies a different pressure value.

This pressure is held constant for 60 seconds and then the pressure is completely released. Following a recovery period of not more than 5 minutes, the pressure is increased to the reference value. After that, the permanent deformation of the panel for this first load increment is recorded. This procedure is repeated in successive increments that do not exceed one sixth of the maximum specified load, until failure is observed or the maximum specified pressure for the specimen is reached. This loading sequence is designed to produce a minimum of six data points in order to develop the load-deflection curve for the roof panels (ASTM 2017).

Figure 2-30 illustrates the ASTM E1592 test conducted at the Missouri Institute of Technology on 16 in., 24 gauge Gr 50 steel metal sheets, placed at a 5 ft - 1 in., purlin spacing. The roof panel profile and the layout was selected to withstand a design uplift wind load of 30-35 psf and the test was conducted until failure. Figure 2-30(b) shows the seam line failure, which resulted in the panels' loss of integrity under the load (Sinno 2008).



(a) Roof panels during loading **(b) Failure at seam lines**

Figure 2-30. Roof test specimen under ASTM E1592 test (Sinno 2008)

2.7.1.3 UL 580: Tests for Uplift Resistance of Roof Assemblies

UL 580 evaluates the uplift resistance of any roof assembly that can be adaptable to the test apparatus. The test apparatus mainly has three parts: a vacuum chamber to apply steady and oscillating negative pressures, a test frame to place the testing roofing assembly, and a pressure chamber to apply a steady positive pressure to the test specimen (as illustrated in Figure 2-31).

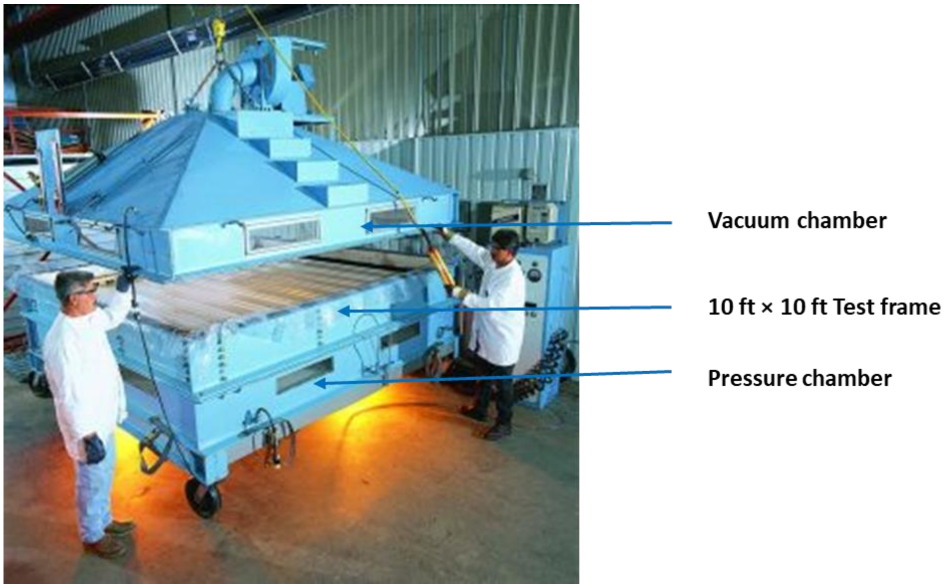


Figure 2-31. Test apparatus of UL 580 (Allen 2016)

Unlike FM 4474, UL 580 is not a pass or fail test. In UL 580, four rating classes namely UL 15, UL 30, UL 60, and UL 90 are specified for the roofing assemblies (Table 2-1, column a). In order to achieve a particular rating class, a roofing assembly has to undergo a loading sequence composed of five phases (Table 2-1, column b). During each of these phases, a positive and a negative pressure are applied simultaneously for a specified duration (Table 2-1, columns c-e). The total duration of the test for a rating class is 80 minutes. During test phase 3, the negative pressure magnitude is allowed to fluctuate while the positive pressure is held constant.

Table 2-1. UL Loading Sequence

Rating (a)	Test Phase (b)	Duration, min (c)	Negative Pressure, psf (kPa) (d)	Positive Pressure, psf (kPa) (e)
UL 15	1	5	9.4 (0.45)	0.0 (0.0)
	2	5	9.4 (0.45)	5.2 (0.25)
	3	60	5.7 – 16.2 (0.27 – 0.78)	5.2 (0.25)
	4	5	14.6 (0.7)	0.0 (0.0)
	5	5	14.6 (0.7)	8.3 (0.4)
UL 30	1	5	16.2 (0.79)	0.0 (0.0)
	2	5	16.2 (0.79)	13.8 (0.66)
	3	60	8.1 – 27.7 (0.39 – 1.33)	13.8 (0.66)
	4	5	24.2 (1.16)	0.0 (0.0)
	5	5	24.2 (1.16)	20.8 (1.0)
UL 60	1	5	32.3 (1.55)	0.0 (0.0)
	2	5	32.3 (1.55)	27.7 (1.33)
	3	60	16.2 – 55.4 (0.79 – 2.66)	27.7 (1.33)
	4	5	40.4 (1.94)	0.0 (0.0)
	5	5	40.4 (1.94)	34.6 (1.66)
UL 90	1	5	48.5 (2.33)	0.0 (0.0)
	2	5	48.5 (2.33)	41.5 (1.99)
	3	60	24.2 – 48.5 (1.16 – 2.33)	41.5 (1.99)
	4	5	56.5 (2.71)	0.0 (0.0)
	5	5	56.5 (2.71)	48.5 (2.33)

The UL class numbers (15, 30, 60 and 90) are not related to the maximum pressure applied during testing. For example, for the classes of UL 30 and UL 60, the summation of negative and positive maximum pressure applied during test phase 5 to a roof assembly is 45 psf and 75 psf, respectively. Thus, the maximum pressure value is not the same as the class number. The UL class number denotes the nominal static uplift pressure for that class (Underwriters Laboratories 2010). If a roof assembly remains intact throughout the loading sequence for a particular class, the assembly is assigned with that class rating with the performance increasing in the order of UL 15, UL 30, UL 60, and UL 90. A significant drawback of UL 580 is that it does not specifically determine the magnitude of the resistance of a roof assembly. Further, testing of a roofing system over a solid deck will not apply the positive pressure to the roofing system from underneath, but rather to the solid deck, which limits the loading applied on roofing assembly.

2.7.1.4 UL 1897: Uplift Tests for Roof Covering Systems

UL 1897 evaluates the resistance of the mode of attachment of roof coverings, membranes, base sheets, and insulations to the roof deck, when subjected to differential pressures. The test apparatus used for UL 1897 is similar to the one used for UL 580 (Underwriters Laboratories 2010). The roofing system to be tested is placed on the roof deck. The test is conducted by applying a vacuum from above to pull the assembly or, by applying a pressure by using the bottom chamber or, an air bag is placed loosely between the roof deck and the roof covering of the test assembly. The applied pressure is raised while holding it for 60 seconds at every 15 psf increment. At every 15 psf increment, the roofing system is observed for any signs of failure. Unlike UL 580, UL 1897 is continued until a failure of the roofing system (such as the possible loss of adhesion, pullout of fasteners, fatigue failure of metal panels, or a combination thereof) is observed. In addition, the vertical movement of the roofing system is recorded. Since a test is run to failure, the result is reported as the highest uplift pressure achieved by the roofing system prior to failure (Intertek n.d.).

2.7.1.5 NT BUILD 307: Roof Coverings - Dynamic Wind Load Resistance (Static Pressure Test and Pulsating Pressure Test)

The Norwegian Building Research Institute (NBI) introduced the NT Build 307 in 1986 as a static pressure test and a pulsating pressure test, to evaluate the uplift resistance of roof assemblies. This test method is also called the NORDTEST (NT) method (NORDTEST 1986). As shown in Figure 2-32, the test apparatus consisted of an upper box (vacuum chamber), a lower box (pressure chamber) and an 8 ft × 8 ft test frame to support the roof assembly sealed in between the two boxes.

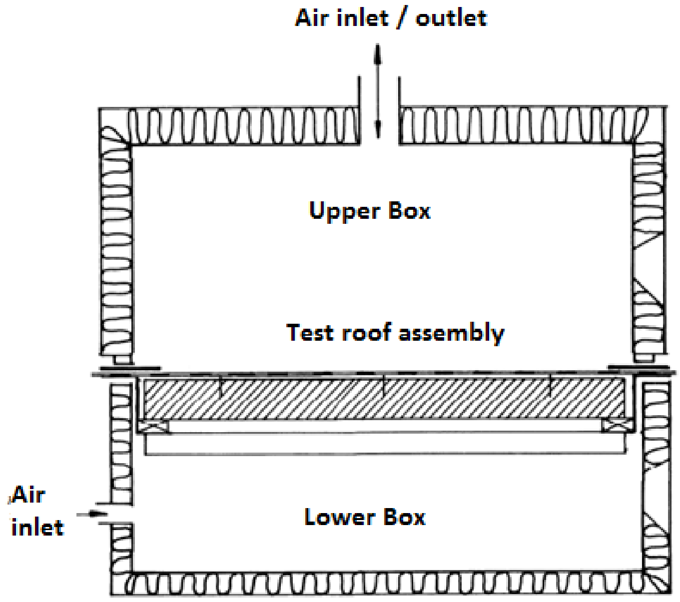


Figure 2-32. Schematic of the apparatus used for NORDTEST (NORDTEST 1986)

During a static test, a suction load is applied using the vacuum chamber and held for 5 minutes to measure deflection of the assembly. Then, the load is decreased to zero. Following this procedure, a 10.445 psf (500 Pa) load is applied during the first cycle. In subsequent cycles, the load is increased by 10.445 psf (500 Pa) so that the load applied during the last cycle is 146.23 psf (7000 Pa). Table 2-2 column (a) shows the load interval while column (b) shows the top and bottom chamber pressure. Column (c) shows the total pressure load acting on the roof assembly. Column (d) shows the duration that the load is held constant before reducing the load to zero. This procedure is similar to the one described in ASTM E1592, where the test specimen is visually examined for signs of damage after removing the loads.

For the pulsating pressure test, the vacuum chamber applies the pulsating negative pressure while the bottom chamber applies a constant pressure. Figure 2-33 shows the loading pattern. Columns (e) and (f) of Table 2-2 show the upper and lower limits of the pulsating load. Column (g) shows the pulsating load duration and column (h) shows the maximum total load acting on the roof assembly.

Table 2-2. Loading Sequence of the Pulsating Pressure Test (NORDTEST 1986)

Load Interval	Static Load in psf (Pa) and Duration in Min.			Pulsating Negative Pressure in psf (Pa) and Duration in Min.			Maximum Total Load, psf (Pa) P + 0.4P
	Top and Bottom Chamber Pressure	Total Static Load (P)	Duration	Upper Limit (P)	Lower Limit 0.2P	Duration	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
1	-6.27 (-300) 4.18 (200)	10.44 (500)	5	10.44 (500)	2.09 (100)	20	14.62 (700)
2	-12.53 (-600) 8.35 (400)	20.89 (1000)	5	20.89 (1000)	4.18 (200)	20	29.24 (1400)
3	-18.8 (-900) 12.53 (600)	31.33 (1500)	5	31.33 (1500)	6.27 (300)	20	43.86 (2100)
4	-25.06 (-1200) 16.71 (800)	41.77 (2000)	5	41.77 (2000)	8.35 (400)	20	58.45 (2800)
5	-31.33 (-1500) 20.89 (1000)	52.21 (2500)	5	52.21 (2500)	10.44 (500)	20	73.10 (3500)
6	-37.59 (-1800) 25.06 (1200)	62.66 (3000)	5	62.66 (3000)	12.53 (600)	20	87.72 (4200)
7	-43.86 (-2100) 29.24 (1400)	73.10 (3500)	5	73.10 (3500)	16.71 (800)	20	102.34 (4900)
8	-52.21 (-2500) 31.33 (1500)	83.54 (4000)	5	83.54 (4000)	20.89 (1000)	20	114.87 (5500)
9	-64.74 (-3100) 39.68 (1900)	104.43 (5000)	5	104.43 (5000)	25.06 (1200)	20	144.11 (6900)
10	-77.28 (-3700) 48.04 (2300)	125.31 (6000)	5	125.31 (6000)	29.24 (1400)	20	173.35 (8300)
11	-89.81 (-4300) 56.39 (2700)	146.20 (7000)	5	146.20 (7000)	33.42 (1600)	20	202.59 (9700)

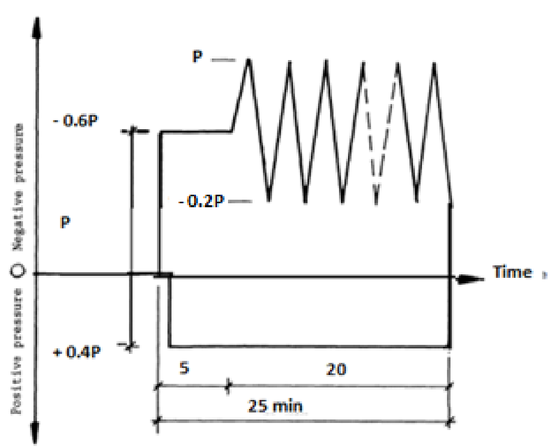


Figure 2-33. Static-pulsating loading pattern used in NT BUILD 307 (NORDTEST 1986)

2.7.1.6 NT BUILD 307: Roof Coverings - Dynamic Wind Load Resistance (Dynamic Test Protocol)

Later in 1987, NBI incorporated a dynamic test protocol to evaluate mechanically attached roofing systems. At present, this standard is known as NBI 162-90: Roof coverings – Dynamic wind load resistance (Murty 2010). Figure 2-34 shows the schematic of the test apparatus used for the dynamic test protocol of NT Build 307. This dynamic test apparatus is similar to that of the static test with a few additions to apply the suction pressure to the test specimen. The lower box applies a constant static pressure of 2.09 psf (100 Pa) throughout the loading process. In addition to the constant static pressure, 15-second gusts of maximum negative pressure of 4.18 psf (200 Pa) are applied as the initial loading, and this combination of static pressure and gust pressure is maintained for 1 hour. Subsequently, the negative pressure is increased in 4.18 psf (200 Pa) increments as shown in Figure 2-35 while maintaining the static pressure at 2.09 psf (100 Pa) until failure occurs (Paulson 1989).

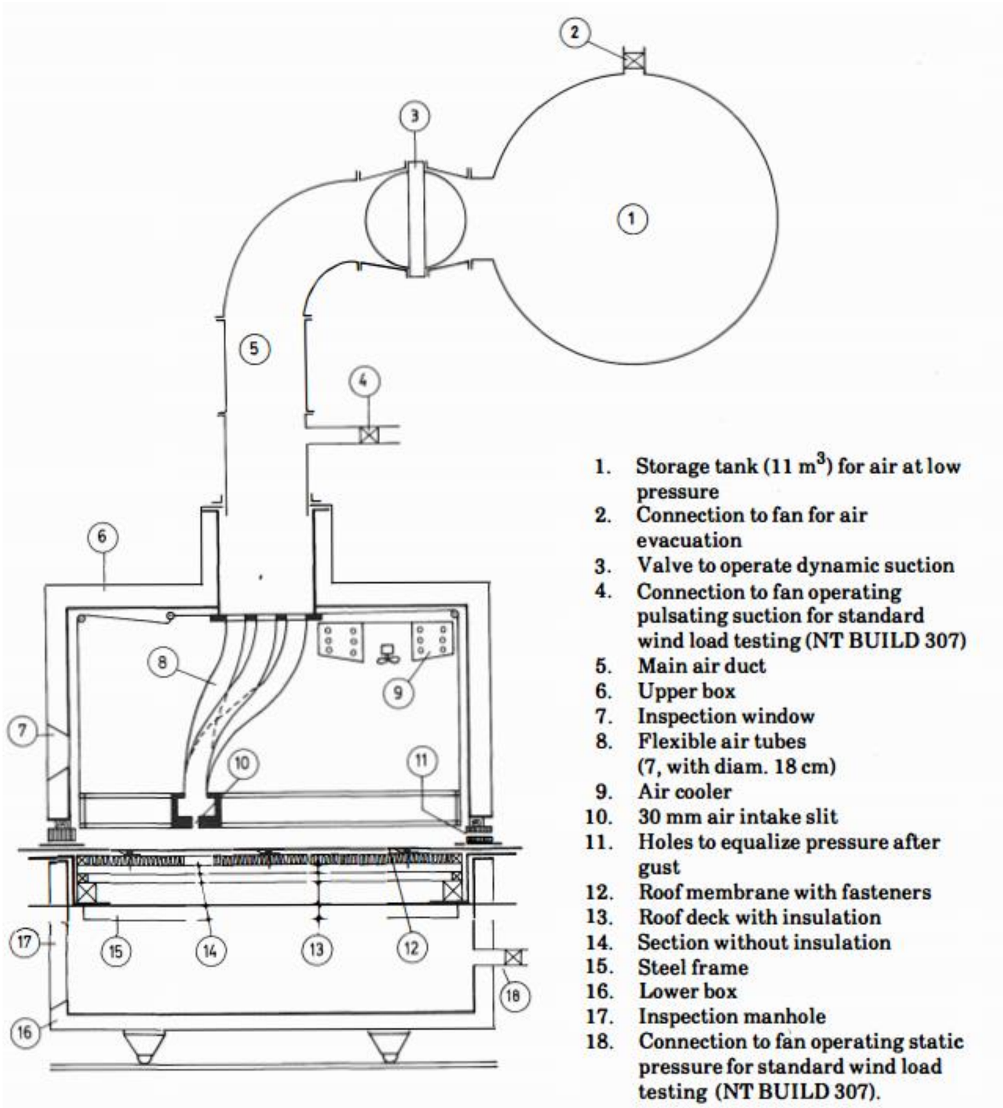


Figure 2-34. The test apparatus used in the NBI 162-90 test (Paulson 1989)

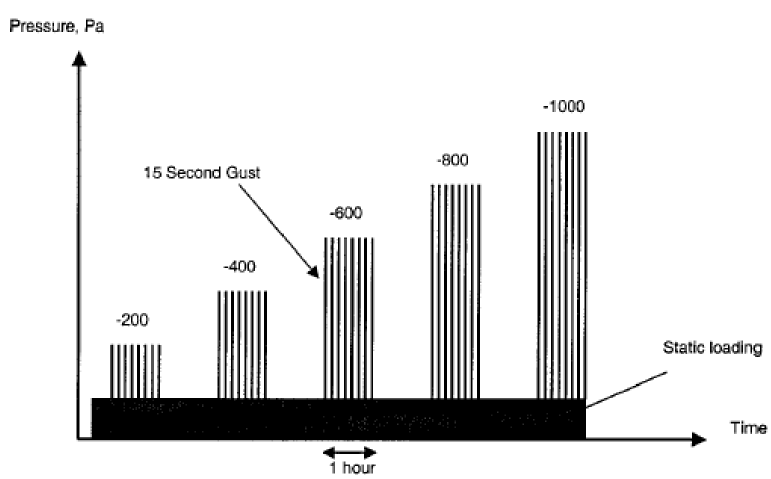


Figure 2-35. The dynamic load cycles used in the NBI 162-90 test (Murty 2010)

2.7.1.7 ETAG 006 Guideline: Guideline for European Technical Approval of Systems of Mechanically Fastened Flexible Roof Waterproofing Membranes

The ETAG 006 Guideline was first introduced in 2000 and later amended in 2012 by the European Union Agreement. This guideline is used to evaluate the uplift resistance of mechanically fastened waterproofing membranes. The dynamic load cycle in this guideline is often referred to as the UEAtc load cycle. The full-scale wind uplift test described in ETAG 006 (2012) is performed on complete roof assemblies of different dimensions with minimum effective dimensions of 6.56 ft × 6.56 ft (2 m × 2 m). A vacuum chamber of sufficient dimensions to accommodate the test assembly is placed over the test specimen. The vacuum chamber contains a fan to apply the gusts in the dynamic load cycle and a controlling equipment to regulate the proportional loading sequence illustrated in Figure 2-36. In addition, recording equipment and observation windows are installed in the pressure chamber. The recording equipment records the measurements such as deflections and pressure in the specimen. The test specimen is visually examined for any failures during the test through the observation windows. One set of cycles in the loading sequence contains 1415 gusts with the intensity of the gusts varying from 40% to 100% (as shown in Figure 2-36). The initial loading on the test specimen is 67.44 lbf (300 N) per fastener (100%) and the subsequent load increment during each load step is 22.48 lbf (100 N) per fastener. The test is carried out until failure occurs or until the capacity of the test equipment is reached (Murty 2010).

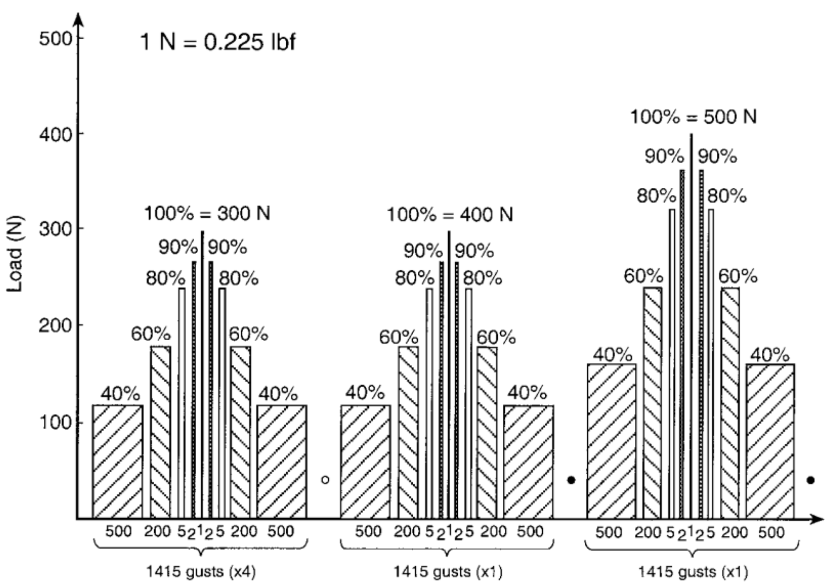


Figure 2-36. Proportional sequence of gust loads (Murty 2010)

A major drawback of this test procedure is that one cycle of 1415 gusts consumes nearly 3.5 hours to complete. Gerhardt and Kramer (1988) validated the efficiency of UEAtc load cycle by obtaining similar failure patterns for a roofing system in a laboratory setting, to those observed in the field for the same roofing system (Gerhardt and Kramer 1988).

2.7.1.8 CSA A123.21: Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane Roofing Systems by the Canadian Standards Association

In 1994, the National Research Council, Canada, formed a Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS). The aim of the group was to developed a dynamic load cycle that mimics the actual wind conditions, achieves failure modes similar to real cases, provides easier implementation in a laboratory, produces quick results, and meets the North American building code requirements. Within the first three years of forming the SIGDERS group, a dynamic load cycle was proposed to evaluate the uplift resistance of mechanically attached roof systems under wind loads. This dynamic load cycle was based upon the wind tunnel studies carried out on full-scale roof systems with PVC and EPDM roof membranes (Baskaran et al., 1999b).

The outcomes of the research work performed by SIGDERS were the basis for the standard A123.21 by the Canadian Standards Association (CSA). When A123.21 was first introduced in 2004 as CSA A123.21-04, the standard described a dynamic test method to evaluate the uplift resistance of mechanically attached roof systems (MARS) only. Later in 2005, this dynamic test method was modified to incorporate the evaluation of adhesive applied roof systems (AARS) and was reintroduced as CSA A123.21-10 in 2010. Wind tunnel tests carried out on rigid models by varying the building height, building aspect ratio, and the wind speed, facilitated the development of a dynamic load cycle for the evaluation of AARS. Experimental work validated the developed load cycle for AARS. The dynamic load cycle of AARS produced reliable results within a relatively shorter duration of testing compared to the dynamic uplift testing of MARS (Murty, 2010).

CSA A123.21-10 discusses two test methods: Method 1 and Method 2, to evaluate the wind uplift resistance under dynamic loading. Method 1 is for mechanically attached roofing systems (MARS) and Method 2 is for adhesive applied roofing systems (AARS). However, not all

AARS and MARS can be tested under the outlined procedures. MARS (with fastener row separation less than 114 in. and fastener in-line spacing less than 24 in.) and AARS bonded with cold adhesives are the only roof systems that can be evaluated as per the CSA A123.21-10 standard. The test apparatus consists of a 240 in. × 86 in. × 32 in. adjustable bottom frame over which the test specimen is installed. A vacuum chamber containing the gust simulator, fan chamber and the observation windows is placed over the test specimen as illustrated in Figure 2-37 (CSA 2010).

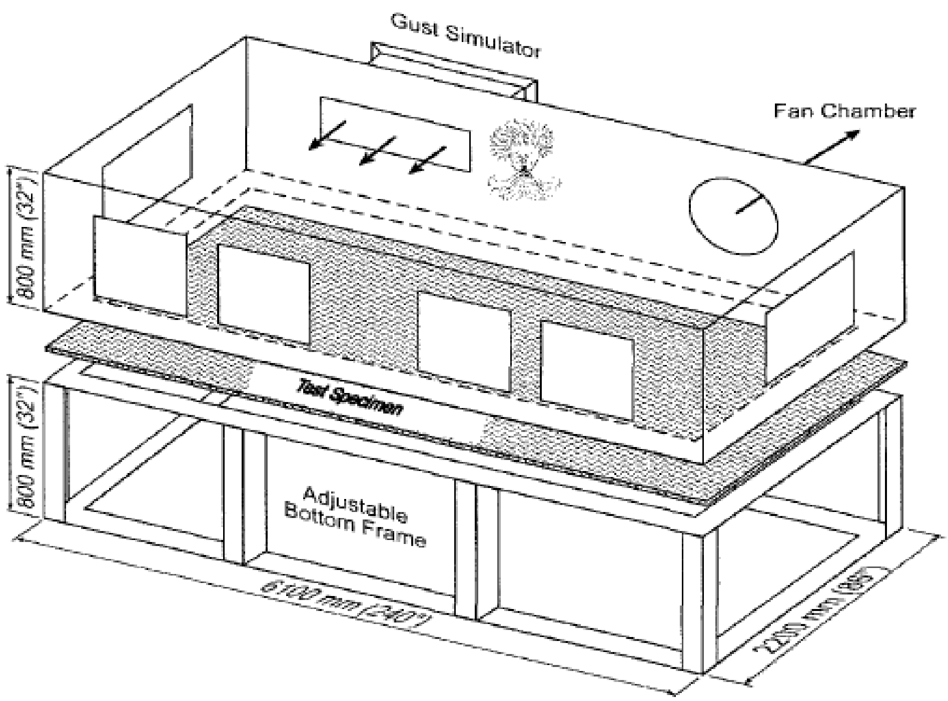


Figure 2-37. Test apparatus and test arrangement (CSA 2010)

The dynamic loading pattern of CSA A123.21-10 is illustrated in Figure 2-38. This loading pattern consists of five load levels (from A to E) with each load level having eight loading patterns representing a different number of gusts, pressure magnitudes and durations. These eight loading patterns are further divided into two groups: Group 1 and Group 2. Each group consists of four loading patterns. The pressure levels of Group 1 loading patterns fluctuate between zero and a predetermined value and emulate the wind suction over a roofing system. The pressure levels in Group 2 loading patterns range between predetermined lower and upper bound values, and they emulate the combination of wind suction over the roofing system and a static constant interior pressure of the building. The test pressure corresponding to a load level is a factored value (that ranges from 1 at Level 1 and 2 at Level 5 with 0.25 increments in between) of the design pressure (P). The design pressure is determined for a specific building in accordance with the governing design building codes (Baskaran et al., 2003a).

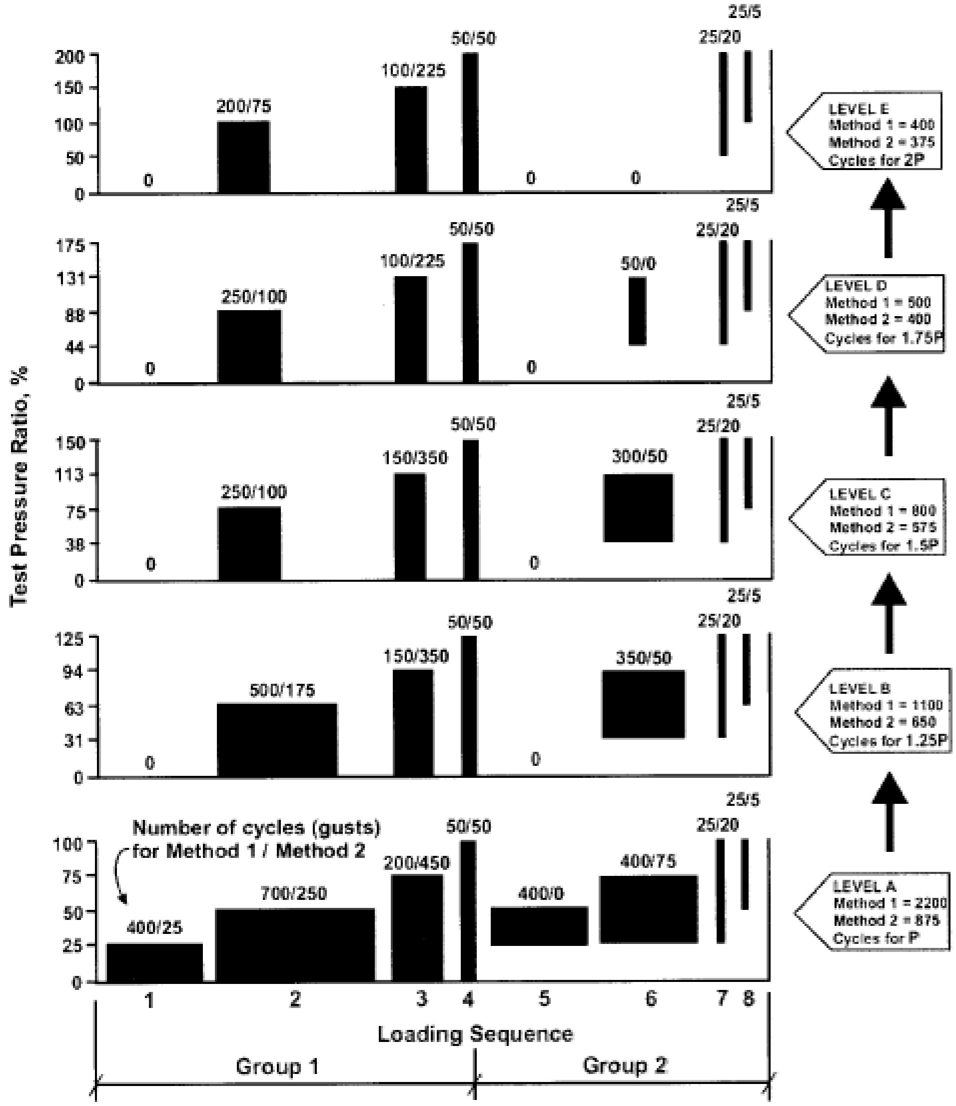


Figure 2-38. Dynamic wind load cycles for MARS and AARS (CSA 2010)

In order to evaluate the ultimate strength of a roofing system, a test is initiated at Level A and continued from one level to another sequentially until all the levels are completed or until the damage signatures specified for MARS or AARS in the standard are documented. A test is terminated when damage signatures are observed or the client specified loads (or gust cycles) are completed. A rating pressure is assigned based on the pressure magnitude of the last completed pattern of the eight patterns defined in the specification (CSA 2010).

2.7.1.9 ASTM D3161: Standard Test Method for Wind-Resistance of Steep Slope Roofing Products (Fan-Induced Method)

ASTM D3161 was introduced in 1972 and later modified with the latest version being in 2016. This test method evaluates the wind resistance of discontinuous, air permeable, steep slope roofing products namely asphalt shingles, polymer-based shingles, fiber-cement shingles, concrete tiles, clay tiles, metal shingles, and photovoltaic shingles. Similar versions of ASTM D3161 are also used in practice. One example is Testing Application Standard (TAS) No. 107-95: *Test Procedure for Wind Resistance Testing of Non-Rigid, Discontinuous Roof System Assemblies*.

A test specimen of size not less than 50 in. × 60 in. is prepared using a typical deck material and the roofing products as shown in Figure 2-39(a). The panel is conditioned by heating up and cooling down as specified in the standard. Once the specimen's heat is at room temperature, it is mounted on a test carriage with a slope of 17% or lower, as per the manufacturer's recommendations. As shown in Figure 2-39(a), the wind is simulated using a fan and a duct. The duct is placed closer to the lower end of the specimen, and the fan is operated to generate testing wind velocities for 2 hours or until specimen failure. At least two test panels for each product need to be tested. Observations are made visually or by recording videos to identify any failures during the test. Any detachment of the product from the panel, any observable damage to the product, or any failure of a sealant are recorded with its time of occurrence. If no failures were observed within the duration of the test, the product is considered to have passed the test. Based on the passing test velocities (60 mph, 90 mph, and 110 mph), three classes (Class A, Class B and Class C) are specified for roofing products (ASTM 2016).

Figure 2-39 shows the status of composite shingles that are subjected to two different wind velocities. This is a rather simple and direct test that can be used to evaluate quite a few steep slope roofing products. However, this test method is not applicable for continuous and impermeable roof systems or roof coverings. The test method neither provides a value for the wind uplift resistance nor measures the structural performance of the system. In addition, the simulated wind does not represent the characteristics of an actual wind in terms of intensity, turbulence, and duration, (ASTM 2016).

(a) At 14 mph

(b) At 115mph

Figure 2-39. Behavior of composite shingles under different wind speeds (Haag Engineering 2015)

2.7.1.10 UL 997: Wind Resistance of Prepared Roof Covering Materials

UL 997 was first published in 1960 and was later revised in 1995. This test procedure is used to evaluate the wind resistance of prepared roof covering materials. Factory applied adhesives, field applied adhesives, or interlocking mechanisms of the coverings provide the wind resistance. The test measures the resistance of roofing materials when subjected to wind velocities in the range of 55 mph - 63 mph (UL 1995).

This test method is similar to the ASTM D3161 fan induced method (Graham 2006). The roof coverings are installed on a 3 ft × 4 ft test deck, and the test specimen is cured under a specified temperature for a specified period. The cured specimen is then subjected to wind speeds of 60 mph for 2 hours or until failure occurs (Dixon 2013).

2.7.1.11 ASTM D6381: Standard Test Method for Measurement of Asphalt Shingle Tab Mechanical Uplift Resistance

ASTM D6381 was published in 1999 and was later revised in 2013 and 2015. The test method describes two procedures to evaluate the wind uplift resistance of factory applied or field applied asphalt shingles. The two procedures, Procedure A and Procedure B, employ mechanical means to measure the uplift resistance of asphalt shingles.

The procedure A test specimen consists of a 3 3⁄4 in. × 7 in. bottom piece and a 3 3⁄4 in. × 4 1⁄2 in. top piece, both cut from the same shingle as described in the standard. The top piece is laid over the bottom piece and adhered using a sealant strip, as shown in Figure 2-40. As shown in

Figure 2-41, the test setup consists of a tensile testing machine with fixtures to secure the specimen (ASTM 2015).

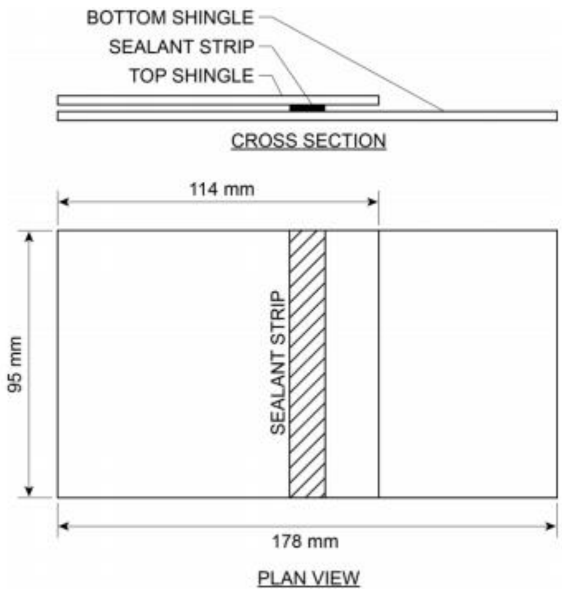


Figure 2-40. Plan and sectional view of the test specimen for Procedure A (Dixon et al. 2014)

Once the specimen is prepared and cured as per the specifications, it is mounted on the testing machine as shown in Figure 2-41. The test is performed, and the maximum force withstood by the specimen prior to breaking the bond is recorded to the nearest 0.225 lbf (1.0 N). Ten specimens per test condition are required as per the standard.

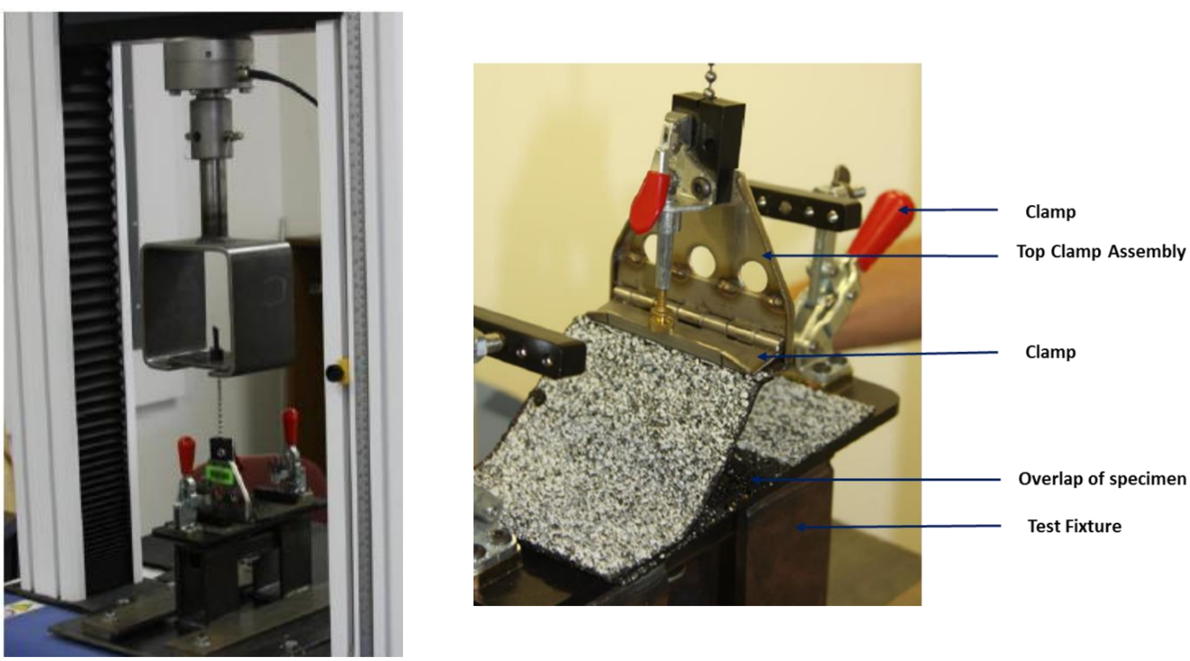


Figure 2-41. ASTM D6381 test Procedure A (Romero 2012)

The test specimen for Procedure B consists of 4 in. × 6 in. bottom and a 1 1/2 in. × 3 ¾ in. top shingle pieces that are cut from the same shingle. The top piece is centered and laid over the bottom piece as shown in Figure 2-42. As shown in Figure 2-43, an inverted T section is attached on top of the top piece using a suitable adhesive. The adhesive is allowed to cure, and the test specimen is conditioned as per the specifications.

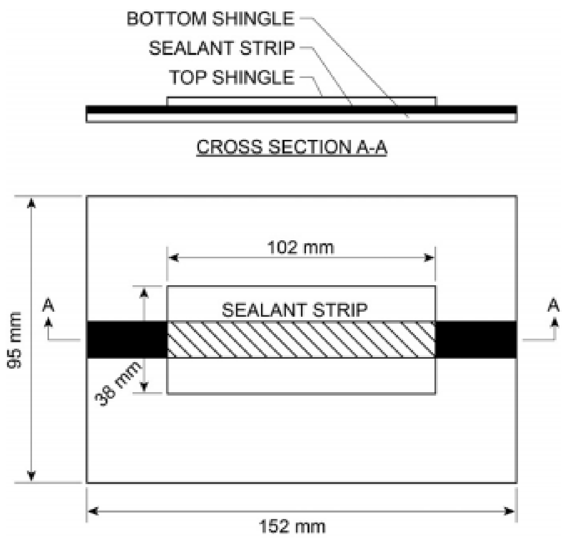


Figure 2-42. Plan and sectional view of the test specimen for Procedure B (Dixon et al. 2014)

The specimen is mounted on the testing machine as shown in Figure 2-43. The specimen is loaded until the T section detaches from the specimen. The maximum force is recorded to the nearest 0.225 lbf (1.0 N).

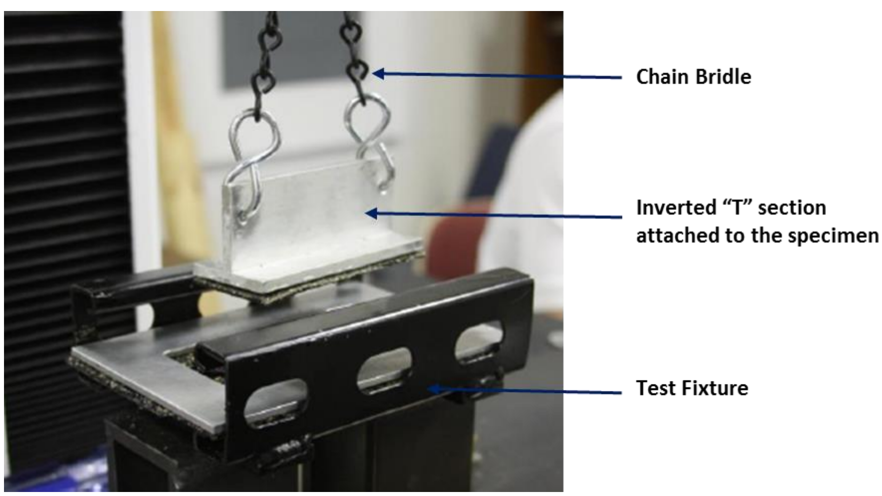


Figure 2-43. ASTM D6381 test Procedure B (Romero 2012)

Procedure A evaluates the tearing off of shingles whereas Procedure B evaluates direct tensile bond strength. Hence, the results of Procedure A are lower than those of Procedure B. The performance of shingles depends on the shingle design, geometry and the rigidity. The evaluation of uplift resistance of shingles that are applied without factory applied or field applied sealants are out of the scope of ASTM D6381 test procedure.

2.7.1.12 ASTM D7158: Standard Test Method for Wind Resistance of Sealed Asphalt Shingles (Uplift Force/Uplift Resistance Method)

ASTM D7158 was introduced in 2005 and revised in 2016 and 2017. The standard describes a test method to evaluate the wind resistance of any asphalt shingle surfaced with mineral granules and installed with a factory or field applied sealant in a pattern aligned parallel to the windward edge of the shingle.

As the first step of this test procedure, uplift coefficients for the shingles are determined by measuring the pressure differences above and below the shingle as air moves over the surface of a deck of sealed shingles at a defined velocity. Using these uplift coefficients, the uplift forces acting on the shingles are calculated. Then, the mechanical uplift resistance of shingles is measured following the ASTM D6381 test method. The calculated uplift force is then compared with the mechanical uplift resistance of the shingle to assign a Class as per ASTM D7158. According to ASTM D7158, asphalt shingles are assigned a Class (D, G or H) based on passing wind speed (115 mph, 150 mph, or 190 mph, respectively) (ASTM 2017).

2.7.1.13 ANSI/UL2390: Test Method for Wind Resistant Asphalt Shingles with Sealed Tabs

UL 2390 was first published in 2003 and revised in 2009. UL 2390 is identical to the ASTM D7158 published in 2005 (Dixon 2013). For high wind regions, the use of shingles whose wind performance is evaluated using UL 2390 is advised over UL 997 or ASTM D3161 test procedures (FEMA 2005).

2.7.1.14 ASTM C1568: Standard Test Method for Wind Resistance of Concrete and Clay Roof Tiles (Mechanical Uplift Resistance Method)

ASTM C1568 was approved in 2003 and revised in 2008 and 2013. This standard is used to determine the mechanical uplift resistance of concrete and clay roof tiles that are mounted using mechanically fastened attachment systems, adhesive-set attachment systems, mortar-set attachment systems, or a combination thereof. The roof section shall be prepared similar to that of an actual roof as per the manufacturer's guidelines, along with or without other components such as roof underlayment and sheathings. Tile installation and curing procedures are provided in the standard. After preparing the roof section, it is installed on a framing. The test tile is drilled to connect the load transfer device as shown in Figure 2-44. The load is applied at a rate that causes nearly 1 in. per minute deflection at the tile nose (ASTM 2008). The loading is continued until the failure criteria stated in the standard is achieved.

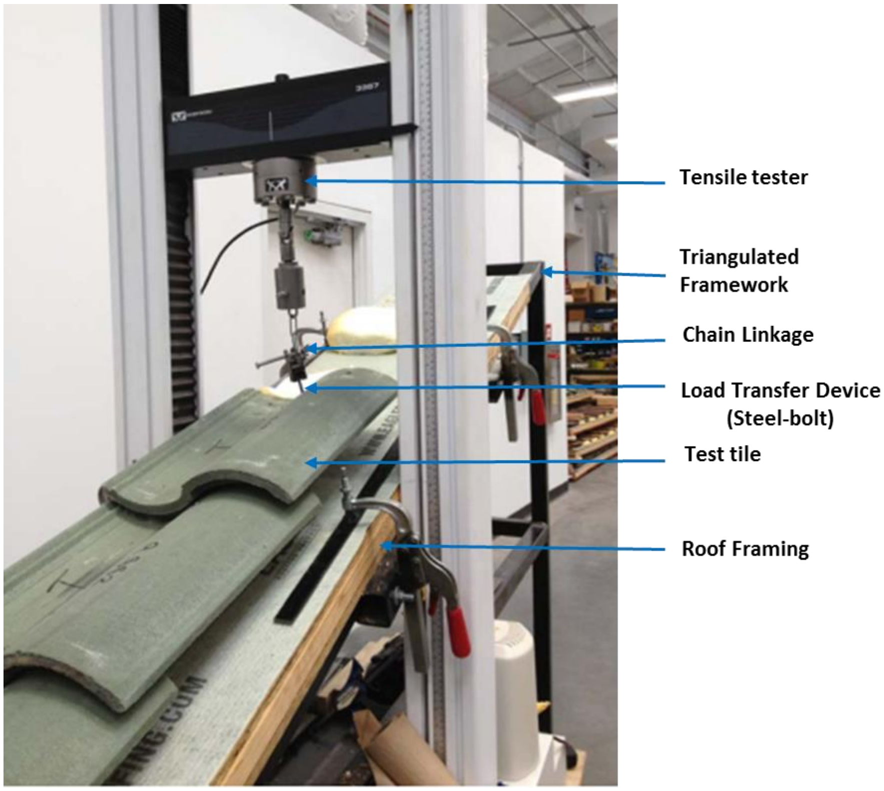


Figure 2-44. ASTM C1568 test set up (Smith and Masters, 2015)

2.7.1.15 ASTM C1569: Standard Test Method for Wind Resistance of Concrete and Clay Roof Tiles (Wind Tunnel Method)

ASTM C1569 was published in 2003 and revised in 2009 and 2016. This standard procedure uses a wind tunnel to evaluate the performance of concrete and clay roof tiles under simulated wind velocities ranging from 70 mph to 130 mph (ASTM 2003). Figure 2-45 shows a specimen prepared for wind tunnel testing at the University of Florida (Smith 2014).

Figure 2-45. A specimen with roof tiles used in wind tunnel testing (Smith 2014)

The wind tunnel is operated up to a wind speed of 70 mph. This speed is held steady for 60 s, and the pressure readings are taken. The wind speed over the test assembly is measured using a pitot-static tube positioned 4 in. above the tiles in the free stream. The wind speed is then increased to 80 mph, held steady for 60 s, and the pressure readings are taken. This procedure is repeated in 10 mph increments until a wind speed of 130 mph is reached, the wind tunnel capacity is reached, or the specimen fails. Figure 2-46 shows the failure of roof tiles during an experiment conducted at the University of Florida (Smith 2014).

Figure 2-46. Failure of a specimen with roof tiles (Smith 2014)

The pressure distribution on the top surface of the tile is measured using 20 pressure taps placed on a single tile. The pressure on the bottom surface of the tile is measured using pressure taps open to the underside of the tile. When the building's internal pressure effect is incorporated into the testing procedures, a plenum chamber is placed underneath the specimen, as shown in Figure 2-47. The total pressure head and the static pressure is measured using pressure tubes. The difference between the total and the static pressures is the dynamic pressure of the free stream. The net pressures on the tile are used to calculate the uplift force.

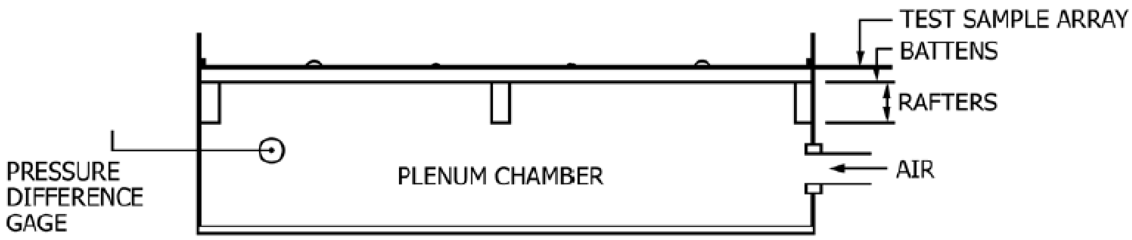


Figure 2-47. Location of the plenum chamber in the test set up (ASTM 2003)

ASTM C1568 and C1569 standards are based on the International Code Council's ICC/SBCCI SSTD 11 and a study by Redland Technology (ASTM 2003). The Redland study was an experimental program initiated in 1999 by an independent testing agency named Redland Technology. The aims of the experimental program were to investigate the wind loads on tiled roofing systems and to develop a design standard. Under the Redland study, wind tunnel tests were conducted to estimate the wind loads through surface pressure measurements on tiles. Further, wind uplift resistance of roofing tiles with various attachment methods was estimated from constant displacement rate uplift tests. The resultant design methodology was incorporated into several standards such as the Standard Building Code (SBC), the Florida Building Code (FBC), Testing Application Standards (TAS) 101, 102, 102A, 108, the Southern Building Code Congress International (SBCCI) SSTD 11-99, and ASTM standards C1568, 1569 and 1570 (Smith 2015).

2.7.1.16 FM 4475: Approval Standard for Class 1 Steep Slope Roof Covers

FM 4475 does not outline a separate test procedure to evaluate the steep sloped roofs. The 12 ft × 24 ft uplift test procedure in FM 4474 is to be followed to evaluate the uplift performance of steep slope roof coverings. The coverings should be able to withstand a minimum of 60 psf in order to pass the test. In addition, if the shingle attachment withstands a minimum wind velocity of 110 mph under the ASTM D3161 test procedure, the shingles are qualified under FM approval criteria (FM 2015).

2.7.2 Field Wind Uplift Tests

The performance of a roofing system just after installation or after being in service for many years can be evaluated using field wind uplift tests. According to FM 1-52 (2012) datasheet, field uplift testing is conducted on structures with suspected or confirmed inferior roof construction or where a partial blown off in the roof has occurred. The results of the field wind uplift tests are used to make maintenance or replacement decisions. However, field uplift testing is not applicable for certain roofing systems such as metal panel roofs, ballasted roofs, and mechanically attached roofs with fastener spacing greater than 2 ft (FM 2012). FM 1-52 and ASTM E907 describe two commonly used field static wind uplift tests.

2.7.2.1 FM 1-52: Field Verification of Roof Wind Uplift Resistance

FM 1-52 was originally introduced in 2009 and revised in 2012. This standard covers two field tests: negative pressure test and bond uplift test. Table 1 of FM 1-52 lists the roofing systems that can be evaluated using these two test methods. Since these tests are performed on as-built or in-service roofs, none of these tests is continued until failure. Hence, a parameter known as the passing uplift pressure is determined for the roof at three locations - field, perimeter, and corner. This passing uplift pressure is simply the design’s wind pressure at these three locations calculated as per design codes and multiplied by a safety factor of 1.25. The tests are continued until the applied pressure reaches the passing uplift pressure defined for the roof.

The negative pressure test apparatus is shown in Figure 2-48. A 5 ft × 5 ft area of the roof is evaluated using this apparatus. Prior to testing, the roofing surface is prepared, and a horizontal bar with a deflection gauge is placed on the prepared surface to measure roof vertical defection. The dome shaped chamber is placed over the prepared surface and sealed using a PVC foam strip seal. The dome accommodates a vacuum pump to apply negative pressure to the roof and a manometer to read the applied pressure (FM 2012).

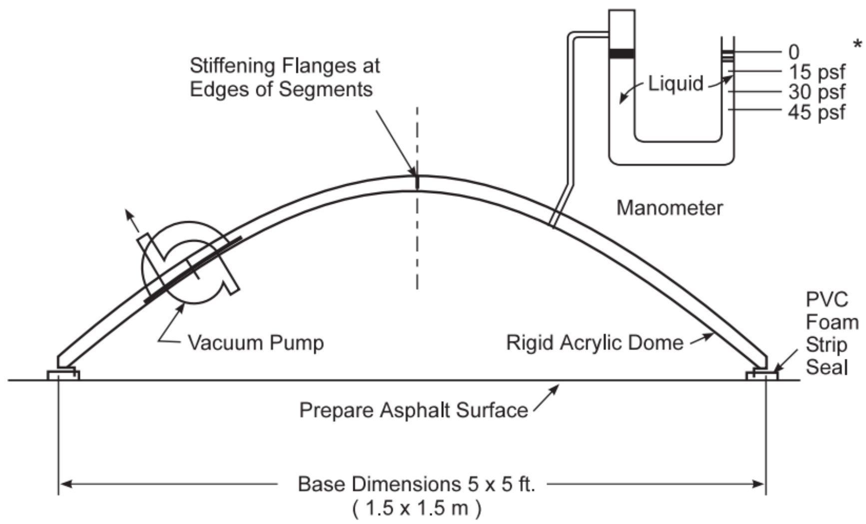


Figure 2-48. Negative pressure test apparatus (FM 2012)

An initial negative pressure of 15 psf is applied to the roof surface, held for 60 seconds, and the deflection is recorded. Successively, the pressure is increased by 7.5 psf, and at the end of each pressure increment, the pressure is held constant for 60 sec during which the deflection of the roof is recorded. The roof is said to have passed the test if it sustains an applied pressure equal to the specified passing uplift pressure for 60 seconds without showing any failure signs or exceeding the specified deflection limits in Table 5 of FM 1-52. In case of failure, the maximum uplift pressure the roof can withstand for 60 seconds prior to failure is recorded as its wind uplift resistance (FM 2012).

On the other hand, the bonded uplift test can be performed only on a 2 ft × 2 ft area. The experimental setup used for the bond uplift test is shown in Figure 2-49. For this test, a plywood panel with an eyebolt inserted at its center (as shown in Figure 2-50) is adhered onto the surface. The uplift load is applied through the eyebolt using a tripod (or an equivalent support system) attached with a block and tackle (or a hand chain hoist or a hydraulic lift device).

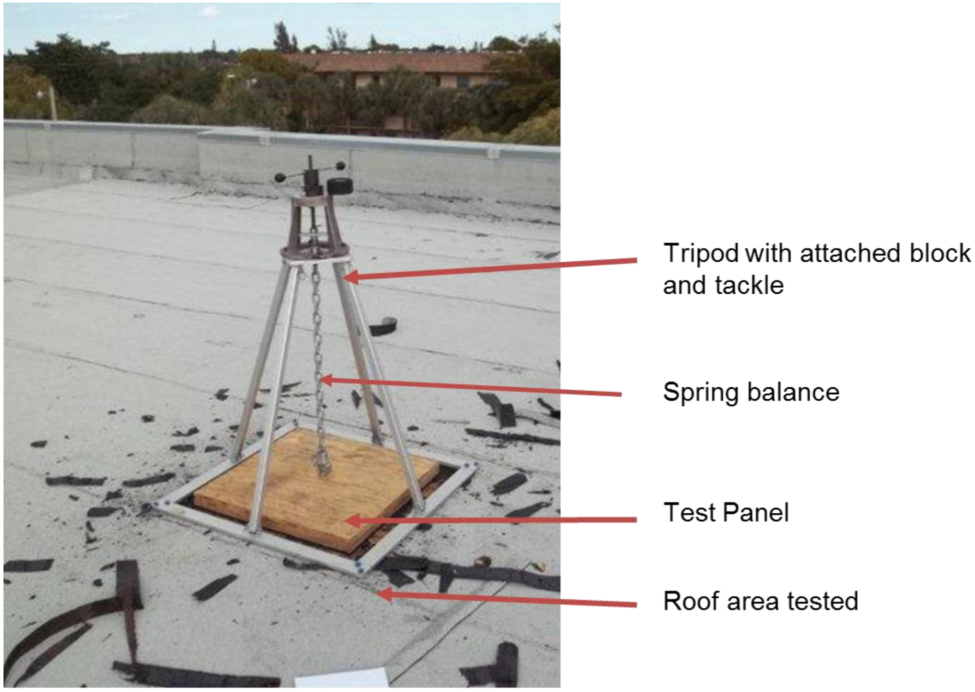


Figure 2-49. Test apparatus of a bonded uplift test (Federal Engineering & Testing Inc. 2012)

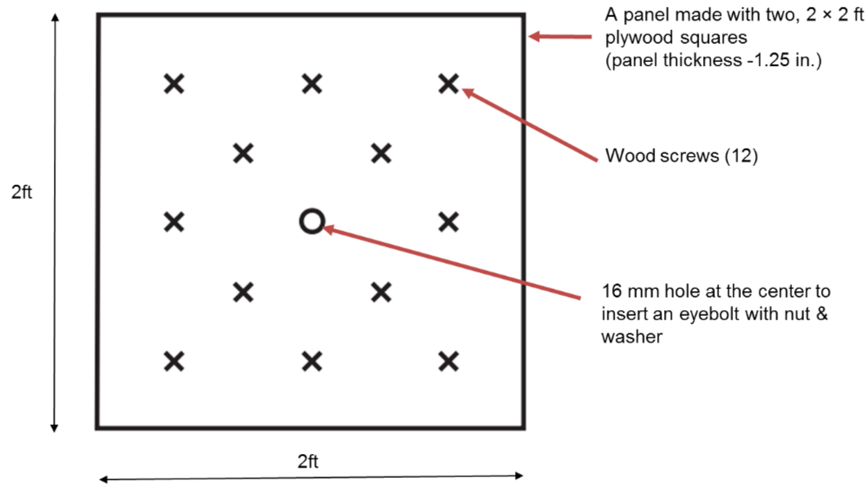


Figure 2-50. Plywood panel used in a bonded uplift test

Prior to applying the load, the weight of the test panel with the eyebolt is recorded. One end of a spring balance is connected to the test panel while the other end is connected to the top of the tripod, to record the applied load. The uplift pressure of the panel would be the ratio of the difference between the scale reading and the weight of the panel with the eyebolt to the panel area. The test is continued until the uplift pressure reaches the passing uplift pressure defined for the tested surface. The roof passes the test when the roof successfully withstands an applied pressure equal to passing uplift pressure without any detachments of the membranes within the assembly or from the roof deck. If the roof fails before the passing uplift pressure, the highest pressure withstood by the roof surface for 60 seconds prior to the failure is considered as the uplift resistance of the roof. The minimum number of tests required for a specific roof depends on the total roof surface area and the locations (field, perimeter, and corner) (FM 2012).

2.7.2.2 ASTM E907: Standard Test Method for Field Testing Uplift Resistance of Adhered Membrane Roofing Systems

ASTM E907 was originally introduced in 1983 and revised in 2004. The ASTM E907 test procedure is similar to the negative pressure test described in FM 1-52. The test apparatus for ASTM E907 is shown in Figure 2-51. The test is performed using the same loading sequence specified for the negative pressure test in FM 1-52. The test is continued until roofing system failure or until a predefined negative pressure is reached. This is similar to the negative pressure test where the test is terminated upon reaching the passing uplift pressure. In the ASTM E907 test procedure, a deflection limit of 0.984 in. (25 mm) or greater is defined at the center of the test area as the failure criteria. A minimum number of tests is specified based on the total roof area. However, unlike the negative pressure test, ASTM E907 (2004) suggests conducting follow-up examinations of the failed areas using roof section cuts (ASTM 2004).

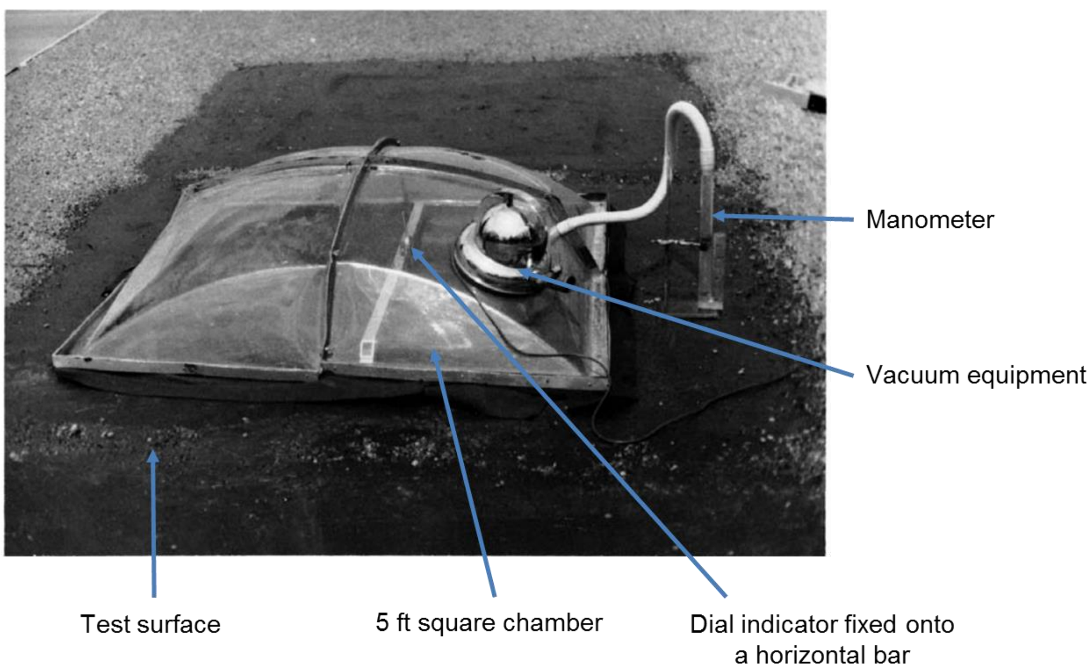


Figure 2-51. ASTM E907 test apparatus (ASTM 2004)

2.7.3 Summary of Wind Uplift Test Procedures

FM 4474, UL 580, ASTM E1592, UL 1897, and NT BUILD 307 are the specifications widely used for static wind uplift test of flat roofs. FM 4474 and UL 580 outline test procedures to evaluate complete roof assemblies, whereas UL 1897 excluded the roof deck from the roof assembly and ASTM E1592 evaluates only the metal roof panels (i.e. roof covering). In addition, FM 4474, UL 1897, ASTM E1592, and NT BUILD uplift tests are continued until failure, whereas UL 580 uses a set of predefined pressure loads to designate a class for the tested assembly. The loading procedures of the above stated five tests relatively differ from each other. For FM 4474 and UL 1897, an initial pressure is applied to the test specimen and is held constant for 1 minute. Subsequently, pressure is continuously increased in equal increments while maintaining the pressure at the end of each increment for 1 minute. For ASTM E1592 and NT BUILD 307, the pressure is not continuously increased from one loading level to the next. Instead, the pressure is reduced to a reference pressure (ASTM E1592) or zero (NT BUILD 307) at the end of a loading interval before proceeding to the next loading level. UL 580 and NT BUILD 307 are the only static tests to incorporate a cyclic loading out of all the static tests discussed herein.

The three laboratory dynamic test procedures commonly used for flat roofs (NT BUILD 307, ETAG 006 guidelines, and CSA 123.21) require a relatively longer duration to complete. ETAG 006 requires the longest duration when compared to the duration of a static test. In addition, the fatigue effects have been considered when developing all three dynamic test procedures. Further, the ultimate result of the NT BUILD 307 dynamic test procedure is a design load per fastener, whereas for the ETAG 006 guideline and CSA A123.21-10 test procedures, the ultimate result is a design pressure. CSA 123.21-10 provides a method to evaluate wind uplift resistance of Adhesive Applied Roofing Systems (AARS) and Mechanically Applied Roofing Systems (MARS) under certain limitations, whereas the dynamic test of NT BUILD 307 only evaluates the wind uplift resistance of MARS.

ASTM D3161, UL 997, ASTM D7158, UL 2390, ASTM D6381, ASTM C1568, and ASTM C1569 are the wind uplift test procedures for steep sloped roofs discussed herein. ASTM D3161 and UL 997 test procedures are essentially similar. ASTM D7158 and UL 2390 test procedures are essentially identical. The ASTM D6381 test procedure is only applicable for asphalt shingles, whereas the ASTM C1568 and ASTM C1569 test procedures are applicable only for concrete and clay roof tiles. ASTM D3161, UL 997, ASTM D7158, UL 2390, and ASTM C1569 use a wind tunnel to apply a uniform wind velocity to evaluate the wind uplift resistance of steep slope roof coverings. However, this does not emulate the real variation of wind in terms of intensity, duration and turbulence. In contrast, ASTM 6381 and ASTM C1568 calculate the load required to reach failure of the shingle/tile attachment by applying a tensile load to the shingle/tile using a mechanical apparatus.

Compared to the number of laboratory wind uplift test procedures available, quite a few standardized test procedures are available for evaluating field wind uplift resistance of roofs. ASTM E907 (2004) and FM 1-52 (2012) are the widely used standards in evaluating the wind uplift resistance of roofs in field. Both standards specify static field test procedures. These field tests require a minimum number of tests to be performed at the field, perimeter and corners of the roof based on the total roof area. Neither ASTM E907 test procedure nor the two tests specified in FM 1-52 (bond uplift test and negative pressure test) are used to evaluate the wind uplift resistance of loose laid ballast roofs. A significant drawback with field uplift tests is that none of them emulates the actual loading and deformations that result from the wind uplifting such as progressive membrane peeling and lifting of edge flashing. Further, the simulated static loading applied during field tests do not mimic the actual wind conditions experienced by the roof. However, a certain degree of knowledge on the current performance level of the roof obtained through field tests helps in determining repair or replacement needs.

2.8 NUMERICAL SIMULATION OF ROOFING SYSTEMS AND COMPONENTS

Numerical simulation techniques have the advantage of evaluating the impact of a large number of parameters on roofing loads and performance with relatively less effort and time compared to experimental techniques. Hence, numerical simulations should be conducted to identify the critical parameters for roof system performance and to design experimental studies. This section presents a brief overview of numerical modeling and simulation of roofing systems.

Table 2-3 summarizes the numerical simulation studies conducted during the 1980s and 1990s. There may have been other numerical studies; however, due to lack of available information, such studies are not included in this summary.

Table 2-3. Summary of Numerical Simulations from 1980 to 1990 (Baskaran and Kashef 1995)

Reference	Details
Lewis (1980)	**Objective of the study** Investigate the applicability of FEM to calculate the thermal induced stresses in a bituminous built-up membrane placed on an insulation layer with two types of gaps (overlapped and non-overlapped). **Model parameters** • The investigated roof system comprised of a steel deck, double layered fiberglass insulation, and a three-ply fiberglass membrane applied with asphalt layers. • Finite elements with plane strain material models were used to represent the deck, insulation, and membrane. • Study investigated the effect of several parameters on membrane stresses. The parameters included modulus elasticity of insulation, insulation thickness, width of the gap between insulation and membrane, thickness of the deck, distance between deck and structural supports, location of the insulation gap with respect to the structural supports, and FE mesh refinement. **Findings** • Membranes stresses are adversely affected due to increase in thickness or the stiffness of insulation. • The stress level in the membrane at locations above a continuous gap between two insulation panels were 63% higher compared to an insulation over a panel without a gap. **Remarks** • The model was not verified through experimental methods. • Only the isotropic behavior of the materials was considered. The material properties were assumed to be time and temperature independent.
Rossiter and Batts (1985)	**Objective of the study** Calculate the stresses induced in a single ply roofing membrane due to thermal gradients using a linear FEM. **Model parameters** • The investigated roof system comprised of a steel deck, double layered fibrous glass insulation, and an EPDM membrane. Two roof systems were modeled – an adhered system and a loose laid system. • The study used the FEM code of MacNeal- Schwendler Corporation (MSCINASTRAN). 2D plane strain models of the systems were built using eight node iso parametric elements. • Both roof systems were subjected to a temperature differential of 100 ^{0}F and a surface load was applied to represent the ballast weight. The surface load on adhered system was for comparison purposes. • In the adhered EPDM system, the membrane was constrained at all the nodes and the adhesive layer was not included in the model. The loose laid membrane was only constrained at the edges, allowing horizontal movement with respect to the insulation layer. • Isotropic material properties were assigned in the model. The material properties were assumed to be time and temperature independent. • The membrane was assumed to have no seams, flaws, or other stress concentrations.

	• Study investigated the effect of membrane properties (modulus, coefficient of linear expansion, and thickness) on membrane stresses. **Findings** • The peak stresses over the gaps of the insulation board were about 4177 psf (0.2 MPa) and 2506 psf (0.12 MPa) for the adhered system and loose laid system, respectively. • When the membrane modulus of elasticity was increased in the adhered system, the thermal stresses induced in the membrane increased nonlinearly from 2715 to 135755 psf (0.13 to 6.5 MPa). • In the adhered system, the coefficient of linear expansion was decreased from 1120 x 10^{-6} ºF to 572 x 10^{-6} ºF (660 x 10^{-6} ºC to 300 x 10^{-6} ºC), and the peak induced stresses in the membrane decreased from 4177 to 2715 psf (0.20 to 0.13 MPa). • The effect of the membrane thickness on the thermal stresses in the adhered system was found to be negligible. **Remarks** • Only 2D models of the systems were used. • The stresses were evaluated under a constant surface load. • Only the isotropic behavior of the materials was considered in the analysis. • Material properties were not functions of time and temperature.
Broadland et al. (1993)	**Objective of the study** Investigate the effect of fully adhered membrane response to differential movements between adjacent substrates. **Model parameters** • The investigated roof system comprised of an adhered roofing membrane with a cap sheet and a base sheet. The membrane was bonded to a rigid substrate with a joint at the center of the sample. • A PC based finite element software called REMA (Reinforced Membrane Analysis) was used for the analysis. • Displacements were applied to the substrate at a constant temperature to widen the gap in the substrate. **Findings** • The sequence of the membrane failure due to the widening of the gap in the substrate was studied. • The load-deflection results of FEM analysis were compared with the experimental results. **Remarks** • Only the membrane was considered in the analysis. • Other types of load induced strains were not considered. • Material properties were not functions of time and temperature.
Easter (1990)	**Objective of the study** Investigate the response of EPDM membranes due to wind uplift forces. **Model parameters** • The FE model was built using PATRAN program and the analysis was performed using SAFEM software. • The membrane was modeled using shell elements. • The edge nodes were restrained against movement in all directions.

	Findings • Ballooning phenomenon was predicted in the analysis with a maximum height of 6 ft (1.829 m). • Stresses at the edges of the uplift table were higher due to edge effect than stresses at batten plates. • FEM modeling was found to be applicable to model large-scale wind uplift tests of roof systems. **Remarks** • Only the membrane was considered in the analysis. • The dynamic nature of the external pressures was not considered. • Only the vertical forces of the batten strips were obtained.

Molleti (2006) numerically modeled mechanically attached roofing systems with wider thermoplastic and thermoset membranes. One of the aims of the study was to investigate the effect of the wind uplift table size on the performance of a mechanically attached roofing system. Figure 2-52 shows the finite element representation of the mechanically attached roofing system used in this study. ABAQUS 6.3 was used as the pre–processing and post-processing tool for numerical simulation. Only the membrane was modeled using 4-node shell elements (S4 elements in ABAQUS), assuming that the deflection of the membrane is significant when compared to the deflection of the insulation and the deck. Seam details were modeled by doubling the thickness of the shell elements at the seam locations. The material properties of the thermoset and thermoplastic membranes were evaluated through mechanical tests performed in accordance with ASTM standards and were assigned to the FE model. The fasteners used to attach the membrane to the deck were modeled using SPRING elements defined with an axial stiffness. The axial stiffness value assigned to the SPRING elements were from the force and displacement measurements obtained for the fasteners through experimental testing. The fastener plates were simulated as discs by changing the material properties of the shell elements at fastener plate locations. The nodes at the perimeter of the membrane were restrained against translation but not against rotation. This boundary condition was assigned to simulate the clamping of the membrane to the uplift table. The model was subjected to a uniform static uplift pressure up to 90 psf. Static stress analysis was used in the numerical modeling.

The numerical model was benchmarked with the experimental results obtained for thermoplastic and thermoset systems that had different fastener row spacing and fastener spacing. The experimental procedures were conducted as per FM load cycle and SIDGERS load cycle. The time histories of the pressure, fastener force, and the membrane deflections were recorded. The average of the two values obtained from FM load cycle and SIDGERS load cycle for pressure, fastener force and deflection were considered as the experimental results. The deviation of these experimental results from the numerical results in the FE analysis was calculated. This experimental and numerical study showed that the FE model could be used to predict the fastener loads and membrane deflections of thermoset roof systems at any pressure level with sufficient accuracy.

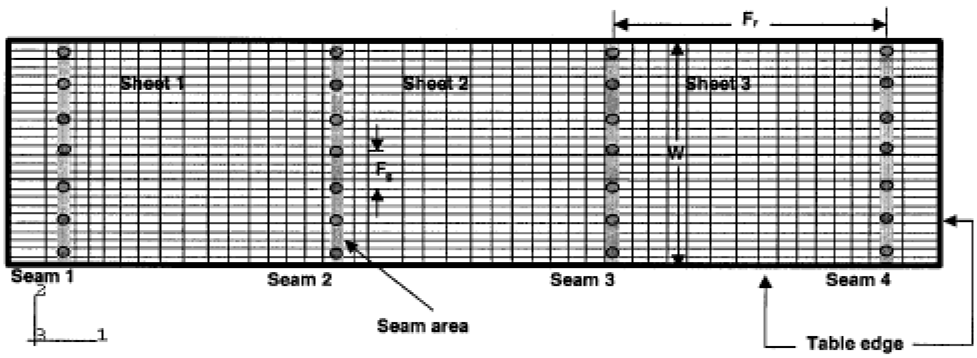


Figure 2-52. FE model representation of a typical mechanically attached system (Molleti 2006)

The benchmarked numerical model was then used to investigate the performance of wider thermoplastic and thermoset membranes. The results showed that when the membranes were tested on table widths narrower than the membrane width, the table edges restricted the lateral deformation of the membrane. In addition, the load was transferred along the table edges, transferring lesser loads to the fasteners. Further, the effects of the length and the width of the uplift table to the system response were studied. As a result, the Required Table Widths (RTW) (table width that has the minimum table edge effect on the roofing system performance) for thermoset and thermoplastic roofing systems, based on their fastener spacing and fastener row spacing, were suggested. Further, to account for the edge effect in uplift tables with widths less than the RTW, a correction factor was suggested. The effect of the table length to the performance of thermoplastic systems was found to be negligible as long as the table length has a minimum of three seams. The limitations of this study were that the validation of the numerical model was performed through experimental work conducted on smaller width membranes (not through wider membranes) and the concept of RTW was not validated using experimental work. Further, only a 2D model of the membrane was used in the analysis.

Murty et al. (2008) published the results of a pilot study conducted to evaluate the wind uplift resistance of adhesive applied roofing systems (AARS). The aim of the study was to verify if the failure of AARS is at the insulation and adhesive interface. A simplified 3D model was created using ABAQUS. The model consisted of three parts: a bottom insulation, an adhesive layer, and a top insulation. The thickness of top and bottom insulation layers was 2 in. (51 mm), and the adhesive layer thickness was 0.079 in. (2 mm). These three components were modeled using eight node continuum elements. The adhesive and the insulation were modeled as homogenous isotropic elastic material, and the assigned mechanical properties were extracted from previous studies conducted by Henry in 2006 and Baskaran & Borujerdi in 2001. A uniform pressure load was applied to the top surface of the top insulation layer in four steps as 0.2 psf, 0.58 psf, 0.74 psf, and 1.04 psf. A fixed boundary condition was assigned at the bottom insulation. Contact at the insulation and adhesive interface was defined using tie constraints. The geometry of the numerical model is illustrated in Figure 2-53. A mesh sensitivity analysis proved that a maximum mesh size of 1.32 in. was suitable in the model. A linear static analysis was conducted.

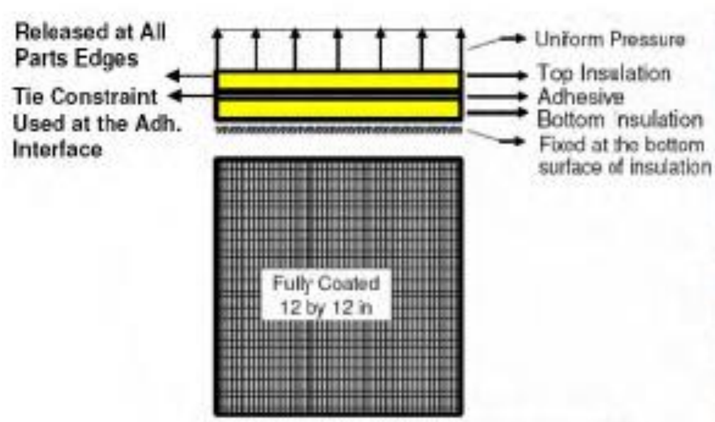


Figure 2-53. Details of the numerical model (Murty et al. 2008)

The model was validated by fabricating six specimens similar to the numerical model and by loading the specimens in tension. The maximum normal stress values and the failure modes observed during experimental study were compared with those of the numerical models (Figure 2-54). The results showed that the FE model was capable of representing the maximum stress locations and failure model.

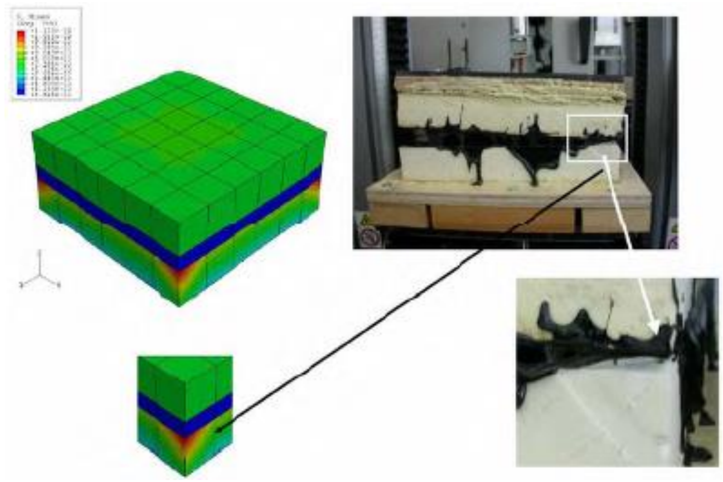


Figure 2-54. Comparison of the numerical and experimental failure modes (Murty et.al 2008)

However, the FE model overestimated the maximum capacity of the AARS. The experimental capacity was less than the numerical model predictions due to the challenges of maintaining a uniform adhesive layer and the presence of trapped air bubbles in the adhesive layer. Therefore, numerical models were used to investigate the effect of adhesive thickness, adhesive application techniques (fully coated and ribbon method), and the presence of insulation joints on the uplift resistance performance. It was discovered that the system performance decreased nonlinearly with the reduction of the adhesive contact area. The variations in the uplift resistance capacity of the AARS for adhesive thicknesses less than 0.394in. (10 mm) was found to be insignificant. Further, the type of insulation joints did not have much influence on the uplift resistance. However, only one type of adhesive and 0.197 in. (5mm) wide insulation joints were considered in this study. Moreover, only the static loads were used for the numerical simulation (Murty et al. 2008).

In addition to finite element modeling, computation fluid dynamic (CFD) simulations have been performed to evaluate the wind flow patterns around roofing systems. Wind loads on roofs, rooftop structures, and rooftop equipment have been determined through CFD simulations. Tominga et al. (2014) investigated the effect of the roof pitch to the airflow around isolated gable roof buildings using CFD simulations. Three different roof pitches; 3:10, 5:10, and 7.5:10, were considered in the study. The CFD analysis was performed using ANSYS FLUENT. The computational domain of the model corresponded to the wind tunnel test arrangement of the model building. The profile of the stream wise velocity and the turbulent kinetic energy was assigned as the inlet boundary conditions. The standard wall functions were assigned as the wall boundary conditions. These wall functions modified with roughness was assigned as the floor boundary condition. Symmetric boundary conditions were assigned at the sides and the top of the computational domain. At the outlet, zero pressure was assigned as the boundary condition. Re-Normalization Group (RNG) k-ε model was assigned as the turbulence model. The results obtained from the CFD analyses were compared with the experimental results from wind tunnel testing. Figure 2-55 shows the streamlines of the velocity observed for the three different pitched models through CFD analysis.

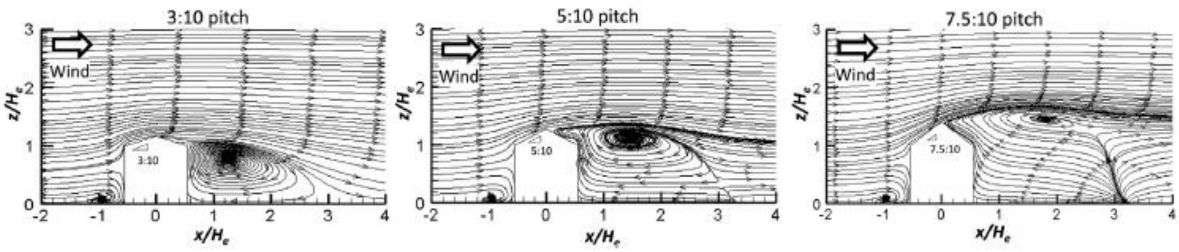
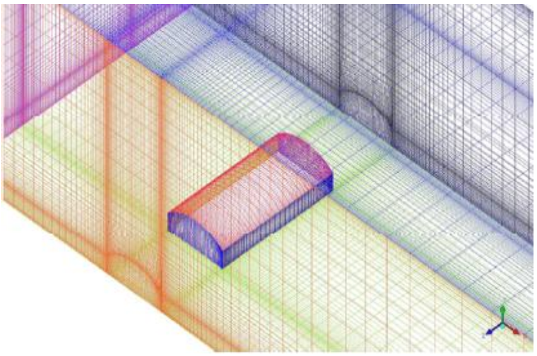


Figure 2-55. Streamlines for different roof pitches (Tominga et al. 2014)

The results showed that the flow pattern around a pitched roof changes critically at a roof angle of around 20°. However, this study was limited to a specific building geometry.

Ntinas et al. (2017) tested the accuracy of various CFD turbulence models in predicting the performance of three types of common agricultural buildings with arched type, pitched type, and flat type roofs. The CFD analysis was performed using ANSYS FLUENT. The computational model used in the CFD analysis is shown in Figure 2-56(a). Wind tunnel testing was performed on similar building models to validate the CFD model (as shown in Figure 2-56(b)). The inlet velocity of the model was assigned a uniform value of 12.6 in./s (0.32 m/s) resulting in a Reynolds number of 1270.



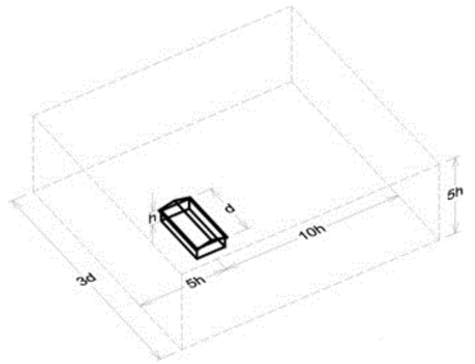
(a) Computational grid

(b) Experimental model

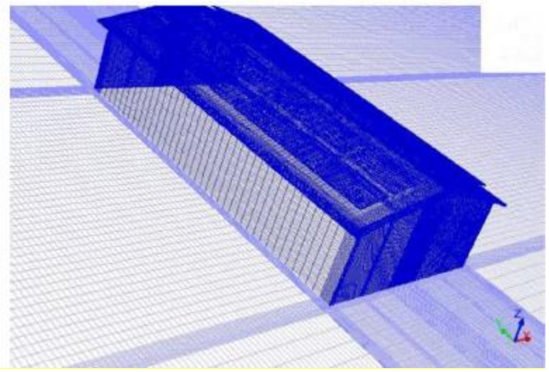
Figure 2-56. CFD and experimental study of an arched type building (Ntinas et al. 2017)

The velocity and turbulence kinetic energy measured from wind tunnel testing was compared with the values obtained from CFD analyses. The magnitudes of the velocity and turbulence kinetic energy from the CFD model and experimental model were approximate at the upstream of the building, but varied over the roof and downstream. Further, the performance of the turbulence models varied based on the building's roof type. In this study, suggestions were made to refine the mesh over the roof area, where higher stresses were observed during the CFD simulations, to improve the accuracy of the numerical results.

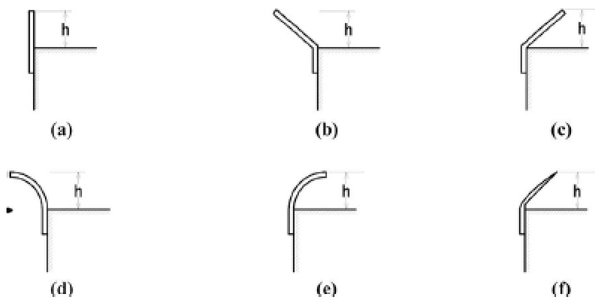
Aly et al. (2017) performed CFD simulations to identify the effect of certain architectural features and solar panel arrangements on reducing the wind induced suctions on flat and gable roof buildings. The aim was to identify the features that reduce loads on the roof, while minimizing the lift and drag forces on the features or devices themselves. ANSYS was used to perform the CFD analysis. Figure 2-57(a) and Figure 2-57(b) show the schematic view and the actual computational domain used in the CFD analysis. This computational model was then used to analyze the effect of solar panels on gable roof buildings. The suggested roof mitigation features and the computational grid with one such feature incorporated, are shown in Figure 2-57(c) and Figure 2-57(d), respectively. A user defined function was used for velocity and turbulent kinetic energy of the flow profile as the inlet boundary condition. All the walls were assigned no slip boundary conditions. The sides and the top surfaces of the domain were assigned symmetry boundary condition. At the outlet, outflow boundary conditions were assigned.



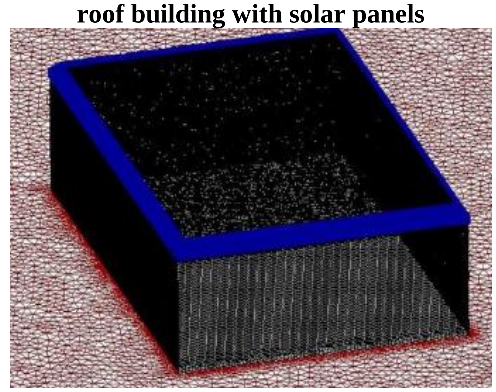
(a) Schematic representation of the computational domain with the test building



(b)) Computational grid used in modeling a gable roof building with solar panels



(c) Roof mitigation features



(d) Computational grid used in modeling a flat roof building with a mitigation feature

Figure 2-57. Details of the computational grids used in CFD analysis (Aly et al. 2017)

It was found that addition of aerodynamic features to flat roofs significantly reduced the uplift forces on the buildings, with a minimal drag force on the feature itself. Out of all the mitigation features suggested in the study, the mitigation feature known as the airfoil (indicated as (f) in Figure 2-57(c)) produced the lowest uplift forces in the structure. The CFD modeling of the solar panels on gable roofs showed that installation of the solar panels away from the roof corners and edges minimized the wind loads on both the panels themselves and the structure.

3 ASSESSMENT OF ROOFING INDUSTRY PRACTICES AND NEEDS

3.1 OBJECTIVES AND APPROACH

A survey questionnaire was developed to gather information and facts that are not typically available in the state-of-the-art and practice literature. The objective was to document industry experience on the performance of various roofing systems, quality assurance and quality control strategies, and the methodologies used for developing guarantee or warranty clauses. Before the questionnaire was disseminated, a selected group of roofing industry representatives was invited to review the questionnaire and provide feedback to enhance the clarity of the questions and use of industry specific terms. The questionnaire was disseminated to four groups: roofing adhesive manufacturers, roofing product manufacturers, roofing contractors and roofing consultants**.** The support of major associations and councils was sought for this purpose. The questionnaire is given in Appendix C.

3.2 RESULTS AND DISCUSSION

The results are categorized under five major topics as shown in Figure 3-1. The following sections discuss these topics in detail.

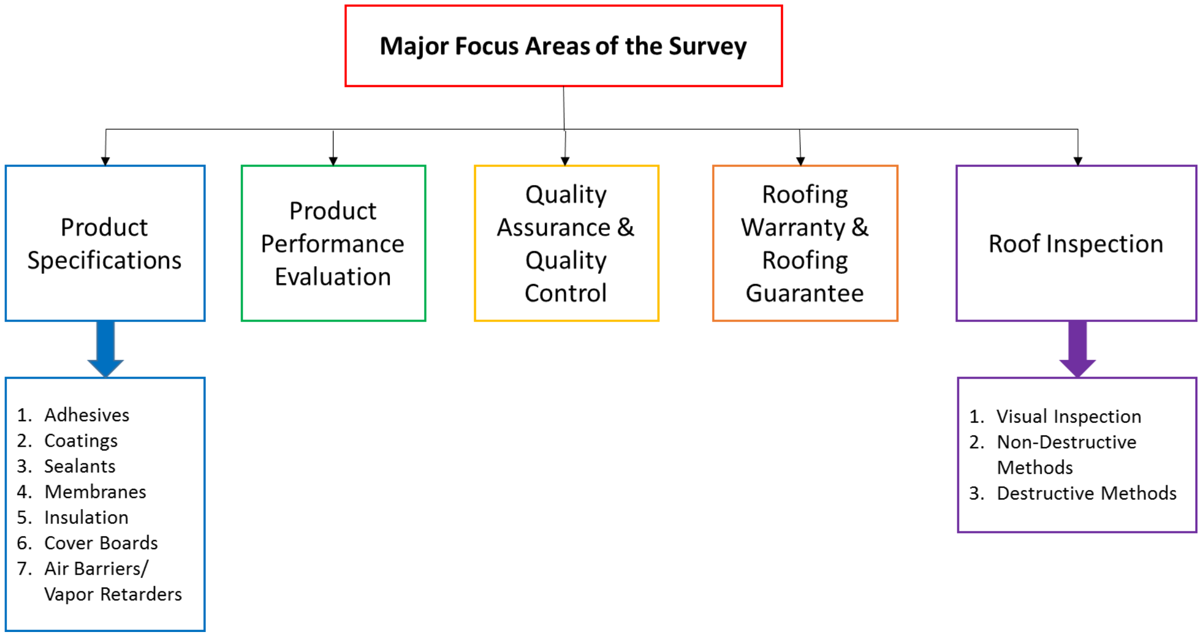


Figure 3-1. Structure of the survey questionnaire

3.2.1 Product Specifications

The survey responses from roofing product manufacturers and roofing adhesive manufacturers either included links to relevant specifications or guidance to navigate through relevant websites to access necessary publications.

The roofing products are categorized as adhesives, coatings, membranes, insulation etc., while the specifications are summarized under sub-topics: physical properties, application method, application requirements, methods of attachments, safety concerns, etc.

3.2.1.1 Adhesives

Adhesives are selected for specific roofing components. For example, the GAF 2-part roofing adhesive (G2PRA) is a two component elastomeric polyurethane adhesive, ideal for adhering insulation boards and fleece-back membranes. The Matrix 101 premium SBS membrane adhesive is used for SBS modified bitumen membranes only. Nevertheless, some adhesives are only compatible with certain roofing components. For example, the G2PRA is recommended to be used only with compatible roof decks (made of structural concrete deck, precast concrete deck, gypsum board, etc.) and compatible insulations and cover boards (made of polyisocyanurate, high-density wood fiber, extruded and expanded polystyrene, etc.). Physical properties listed in product specifications include weight/Gallon, volatile organic compound (VOC) level, flash point, viscosity, solids by weight, and coverage rate.

Adhesives are available as liquid and foam or froth. Roof slope is one parameter for adhesive selection. The typical application techniques for adhesives are fully covered, ribbons or beads and foam pads. The percent coverage per unit area, distance between ribbons or beads are defined as the application parameters. Application methods are selected based on the type of adhesive. For example, hand brushes, mops, rollers or sprayers are commonly used for liquid adhesive application while spray guns are commonly used for foam adhesives. Figure 3-2 to Figure 3-6 illustrate the application of different types of adhesives. In certain cases, specific equipment are used to enhance efficiency and workmanship during adhesive application. As shown in Figure 3-6, a Multi-Bead Applicator (MBA) machine is used for high speed and accurate application of the Dow Insta-Stik adhesive on roof panels.

Figure 3-2. EPDM membrane installation – a roller brush is used to apply a liquid adhesive (ERA 2010)

Figure 3-3. Insulation board installation – a spray gun is used for foam adhesive application (ICP Adhesives & Sealants 2018)

Figure 3-4. Membrane installation using hot asphalt in modified bitumen asphalt roofs - application using hand held mops (Crown Roofing LLC 2016)

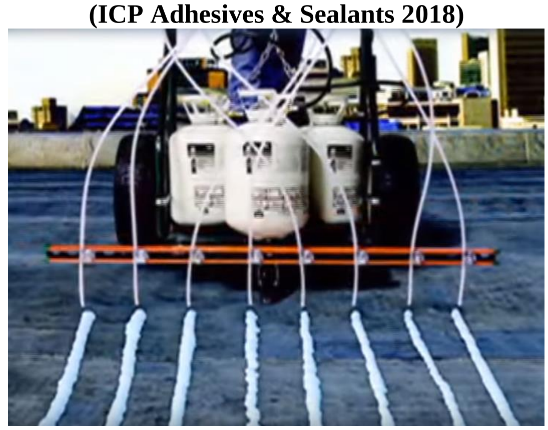


Figure 3-5. Adhesive application using a Multi-Bead Applicator (MBA) (Dow Building 2012)

In addition, favorable conditions for application such as ambient conditions (temperature, wind, and humidity), surface temperature, adhesive temperature, surface conditions, and curing requirements are specified to attain sufficient adhesive bond strength. Current practice is to follow manufacturer's recommendations for application and curing of adhesives. Adhesive and Sealant Council (ASC) is the national organizational body of US, responsible for the industry education, innovation and community and industry knowledge sharing for the growth of the adhesive industry.

3.2.1.2 Roof Coatings

Roof coatings are applied over existing or new roofs for enhancing waterproofing, solar reflectivity, corrosion resistance of metal roofs, resistance to algae growth, and resistance to cracking and peeling. For example, the APOC 207 Silver Guard-NF is a non-fibered roof coating containing aluminum pigment that increases solar reflectivity. The X-Tenda Coat Plus-K is an elastomeric coating used for improved durability, weatherproofing, ultraviolet resistance, algae resistance and fire resistance. Depending on the product and manufacturer's recommendations, base coats or primers are applied prior to application of the roof coating to enhance the bond between the coating and membrane. For example, the SIKACOAT P430 is a water-based primer applied prior to the application of SIKACOAT roof coatings to aged TPO membranes. Similar to adhesives, the coatings are applied with brushes, rollers, sprayers or squeegees, as shown in Figure 3-6 and Figure 3-7. A dry thickness is specified for a finished roof coating. In roof repairs, a compatible fabric is used as reinforcement when repairing existing roof defects such as cracks, tears, open seams, and deteriorated flashings prior to applying the roof coating. As an example, the SIKACOAT RF400 D is a stich bonded polyester fabric used as reinforcement in roof repairs with SIKACOAT roof coating systems (Sika 2015).

Figure 3-6. A waterproofing coating applied over the membrane using a squeegee (Conspec material Inc. n.d.)

Figure 3-7. Roof coating being sprayed over a metal roof after screw heads are sealed with mastic (Armor Garage 2018)

Roof coatings are available as water based and solvent based coatings, fibered coatings, and solvent free coatings. For example, the SRC 740 is a solvent free high solids silicone roof coating while the EnergyGuard silicone roof coating is a solvent based high solids roof coating. Physical properties and expected performance such as solids by weight (or volume), viscosity, elongation, tensile strength, reflectivity, permeability, flammability, etc., are provided in the product datasheet. The manufacturer specifies the application and curing requirements.

3.2.1.3 Sealants

Sealants are used at membrane seams, flashings, curbs, penetrations, and repairs. Solvent based, solvent free, water based, and fiber reinforced solid and liquid roofing sealants are available. Adhesion, waterproofness, ease of application, low odor, fast cure, and weather resistance are a few desired properties of a sealant. Figure 3-8 shows the application of a sealant during a roof repair, and Figure 3-9 illustrates the application of a sealant to seal the area around a roof penetration. In both of these applications, caulking guns are used as the method of sealant application.

Figure 3-8. Application of a sealant using a caulking gun during an EPDM roof repair (Jurin Roofing Services n.d.)

Figure 3-9. Application of a pourable, waterproofing sealer inside a curb surrounding a roof penetration (Conspec materials Inc n.d.)

Figure 3-10 shows the use of APOC 264 Flash N' Seal, a fiber reinforced, reflective and protective sealant, used in combination with reinforcing fabric to seal a flashing around a roof penetration. However, there are flashing sealants such as FG 400 Series Flashing Grade Silicone Sealant, thick, high build silicone mastic, designed to seal flashings without the need of reinforcing fabric. Figure 3-11 illustrates the application of a flashing grade, polyurethane sealant on a metal roof system using a brush. In certain cases, the fasteners of a metal roof system are sealed using mastic prior to the application of the protective roof coating, to prevent the intrusion of water into the system through the fasteners (Figure 3-7).

Figure 3-10. Application of a flashing sealant with reinforcing fabrics around a roof penetration using a brush (RoofSource n.d.)

Figure 3-11. Application of a polyurethane sealant at a seam joint of metal roof system using a brush (Jewett Roofing Company, 2016)

Similar to adhesives and coatings, manufacturer literature presents typical properties, application techniques, application conditions, and curing requirements. A product is applied as per manufacturer recommendations. The Adhesive and Sealant Council (ASC) and the Sealant, Waterproofing and Restoration Institute (SWRI) are two organizational bodies in US responsible for the growth of the sealant industry.

3.2.1.4 Roof Membranes – EPDM, PVC, TPO

Low maintenance, durability, water tightness, UV reflectivity, tear resistance, and adaptability to roof shape, design or pitch are some desired features of a roof membrane. Thermoplastic and thermoset are the two types of membranes. Thermoplastic material properties are sensitive to temperature changes whereas thermoset membrane properties are not. Polyvinyl chloride (PVC) and thermoplastic polyolefin (TPO) are thermoplastic membranes, and ethylene propylene diene monomer (EPDM) is a thermoset membrane. These three membranes are polymer products blended with additional constituents to achieve the desirable characteristics. Mils is the unit used to denote the thickness of a roofing membrane, and 1 mil is a thousandth of an inch.

3.2.1.4.1 PVC

PVC membrane is made up of a naturally inflexible PVC polymer. Therefore, plasticizers are added to the polymer to achieve the flexibility required of a roofing membrane. Polyester or fiberglass is embedded as the reinforcement in the membranes for its dimensional stability. The membranes are adhered, mechanically attached, or adhered and mechanically attached to the substrate. The PVC membranes are applied at different locations on a roofing system (i.e., as surface membrane, flashing, boots, at corners and curbs). A few common thicknesses of PVC membranes available in the market are 48 mil (1.2 mm), 60 mil (1.5 mm), 72 mil (1.8 mm), and 80 mil (2.0 mm). Self-adhered PVC membranes are manufactured with a factory applied adhesive layer. These self-adhered PVC membranes are installed by peeling off the liner to expose the pre-applied adhesive and bonding the membrane to the substrate (Figure 3-12). Self-adhered membranes reduce the complications associated with applying liquid adhesives (such as odor, coverage, etc.,) as well as the labor and installation time. As shown in Figure 3-13, steel rollers are used to press the membranes to expel trapped air underneath the membrane and develop a uniform contact area. Seams and flashings of the adhered membranes are sealed using seam seal tapes, self-adhesive cover tapes or through hot air welding. Hot air welding is performed using a special machine to ensure a continuous layer of membrane impervious to water and moisture infiltration.

Figure 3-12. Installation of a self-adhered membrane (Sika n.d.)

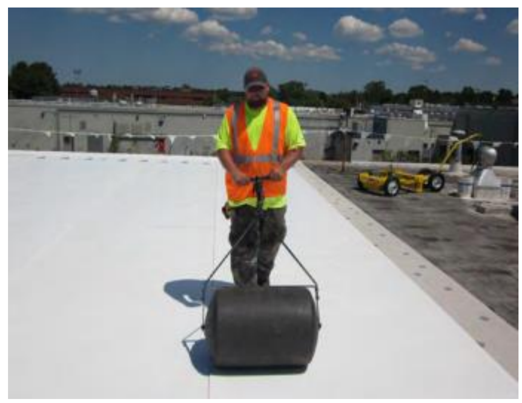


Figure 3-13. Self-adhered membrane pressed into place with a steel roller (Sika n.d.)

Based on the membrane surface type, membranes are categorized as bareback, fleece back or felt back membranes, and as textured membranes. In fleece back or felt back membranes (as shown in Figure 3-14), a fleece material or felt is heat welded to the underside of the membrane to enhance toughness, durability, and puncture resistance to the membrane. There are textured membranes (as shown in Figure 3-15) that can be adhered or mechanically attached, providing the surfacing option for the contractors. For example, the Sarnafill G 410 Textured Roofing Membrane is a fiberglass-reinforced membrane used in adhered and loosely laid systems while the Sarnafill S 327 Textured Roofing Membrane is a polyester reinforced membrane used only in mechanically attached roof systems.

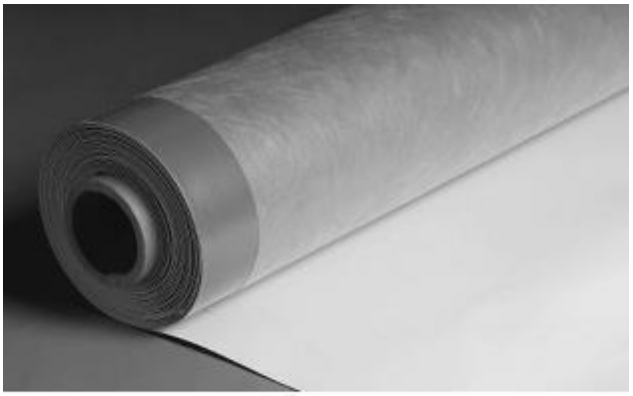


Figure 3-14. JM PVC FB- 80 mil fleece back membrane (Johns Manville n.d.)

Figure 3-15. Sarnafill textured PVC membrane (SIKA n.d.)

The typical properties provided in the product data sheet for a PVC membrane includes thickness, breaking strength, elongation at break, seam strength, tearing strength, low temperature bend, accelerated weathering test, static puncture resistance, and dynamic puncture resistance. One of the main drawbacks of the PVC membrane is that the plasticizers used in combination with the PVC polymer attracts mold and microbes which ultimately breakdown the plasticizer. Loss of plasticizer results in the loss of membrane flexibility, leading to brittle and hard roofs that are vulnerable to impact damages.

3.2.1.4.2 EPDM

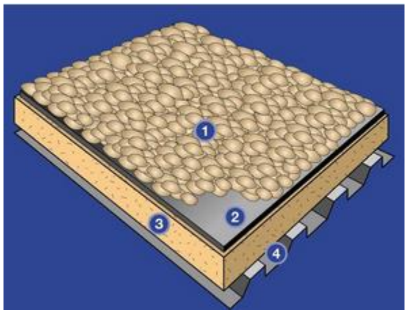
The EPDM single ply roofing membrane has been in the flat roofing commercial industry for over 40 years. EPDM membranes account for nearly 35% of the entire roofing market in the U.S. and 12% in the Europe. EPDM is used worldwide in over 1 billion square feet of new roofs per annum (EPDM Roofing Association (ERA) 2018).

EPDM is an elastomeric material manufactured by combining three polymers: ethylene, propylene, and diene monomer. A few unique and desired physical characteristics of EPDM membranes include resistance to UV radiation, thermal shock, cyclic fatigue, hail damage, brittle and shattering type damage due to low temperature, and moisture absorption. Black and white colored EPDM membranes are available in the market (Figure 3-16 and Figure 3-17). Since black EPDM membrane absorbs and retains heat making the surface warmer, it is suitable for colder climates to melt snow at a faster rate; thus, reducing additional weight on the roof. White EPDM membrane is suitable for warmer climates with its heat reflectance property resulting in a much cooler roof (EPDM Roofing Association (ERA) 2018). EPDM membranes are easy to repair and restore. The typical properties associated with an EPDM membrane such as thickness, tensile strength, elongation, tensile set, tear resistance, brittleness point, ozone resistance, water absorption, weather resistance, air permeance etc., are provided in the product datasheets.

Figure 3-16. Black EPDM membrane – Firestone RubberGard EPDM membrane (Firestone n.d.)

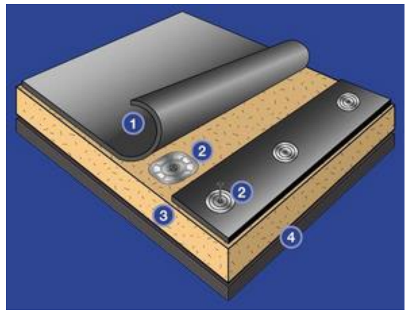
Figure 3-17. White EPDM membrane – Firestone RubberGard Eco White (Firestone n.d.)

The EPDM membrane is used in three types of roofing systems: loose-laid ballast systems (in Figure 3-18), mechanically attached systems (Figure 3-19), and fully adhered systems (Figure 3-20). The membrane can be placed either above or below the insulation. When the membrane is placed below the insulation layer, it is considered as an Inverted Roof Membrane Assembly (IRMA). The EPDM membrane can be either reinforced or un-reinforced and fleece back or bareback. In reinforced EPDM membranes, an internal fabric is encapsulated within the membrane. In fleece back EPDM membranes, fleece layers are added to the underside of an EPDM membrane. For example, the Carlisle's Sure –White EPDM membrane is a non-reinforced membrane, whereas the Sure-Tough EPDM is a reinforced membrane, and the FleeceBACK RL EPDM membrane is a fleece back membrane.



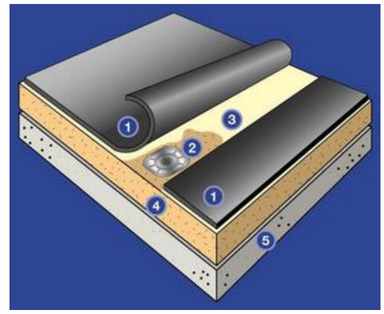
1. Ballast
2. Non-reinforced EPDM
3. Insulation
4. Approved Roof Deck

Figure 3-18. Ballasted EPDM roof system (ERA 2018)



1. Reinforced EPDM
2. Fasteners and Plates
3. Insulation
4. Approved Roof Deck

Figure 3-19. Mechanically fastened EPDM roof system (ERA 2018)



1. EPDM
2. Fasteners and Plates
3. Contact Adhesives
4. Insulation
5. Approved Roof Deck

Figure 3-20. Fully adhered EPDM roof system (ERA 2018)

Further, EPDM membranes are produced as vulcanized or non-vulcanized membranes. The physical properties of vulcanized or cured membranes are permanently set and show a consistent behavior throughout the sheet. On the other hand, non-vulcanized or uncured membranes can be stretched, formed, and the shape can be changed. Based on the properties of the two types, non-vulcanized EPDM membranes are suitable for applications such as flashings, whereas the vulcanized EPDM membranes are suitable as the roofing membranes.

The EPDM membranes are available in thicknesses of 45 mil, 60 mil, 75 mil, and 90 mils, with their widths varying from 10 ft to 50 ft and lengths extending up to 200 ft. The 90 mil thick EPDM membrane is a recent addition to the market after 25 years of off market testing for its performance. This 90 mil thick membrane is reputed for its higher puncture resistance and toughness and is the thickest monolithic waterproof membrane in the roofing industry (ERA 2018). The two most common methods of splicing EPDM membranes are either using liquid adhesives or using splice tapes. When a liquid adhesive is used, the adjoining sheets are cleaned with a splicing cleaner and the sealant is applied to prevent moisture intrusion. When a splice tape is used, the adjoining membranes are primed and allowed to dry before the splice tape is applied. Unlike the use of a liquid adhesive, the use of splice tapes is favored due to ease of application and quality control.

According to a Life Cycle Inventory and Assessment (LCA) study performed in 2010, the potential life expectancy of an EPDM membrane is about 50 years, and the membrane is considered as one of the most sustainable and environmental friendly materials (ERA 2018). Warranty periods for the EPDM membrane vary from 5 to 30 years. This 30-year warranty decision is based on the historical performance of EPDM membranes. Innovations related to EPDM membranes have remained relatively constant for the past thirty years. However, the EPDM accessory products such as the seam tapes and installation equipment have continued to evolve in order to reduce the work fatigue, improve the quality of roof systems, and enhance the roofing installation and performance. The EPDM Roofing Association (ERA) was established in 2003 to represent EPDM single-ply roofing product manufacturers and their leading suppliers. The ERA also provides technical and research support to the public and the construction industry.

3.2.1.4.3 TPO

Thermoplastic Polyolefin (TPO) membranes were first introduced to the U.S. in 1992, though they have been in use in the Europe since 1980s. Since 2006 to 2013, the market for TPO membranes has grown from about 23% to about 41% in the U.S. TPO membranes were originally created to overcome the limitations of PVC membranes. TPO is a thermoplastic membrane made by polymerizing polyprophylene and ethylene propylene together (Firestone, 2018). Unlike PVC, TPO is naturally a flexible material. This is one of the advantages of TPO over PVC, where artificial plasticizers are unnecessary to provide the flexibility. Since it is a thermoplastic material, it can be heat welded to splice up with the adjacent membrane to prevent water intrusion. In addition to the main polymer, additional constituents like UV light stabilizers, fire retardants, titanium dioxide, and heat stabilizers are blended to achieve the desired characteristics. UV light stabilizers provide weathering resistance and long-term strength while titanium oxide enhances UV reflectivity. In terms of sustainability, TPO is easily recyclable and the white TPO reflective membrane results in a cool roof there by improving the energy efficiency. However, TPO membranes differ from manufacturer to manufacture. TPO producers have their own chemical formula, product design and manufacturing process, thus differencing one TPO product from another. The TPO membranes are generally light colored (white, tan or gray) to enhance UV reflectance. Typical thicknesses of the TPO membranes available in the market range between 45 mil and 80 mil. TPO membranes are reinforced with polyester reinforcement with or without a fleece back cover. As an example, JM TPO -45 mil (as shown in Figure 3-21) is a TPO membrane without fleece backing (smooth back or bare back) and JM TPO FB 115 (as shown in Figure 3-22) is a reinforced TPO membrane with a polyester fleece backing.

Figure 3-21. JM TPO – 45 mil – TPO membrane (Johns Manville n.d.)

Figure 3-22. JM TPO FB 115 – Fleece backed TPO membrane (Johns Manville n.d.)

TPO membranes are used in both mechanically attached and adhered roof systems. Use of fasteners and screws (as shown in Figure 3-23) and induction welding (as shown in Figure 3-24) are the common methods used in mechanically attached systems to install TPO membrane on a substrate. For induction welding, an induction-welding machine is used to fuse the membrane to the plates. After fusing the membrane to the plates, a weighted magnet is placed on top of the plate for a specified duration (usually a minimum of 60 seconds) to provide an adequate clamping force to ensure a strong bond.

Figure 3-23. In lap mechanical fastening using plates and screws (Dykstra 2016)

Figure 3-24. Induction welding and its components (Sika n.d.)

In adhered systems, water based, solvent based, or non-solvent based adhesives are used to attach the TPO membranes to the substrate. Use of self-adhered TPO membranes with embedded factory applied, pressure sensitive, adhesive is the latest innovation to ensure uniform adhesion coverage across the membrane. The membrane seams are made watertight by using an automatic heat welder (as shown in Figure 3-25) or using a hand held heat gun with a hand held roller (as shown in Figure 3-26).

Figure 3-25. Automatic heat welder (Dykstra 2016)

Figure 3-26. Hand held heat gun with a roller (Sika n.d.)

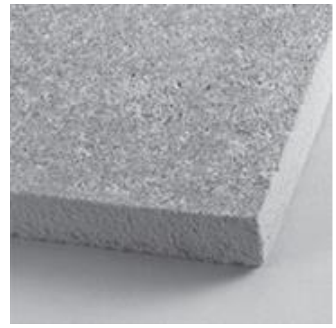
The physical properties stated in the product datasheet for TPO membranes are thickness, breaking strength, elongation at break, tear strength, low temperature bend, emissivity, puncture resistance, cold brittleness, permeance, water absorption, hydrostatic resistance, ozone resistance, and weather resistance.

3.2.1.5 Insulation

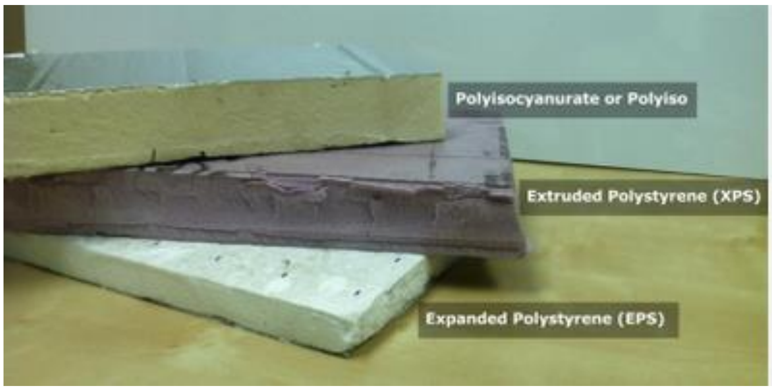
Different types of rigid insulation boards are available for roofing systems. Figure 3-27 shows a few examples (wood fiber, rock wool, perlite, expanded or extruded polystyrene, cellular glass, and polyisocyanurate). Wood fiber is an organic insulation board made of wood, cane or vegetable fibers mixed with binders and fillers. In order to improve the moisture resistance of wood fiber insulation, the insulation is asphalt embedded or asphalt coated. Rock wool is made from rock or blast furnace slag by melting and spinning into fibers to resemble the wool texture. The Sarnatherm Mineral Wool Dual Density insulation is an example of a mineral wool that is manufactured from basalt rock and slag to be used in commercial and industrial mechanically fastened roof systems. Perlite insulation board is made of the inorganic perlite (expanded siliceous volcanic glass) combined with organic fibers and binders. Similar to wood fiber insulation, an asphalt or similar coating is applied to prevent the moisture infiltration into the insulation. Expanded and extruded polystyrene are two types of insulations are available in the market. Expanded polystyrene (XPS) consists of a polystyrene polymer embedded with a foaming agent, which expands upon heat to form a closed cell insulating material. For example, the Sarnatherm XPS is an insulation with a XPS foam core and smooth face and back surface intended to be used in any conventional roof assembly. Extruded polystyrene (EPS) consists of a blended polystyrene polymer that is heated and extruded before exposing to the ambient conditions. Once it is exposed to ambient conditions, it expands and forms the closed cell insulating material. The Foam Control EPS 100 and the Foam Control EPS 130 are two architectural grade EPS insulations, used in all types of construction applications. Polyisocyanurate or polyiso insulation is a closed cell foam insulation, with its foam core sandwiched between organic or inorganic felt facers, glass-fiber mat facers or glass-fiber-reinforced aluminum foil facers. A blowing agent is used to expand the foam, thus creating a closed cell structure that enhances its thermal resistance. The main purpose of the inorganic felt or glass facers is to improve the resistance to mold growth, as well as to act as a smooth surface when mounted on fully adhered single ply systems with adhesives or using self-adhering technology.

Wood fiber (NBT n.d.)

Rock wool (Shree Gayatri Insulation n.d.)



Perlite (GAF n.d.)



Polyisocyanurate, EPS and XPS (Green Audit USA n.d.)

Cellular glass (Owens Corning n.d.)

Figure 3-27. Insulation boards for roofing systems

The R-value for an insulation is a measure of its thermal resistance. As is clear from Figure 3-28, the highest R-value is obtained for Polyiso. This is one of the primary reasons for using Polyiso in roofing applications. However, combustibility of foam insulation is a major drawback.

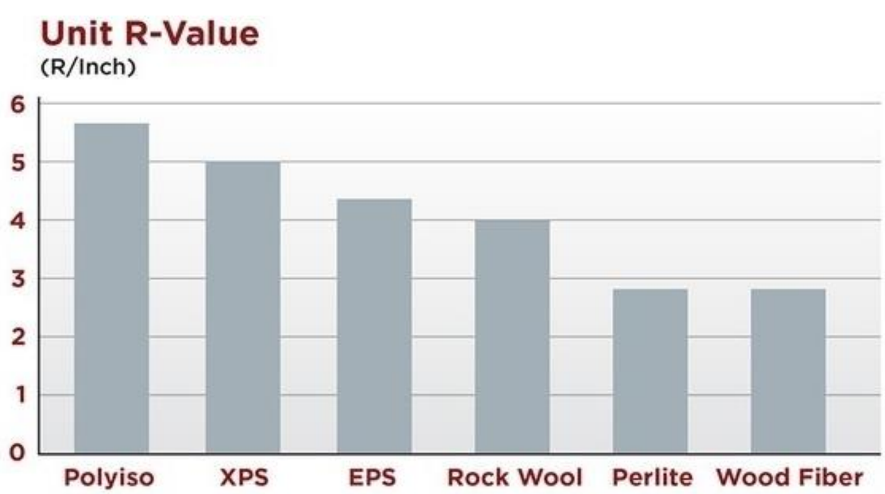


Figure 3-28. R-value of different insulation materials (Hoff 2018)

The insulations are installed to a desired thickness based on the required total thermal resistance. Composite roof panels, as shown in Figure 3-29 and Figure 3-30, are designed with two or more insulation materials to fulfill this purpose. The Rich-E-Board (Figure 3-29) is a composite panel with a vacuum insulated core sandwiched between two high-density polyisocyanurate mineral surfaced foam boards along with fiberglass-reinforced facers. The insulated core has a high R-value and thus acts as a thermal barrier, and the high-density polyisocyanurate foam acts as an added insulation while providing protection to the panel. On the other hand, the Invinsa Foam, shown in Figure 3-30, is a composite board with polyisocyanurate foam of two different densities (high and normal) coated with glass facer layers. The normal density foam acts as a thermal barrier. The high-density foam acts as an added insulation as well as a protective layer for the normal density foam. The coated glass facers provide resistance to mold growth while providing a smooth surface for self-adhered systems and adhesive applied systems.

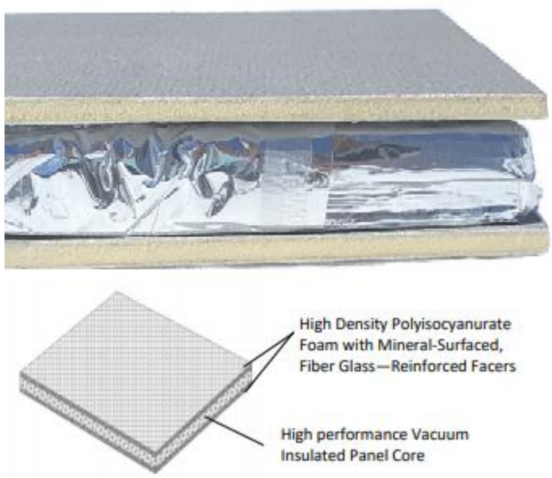


Figure 3-29. High Density Composite Vacuum Insulated Panel – Rich-E-Board (Sika n.d.)

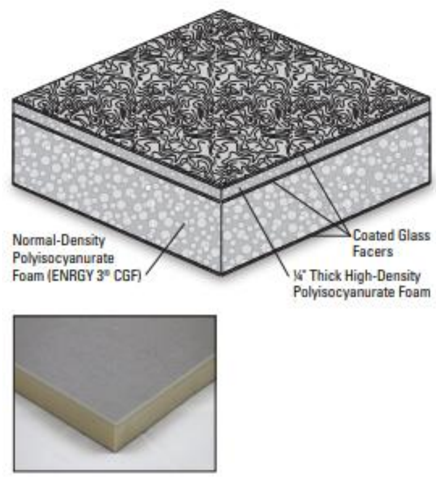
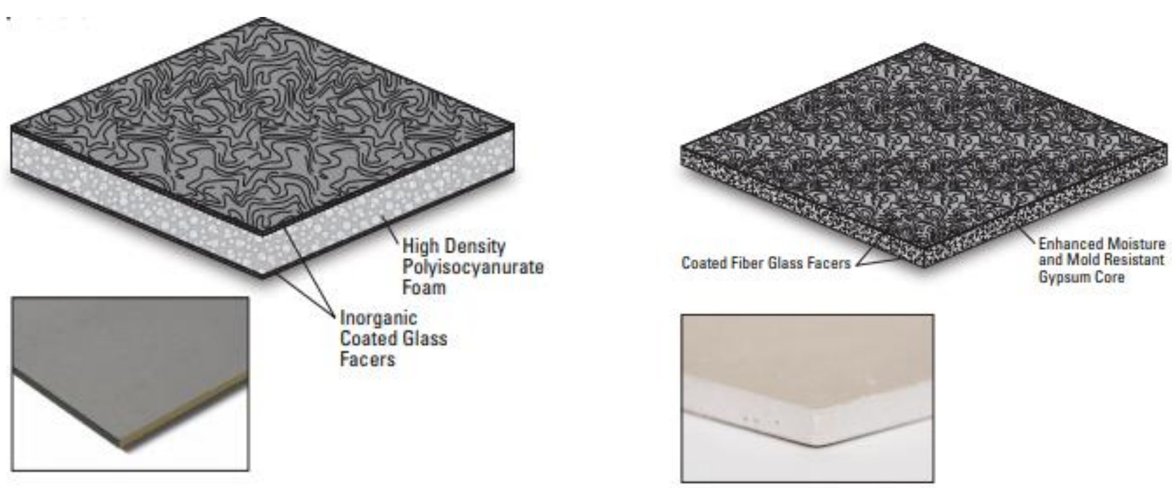


Figure 3-30. Dual-Density Polyisocyanurate Composite Board – Invinsa Foam (Johns Manville n.d.)

Physical properties listed in roofing insulation manufacturer datasheets include water absorption, dimensional stability change, compression strength, tensile strength, moisture vapor transmission, flame spread index and service temperature. Compatible roof systems and substrates as well as suitable attachment methods to the substrate (fastening patterns or adhesive application) are further illustrated in the product datasheets.

3.2.1.6 Cover Boards

A roof cover board is primarily used to serve as a rigid substrate for the membrane while providing an added protection to the insulation layer. Further, a cover board acts as a temporary protection against foot traffic, and weather, until a membrane is installed in a roofing system. Typically, a cover board has a core and facers. The core is made of gypsum, gypsum fiber, high-density polyiso, low-density polyiso, XPS, wood fiber, etc. The facers are coated with fiberglass, asphalt or glass. The facer material needs to be compatible and perform well with the adhesive applied membrane attachment. Fire resistance, dimensional stability, durability, strength, impact resistance, mold resistance, wind uplift resistance, and sound insulation are a few desired properties of a roof cover board. In certain cases, cover boards act as a thermal barrier (Hutchinson 2017). For example, the JM Invinsa Roof Board shown in Figure 3-31(a) is a high density (HD), closed cell, polyiso foam, coated with inorganic glass facers on the top surface. The HD foam provides additional insulation, and the glass facers provide improved resistance to mold growth while providing a smooth surface for effective adhesive application. Cover boards are either mechanically fastened or adhered. Cover boards are also available with self-adhered technology. The JM DEXcell Glass Mat Roof Board shown in Figure 3-31(b) is a glass mat faced gypsum cover board used in mechanically fastened systems. The Fesco Board HD, on the other hand, is a cover board with high-density perlite core embedded with reinforcing cellulosic fibers and binders. The board is used in both adhered and mechanically attached systems.



(a) JM Invinsa Roof Board (Johns Manville n.d.) **(b) JM DEXcell Glass Mat Roof Board (Johns Manville n.d.)**

Figure 3-31. Roof cover boards

Density, compressive strength, laminar tensile strength, flexural strength, moisture content, and water absorption are a few physical properties listed in the product datasheet.

3.2.1.7 Air Barriers/ Vapor Retarders

Air barriers restrict the air intrusion while vapor retarders restrict the vapor movement into the roofing system from the interior of the building. Puncture resistance, UV resistance, and non-slip are some required characteristics of an air barrier/vapor retarder. Most of the time thesame membrane product is used as an air barrier as well as a vapor retarder. As an example, the Firestone V-Force, shown in Figure 3-32, is a self-adhered vapor barrier while the Carlisle's VapAir Seal 725TR, shown in Figure 3-33, is used as an air barrier as well as a vapor retarder.

Figure 3-32. Firestone V-Force vapor barrier membrane applied on a primed substrate (Firestone n.d.)

Figure 3-33. Air barrier/vapor retarder with an SBS backing - Carlisle's VapAir Seal 725TR (Carlisle Syntec Systems n.d.)

The air barriers/vapor retarders are made of using a proprietary formulation of elastomeric styrene-butadiene styrene (SBS) polymer modified bitumen. The SBS polymer modified bitumen is occasionally combined with a reinforcing material such as polyester or glass fiber. The top side of an air barrier/vapor retarder is prepared as a smooth polyethylene surface or is applied with a fine mineral aggregate layer (sand) to ensure better adhesion with the subsequent layers. Approved substrates for air barriers/vapor retarders are listed in the product datasheets. As per the manufacturer's requirements, the substrate needs to be primed before applying a vapor barrier. For example, except on steel decks, the Firestone V-Force vapor barrier membrane is applied on a substrate primed with a solvent based or water based primer (Figure 3-32). After the substrate surface preparation, an air barrier/vapor retarder is adhered to the substrate using a compatible adhesive, adhesives and fasteners, self-adhesive layer or by heat welding the burn off film present in certain products. Styrene Butadiene Styrene (SBS) is the abundantly used adhesive in these self-adhered air/vapor barriers. For example, the Carlisle's VapAir Seal MD is a reinforced composite aluminum foil with a self-adhesive SBS backing. The seams are attached using lap sealants and applied with a hand roller or a stand-up seam roller to ensure proper attachment at the seams. Thickness, tensile strength, elongation, peel adhesion, puncture resistance, permeability, and air permeance are a few physical properties listed in the product datasheets.

3.2.1.8 ASTM Specifications Relevant for Roofing Products

A list of ASTM specifications related to various roofing products is provided in Appendix D.

3.2.2 Product Performance Evaluation

The roofing products are evaluated at product level or in a system to determine their physical properties and to assess their performance. The evaluation is performed according to test procedures outlined in standards published by organizations such as ASTM, FM, or UL. Appendix E lists the testing standards used for evaluating the performance of roofing components. However, these are not the only standards related to roofing product performance evaluation. It is not practical to summarize all available evaluation test procedures due to the sheer variety of subject matter related to roofing materials.

Products are assigned an approval or a certification based on the evaluation results. This approval or certification is noted in the product label and the product datasheet. Such approvals and certifications help designers, contractors and consumers select products for a given job. Factory Mutual (FM) approval, Underwriters Laboratory (UL) classification, Florida Building Code (FBC) listing, and Miami Dade County approval are few examples. In addition, certifications are issued based on energy efficiency and sustainability performance of a product. A few examples of the agencies that issue such certifications include the United States Environmental Protection Agency (EPA) energy star certification, Leadership in Energy and Environmental Design (LEED) certification, Green Globes certification, the Cool Roof Rating Council (CRRC), the NSF/ANSI 347 Sustainability Rating, BBA Life Expectancy certification, Title 24 of California Energy Commission, and the National Sanitation Foundation (NSF) International certification.

A list of product performance evaluation specifications related to various roofing products are listed in Appendix E.

3.2.3 Quality Assurance/Quality Control

The inspection and testing conducted for quality assurance (QA) and quality control (QC) are typically the same. However, such activities are considered as QA or QC if the activities are performed for the client or the contractor. Quality assurance represents the measures taken by a building owner (client) or a client's representative to ensure that the roofing system is installed as per the specifications, manufacturer guidelines, or the contract documents. Quality control represents the measures taken by a contractor or a product manufacturer representative to demonstrate that the roofing system is installed as per the specifications, manufacturer guidelines, or the contract documents. Prior to installation, several actions are taken as part of the QA process such as reviewing the installation plans, preparing the checklists to be used during inspection and verifying the compliance by taking roof test cuts and other sampling techniques.

Typically, three parties are involved in a QA/QC process: a product manufacturer's representative, an architect's or owner's representative, and a roofing consultant. The manufacturer's representative will be present only if the roof is covered by the manufacturer's warranty. The manufacturer's representative is present prior to the installation, during installation and at final inspection to make sure none of the terms of warranty is violated prior to the issuance of the warranty. The architect or the owner can employ an inspector to perform QA activities. The roofing consultant can be a professional engineer or an architect who is involved from the beginning of the project by recommending products, writing or reviewing specifications, ensuring that the standards and application techniques are followed by performing daily inspections during installation, and providing a detailed inspection report on the contractor's work. The roof inspectors are also known as roofing observers. The Roofing Consultants Institute (RCI) provides necessary education and training to become a registered roofing observer (RRO).

ASTM D7186: *Standard Practice for Quality Assurance Observation of Roof Construction and Repair*, describes the basic procedures for performing visual inspection on new roof construction or roof repairs. Thermometer, camera, level, straight edge, measuring tapes, seam probe, clipboard, and moisture meter are few of the instruments needed for inspection. Further, the inspector needs to be accessible to the roof plans, shop drawings, installation manuals, contract documents, roof materials, etc. Inspectors often use checklists to facilitate their inspection procedure.

Prior to installation, the roofing products and their storage conditions are inspected to ensure the delivery of the selected products and their condition. As a part of this inspection, product labels are checked to verify the brand name, batch number, type, and physical properties. In addition, the storage conditions are checked to verify that the manufacturer's specified conditions are maintained. Figure 2-34 shows an instance where the roofing materials are properly stored on a roof deck with adequate cover and ventilation.

Figure 3-34. Proper storage of roofing materials prior to installation (SIG Design Technology 2014)

During deck preparation, the inspector checks for the slope, smoothness, joint tolerances (in the case of panelized decks), lap locations, adequate support and openings, drainage, etc. Importantly, if the deck was used as a material storage, unnecessary deflections or damages should be noticed and attended to. Before the installation, the site conditions (especially the weather conditions) are evaluated to prevent possible complications during installation. During application of other roofing components such as insulations and membranes, an inspector verifies if the contractor follows the manufacturer's guidelines and other project specifications.

The contractor should immediately correct the defects, irregularities and deficiencies identified during the inspection. Guidelines such as the NRCA's *Quality Control and Quality-assurance*

Guideline for the Application of Membrane Roof Systems are available for guidance on QA and QC procedures.

The destructive and non-destructive testing techniques that can be incorporated as part of QA and QC procedures are discussed later in this chapter.

3.2.4 Periodic Inspection and Maintenance

The owner needs to maintain a periodic inspection and maintenance schedule. The typical practice is to inspect large commercial building roofs once in early spring to assess and rectify the damages occurred during winter, and once in early fall to prepare the roof for the upcoming winter. An immediate inspection is performed following a severe event such as a hurricane, hailstorm, or a thunderstorm to address all the required repairs. Periodic inspection is also a requirement to maintain a roof warranty. A certified inspector performs the inspection.

Visual inspection is the most common approach. However, destructive and non-destructive evaluation methods are implemented as needed. Usually, the defects identified using non-destructive methods are to be verified by performing a limited number of destructive tests, such as core sampling. The severity of damages discovered during inspection helps with repair and replacement decisions. Non-destructive and destructive evaluation methods implemented by the roofing industry are discussed in the next section.

3.2.5 Destructive and Nondestructive Evaluation Methods

3.2.5.1 Visual Inspection

The typical approach is to walk on a roof to visually identify problematic areas and document them on a template prepared from the roofing plans. However, going beyond the tradition, drones are currently being used for roofing inspection. The waterproofing membranes are inspected for any obvious signs of water penetration, ponding areas, or sagging spots. In addition, the membrane seams, flashings, fasteners and adhesives are inspected for indicators of aging, wearing, tearing, and rust. Figure 3-35 shows a situation where algae growth was discovered after detecting a roof leak. Figure 3-36 illustrates ponding on a flat roof. Ponding can lead to excessive deflection of the roof resulting in structural damage. Excessive durations of ponding could result in growth of algae and vegetation, along with attracting organisms that consume roofing materials.

Figure 3-35. Algae growth due to water leakage (InspectAPedia 2015)

Figure 3-36. Water ponding areas (Roof Slope 2016)

Figure 3-37 shows the rusting of steel metal flashings and fasteners over time. Unless repaired and replaced, water can seep through these rusted locations causing interior damages to the roof. Figure 3-38 shows a damage that compromised the integrity of the membrane.

Figure 3-37. Rusting of metal flashing and fasteners (Kelly Roofing 2018)

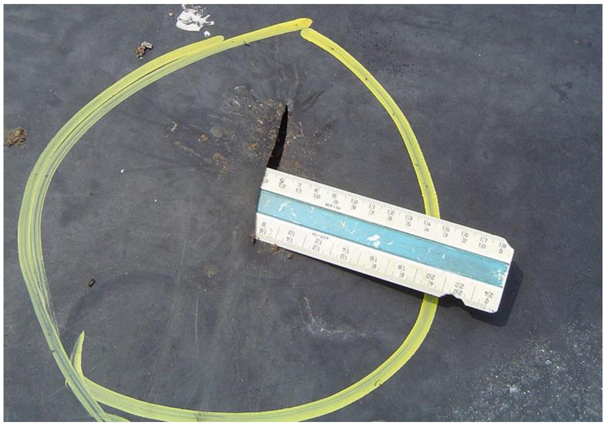
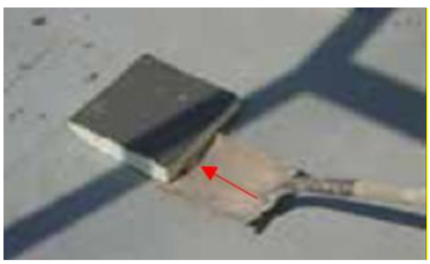


Figure 3-38. Cut in EPDM (Independent Roof Services Inc. n.d.)

3.2.5.2 Adhesion Testing

This test is performed to evaluate the mechanical uplift resistance performance of a specific roof insulation/adhesive combination. Roofing contractors or third parties of qualified personnel are required by the product manufacturers to perform an adhesion test before issuing their guarantee. The acceptable adhesion test methods are the "Shovel Method" and the one outlined in the ANSI/SPRI IA-1 2010: *Standard Field Test Procedure for Determining the Mechanical Uplift Resistance of Insulation Adhesives over Various Substrates*. For the shovel test, the adhesive is applied on the roof deck or the substrate as per the manufacturer's guidelines. A piece of roof insulation or plywood with a minimum size of 12 in. × 12 in. is placed on the adhesive. The adhesive is cured for an hour. A shovel is placed squarely under the corner or at the end of the adhered insulation or the board, as shown in Figure 3-39(a), and is pulled up. The shovel is pushed down gently until the bond between the adhered insulation or the board is broken with the substrate, as in Figure 3-39(b). The insulation or the board and the substrate is examined to determine the location of the bond failure. If the failure lies within the adhesive or the adhered insulation or plywood, as shown in Figure 3-39(c), the adhesive is compatible with the underlying roof deck or the substrate. However, if the failure occurs in the deck, as shown in Figure 3-39(d), or the foam adhesive separates from the substrate or the deck, the adhesive should not be used for this roofing application (GAF 2017).



(a) Placement of the shovel (red arrow shows the direction of shovel movement)

(b) Downward push on the shovel (red arrow shows the direction of shovel movement)

(c) Bond Failure - Separation of the insulation from the adhesive

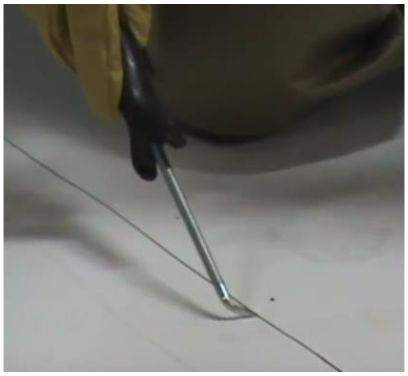
(d) Bond failure – Failure at the deck – insulation interface

Figure 3-39. The shovel test (GAF 2017)

3.2.5.3 Seam Weld Evaluation

Visual inspection, physical probing, and test cuts are the three basic methods of evaluating the quality of a heat weld. The purpose of visual inspection of a heat weld is to document the adequacy of the weld width, presence of fasteners and plates within the weld area, overheating or tearing within the weld area, special sealing at T-joints, and under heating or skipping of seam areas.

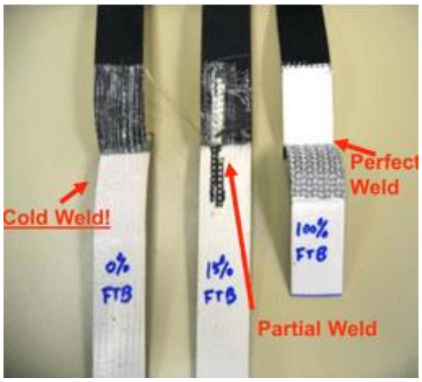
The physical probing involves the use of a blunt seam probe such as a dulled cotton pin puller. After the weld is allowed to cool the probe is pressed against the welded edge as shown in Figure 3-40(a) and drawn along the seam. Presence of a void or a partial weld will allow the probe to enter at locations between two layers of membrane. When performing the seam cut test, the weld is allowed to cool and a small portion of the welded seam (1 in. × 10 in.) is removed as shown in Figure 3-40(b)). Then, the seam is pulled apart by applying an even pressure, as shown in Figure 3-40(c). Weld performance is unsatisfactory if the seam peels off without any delamination of the membrane (GAF 2017). Figure 3-40(d) illustrates possible failure modes of a welded seam.



(a) Seam probe testing (Roof Repair 2014)

(b) Test cuts – Performing the test cuts (IBRoofSystems1978 2012)

(c) Test cuts – Peeling off at the seams (IBRoofSystems1978 2012)



(d) Test cuts - Results of peeled off test cuts (McCabe 2015)

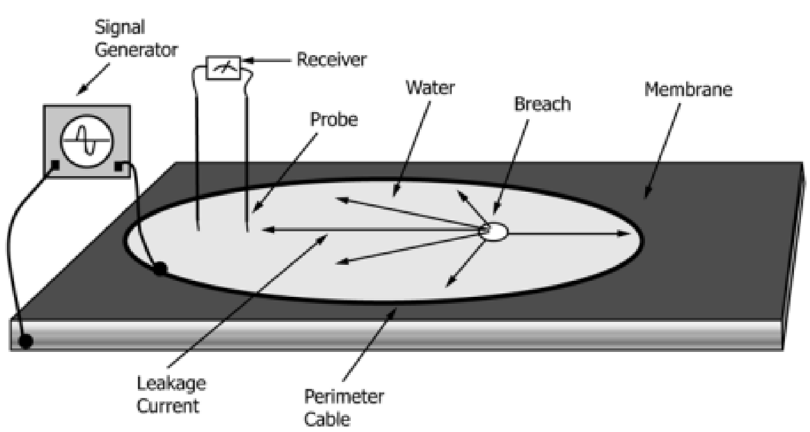
Figure 3-40. Quality control of seam welds

3.2.5.4 Electronic Testing for Waterproof Membranes

Upon completion of a roofing, the roof is inspected to verify that water has not infiltrated the roofing system during the project. Prior to employing any advanced technology, a through visual inspection is performed to identify any problematic areas. Infrared thermography, nuclear metering, impedance (capacitance) testing, and the ASTM D7877 low voltage and high voltage test methods can be used for leak detection and integrity of roofing systems. These five methods are not only used as QA and QC techniques for new roof installations, but also for evaluating existing roof systems. Only low voltage and high voltage test methods are discussed in this section.

As shown in Figure 3-41(a), the low voltage test method (also known as the low voltage membrane Electric Field Vector Mapping (EFVM)) utilizes a sensitive voltmeter and probes to locate membrane leaks. The process includes installation of a conductor cable loop (perimeter cable) around the area to be tested for leaks. Next, the area within the loop is sprayed with water to form a continuous conductive surface. Subsequently, one end of the signal generator is connected to the perimeter cable and the other end to the roof deck to form a continuous electric path to the deck through the water leaking on the deck below, if any, creating a potential gradient. This potential difference is identified by moving the probes within the wet area while observing the voltmeter readings. This basic circuit formed in the low voltage test method is shown in Figure 3-41(b). However, if any gaps are formed within the area covered with water, erroneous readings result. Further, other non-conductive components within the roof system, such as the insulation and air /vapor barriers, can interrupt the signal or offset the leak location (ASTM 2014).

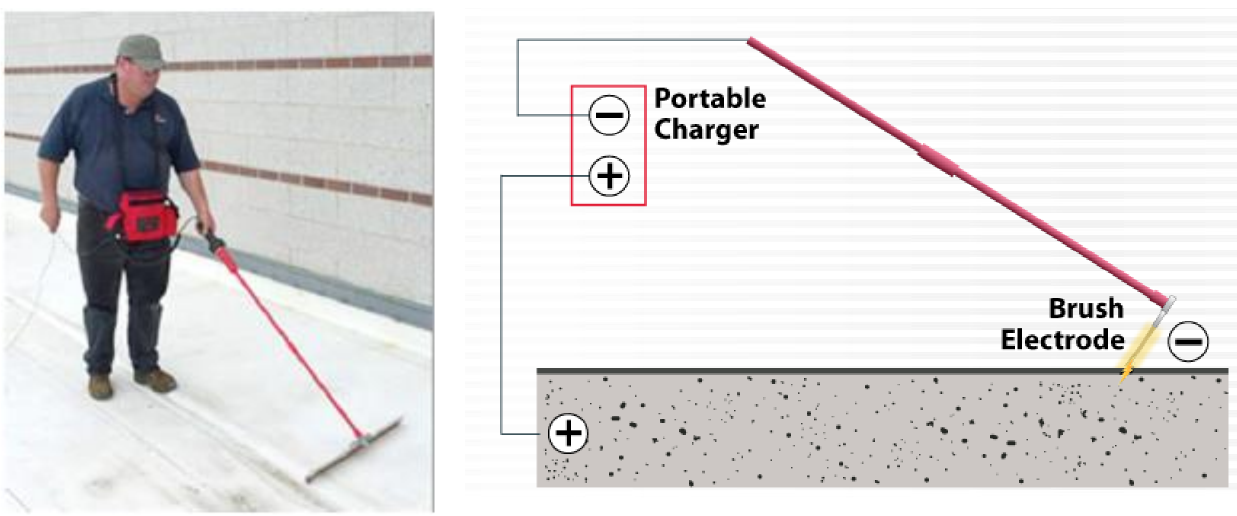

(a) EFVM probes and receiver



(b) Basic circuit of EFVM

Figure 3-41. Low voltage electric field vector mapping (EFVM) method (ASTM 2014)

Unlike the low voltage test method, the high voltage test method is performed on a dry surface. As in Figure 3-42 a charged metal broom is swept over the membrane while the deck is earthed to the ground, creating a high potential difference. Once a breach is detected in the membrane, the circuit is completed allowing a current to flow (as shown in Figure 3-42(b)). The test unit detects this current by emitting an audible tone to the operator. This test method can be employed for horizontal locations as well as at vertical locations such as at flashings and at penetrations. A limitation of the high voltage test method is that this test can only be conducted on non-conductive roof membranes with conductive substrate. In addition, the excess voltage could damage the membrane and the operator needs to be protected from the voltage source (ASTM 2014).



(a) Charged metal broom **(b) Basic circuit of high voltage method**

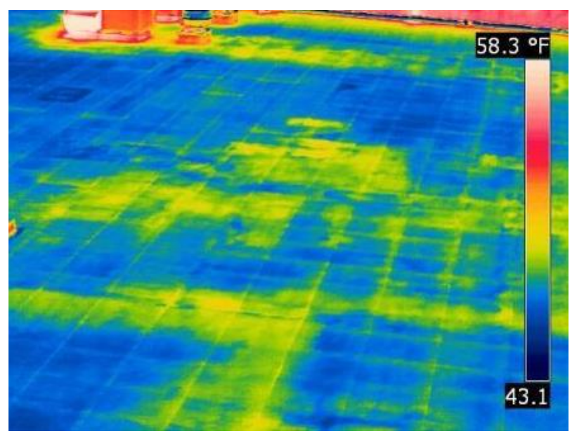
Figure 3-42. High voltage test method (ASTM 2014)

ASTM D7877: *Standard Guide for Electronic Methods for Detecting and Locating Leaks in Waterproof Membranes* (2014) describes the equipment and methods used for locating membrane breaches using electrical conductance. These two voltage methods are both non-destructive and have the ability to locate large tears as well as pinholes within the membrane. However, neither of these two methods are applicable on black EPDM membranes, which are electrically conductive due to the presence of carbon black. One advantage of the low voltage test method over the high voltage test method is that the latter cannot be employed over roofs with overburden materials such as ballast, vegetation, and pavers. Similar technologies are used in building and bridge inspection, and the expertise is available to help the roofing industry.

3.2.5.5 Infrared (IR) Thermography

Roof inspection is conducted in accordance with the ASTM C1153-10: *Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging* (2015). The IR imaging is best performed at sunset. The roof absorbs heat during daytime. When all the components are intact, a uniform temperature distribution is observed. At dawn, as the surface cools down, the locations with dry interior layers cool down much faster than the other areas. Under the same conditions, the locations with moisture intrusions take much longer to cool down. An IR camera could record this difference using different color contours as shown in Figure 3-43(b). In Figure 3-43(b), the red/yellow areas represent areas with wet insulation. The IR equipment can be a simple hand-held infrared camera (as shown in (a)), a manned plane with an externally mounted IR camera, or an aerial drone affixed with an IR camera. The advantages of this non-invasive technology include area of coverage, speed of inspection, ease of understanding graphical presentation of results, light weight, and portability. However, the results can be influenced by under deck heating units or cooling units, shades of nearby structures and trees, windy conditions and moisture on the roof surface (ICC 2007). This technology is widely used in building and bridge inspection. Hence, the experience can be leveraged to help the roofing industry.

(a) Use of a handheld IR camera for roof inspection (Mullen n.d.)



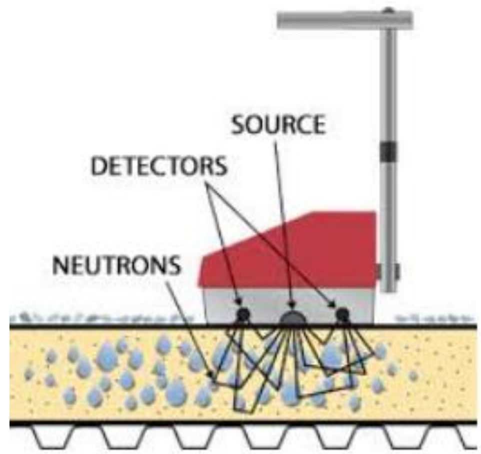
(b) A thermal image of a roof (Gromicko and Ward n.d.)

Figure 3-43. Use of IR imaging for flat roof inspection

3.2.5.6 Nuclear Radioisotopic Thermalization

ANSI/SPRI/RCI NT-1: *Detection and Location of Latent Moisture in Building Roofing Systems by Nuclear Radioisotopic Thermalization* provides a minimum set of procedures used to conduct moisture surveys. Figure 3-44(a) shows the equipment. After calibration, the equipment is placed on the surface to record readings. Figure 3-44(b) shows the working principle of the technology. Neutrons are emitted downward through the roof assembly by a radioactive source within the nuclear meter. These neutrons when encountered with hydrogen atoms slow down and a portion of them bounce back. A detector in the nuclear scanning meter counts the number of reflected neutrons. Based on the equipment calibration and post processing capabilities, either moisture values or other indicators are displayed. A comparison of the readings over multiple locations could indicate the potential areas of moisture intrusion.

(a) Nuclear scanning meter (Independent Roof Services (IRS) Inc. n.d.)



(b) Working principle behind nuclear testing (StructureTec 2016)

Figure 3-44. Nuclear moisture survey

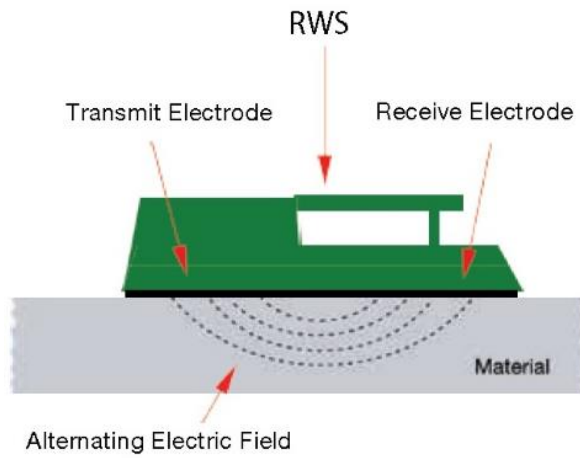
Testing is performed on 5 ft × 5 ft grids on the roof. If a moist area is detected within this 5 ft × 5 ft area, the grid is reduced to 5 in. × 5 in. to isolate the moist location. However, ponded areas and components in a roofing system containing hydrogen atoms could lead to erroneous results.

3.2.5.7 Impedance (Capacitance) Testing

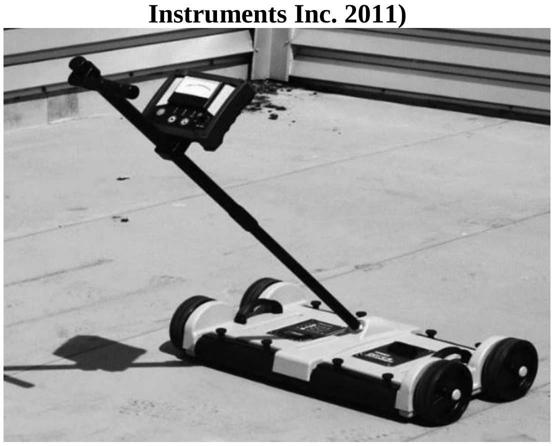
ASTM D7954: *Standard Practice for Moisture Surveying of Roofing and Waterproofing Systems Using Non-Destructive Electrical Impedance Scanners* presents the application procedures. The impedance meter used for such testing emits low frequency electronic signals when conductive materials are encountered. When the electrodes located at the base of the equipment are placed over a wet substrate, a complete circuit is formed and a higher conductance values are recorded. Hand held capacitance meters, similar to the one shown in Figure 3-45(a), are used in a grid pattern to obtain readings within a limited area. Scanners similar to the one shown in Figure

3-45(c) are used to take readings continuously over an area. Figure 3-45 and Figure 3-45 illustrate the working principles behind the hand held scanner and the continuous scanner, respectively.

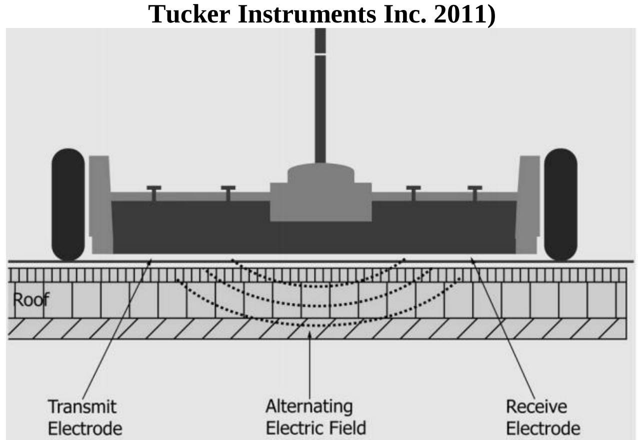
(a) Hand held capacitance meters (Stone Tucker Instruments Inc. 2011)



(b) Working principle of the hand held scanner (Stone Tucker Instruments Inc. 2011)



(c) Continuous impedance scanner (ASTM 2015)



(d) Working principle of the continous scanner (ASTM 2015)

Figure 3-45. Impedance testing equipment and working principle

However, impedance testing can only be used over a dry roof surface. Further, it is difficult to establish the actual boundaries of an identified problematic area, and impedance testing is not suitable on EPDM associated roof systems (ASTM 2015).

3.2.5.8 Destructive Methods of Inspection

The destructive method of inspection involves conducting verification testing for nondestructive testing and extracting core samples for moisture testing. Figure 3-46 illustrates proof testing performed after the initial discovery of moisture within the roof system using nondestructive moisture surveys (impedance testing).

(a) Wet roof reading on electrical capacitance meter

(b) Test cut reveals standing water between membrane and BUR

(c) Significant amounts of water between felt layers in BUR

(d) Use of a penetrating moisture probe to evaluate the extent of moisture damage

Figure 3-46. Proof testing for nondestructive moisture evaluation (Roof Maintenance Systems 2014)

Figure 3-46(a) illustrates the initial discovery of moisture trapped in a BUR through electrical capacitance meters. After the initial discovery, test cuts are performed to locate the moisture tapped within the top membrane. This is illustrated in Figure 3-46(b) and Figure 3-46(c). After verifying the nondestructive testing results, the moisture condition of the remaining layers can be investigated using moisture meters as illustrated in Figure 3-46(d).

After the moist locations are identified, core samples are extracted and sealed in watertight containers. These samples are used to perform the gravimetric testing to determine the moisture content. For gravimetric testing, the initial weight measurement of each component in wet state is recorded separately. Then, the components are oven dried as per the specifications to achieve the dry state and the weights are measured. Percentage of moisture is the ratio between the moisture weight in the component to the oven dry weight. Each component has a moisture limit at which it loses its desirable and intended properties. By comparing the moisture limit with the moisture percentage obtained for the component through gravimetric testing, one can decide the condition of the component in the roofing system (D'Annunzio 2005).

3.2.6 Roofing Warranty and Roofing Guarantee

The product manufacturers issue the warranty for the roofing products: also known as the manufacturer warranty. The contractors issue the roofing guarantee for a roofing job: also known as the contractor warranty. The manufacturer warranty for a certain product differs based on its features and the manufacturer. Manufacturers provide warranties either for material or the entire roofing system. Unlike the manufacturer warranty, the contractor warranty covers only the workmanship (Shultz 2015).

Two types of manufacturer warranties, material roofing warranty and system warranty, are available. A material roofing warranty has a lower cost compared to the system warranty. This warranty covers the cost incurred in purchasing a new material or repairing the existing one. However, the costs incurred for labor, leakage repairs and rectifying installation errors are not covered. On the other hand, a full system warranty typically covers the full cost of materials, with the labor cost included. Still, the cost of installation errors is not covered under the system warranty. The contractor warranty could be either a labor warranty or a workmanship warranty. A labor warranty covers the cost of labor for roof repairs that are within the system coverage but typically does not include the cost of rectifying the installation errors. On the other hand, the workmanship warranty covers the cost of rectifying installation failures in addition to the cost of labor for roof repairs (Shultz 2015).

However, a common condition imposed by the product manufacturers is that, in order to issue the product warranty, the product installation needs to be carried out as per the manufacturer's guidelines using a licensed applicator. A representative from the product manufacturer present at the site verifies the fulfillment of this condition during roof installation. The terms, conditions, and limitations of the warranty are explicitly laid out in the warranty sheet. A typical roof warranty does not cover ponding water, consequential damages and interior damages from roof leaks, acts of god (hurricanes, hails, high wind, fire, snowstorms, etc.), existing moisture in the existing roof (in the case of an installation of a new roof over an existing one), improper roof repairs, and unauthorized alterations. However, in disaster prone areas such as hurricane prone regions and hail prone regions, upgrades to the typical warranty are available to cover the possible high wind and hail damages. This may require additional reinforcements to the roofing system, thus increasing the total cost of a roofing system. Still the total cost of repair of damaged roofs could be compensated by upgrading to a better roof warranty coverage. As required by most roof warranties, regular roof inspections will help in identifying the problems beforehand and thus avoiding the void of the warranty (Shultz 2015).

4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 SUMMARY AND CONCLUSIONS

According to FEMA P-55, it was in 1980 that the Mobile County, AL, adopted the specific requirements for roof coverings, roof reinforcements, and anchoring details to enhance the performance of roofing systems under damaging winds. It was in 1985, during Hurricane Elena, that the performance of new requirements was field tested and proved to be successful. However, it was not until after observing the damages due to 1992's Hurricane Andrew, that the importance of maintaining the integrity of a building envelope and continuous load paths was acknowledged. Following Hurricane Andrew, wall and roof sheathing attachment practices and foundation requirements were changed. During the same period, APA published the guidance for roof sheathing attachment. Also, FEMA formed the Building Performance Assessment Team (BPAT) in 1989 following Hurricane Hugo. These evidences show that researchers, government agencies, and the industry have spent less than 40 years so far to understand structural systems (including roofing systems) in response to wind loading to develop design loads, design details, construction methods, and assessment of in-service structures to enhance structural resilience under damaging wind events.

This report presents details, performance, and performance evaluation of steep-sloped and flat roof systems. In order to limit the scope of this study, the primary focus was limited to flat roof systems, and chapter 3 was primarily dedicated to document flat roof construction, quality assurance, and quality control during construction, along with performance evaluation techniques. Figure 4-1 illustrates the summary of findings for flat roof systems based on the three broad categories: flat roof components, design and performance.

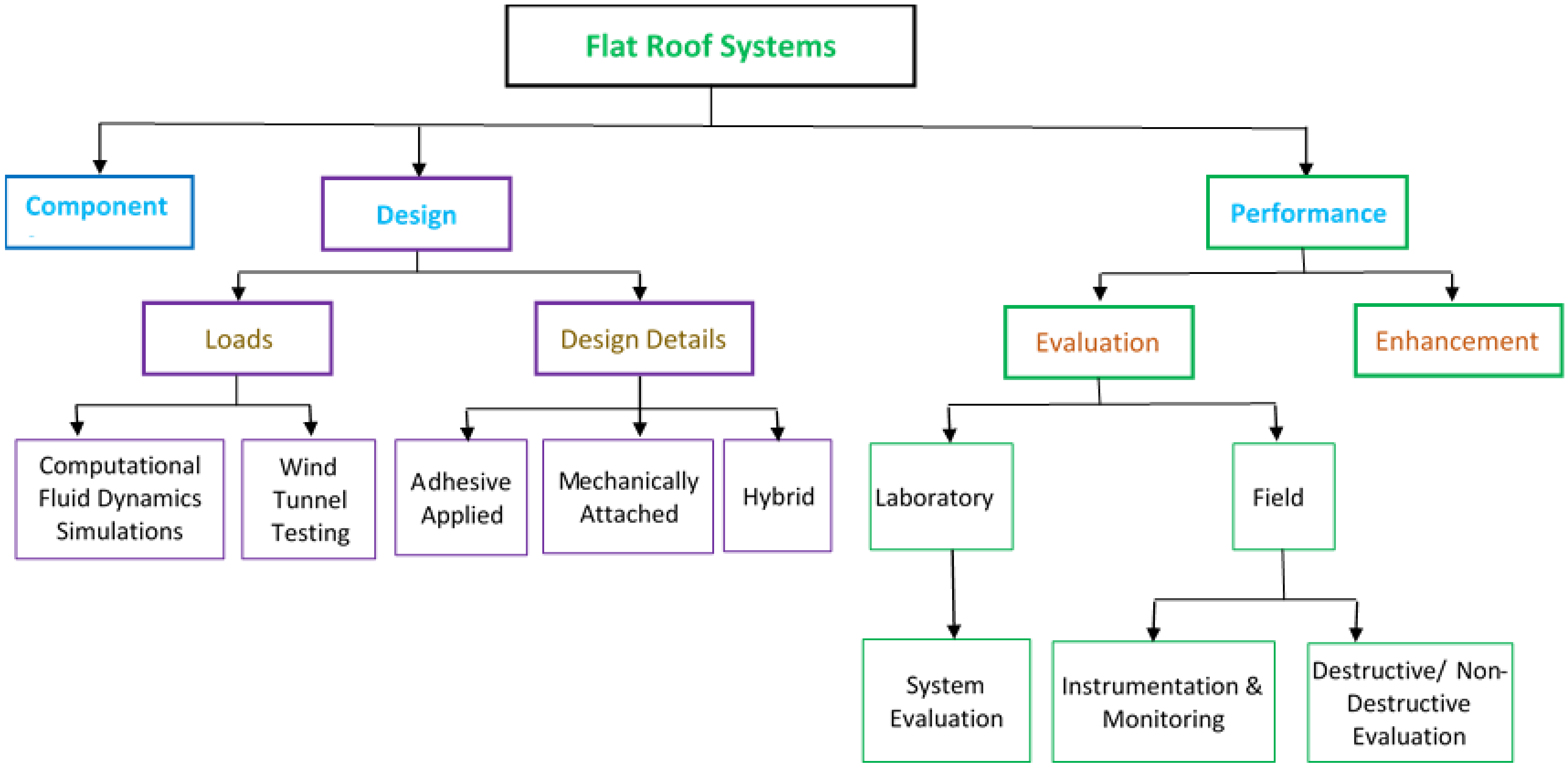


Figure 4-1. Flat roof systems – components, design, and performance

4.1.1 Components of a Flat Roof System

The typical components of a flat roof system include the roof covering (membranes such as TPO, PVC or EPDM, or metal panels), cover board, insulation and the vapor barrier/air barrier. The main purpose of the roof covering is to act as the external protective layer against extreme weather conditions and external loading along with adding strength to the roofing system. Currently, EPDM is the popular roofing membrane in US with a 35% share in the flat roof market. The roof covering is either adhered or mechanically attached to the substrate or loosely laid with ballast. A cover board is placed underneath the roofing membrane but over the insulation to prevent any damage to the underlying insulation. Review of literature and industry practice shows that the damage to the cover boards due to various roof top equipment and their placement methods (for example: solar arrays held down by concrete blocks) are not well evaluated. Moreover, the insulation in a roofing system maintains the temperature within the building by preventing the heat migration from the inside of the building to the outside of the building or vice versa. Foam type insulations are predominantly used in flat roof systems. The most recent applications show that the insulation is sandwiched between two rigid boards to form composite insulation boards rather than providing discrete components to the contractors. In addition, a vapor barrier or an air barrier is installed between the insulation and the deck to prevent the moisture/air migration into the roofing system. Although optional in certain roofing systems, an air barrier is an essential component in mechanically attached membrane roofing systems to prevent the fluttering of the roofing membrane. Based on the arrangement of these different components within the roofing system and the methods of attachment, flat roofs are classified into four groups: build-up roofs, SPF roofs, single ply membrane roofs, and metal panel roofs. Procedures to evaluate the physical properties of these components and their acceptable limits are given in ASTM standards.

Components (products) from various manufacturers are integrated to develop a flat roof system. Selection of a component from a certain manufacturer is decided based upon the previous product performance, product certifications and ratings, designer approval and the cost. The manufacturers provide product warranty while the contractors provide a guarantee of the workmanship. In limited cases, the manufacturers provide a warranty for the entire roofing system. Such warrantees are provided based on the ratings obtained from standard testing and having a certified and approved installer completing the job. Since the components are used from various manufacturers, such assemblies need to be evaluated using standard tests. Product manufacturers define a life span for each of their products in warranty clauses. It was learned that the product life is defined based on available data. However, such databases are not publicly available to verify such claims. Apart from that, there are no meaningful methods to assure that a roofing system is going to maintain at least the required minimum load capacity at the time of a damaging wind event.

4.1.2 Design of Flat Roofs

A flat roof has three design types: adhesive applied, mechanically attached, or a hybrid (combination of adhesive applied and mechanically attached) roofing system. In designing any of these flat roof systems, the possible wind load on the roof is estimated either using wind tunnel tests or using numerical simulations. The specifications given in ASCE 7 to calculate the wind loads on different structures and rooftop equipment were based on the experimental work conducted using wind tunnels. In recent years, computational fluid dynamic (CFD) simulations are performed to measure the pressure distribution on a structure due to wind pressure. CFD simulations have been performed primarily to understand the wind flow pattern and loads developed on rooftop equipment (mainly solar arrays), rooftop features designed to mitigate damages at specific locations of a roof, and the structures with complex roof geometries. For CFD analysis, a fluid component was modeled while the obstacle to the flow (a roof top attachment or a structure) was basically placed in the path of the wind as a rigid, geometric obstacle. This approach is useful to identify the changes in the flow around rigid structures and the corresponding pressure loads. However, most of the flat roofs are not rigid, and the response of the combined system (roof top attachment and the roof) depends on its inherent properties, which is not considered in recent studies. Hence, the structural system of a roof needs to be incorporated into CFD modeling. Also, modeling of advanced features such as flow reversals, vortex shedding, etc., needs to be considered.

4.1.3 Performance of Flat Roofs

Standardized laboratory test procedures are used to evaluate flat roof system performance. These test procedures typically involve placing a specimen, a replicate of the roofing system, on a wind uplift table and subjecting it to a static or dynamic load cycles. Based on the specific standard test procedure used for the evaluation, a negative pressure (a vacuum) at the top of the specimen and/or a positive pressure (uplift pressure) at the bottom of the specimen are applied. ASTM E1592, FM 4474, NT BUILD 307, UL 580, and UL 1897 outlines the specifications for the static wind uplift test of flat roofs. CSA 123.21, ETAG 006 guidelines, and NT BUILD 307 outline the specifications for dynamic wind uplift test procedures for flat roofs. However, none of these static or dynamic wind uplift tests evaluates the performance of flat roofs with the presence of rooftop equipment.

In-service performance of flat roof systems is evaluated primarily through visual inspection and supported with limited destructive and nondestructive testing techniques. Several nondestructive test methods are used for leak detection and structural integrity evaluation of a roofing system. FM 1-52 and ASTM E 907 describe field static wind uplift test procedures for flat roofs to evaluate performance against wind loads. Infrared (IR) thermography, nuclear metering, impedance (capacitance) testing, and low and high voltage test methods are the nondestructive evaluation methods. The last two test methods utilize the potential difference within an area to identify the presence of moisture, an indication of the waterproofing system's performance. All of these five methods are not only used as QA and QC techniques for new roof installations, but also for evaluating existing roof systems. The following list comprises some of the identified limitations of these nondestructive test methods:

- IR thermography: Results are influenced by the type, thickness, and color of membrane as well as the time of inspection.
- The low voltage membrane Electric Field Vector Mapping (EFVM): Any gaps within the area covered with water, the presence of other non-conductive components within the roof system such as the insulation and air /vapor barriers, presence of black EPDM membranes (which are electrically conductive due to the presence of carbon black) affect the readings. This method requires having a conductive substrate.

- High voltage method: The presence of overburden materials (such as ballast, vegetation and pavers) and black EPDM membranes (which are electrically conductive due to the presence of carbon black) affects the readings. This method requires having a conductive substrate.
- Electronic scanning: This method requires a conductive surface directly underneath the membrane.
- Nuclear Radioisotopic Thermalization: Ponded areas and components in a roofing system containing hydrogen atoms that could lead to erroneous results. Application of this method requires having a certified technician and approved facilities for the equipment.
- Impedance testing: This method can only be used over dry roof surfaces. It is difficult to establish the actual boundaries of an identified problematic area. This method is not suitable on black EPDM membranes that contain carbon black.

Even though it is not directly related to the performance of flat roof systems, while enhancing roofing system performance, load path integrity needs to be considered for enhancing structural resilience. A continuous load path from the roof to the foundation is necessary to transfer wind loads acting on a roof safely to the ground. Several MAT reports published by FEMA illustrate instances in which the structures collapse partially or fully under high wind events. These failures occurred due to the inadequacy of a connection(s) or a component(s) in the load path to provide a continuous load path.

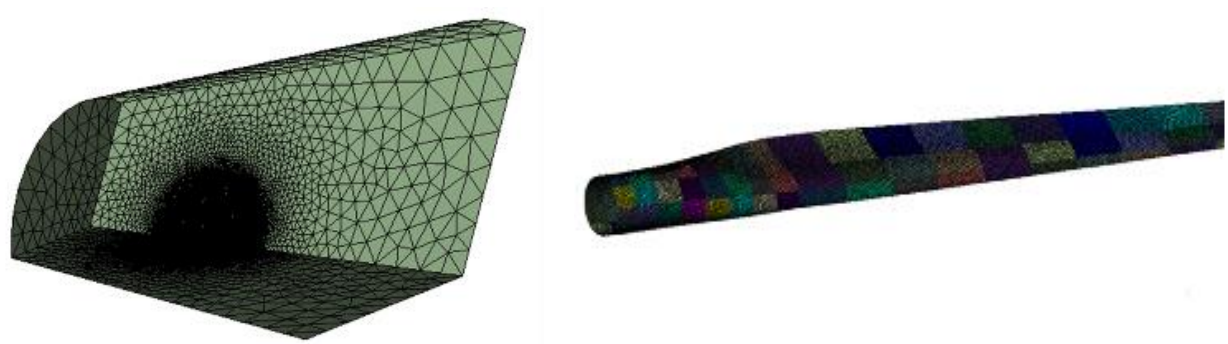
4.2 RECOMMENDATIONS

Based on the findings of this project, the following recommendations are developed covering design loads and details, laboratory evaluation of flat roof systems, and asset management.

4.2.1 Flat Roof Design Loads

The limitations and the capabilities of available CFD tools need to be evaluated in order to identify appropriate tools for calculating the loads acting on flat roofs, rooftop equipment and other features integrated into a roof system to mitigate potential damages.

Modeling of the wind (fluid) behavior alone does not provide an accurate representation of the problem. The structural system (roof system) has to be modeled in detail (i.e., the geometric and material properties of the roofing system, interface properties and boundary conditions); the structural system also must be incorporated into the simulation environment to define fluid structure interaction (FSI). As an example, Figure 4-2 illustrates the CFD mesh and the FEA mesh used to model the FSI of a wind turbine blade under wind load (Wang et. al 2016). ANSYS FLUENT was used to develop the CFD model to determine the aerodynamic loads. The ANSYS Static Structural module was used to develop the FEA model of the blade to determine its structural response, i.e. maximum stresses and blade tip deflection, when subjected to the aerodynamic loads.



(a) CFD mesh **(b) FEA mesh of the blade**

Figure 4-2. Modeling FSI of a wind turbine blade (Wang et, al 2016)

The concept of FSI modeling is simply illustrated in Figure 4-3. This concept can be implemented to obtain the response of a roof system or to obtain the response of rooftop equipment under wind loads. This can be used to evaluate the structural system performance and calculate the loads acting on the roof and rooftop mounted equipment.

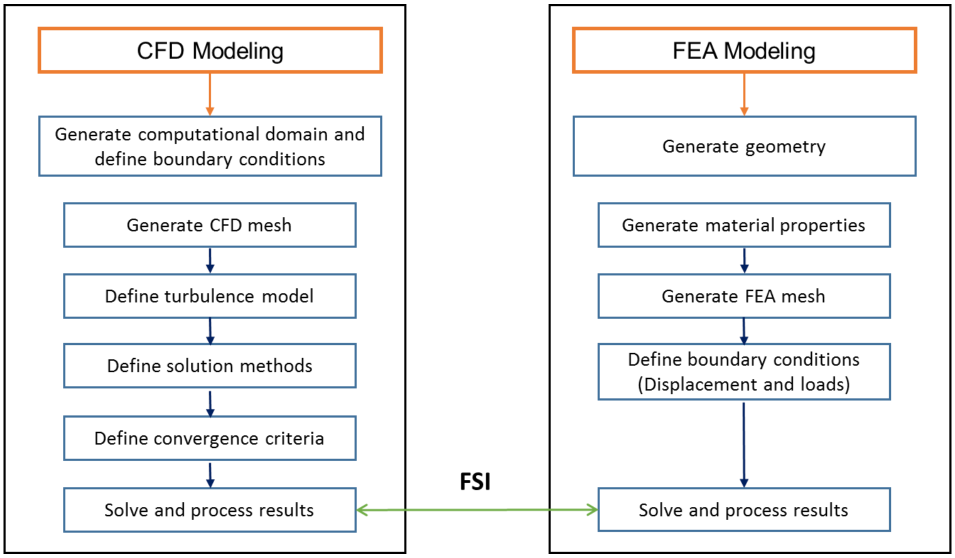


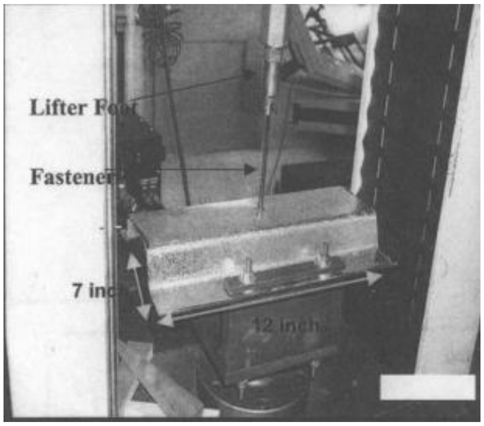
Figure 4-3. Schematic of FSI modeling

In order to use the simulation models effectively and confidentially, the models need to be verified and calibrated. This requires using existing databases or conducting additional wind tunnel testing. Another aspect of simulation is to use the wind patterns collected through instrumentation of existing structures. Also, the instrumentation needs to be utilized to capture the structural performance of roofing systems. This requires identifying various types of sensors and evaluating them under field conditions. Also, the sensor mounting process needs to be considered since most of the sensors require causing some sort of damage to the roofing system, which leads to liability issues. For this purpose, a prototype building model with adjustable features (such as the roof slope, roof material, etc.) can be used to evaluate the performance of such sensor systems in adverse climatic conditions. Once such sensors are identified, evaluated, and limitations are addressed, implementation plans for in-service structures can be developed. With such instrumentation, the real-time wind loads can be captured and compared with the wind loads induced by standardized wind uplift tests to identify how well these load cycles given in standardized wind uplift tests represent the actual field conditions. In addition, such instrumentation can be used to capture loads at critical or failure prone locations to be used for simulation and testing.

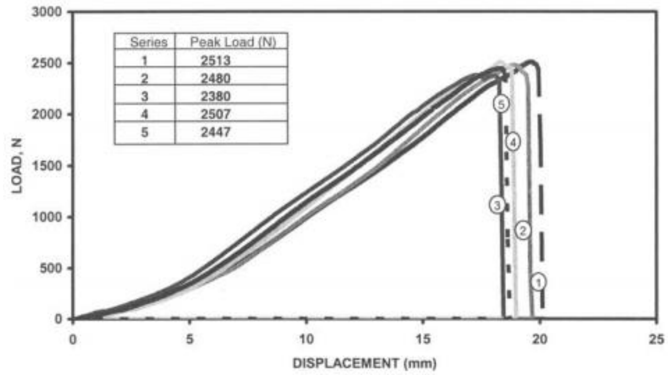
4.2.2 System Evaluation of Flat Roofs

Even though several static and dynamic test methods are available, CSA A123.21-10: *Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane Roofing Systems* by the Canadian Standards Association is considered to have loading cycles that mimic the actual wind conditions to achieve failure modes similar to real cases. Since GCRC has such a system, limited studies can be conducted to evaluate the performance enhancement alternatives of membrane roofing systems. In addition to that, as a service provider, the facility can be used to evaluate the uplift resistance of proprietary membrane roofing systems. Further, the performance of flat roofs with the presence of rooftop equipment should be experimentally evaluated. To assure that a roofing system is going to maintain at least the required minimum capacity at the time of a damaging wind event, accelerated durability testing needs to be performed. Since such facilities are not currently available at the Center, developing collaborative projects with other institutes is a necessity.

Prior to stepping directly into experimental evaluation, FE and CFD simulations need to be performed to develop experimental programs. The suggested performance enhancement techniques can be incorporated into the roofing system and numerically modeled prior to an experimental verification. This process saves the unnecessary time and money spent on testing any number of specimens randomly to obtain the desired results. In order to perform the FE simulations, several parameters such as material properties, interface properties, boundary conditions, loads, etc., are required. Based on the type of roofing system (mechanically attached, adhesive applied or hybrid) a database of required parameters for such simulations needs to be developed. These properties can be determined by testing these components according to the ASTM standards discussed in Appendices D and E. In FE modeling of mechanically attached and hybrid roof systems, the fastener load-displacement characteristics are defined. Therefore, the load-displacement behavior of a fastener needs to be experimentally evaluated under both static and dynamic loads and introduced to the FE model. In the FE modeling of adhesive applied and hybrid roof systems, the adhesive properties are needed for defining the interface behavior. Figure 4-4 shows an evaluation of fastener and adhesive load-deformation characteristics. Until such data is acquired through standard testing or available resources, typical material characteristics can be used in the simulation models to evaluate challenges in modeling and analysis as well as to understand the potential failure mechanisms. Further, collaborative research can be developed to have the experimental work completed at another institute.

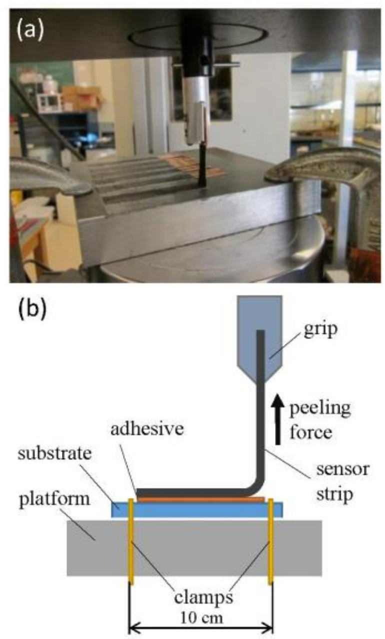


Specimens with fasteners evaluated using Instron 4502 testing machine (Baskaran et al. 2003b)



Load-Displacement curve for the fasteners (Baskaran et al. 2003b)

ASTM D6381 test procedure using Instron 3367 UTM (Dixon et al. 2014)



Evaluation of peel resistance of adhesives using Instron 5569 (Zeng et al. 2015)

Figure 4-4. Experimental evaluation of fastener and adhesive characteristics

4.2.3 Asset Management for Flat Roofs

The roofing contractors and consultants primarily carry out the asset management related activities. Inspection is a major component in asset management. As discussed in the report, roofing systems are primarily evaluated by conducting visual inspection supported with limited nondestructive and destructive evaluation methods. All the nondestructive test methods currently being implemented have limitations, and they require conducting additional research to improve the technology or developing an approach that combines technologies for assessment. As an example, most of the technologies are not suitable for roofing systems with black EPDM membranes. Since black EPDM is a popular system that has a market share of about 35%, additional research is needed for identifying technologies or refining existing technologies for inspection of roofing systems with black EPDM membranes.

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APPENDIX A: ABBREVIATIONS

A

AARS	Adhesive Applied Roofing Systems
ANSI	American National standards Institute
AL	Alabama
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials

B

BLWTBL	Boundary Layer Wind Tunnel Test Laboratory
BSC	Building Science Corporation
BUR	Built Up Roof

C

CA	California
CFD	Computational Fluid Dynamics
CRRC	Cool Roof Rating Council
CSA	Canadian Standards Association
CTBUH	Council on Tall Buildings and Urban Habitat
CUR	Council on Undergraduate Research

E

EFVM	Electric Field Vector Mapping
EOTA	European Organization for Technical Approvals
EPDM	Ethylene Propylene Diene Monomer
EPA	Environmental Protection Agency
EPS	Extruded Polystyrene
ERA	RPDM Roofing Association
ETAG	European Technical Approval Guideline

F

FBC	Florida Building Council
FEMA	Federal Emergency Management Agency
FIA	Federal Insurance Administration
FL	Florida

FM	Factory Mutual
FSI	Fluid Structure Interaction
G	
GCRC	Georgeau Construction Research Center
H	
HD	High Density
HVAC	Heating, Ventilation and Air Conditioning
I	
IBC	International Building Code
IBHS	Insurance Institute for Business & Home Safety
ICC	International Code Council
IR	Infra-Red
IRMA	Inverted Roof Membrane Assembly
J	
JM	Johns Manville
L	
LCA	Life Cycle Inventory and Assessment
LEED	Leadership in Energy and Environmental Design
LLC	Limited Liability Company
M	
MARS	Mechanically Attached Roofing Systems
MAT	Mitigation Assessment Team
MBA	Multi Bead Applicator
MS	Mississippi
MWFRS	Main Wind Force Resisting System
N	
NA	Not Applicable
NBI	Norwegian Building Research Institute
NBT	National Building Technologies
NRCA	National Roofing Contractors Association
NRCC	National Research Council, Canada

NSF	National Sanitation Foundation
NT	NORDTEST
O	
OSB	Oriented Strand Board
P	
PIV	Particle image Velocimetry
PV	Photo Voltaic
PVC	Poly Vinyl Chloride
Q	
QA	Quality Assurance
QC	Quality Control
R	
RCI	Roofing Consultants Institute
REMA	Reinforced Membrane Analysis
RNG	Re-Normalization Group
RRO	Registered Roof Observer
RTW	Required Table Width
S	
SBC	Standard Building Code
SBCCI	Southern Building Code Congress International
SBS	Styrene-Butadiene-Styrene
SEAOC	Structural Engineers Association of California
SIGDERS	Special Interest Group for Dynamic Evaluation of Roofing Systems
SPF	Spray Polyurethane Foam
SPRI	Single Ply Roofing Institute
SWRI	Sealant, Waterproofing and Restoration Institute
T	
TAS	Testing Application Standard
TPO	Thermoplastic polyolefin
TRF	Transient Response Factor
TX	Texas

U

UL	Underwriters Laboratories
US	United States
UV	Ultra Violet

V

VOC	Volatile Organic Compound

W

WoW	Wall of Wind

X

XPS	Expanded Polystyrene

APPENDIX B: RECOMMENDATIONS FOR IMPROVING BUILDING ENVELOPE INTEGRITY AND PERFORMANCE DURING HIGH WIND EVENTS

Note: D-Designer, C-Contractor, G-Government Official, O-Building Owner, M-Manufacturer, CFO-Critical Facility Manager/Owner

Table B.1 1. Design and Construction Recommendations for Wind Hazard (1) (FEMA 490 2005)

Building Component	Recommendation	Action Required by
Accessory Structures		
Attached & detached	Add additional; anchors at corner post connections to concrete	D, C
	Use AAF Guide to aluminium Construction in High wind Areas until FBC 2004 is adopted	D
	Increase wind resistance of accessory structure walls parallel to primary building (e.g., tension cable, solid ‘K’ bracing)	D
	Provide lateral bracing in roof planes using rigid diagonal structural members	D, C
Attached	Ensure attached building and primary building can withstand equal wind pressures	D, C
	Determine implications to primary building if attached structure collapses	D,C
Detached	Determine ability to withstand windstorm events to reduce windborne debris	D,C
Building Envelope		
Roof Systems	Testing: Roof assemblies susceptible to dynamic loading should be dynamically tested to obtain realistic measure of their wind resistance. Higher safety factors should be used for those assemblies requiring dynamic testing, but for which dynamic test methods are not available	D,C,G
Re-roofing	Tear off old roof(do not recover) in areas where basic wind speed is 100 mph or greater	D,C
	Install additional sheathing fasteners if existing sheathing attachment is not in compliance with current building code	D, C
Asphalt Shingles	Ensure manufacturer’s installation instructions are followed (i.e. starter strips and nail locations) and use Recovery Advisory Nos. 1 and 2	D, C
	Re-evaluate attachment of factory laminated tabs	M
Metal Panel roof system	Ensure that chalk line clip locations for panels with concealed clips are not excessively spaced.	C
	Base uplift resistance on ASTM E1592	M,D
	Specify close spacing of fasteners at eaves, and hip, and ridge flashings	D
Tile roof system	Use Recovery Advisory No. 3	D, C
	Develop tiles with improved ductility via internal or backside reinforcement or bonding film in hurricane prone-regions (e.g. develop tile similar to laminated glass)	M
Tile roof (foam set) system	For foam set tile, simplify number of installation options and clarify requirements	M
	Modify training and certification programs to ensure that foam-set roof installers are adequately trained	M, C

	Use a high factor of safety (e.g. 4) to account for application and testing issues.	M,D
Mechanically attached roof systems	FRSA/TRI re-evaluates use of safety factor of 2. Either develop dynamic test method or use existing test method with higher safety factor (e.g. 3)	M, D
Built Up Roofs	Develop and codify technically based criteria for aggregate surfacing on built up and sprayed polyurethane foam roofs.	M, G
Edge flashing & Copings	Comply with ANSI/SPRI Es-1 (2003). Use a safety factor of 2-3.	D
	Install edge flashing on top of membrane to clamp it down.	D, C
	Place a bar over roof membrane near edge of flashing and coping to provide secondary protection.	D, C
Gutters & downspouts	Use professional judgment to specify and detail gutter uplift resistance.	D
	Design Guidance: Develop design guide, test method, and code criteria for gutters, including attachment of downspouts.	M, C
Rooftop walkway pads	Research wind resistance of roof walkway pads	M, G
Soffits	Design Guidance: Develop design guidance for attaching soffits, including design of baffles or filter media to prevent wind-driven rain from entering attics.	M, G

Table B.1 2. Design and Construction Recommendations for Wind Hazard (2) (FEMA 490 2005)

Edge flashing and Coping	FBC Section 1503 (Weather protection) should require compliance with ANSI/SPRI ES-1 for edge flashings and copings.
Gutters	FBC Section 1503(Weather protection) and IBC/IRC: Develop and add criteria regarding uplift resistance of gutters.
Metal Panel Roof system	FBC Section 1504(Performance Requirements): Require compliance with ASTM E 1592 for testing the uplift resistance of metal panel roof systems.
Roof System	FBC Section 1510.3(Recovering vs. Replacement) and IBC /IRC: Require removal of existing roof covering down to the deck and replacement of deteriorated sheathing in areas where basic wind speed is 110 mph or greater. If existing sheathing attachment does not comply with loads derived from Chapter 16, then require installation of additional fasteners to meet loads.
Asphalt shingles	FBC Section 1507.2(Roof Covering Application) and IBC/IRC: Require compliance with UL 2390. Also require six nails per shingle and require use roof asphalt roof cement at eaves, rakes, hips, and ridges where basic wind speed is 110 mph or greater (refer to Recovery Advisory No.2)
Mortar set tile roof system	FBC Section 1507.4 (Clay and concrete Tile) and IBC/IRC: Provide an alternative to the use of mortar attached field tiles and hip/ridge tiles.
Build up roofs	FBC Section 1508(Roof Coverings with Slopes less than 2:12): Add technically base criteria regarding blow off resistance of aggregate on built up and sprayed polyurethane foam roofs.
Ridge vents	FBC Section 1503(Weather Protection) and IBC/IRC: Add criteria regarding wind and wind driven rain resistance of ridge vents. Attachment criteria development , but TAS 110 could be referred for rain resistance
Soffit	FBC/IBC/IRC: Criteria regarding wind resistance of soffits should be added, and wind load criteria for soffits require development. Wind driven rain resistance of ventilated soffit panels should also be added. TAS 110 may be a suitable test method, modified as necessary.

Table B.1 3. Public Outreach Recommendation for Wind Hazard (FEMA 490 2005)

Education Topic	Outreach Method
Building Owners and Homeowners	
Plan and budget construction projects that incorporate natural hazard mitigation measures. Select design and construction teams knowledgeable in effective construction methods in hurricane-prone areas. Prepare and protect building prior to hurricane landfall. What to do after hurricane passes (building inspection for damage, emergency repairs, and drying out building interiors). Rebuild damaged structures in manner that protects against future damage. Inspect exterior connections and fasteners for wear, corrosion, and other deterioration. Educate building owners on how wind driven rainwater enters buildings, the resulting implications (loss of electricity, mold) and prevention methods.	• Tailor informational pamphlets to homeowners and building owners. • Develop strategy to distribute information (e.g. standardized information sheets during sale of building). • Enlist assistance of real-estate companies and organizations such as Building Owners and Managers Association. • Provide public service notices at start of each hurricane season. • Develop informational materials on how wind driven rainwater enters buildings, the resulting damage and prevention methods.
Architects, Engineers, Consultants	
Improve the technical proficiency of building envelope design. Provide adequate level of design details of connecting rooftop equipment, including mechanical, electrical and lighting protection. Share post-disaster building performance information to maximize the value of lessons learned.	• Prepare monographs for trade wide distribution. • Prepare web based tutorials and seminars. • Encourage colleges and universities to augment existing curriculum with hurricane resistant design instruction.
Building Officials	

Share post-disaster building performance information to maximize the value of lessons learned.	• Conduct annual seminars for building officials and plan reviewers in coastal areas to share lessons learned.
Train building officials to identify structural weaknesses that may cause structure or building component failure during a hurricane (e.g. unbraced gable ends, missing truss anchorage, window/door anchorage). Implement effective enforcement techniques to maintain a high construction quality.	• Implement hurricane disaster building inspection training program and 'train the trainer' program.
Contractors	
Educate contractors who construct building envelopes and install rooftop equipment on hurricane resistant fastening and anchoring systems. Educate contractors on how wind-driven water enters buildings, the resulting implications (loss of electricity, mold), and prevention methods.	• Develop and distribute visual tools such as instructional videos or DVDs. • Conduct on-the-job training to highlight failures that occur when simple anchoring techniques are not applied. • Encourage trade schools in hurricane-prone areas to augment their curriculum with course on state-of-the-art hurricane-resistant construction.
Manufactures	
Educate manufacturers of building envelope materials and rooftop equipment on the performance of their products during hurricanes. Encourage manufacturers to provide special guidance for use of their products in hurricane-prone areas. Develop improved products and systems for hurricane-prone areas. Manufacturers should educate designers and contractors on their products.	• Develop and distribute informational notices to manufacturers.
Associations, Institutes and Societies	
Advocate hurricane-resistant design and construction to their membership.	• Develop educational materials for distribution to their members and industry.

Table B.1 4. Recommendations Essential to Critical And Essential Facilities (FEMA 490 2005)

Component	Recommendation	Action Required by
General		
Detailing and notations on building plans	Facility plans should delineate the facility area designed to function as a shelter or hardened area. Details of the shelter or hardened area and the envelope elements should be provided to ensure that the construction requirements are clearly understood by the builder and building official. Provide facility design criteria and maximum design pressure for the main wind force resisting system (MWFRS) and for components and cladding.	D, C, CFO
Material selection	Reinforced concrete roof deck and reinforced concrete and/or reinforced and fully-grouted concrete masonry unit (CMU) exterior walls are recommended. FEMA 424, Design Guide for Improving School Safety in Earthquakes, Floods and G=High winds, and FEMS 361, Design and Construction Guidance for Community Shelters, provide detailed guidance on material selection for structural and building envelope systems.	D, C, CFO
General	Develop additional criteria to help insure continuity of function. See FEMA 424 and FEMA 361	CFO
General	Emphasize best practices for schools and shelters described in FEMA 424 and FEMA 361 respectively, and in the latest codes and standards for wind resistance (ASCE 7).	CFO
Design Guidance	Develop a comprehensive design guide to complement FEMA 424 for mitigating existing facilities.	D, G
Perform vulnerability assessment	Perform vulnerability assessment to ensure continuity of operations. The assessment should evaluate the building performance and utilities that service critical/essential facilities so that the building owner understands impacts to the facility during a storm and operational impacts due to limited utility services.	CFO
Structural		
General	Implement mitigation measures or structurally retrofit critical/essential facilities to design levels other than minimum code requirements for general use buildings. Do not house critical facilities in lightly engineered buildings such as pre-engineered metal buildings.	CFO, D
	Educate designers, buildings designed to minimum EPA requirements does not guarantee that building used as shelter will be properly designed and constructed to resist extreme wind events. Emphasize best practices for shelters described in FEMA 361.	D, C
	Educate designers: American Red Cross 4496 provides a baseline for a shelter's integrity and performance, but meeting this criterion does not guarantee that the building will resist wind and windborne debris associated with hurricanes. Emphasize best practices for shelters described in FEMA 361.	D, C

	Conduct special inspections for key structural items and connections to ensure performance of critical facilities.	CFO, C
	Design critical and essential facilities with wind loads using an importance factor of 1.15 in accordance with ASCE 7. For some facilities, design using the 40 mph increase with importance factor of 1 (recommended for shelter EHPA design in FBC Section 423, Part 24).	D
	Incorporate hazard mitigation peer review into design approval process to ensure that critical and essential facilities are adequately designed to resist extreme winds.	D
	Accessory Structures	
Detached	Strengthen the anchorage of structures and portable classroom buildings at schools.	D, C, G, CFO
	Building Envelope	
General	Contract drawings and specifications for new construction and remedial work on existing building envelopes and rooftop equipment should undergo rigorous peer review, field observation (inspection), and testing prior to construction.	D, C, G
	Implement mitigation measures in buildings not built to current building codes to protect roof coverings, wall coverings, window and door systems, and rooftop equipment.	D, CFO
	Conduct special inspections for key building envelope components to ensure performance of critical/essential facilities. Inspect rooftop equipment twice a year. Inspect doors, windows and wall coverings at 5-year intervals. Conduct special inspections of the entire facility (bot structural and building envelope systems) after storms with wind speeds in excess of 90 mph 3-second gust winds.	CFO
Roof Structure	Install hurricane clips or straps on inadequately connected roof beams and joists in those buildings that will be occupied during a hurricane.	C, CFO
Roof Decks	Strengthen inadequately attached roof decks.	CFO
Roofing	Replace aggregate surfaced roof systems with non-aggregate roof systems.	D, c, CFO
Roof system	Design roof system that will prevent water infiltration if roof is hit by windborne debris.	D
Edge flashings and copings	Install exposed fasteners to weal metal edge flashings and copings.	D, C, CFO
Gutters and downspouts	Install tie-down straps on gutters to avoid membrane blow off.	D, C, CFO
Rooftop equipment	Anchor all rooftop equipment.	D, C, CFO

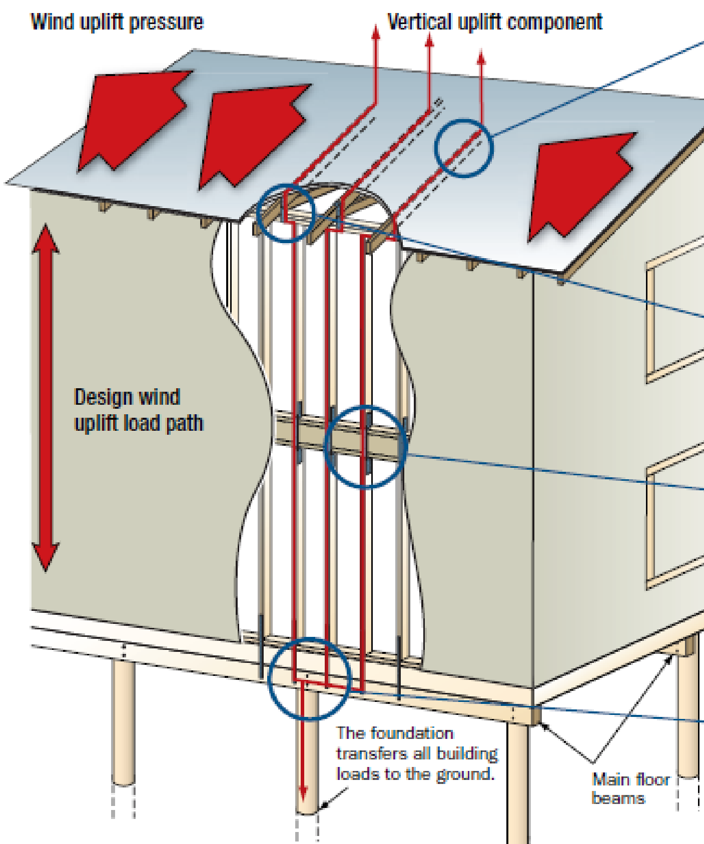
Load Paths

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 4.1

Purpose: *To illustrate the concept of load paths and highlight important connections in a wind uplift load path.*

Key Issues

- Loads acting on a building follow many paths through the building and must eventually be resisted by the ground, or the building will fail.
- Loads accumulate as they are routed through key connections in a building.
- Member connections are usually the weak link in a load path.
- Failed or missed connections cause loads to be rerouted through unintended load paths.



LINK 1
High winds lift the roof upward. Roofing fasteners link the roof covering to the sheathing*, and sheathing fasteners link the sheathing to the roof framing members (see Fact Sheet No. 7.1).

* Although not a structural connection, the attachment of the roof covering to the roof sheathing is an essential part of protecting the building envelope.

LINK 2
Accumulated roof load is routed through roof-to-wall connections. Special roof ties connect the roof framing to the bearing walls (see Fact Sheet No. 4.3).

LINK 3
Upper walls transfer loads directly to the lower walls. The floor framing is bypassed by using metal straps or extended exterior sheathing that directly connects upper wall studs to the lower wall studs. A similar connection is used to connect the lower wall to the main floor beam.

LINK 4
The accumulated uplift force is transferred from the main floor beams to the pile foundation with special brackets or bolts (see Fact Sheet No. 3.3). Note: Some of this load is offset by the weight of the building.

Vertical load path from roof to ground on a platform-and-pile-construction building. Note: Load paths will vary depending on construction type and design. Adjacent framing members will receive more load if a connection fails.

Note: Horizontal load paths transferring shear from upper stories to the ground must also be analyzed.

Figure B.2 1. Important connections in a wind uplift load path (1) (FEMA 2010)

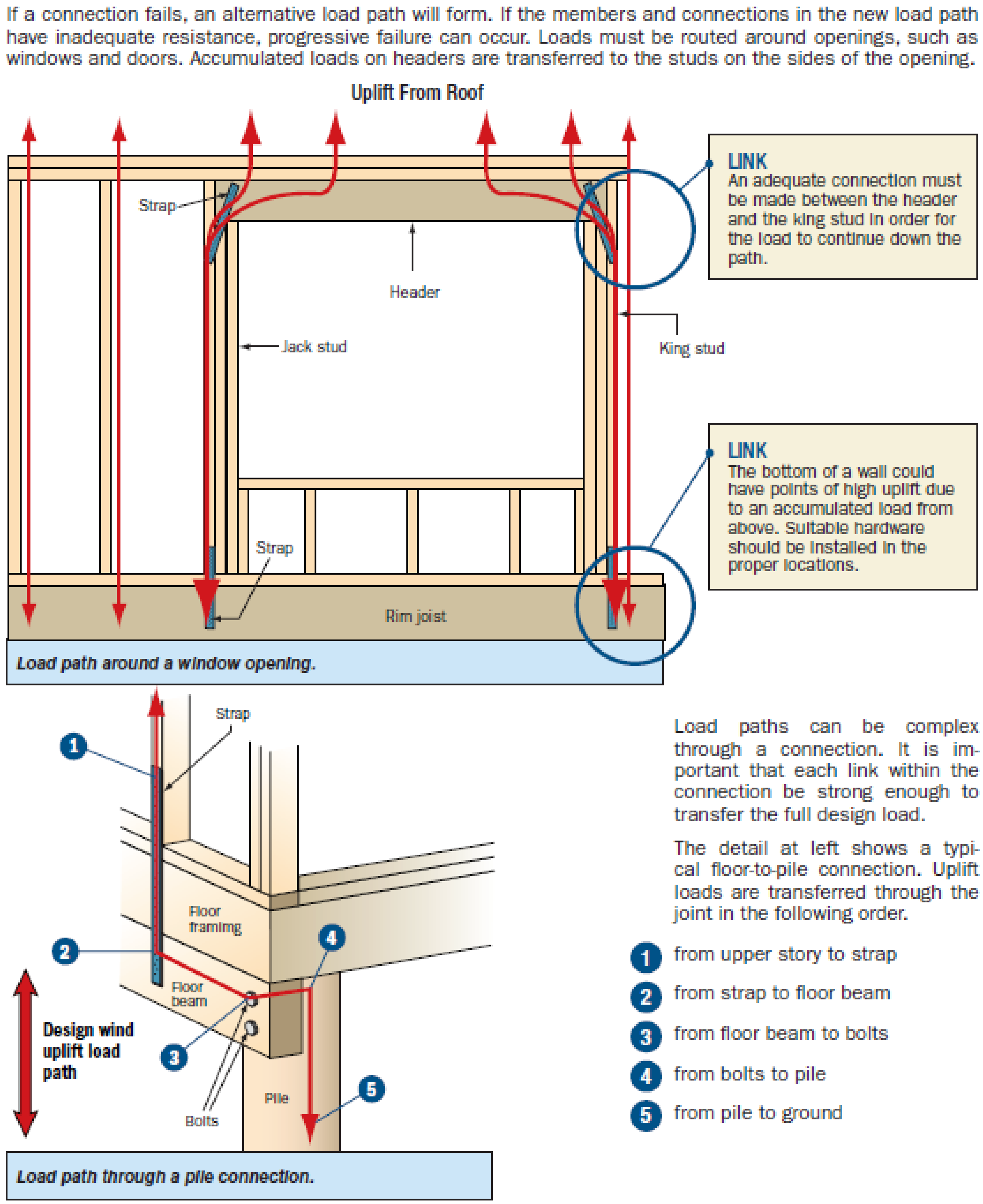


Figure B.2 2. Important connections in a wind uplift load path (2) (FEMA 2010)

Masonry Details

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 4.2

Purpose: *To highlight several important details for masonry construction in coastal areas.*

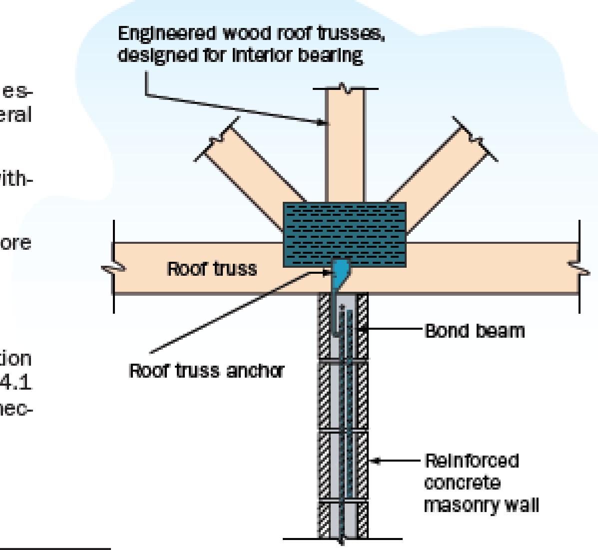
Key Issues

- Continuous, properly connected load paths are essential because of the higher vertical and lateral loads on coastal structures.
- Building materials must be durable enough to withstand the coastal environment.
- Masonry reinforcement requirements are more stringent in coastal areas.

Load Paths

A properly connected load path from roof to foundation is crucial in coastal areas (see Fact Sheets Nos. 4.1 and 4.3). The following details show important connections for a typical masonry home.

Roof framing to interior masonry wall



Roof framing to masonry wall

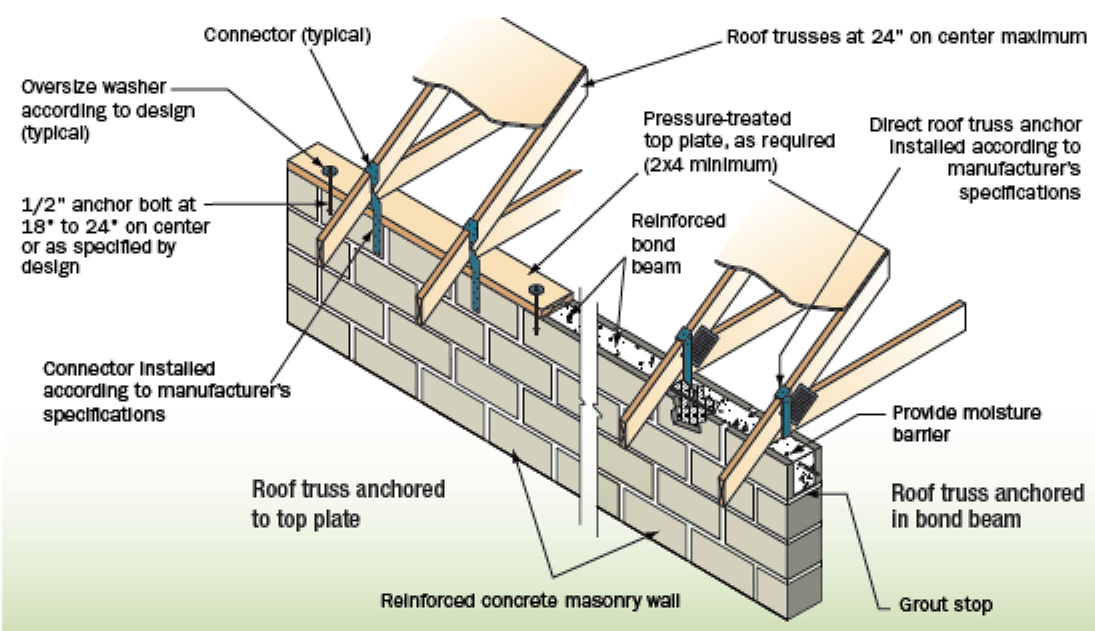
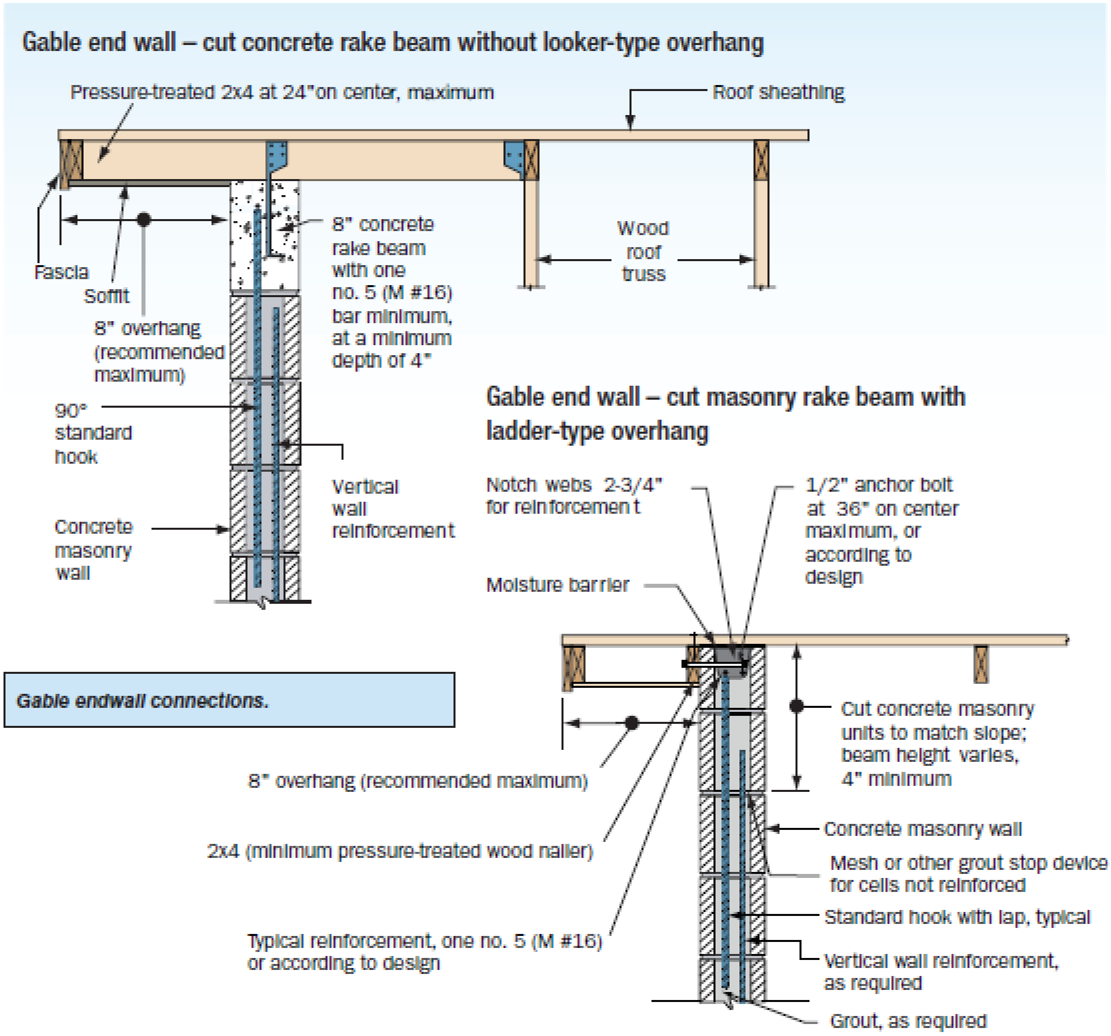


Figure B.2 3. Important details for masonry construction in coastal areas (1) (FEMA 2010)



Durability – High winds and salt-laden air can damage masonry construction. The entry of moisture into large cracks can lead to corrosion of the reinforcement and subsequent cracking and spalling. Moisture resistance is highly dependent on the materials and quality of construction.

Quality depends on:

- **Proper storage of material** – Keep stored materials covered and off the ground.
- **Proper batching** – Mortar and grout must be properly batched to yield the required strength.
- **Good workmanship** – Head and bed joints must be well mortared and well tooled. Concave joints and V-joints provide the best moisture protection (see detail above). All block walls should be laid with full mortar coverage on horizontal and vertical face shells. Block should be laid using a "double butter" technique for spreading mortar head joints. This practice provides for mortar-to-mortar contact as two blocks are laid together in the wall and prevents hairline cracking in the head joint.

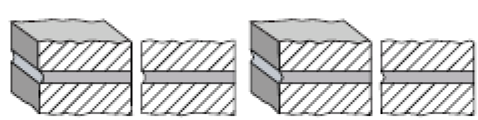
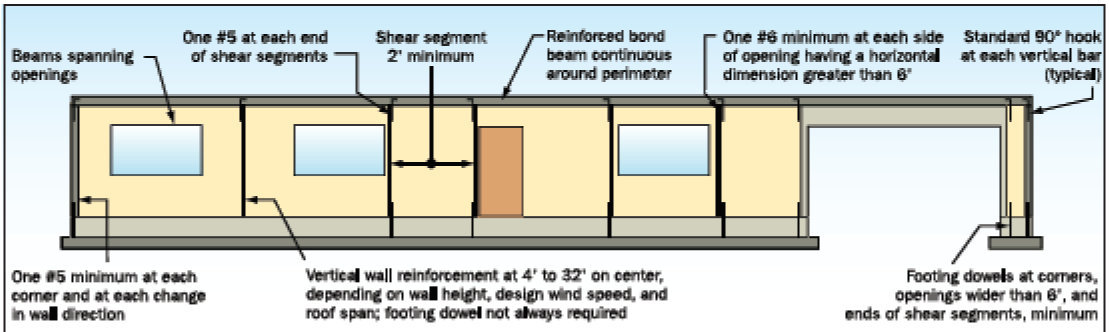


Figure B.2 4. Important details for masonry construction in coastal areas (2) (FEMA 2010)

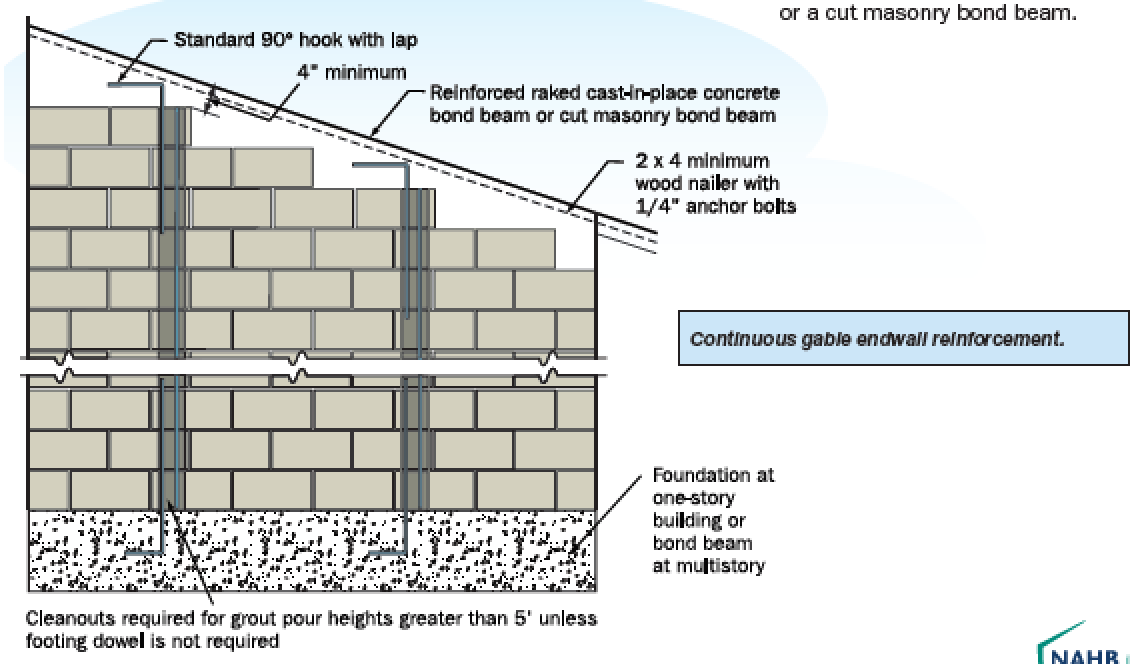
- **Protection of work in progress –** Keep work in progress protected from rain. During inclement weather, the tops of unfinished walls should be covered at the end of the workday. The cover should extend 2 feet down both sides of the masonry and be securely held in place. Immediately after the completion of the walls, the wall cap should be installed to prevent excessive amounts of water from directly entering the masonry.

Reinforcement: Masonry must be reinforced according to the building plans. Coastal homes will typically require more reinforcing than inland homes. The following figure shows typical reinforcement requirements for a coastal home.



Masonry reinforcement.

Gable Ends: Because of their exposure, gable ends are more prone to damage than are hipped roofs unless the joint in conventional construction at the top of the endwall and the bottom of the gable is laterally supported for both inward and outward forces. The figure at right shows a construction method that uses continuous masonry from the floor to the roof diaphragm with a raked cast-in-place concrete bond beam or a cut masonry bond beam.



Continuous gable endwall reinforcement.

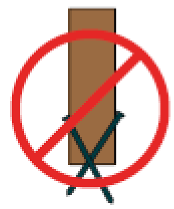
Figure B.2 5. Important details for masonry construction in coastal areas (3) (FEMA 2010)

Use of Connectors and Brackets

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 4.3

Purpose: *To highlight important building connections and illustrate the proper use of various types of connection hardware.*

Key Issues



- In high-wind regions, special hardware is used for most framing connections. Toe-nailing is not an acceptable method for resisting uplift loads in high-wind regions.
- Hardware must be installed according to the manufacturer's or engineer's specifications.
- The correct number of the specified fasteners (length and diameter) must be used with connection hardware.
- Avoid cross-grain tension in connections.
- Metal hardware must be adequately protected from corrosion (see NFIP Technical Bulletin 8-96).
- Connections must provide a continuous load path (see Fact Sheet No. 4.1).

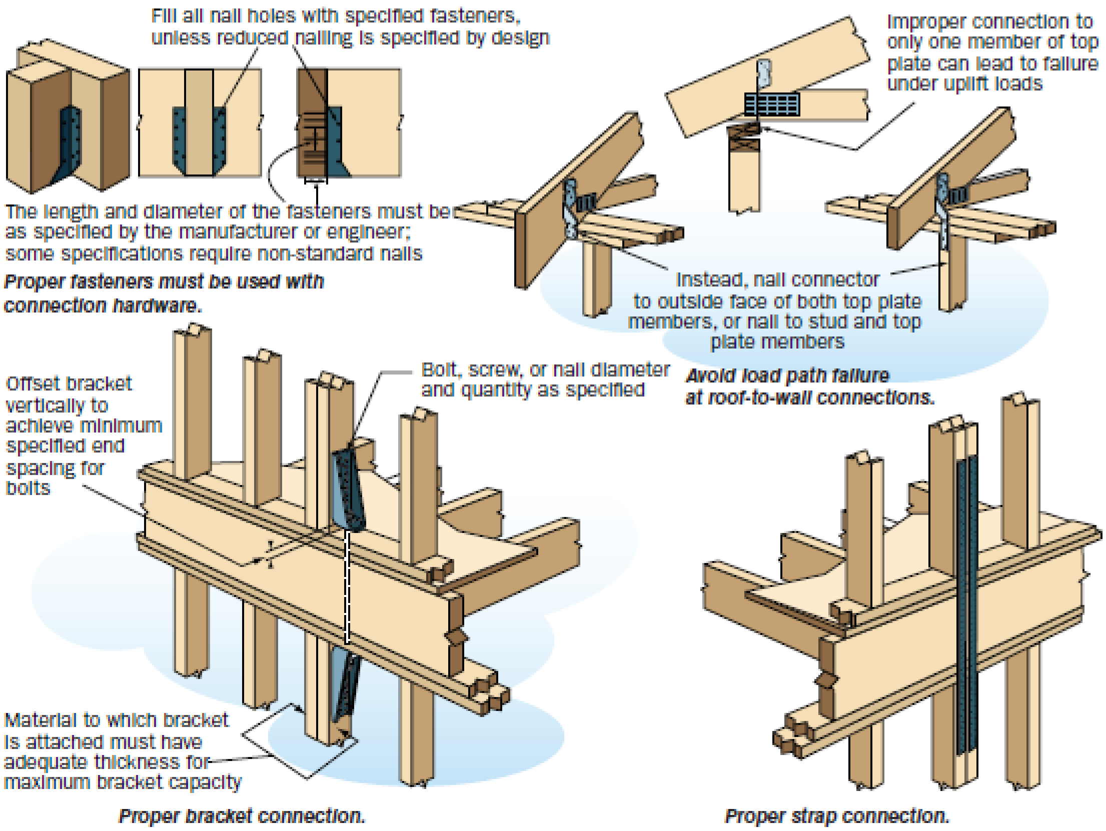


Figure B.2 6. Proper use of various types of building connection hardware in connections (1) (FEMA 2010)

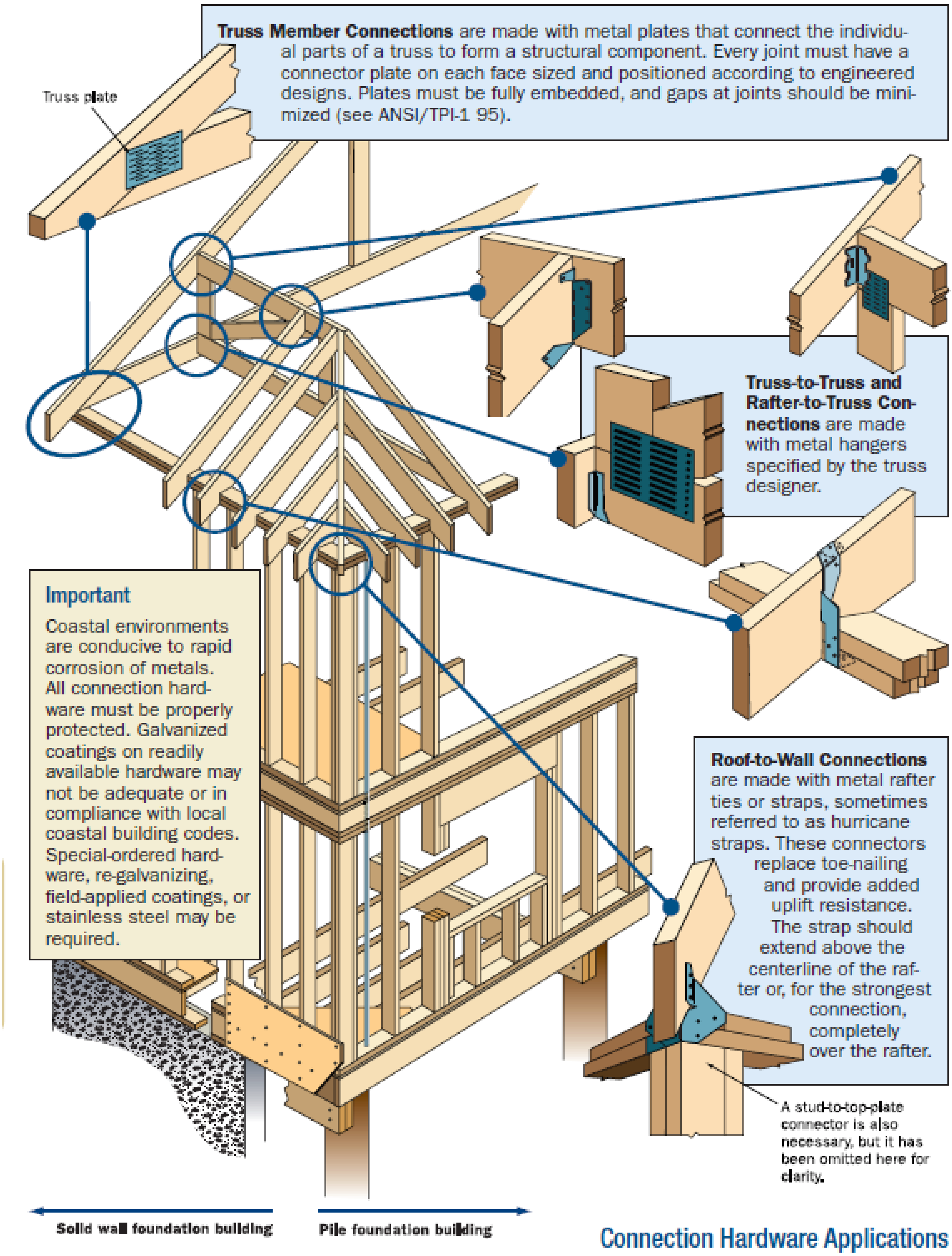


Figure B.2 7. Proper use of various types of building connection hardware in connections (2) (FEMA 2010)

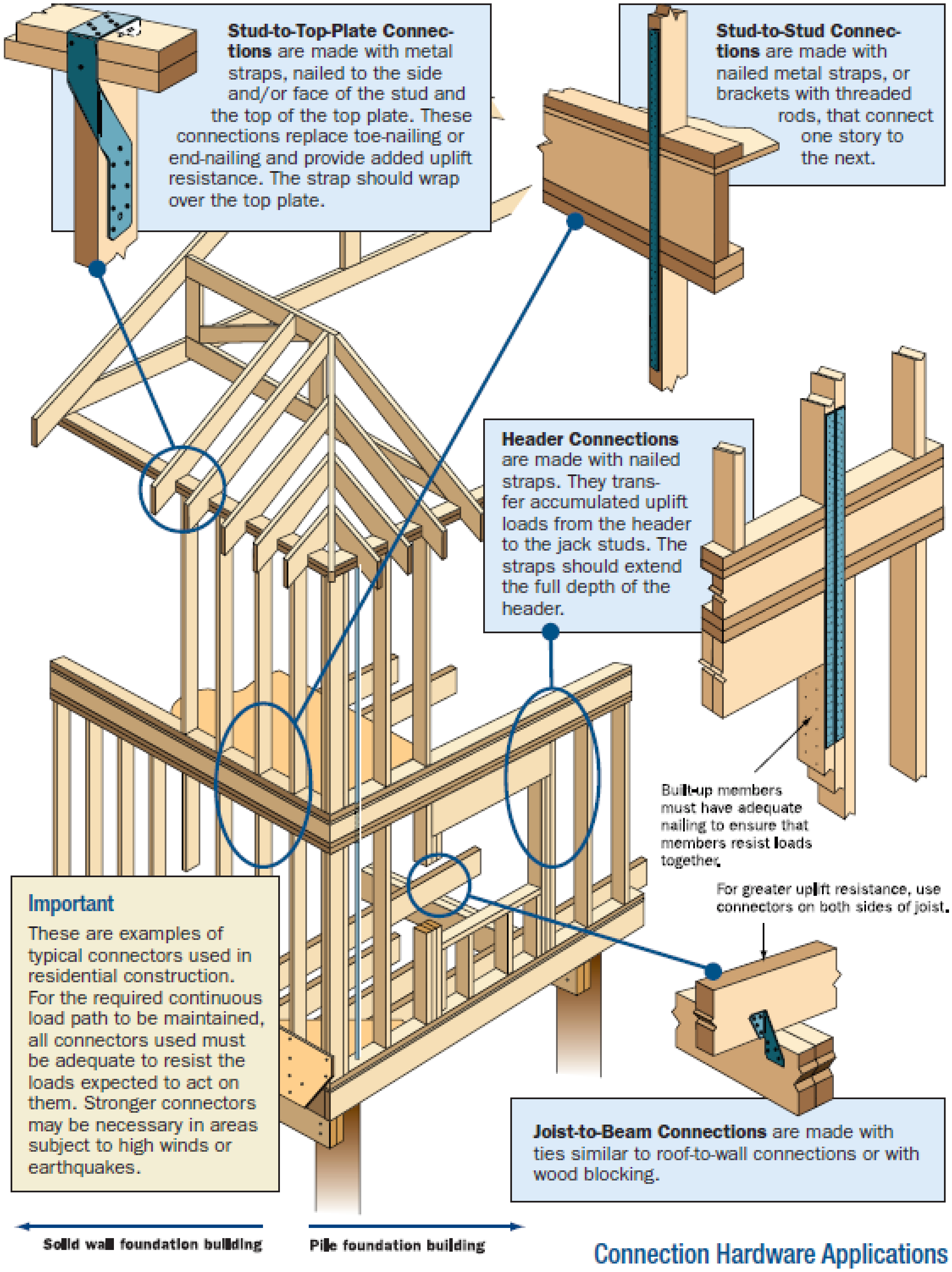


Figure B.2 8. Proper use of various types of building connection hardware in connections (3) (FEMA 2010)

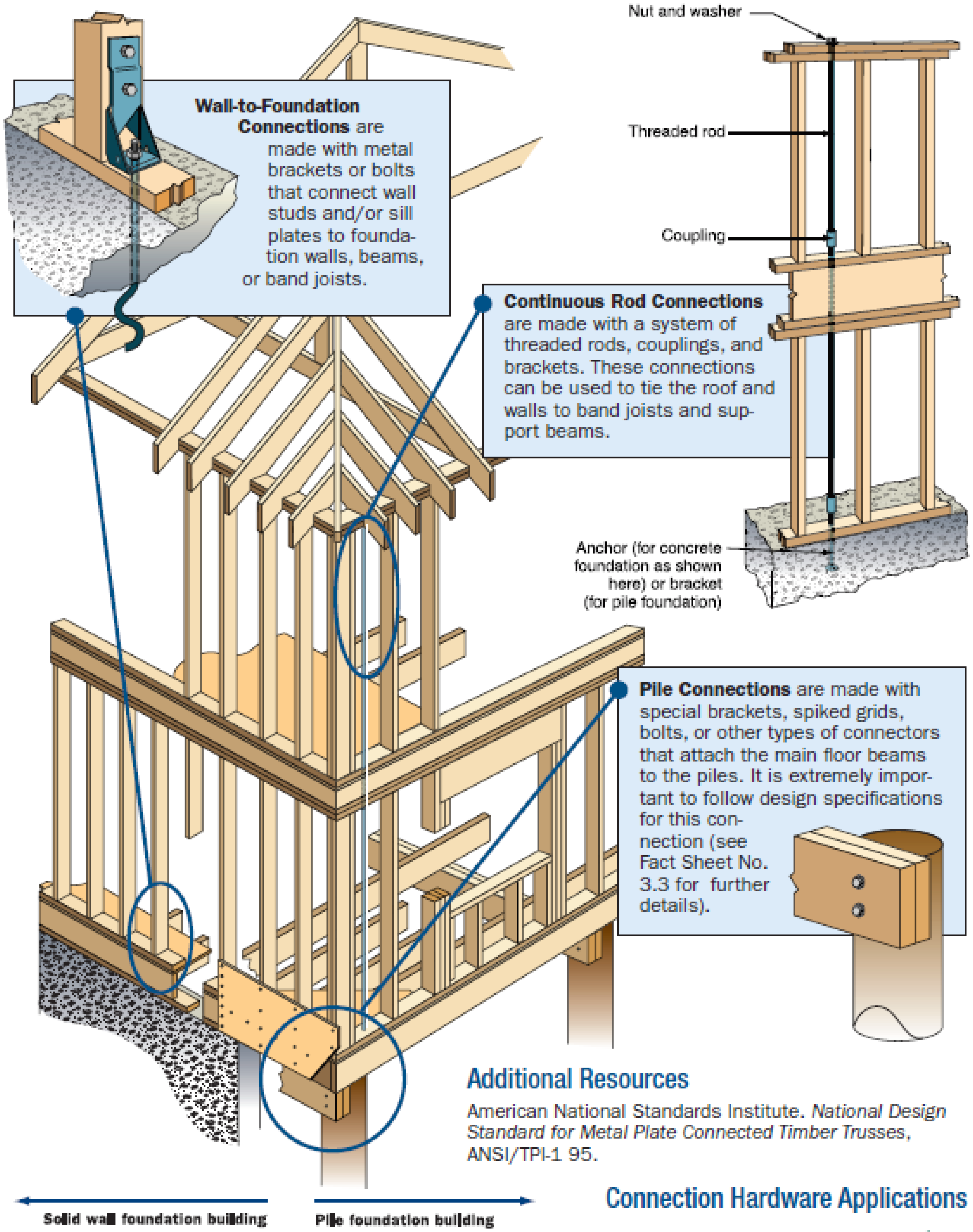


Figure B.2 9. Proper use of various types of building connection hardware in connections (4) (FEMA 2010)

Roof-to-Wall and Deck-to-Wall Flashing

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 5.2

Purpose: *To emphasize the importance of proper roof and deck flashing, and to provide typical and enhanced flashing techniques for coastal homes.*

Key Issues

- Poor performance of flashing and subsequent water intrusion is a ***common problem*** for coastal homes.
- ***Enhanced flashing techniques are recommended*** in areas that frequently experience high winds and driving rain.
- ***Water penetration*** at deck ledgers can cause ***wood dry rot and corrosion of connectors*** leading to ***deck collapse.***

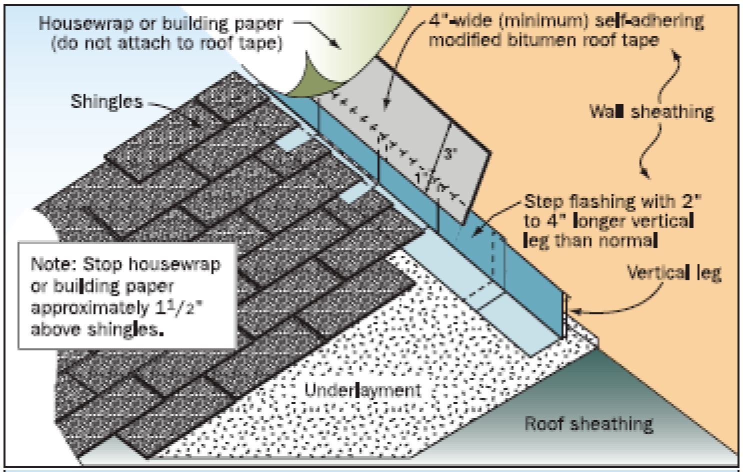


Figure 1. Roof/wall flashing detail.

Roof and Deck Flashing Recommendations for Coastal Areas

- ***Always*** lap flashing and other moisture barriers properly.
- Use increased lap lengths for added protection.
- Do not rely on sealant as a substitute for proper lapping.
- Use fasteners that are compatible with or of the same type of metal as the flashing material.
- Use flashing cement at joints to help secure flashing.
- At roof-to-wall intersections (see Figure 1):
  - Use step flashing that has a 2- to 4-inch-longer vertical leg than normal.
  - Tape the top of step flashing with 4-inch-wide (minimum) self-adhering modified bitumen roof tape.
  - Do not seal housewrap or building paper to step flashing.
- For deck flashing:
  - Follow proper installation sequence to prevent water penetration at deck ledger (see Figure 2).
  - Leave gap between first deck board and flashing to allow for drainage (see Figure 3).
  - Use spacer behind ledger to provide gap for drainage (see Figure 3).
  - Use stainless steel deck connection hardware.

See Fact Sheet Nos. 7.2 and 7.3 for rake and eave details.

Figure B.2 10. Typical and enhanced flashing techniques for coastal areas (FEMA 2010)

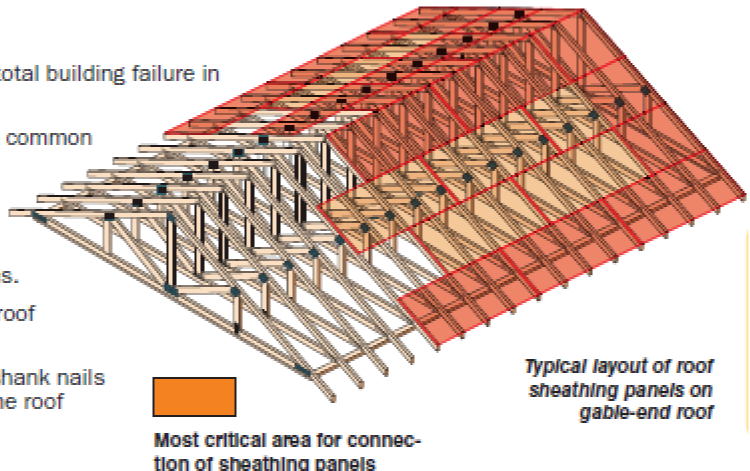
Roof Sheathing Installation

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 7.1

Purpose: *To provide information about proper roof sheathing installation, emphasize its importance in coastal construction, and illustrate fastening methods that will enhance the durability of a building in a high-wind area.*

Key Issues

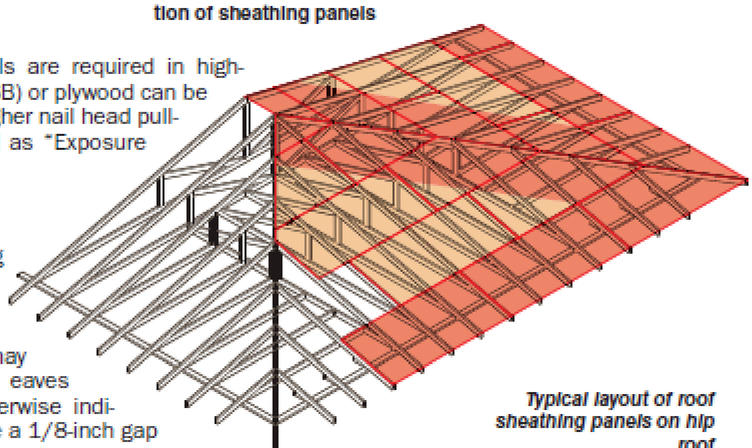
- Insufficient fastening can lead to total building failure in a windstorm.
- Sheathing loss is one of the most common structural failures in hurricanes.
- Fastener spacing and size requirements for coastal construction are typically different than for non-coastal areas.
- The highest uplift forces occur at roof corners, edges, and ridge lines.
- Improved fasteners such as ring shank nails increase the uplift resistance of the roof sheathing.



Sheathing Type

Typically, 15/32-inch or thicker panels are required in high-wind areas. Oriented Strand Board (OSB) or plywood can be used, although plywood will provide higher nail head pull-through resistance. Use panels rated as "Exposure 1" or better.

Sheathing Layout



Install sheathing panels according to the recommendations of the Engineered Wood Association (APA). Use panels no smaller than 4 feet long. Blocking of unsupported edges may be required near gables, ridges, and eaves (follow design drawings). Unless otherwise indicated by the panel manufacturer, leave a 1/8-inch gap (about the width of a 16d common nail) between panel edges to allow for expansion. (Structural sheathing is typically cut slightly short of 48 inches by 96 inches to allow for this expansion gap – look for a label that says "Sized for Spacing.") This gap prevents buckling of panels due to moisture and thermal effects, a common problem.

Fastener Selection

An 8d nail (2.5 inches long) is the minimum size nail to use for fastening sheathing panels. Full round heads are recommended to avoid head pull-through. Deformed-shank (i.e., ring- or screw-shank) nails are required near ridges, gables, and eaves in areas with design wind speeds over 110 mph (3-second gust), but it is recommended that deformed shank nails be used throughout the entire roof. If 8d "common" nails are specified, the nail diameter must be at least 0.131 inch (wider than typical 8d pneumatic nails). Screws can be used for

Figure B.2 11. Proper roof sheathing installation for high wind areas (1) (FEMA 2010)

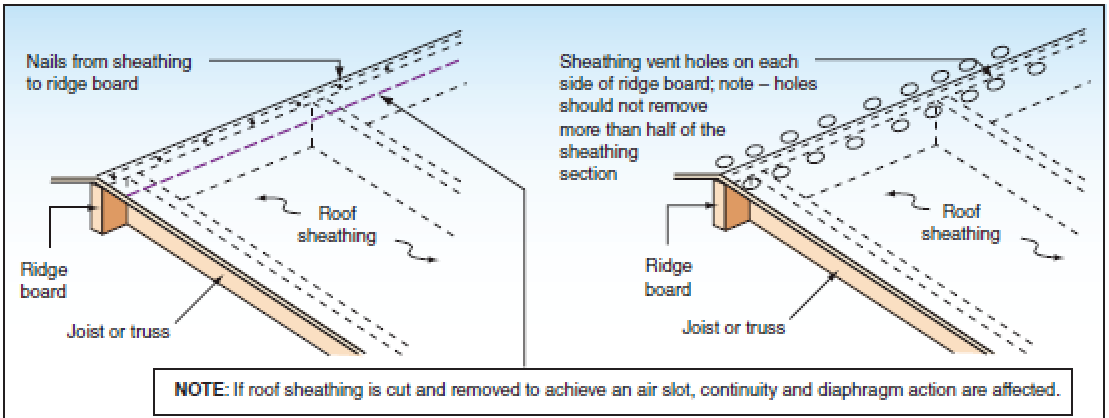
even greater withdrawal strength, but should be sized by the building designer. Staples are not recommended for roof sheathing attachment in high-wind areas.

Fastener Spacing

It is ***extremely important*** to have proper fastener spacing on **all** panels. Loss of just one panel in a windstorm can lead to total building failure. Drawings should be checked to verify the required spacing; closer spacing may be required at corners, edges, and ridges. Visually inspect work after installation to ensure that fasteners have hit the framing members. Tighter fastener spacing schedules can be expected for homes built in high-wind areas. Installing fasteners at less than 3 inches on center can split framing members and significantly reduce fastener withdrawal capacity, unless 3-inch nominal framing is used and the nailing schedule is staggered.

Ridge Vents

When the roof sheathing is used as a structural diaphragm, as it typically is in high-wind and seismic hazard areas, the structural integrity of the diaphragm can be compromised by a continuous vent (see figure A., below left). Maintain ridge nailing by adding additional blocking set back from the ridge, or by using vent holes (see figure B., below right). Verify construction with a design professional.

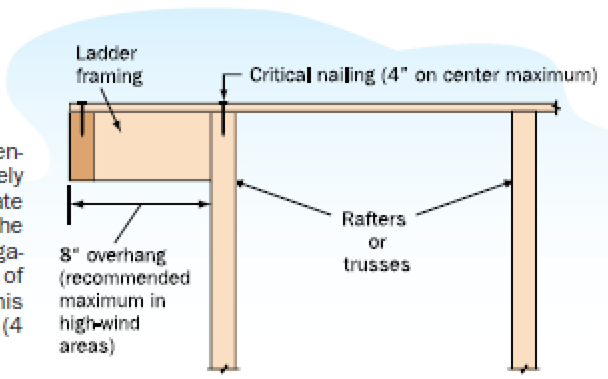


A. Method for maintaining a continuous load path at the roof ridge by nailing roof sheathing.

B. Holes drilled in roof sheathing for ventilation – roof diaphragm action is maintained. (For clarity, sheathing nails are not shown.)

Ladder Framing at Gable Ends

Use extra care when attaching a ladder-framed extension to a gable end. Many homes have been severely damaged by coastal storms because of inadequate connections between the roof sheathing and the gable truss. The critical fasteners occur at the gable-framing member, not necessarily at the edge of the sheathing. Nailing accuracy is crucial along this member. Tighter nail spacing is recommended (4 inches on center maximum).

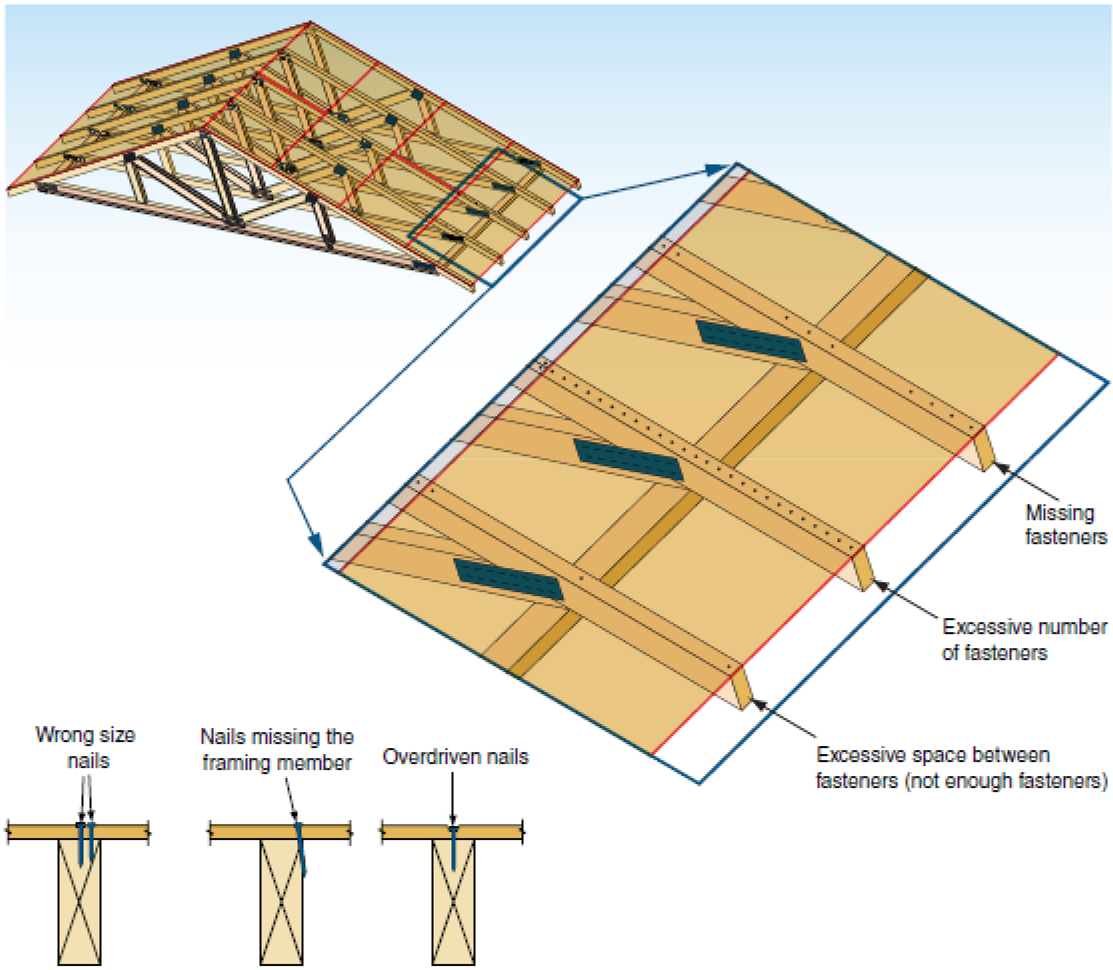


Ladder framing at gable ends.

Figure B.2 12. Proper roof sheathing installation for high wind areas (2) (FEMA 2010)

Common Sheathing Attachment Mistakes

Common mistakes include using the wrong size fasteners, missing the framing members when installing fasteners, overdriving nails, and using too many or too few fasteners.



Additional Resources

Engineered Wood Association (APA), (www.apawood.org)

Figure B.2 13. Proper roof sheathing installation for high wind areas (3) (FEMA 2010)

Roof Underlayment for Asphalt Shingle Roofs

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION — Technical Fact Sheet No. 7.2

Purpose: *To provide recommended practices for use of roofing underlayment as an enhanced secondary water barrier in coastal environments.*

Note: The underlayment options illustrated here are for asphalt shingle roofs. See FEMA publication 55, Coastal Construction Manual, for guidance concerning underlayment for other types of roofs.

Key Issues

- Verifying proper attachment of roof sheathing before installing underlayment.
- Lapping and fastening of underlayment and roof edge flashing.
- Selecting underlayment material type.

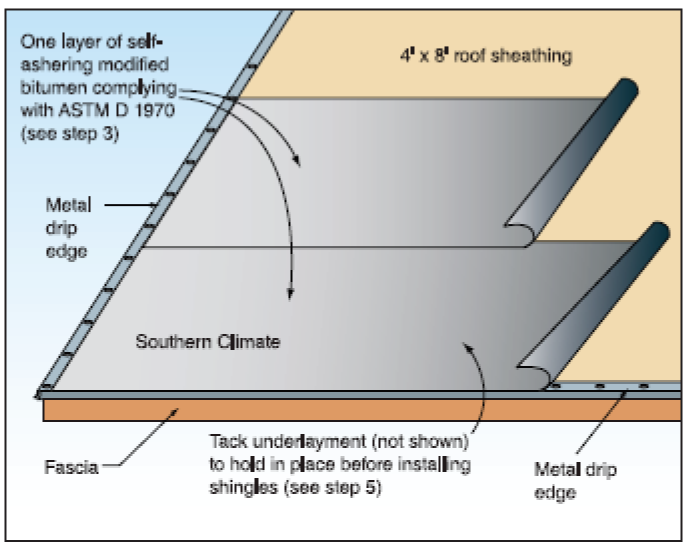
Note: This fact sheet provides general guidelines and recommended enhancements for improving upon typical practice. It is advisable to ***consult local building requirements*** for type and installation of underlayment, particularly if specific enhanced underlayment practices are required locally.

Sheathing Installation Options

The following three options are listed in order of decreasing resistance to long-term weather exposure following the loss of the roof covering. Option 1 provides the greatest reliability for long-term exposure; it is advocated in heavily populated areas where the design wind speed is equal to or greater than 120 mph (3-second peak gust).[1] Option 3 provides limited protection and is advocated only in areas with a modest population density and a design wind speed less than or equal to 110 mph (3-second peak gust).[1]

Installation Sequence – Option 1[2] (for moderate climates)

1. Before the roof covering is installed, have the deck inspected to verify that it is nailed as specified on the drawings.
2. Broom clean deck before installing self-adhering modified bitumen products. If the sheathing is OSB, check with the OSB manufacturer to determine if a primer needs to be applied before installing these products.
3. **In Southern Climates, apply a single layer of self-adhering modified bitumen complying with ASTM D 1970 throughout the roof area.**
4. Seal the self-adhering sheet to the deck penetrations with roof tape or asphalt roof cement.



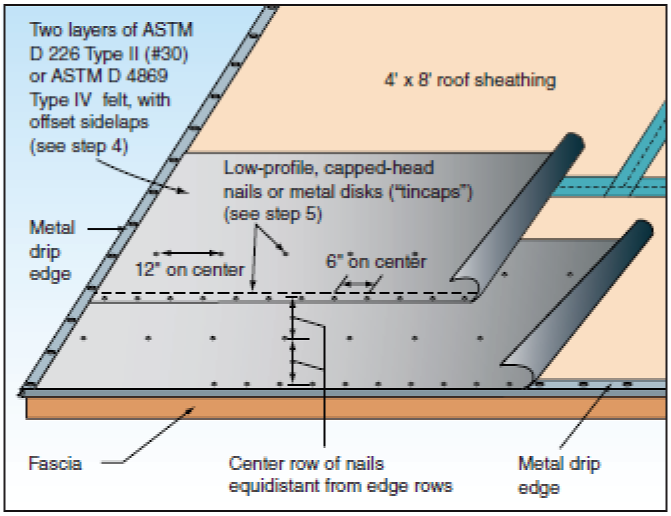
1 The 110 and 120 mph speeds are based on ASCE 7-05. If ASCE 7-10 is being used, the equivalent wind speeds are 139 and 152 mph for Risk Category II buildings.

Figure B.2 14. Recommended practices for use of roofing underlayments (1) (FEMA 2010)

5. **Apply a single layer of ASTM D 226 Type I (#15) or ASTM D 4869 Type II felt.** Tack underlayment to hold in place before installing shingles.
6. **In northern climates**, after step 2, install self-adhering modified bitumen tape (4 inches wide, minimum) over sheathing joints; seal around deck penetrations with roof tape. Roll tape with roller.
7. **Apply a single layer of ASTM D 226 Type II (#30) or ASTM D 4869 Type IV felt. Attach per steps 8 and 9. Then install a single layer of self-adhering modified bitumen per steps 3 and 4, followed by installation of the shingles.**
8. Secure felt with low-profile, capped-head nails or thin metal disks ("tincaps") attached with roofing nails.
9. Fasten at approximately 6 inches on center along the laps and at approximately 12 inches on center along two rows in the field of the sheet between the side laps.

Installation Sequence – Option 2[2]

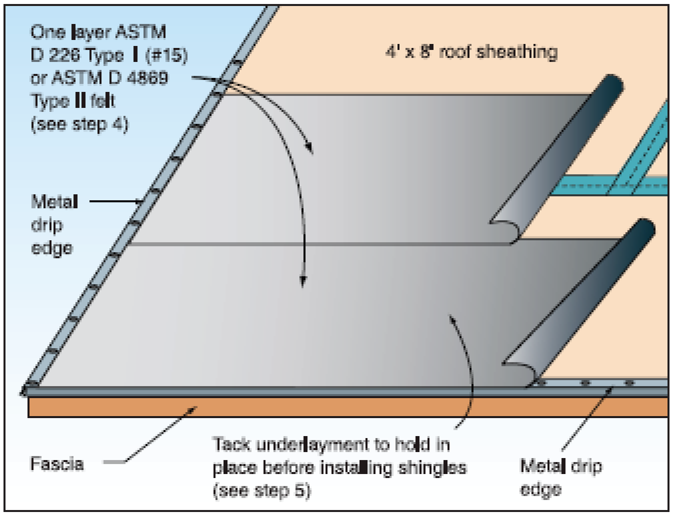
1. Before the roof covering is installed, have the deck inspected to verify that it is nailed as specified on the drawings.
2. Broom clean deck before taping. If the sheathing is OSB, check with the OSB manufacturer to determine if a primer needs to be applied before installing self-adhering modified bitumen products.
3. Install self-adhering modified bitumen tape (4 inches wide, minimum) over sheathing joints; seal around deck penetrations with roof tape. Roll tape with roller.
4. **Apply two layers of ASTM D 226 Type II (#30) or ASTM D 4869 Type IV felt with offset side laps.**



5. Secure felt with low-profile, capped-head nails or thin metal disks ("tincaps") attached with roofing nails.
6. Fasten at approximately 6 inches on center along the laps and at approximately 12 inches on center along a row in the field of the sheet between the side laps.

Installation Sequence – Option 3[2,3]

1. Before the roof covering is installed, have the deck inspected to verify that it is nailed as specified on the drawings.
2 Broom clean deck before taping. If the sheathing is OSB, check with the



2 If the building is within 3,000 feet of saltwater, stainless steel or hot-dip galvanized fasteners are recommended for the underlayment attachment.

3 (1) If the roof slope is less than 4:12, tape and seal the deck at penetrations and follow the recommendations given in The NRCA Roofing and Waterproofing Manual, by the National Roofing Contractors Association. (2) With this option, the underlayment has limited blow-off resistance. Water infiltration resistance is provided by the taped and sealed sheathing panels. This option is intended for use where temporary or permanent repairs are likely to be made within several days after the roof covering is blown off.

Figure B.2 15. Recommended practices for use of roofing underlayments (2) (FEMA 2010)

OSB manufacturer to determine if a primer needs to be applied before installing self-adhering modified bitumen products.

3. Install self-adhering modified bitumen tape (4 inches wide, minimum) over sheathing joints; seal around deck penetrations with roof tape. Roll tape with roller.
4. **Apply a single layer of ASTM D 226 Type I (#15) or ASTM D 4869 Type II felt.**
5. Tack underlayment to hold in place before applying shingles.

General Notes

- Weave underlayment across valleys.
- Double-lap underlayment across ridges (unless there is a continuous ridge vent).
- Lap underlayment with minimum 6-inch leg "turned up" at wall intersections; lap wall weather barrier over turned-up roof underlayment.

Additional Resources

National Roofing Contractors Association (NRCA). The NRCA Roofing and Waterproofing Manual. (www.NRCA.net)

ASTM Standard D6135, 2005, "Standard Practice for Application of Self-Adhering Modified Bituminous Waterproofing," ASTM International, West Conshohocken, PA, 2005, 10.1520/D6135-05, www.astm.org.

Figure B.2 16. Recommended practices for use of roofing underlayments (3) (FEMA 2010)

Asphalt Shingle Roofing for High Wind Regions

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION — **Technical Fact Sheet No. 7.3**

Purpose: *To recommend practices for installing asphalt roof shingles that will enhance wind resistance in high-wind, coastal regions.*

Key Issues

- Special installation methods are recommended for asphalt roof shingles used in high-wind, coastal regions (i.e., greater than 90-mph gust design wind speed).
- Use wind-resistance ratings to choose among shingles, but do not rely on ratings for performance.
- Consult local building code for specific installation requirements. Requirements may vary locally.
- Always use underlayment. See Fact Sheet No. 7.2 for installation techniques in coastal areas.
- Pay close attention to roof-to-wall flashing and use enhanced flashing techniques (see Fact Sheet No. 5.2).

Construction Guidance

1. Follow shingle installation procedures for enhanced wind resistance.

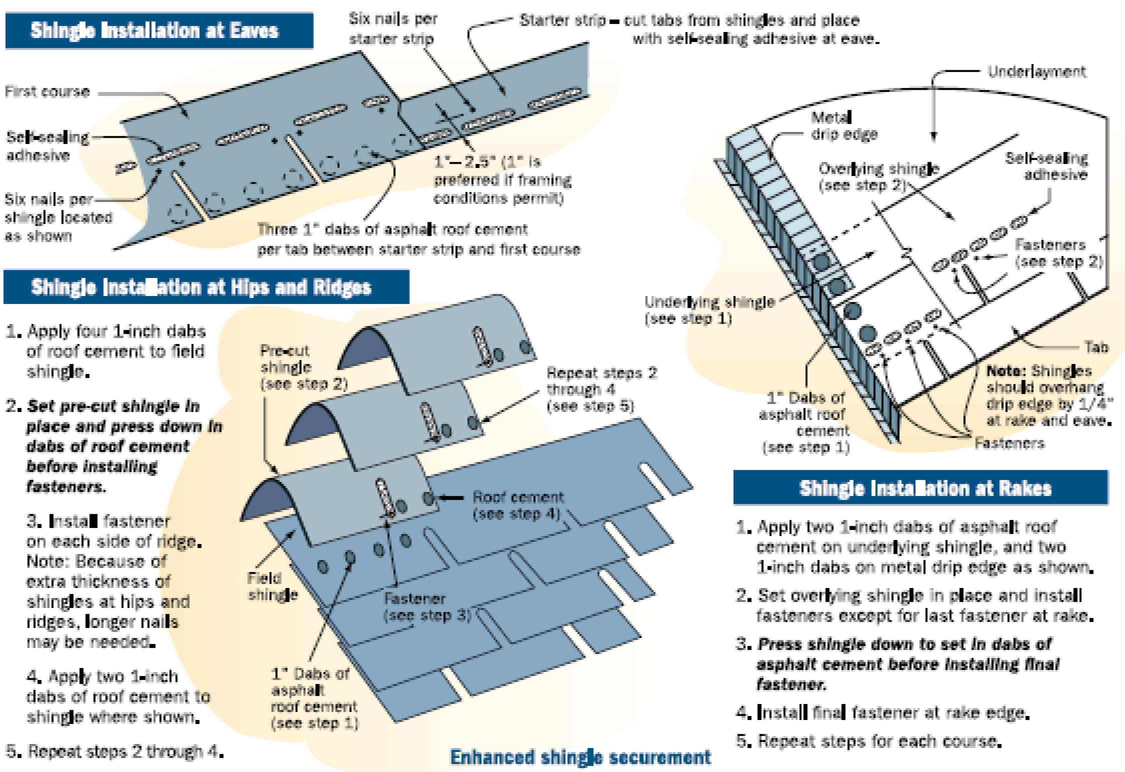


Figure B.2 17. Practices for asphalt roof shingle installation (1) (FEMA 2010)

2. Consider shingle physical properties.

Properties	Design Wind Speed[1] >90 to 120 mph	Design Wind Speed[1] >120 mph
Fastener Pull-Through[2] Resistance	Minimum Recommended 25 lb at 73 degrees Fahrenheit (F)	Minimum Recommended 30 lb

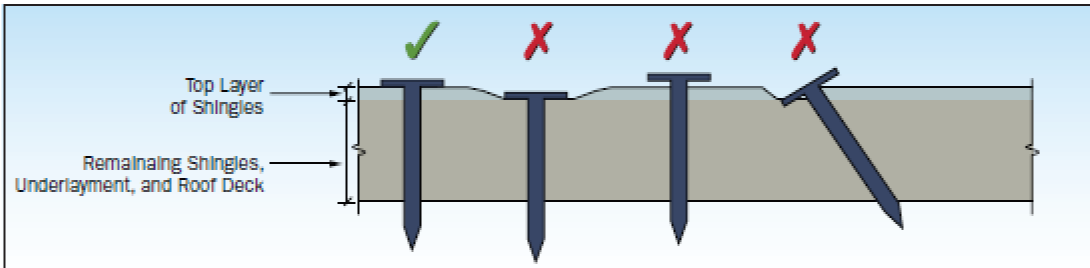
1. Design wind speed based on 3-second peak gust.
2. ASTM D 3462 specifies a minimum fastener pull-through resistance of 20 lb at 73° F. If a higher resistance is desired, it must be specified.

3. Ensure that the fastening equipment and method results in properly driven roofing nails for maximum blow-off resistance. The minimum required bond strength must be specified (see **Wind-Resistance Ratings**, below).

Shingle Type	Standard	Characteristics
Organic-Reinforced	ASTM D 225	Relatively high fastener pull-through resistance
Fiberglass-Reinforced	ASTM D 3462	Considerable variation in fastener pull-through resistance offered by different product
SBS Modified Bitumen	A standard does not exist for this product. It is recommended that SBS Modified Bitumen Shingles meet the physical properties specified in ASTM 3462.	Because of the flexibility imparted by the SBS polymers, this type of shingle is less likely to tear if the tabs are lifted in a windstorm.

Fastener Guidelines

- Use roofing nails that extend through the underside of the roof sheathing, or a minimum of 3/4 inch into planking.
- Use roofing nails instead of staples.
- Use stainless steel nails when building within 3,000 feet of saltwater.



"The Good, the bad, and the ugly" – Properly driving roofing nails.

Weathering and Durability

Durability ratings are relative and are not standardized among manufacturers. However, selecting a shingle with a longer warranty (e.g., 30-year instead of 20-year) should provide greater durability in coastal climates and elsewhere.

Organic-reinforced shingles are generally more resistant to tab tear-off but tend to degrade faster in warm climates. Use fiberglass-reinforced shingles in warm coastal climates and consider organic shingles only in cool coastal climates. Modified bitumen shingles may also be considered for improved tear-off resistance of tabs. Organic-reinforced shingles have limited fire resistance – verify compliance with code and avoid using in areas prone to wildfires.

Figure B.2 18. Practices for asphalt roof shingle installation (2) (FEMA 2010)

After the shingles have been exposed to sufficient sunshine to activate the sealant, inspect roofing to ensure that the tabs have sealed. Also, shingles should be of "interlocking" type if seal strips are not present.

Wind-Resistance Ratings

Wind resistance determined by test methods ASTM D 3161 and UL 997 does not provide adequate information regarding the wind performance of shingles, even when shingles are tested at the highest fan speed prescribed in the standard. Rather than rely on D 3161 or UL 997 test data, wind resistance of shingles should be determined in accordance with UL 2390. Shingles that have been evaluated in accordance with UL 2390 have a Class D (90 mph), G (120 mph), or H (150 mph) rating. Select shingles that have a class rating equal to or greater than the basic wind speed specified in the building code. If the building is sited in Exposure D, or is greater than 60 feet tall, or is a Category III or IV, or is sited on an abrupt change in topography (such as an isolated hill, ridge, or escarpment), consult the shingle manufacturer. (Note: for definitions of Exposure D and Category III and IV, refer to ASCE 7.)

Figure B.2 19. Practices for asphalt roof shingle installation (3) (FEMA 2010)

Tile Roofing for High Wind Regions

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 7.4

Purpose: *To provide recommended practices for designing and installing extruded concrete and clay tiles that will enhance wind resistance in high-wind areas.*

Key Issues

Missiles: Tile roofs are very vulnerable to breakage from windborne debris (missiles). Even when well attached, they can be easily broken by missiles. If a tile is broken, debris from a single tile can impact other tiles on the roof, which can lead to a progressive cascading failure. In addition, tile missiles can be blown a considerable distance, and a substantial number have sufficient energy to penetrate shutters and glazing, and potentially cause injury. In hurricane-prone regions where the basic wind speed is equal to or greater than 110 mph (3-second peak gust), the windborne debris issue is of greater concern than in lower-wind-speed regions. Note: There are currently no testing standards requiring roof tile systems to be debris impact resistant.

Attachment methods: Storm damage investigations have revealed performance problems with mortar-set, mechanical (screws or nails and supplementary clips when necessary), and foam-adhesive (adhesive-set) attachment methods. In many instances, the damage was due to poor installation. Investigations revealed that the mortar-set attachment method is typically much more susceptible to damage than are the other attachment methods. Therefore, in lieu of mortar-set, the mechanical or foam-adhesive attachment methods in accordance with this fact sheet are recommended.

To ensure high-quality installation, licensed contractors should be retained. This will help ensure proper permits are filed and local building code requirements are met. For foam-adhesive systems, it is highly recommended that installers be trained and certified by the foam manufacturer.

Uplift loads and resistance: Calculate uplift loads and resistance in accordance with the Design and Construction Guidance section below. Load and resistance calculations should be performed by a qualified person (i.e., someone who is familiar with the calculation procedures and code requirements).

Corner and perimeter enhancements: Uplift loads are greatest in corners, followed by the perimeter, and then the field of the roof (see Figure 1 on page 2).

However, for simplicity of application on smaller roof areas (e.g., most residences and smaller commercial buildings), use the attachment designed for the corner area throughout the entire roof area.

Hips and ridges: Storm damage investigations have revealed that hip and ridge tiles attached with mortar are very susceptible to blow-off. Refer to the attachment guidance below for improved attachment methodology.

Quality control: During roof installation, installers should implement a quality control program in accordance with the Quality Control section on page 3 of this fact sheet.

Classification of Buildings

Category I	Buildings that represent a low hazard to human life in the event of a failure
Category II	All other buildings not in Categories I, III, and IV
Category III	Buildings that represent a substantial hazard to human life
Category IV	Essential facilities

Figure B.2 20. Practices for concrete and clay tile installation (1) (FEMA 2010)

Design and Construction Guidance

1. Uplift Loads

In Florida, calculate loads and pressures on tiles in accordance with the current edition of the Florida Building Code (Section 1606.3.3). In other states, calculate loads in accordance with the current edition of the International Building Code (Section 1609.7.3).

As an alternative to calculating loads, design uplift pressures for the corner zones of Category II buildings are provided in tabular form in the Addendum to the Third Edition of the *Concrete and Clay Roof Tile Installation Manual* (see Tables 6, 6A, 7, and 7A).[1]

Note: In addition to the tables referenced above, the *Concrete and Clay Roof Tile Installation Manual* contains other useful information pertaining to tile roofs. Accordingly, it is recommended that designers and installers of tile obtain a copy of the Manual and its Addendum. Hence, the tables are not incorporated in this fact sheet.

2. Uplift Resistance

For mechanical attachment, the *Concrete and Clay Roof Tile Installation Manual* provides uplift resistance data for different types and numbers of fasteners and different deck thicknesses. For foam-adhesive-set systems, the Manual refers to the foam-adhesive manufacturers for uplift resistance data. Further, to improve performance where the basic wind speed is equal to or greater than 110 mph, it is recommended that a clip be installed on each tile in the first row of tiles at the eave for both mechanically attached and foam-adhesive systems.

For tiles mechanically attached to battens, it is recommended that the tile fasteners be of sufficient length to penetrate the underside of the sheathing by ¼ inch minimum. For tiles mechanically attached to counter battens, it is recommended that the tile fasteners be of sufficient length to penetrate the underside of the horizontal counter battens by ¼ inch minimum. It is recommended that the batten-to-batten connections be engineered.

For roofs within 3,000 feet of the ocean, straps, fasteners, and clips should be fabricated from stainless steel to ensure durability from the corrosive effects of salt spray.

1. You can order the *Concrete and Clay Roof Tile Installation Manual* online at the website of the Florida Roofing, Sheet Metal and Air Conditioning Contractor's Association, Inc., (www.floridaroof.com) or by calling (407) 671-3772. Holders of the Third Edition of the Manual who do not have a copy of the Addendum can download it from the website.

3. Hips and Ridges

The *Concrete and Clay Roof Tile Installation Manual* gives guidance on two attachment methods for hip and ridge tiles: mortar-set or attachment to a ridge board. On the basis of post-disaster field investigations, use of a ridge board is recommended. For attachment of the board, refer to Table 21 in the Addendum to the *Concrete and Clay Roof Tile Installation Manual*.

Fasten the tiles to the ridge board with screws (1-inch minimum penetration into the ridge board) and use both adhesive and clips at the overlaps.

For roofs within 3,000 feet of the ocean, straps, fasteners, and clips should be fabricated from stainless steel to ensure durability from the corrosive effects of salt spray.

4. Critical and Essential Buildings (Category III or IV)

Critical and essential buildings are buildings that are expected to remain operational during a severe wind event such as a hurricane. It is possible that people may be arriving or departing from the critical or essential facility during a hurricane. If a missile strikes a tile roof when people are outside the building, those people may be struck by tile debris dislodged by the missile strike. Tile debris may also damage the facility. It is for these reasons that tiles are not recommended on critical or essential buildings in hurricane-prone regions (see ASCE 7 for the definition of hurricane-prone regions).

If it is decided to use tile on a critical or essential facility and the tiles are mechanically attached, it is recommended that clips be installed at all tiles in the corner, ridge, perimeter, and hip zones (see ASCE 7 for the width of these zones). (See Figure 1.)

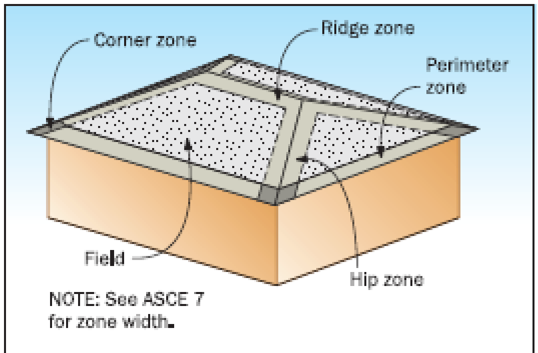


Figure 1. For critical and essential facilities, clip all tiles in the corner, ridge, perimeter, and hip zones.

Figure B.2 21. Practices for concrete and clay tile installation (2) (FEMA 2010)

5. Quality Control

It is recommended that the applicator designate an individual to perform quality control (QC) inspections. That person should be on the roof during the tile installation process (the QC person could be a working member of the crew). The QC person should understand the attachment requirements for the system being installed (e.g., the type and number of fasteners per tile for mechanically attached systems and the size and location of the adhesive for foam-adhesive systems) and have authority to correct noncompliant work. The QC person should ensure that the correct type, size, and quantity of fasteners are being installed.

For foam-adhesive systems, the QC person should ensure that the foam is being applied by properly trained applicators and that the work is in accordance with the foam manufacturer's application instructions. At least one tile per square (100 square feet) should be pulled up to confirm the foam provides the minimum required contact area and is correctly located.

If tile is installed on a critical or essential building in a hurricane-prone region, it is recommended that the owner retain a qualified architect, engineer, or roof consultant to provide full-time field observations during application.

Figure B.2 22. Practices for concrete and clay tile installation (3) (FEMA 2010)

Minimizing Water Intrusion Through Roof Vents in High-Wind Regions

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 7.5

Purpose: *To describe practices for minimizing water intrusion through roof vent systems that can lead to interior damage and mold growth in high-wind regions (i.e., greater than 90-miles per hour [mph] basic [gust design] wind speed).*[1]

Key Issues

- Hurricane winds can drive large amounts of water through attic ventilation openings. The accumulating water soaks insulation and gypsum board, which can lead to mold growth and, in some cases, to the collapse of ceilings.
- Attic ventilation can be provided by a number of devices, most of which have been observed to allow water intrusion under certain conditions and some of which have been observed to blow off. These devices include:
  - Soffit vents
  - Ridge vents
  - Gable end vents
  - Off-ridge vents
  - Gable rake vents
  - Turbines
- Adequate ventilation of attics is generally required to promote the health of wood structural members and sheathing in the attic.
- Attic ventilation can reduce the temperatures of roof coverings, which will typically prolong the life of the roof covering. However, roof color can have more of an impact on roof covering temperature than the amount of ventilation that is or is not provided.
- An unvented attic can be an effective way to prevent water intrusion and this type of attic is gaining popularity for energy efficiency reasons, provided the air conditioning system is sized appropriately. However, an unvented attic is best accomplished when it is specifically designed into the house and all of the appropriate details are handled properly. On an existing house, any attempt to change to an unvented attic configuration needs to be done very carefully with the advice of knowledgeable experts. There are a number of changes that have to be made to produce a successful transition from a ventilated to an unvented attic. One side effect of going to an unvented attic may be to void the warranty for the roof covering.

The following information is intended to help minimize water intrusion through new and existing attic ventilation systems, not to change from a ventilated to an unvented system. With the exception of the plugging of gable rake vents, all other shuttering of openings or plugging of vents should be done on a temporary basis and removed once the storm threat is over so that the attic is once again properly ventilated.

The Unvented Attic

The most conservative approach to preventing wind-driven rain from entering the attic is to eliminate attic ventilation, but unvented attics are controversial. Although allowed by the International Residential Code (IRC), provided the Code's criteria are met, unvented attics may not comply with local building codes.

However, when unvented attics are allowed by the building code or code compliance is not an issue, and when climatic and interior humidity conditions (e.g., no indoor swimming pools) are conducive to an unvented design, an unvented attic is a reliable way to prevent wind-driven rain from entering the attic.

Air barrier: Refer to Fact Sheet 5.3, *Siding Installations in High-Wind Regions* for recommendations regarding attic air barriers.

1 The 90 mph speed is based on ASCE 7-05. If ASCE 7-10 is being used, the equivalent wind speed is 116 mph for Risk Category II buildings

Figure B.2 23. Practices for minimizing water intrusion through roof vent systems (1) (FEMA 2010)

Mitigation Guidance

Soffit Vents

Key Issues

- It is important to keep the soffit material in place. While some water can be blown into the attic through almost any type of soffit vent, the amount of water intrusion increases dramatically when the soffit material is missing (Figure 1).
- Plywood or wood soffits are generally adequately anchored to wood framing attached to the roof structure and/or the walls. However, it has been common practice for vinyl and aluminum soffit panels to be installed in tracks that are frequently very poorly connected to the walls and fascia at the edge of the roof overhang. When these poorly anchored soffits are blown off, water intrusion increases significantly. Properly installed vinyl and aluminum soffit panels are fastened to the building structure or to nailing strips placed at intervals specified by the manufacturer.

Figure 1. Missing soffit material.

Proper Installation

The details of proper installation of vinyl and aluminum soffits depend on the type of eave to which they are attached. The key elements are illustrated in Figure 2.

A. Roof truss or rafter framing should extend across the bottom of the eaves, or be added to create a structural support for the soffit. As an alternative, soffits can be attached directly to the undersides of the angled rafters.

B. Nailing strips should be provided, if necessary, to allow attachment of the soffit at the ends. Intermediate nailing strips may be needed, depending on the maximum span permitted for the soffit. If this is not known, the span between attachment points should not exceed 12" in high-wind regions.

C. A J-channel (illustrated), F-channel, or other receiver as specified by the manufacturer should cover the ends of the soffit panels. Fasteners should be those specified by the manufacturer. Fasteners should be used through the nailing strip of each panel and at any other points (such as in the "valleys" of the soffit) if specified.

D. The overall span (eave depth) of the soffit should not exceed any limits specified by the manufacturer, and any required intermediate attachment points should be used.

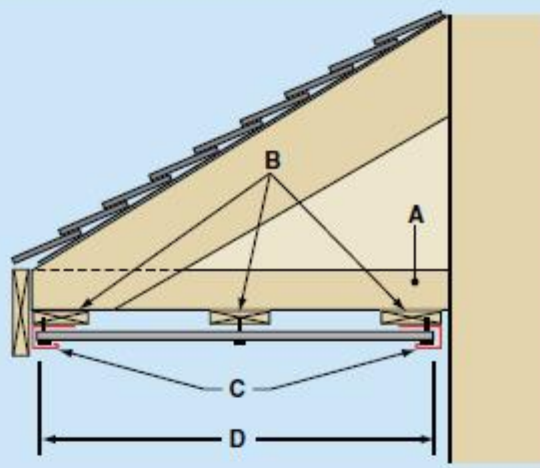


Figure 2. Key soffit installation points.

Figure B.2 24. Practices for minimizing water intrusion through roof vent systems (2) (FEMA 2010)

Checking Soffit Material Installation

As previously noted, the most critical soffit installations to check are those where vinyl or aluminum soffit panels are used. Soffits should be fastened to the eave structure; they should not be loose in the channels. Pushing up on the soffit material and the channels used to support the material can be revealing. If it moves readily or is easy to deform, it probably is not attached very well. Similarly, if the width of the overhang is greater than 12 inches, there should be an intermediate support running along the middle of the soffit and the panels should be attached to this support in addition to the supports at the ends of the panels. If the reader is concerned about the installation but cannot be sure, there are a couple of tools with a viewing screen connected to a small camera lens and light mounted at the end of a flexible tube that can be used to observe the connections. These devices allow inspection through a small hole that is drilled in an inconspicuous location that can be later filled with sealant. In order to ensure that there is a strong connection at the wall, there should be wood blocking running along the wall above the track where the soffit channel is attached and the channel should be fastened to that blocking. If there is no wood blocking, and there is either no vertical nailing surface on the channel or occasional tabs that have been cut and bent up to allow fastening to the wall, strengthening of the anchorage of the soffit material is clearly indicated.

Remedial Measures

If the inspection indicates a poorly attached soffit, the best way to ensure that the soffit material is adequately anchored in place is to remove it and install adequate wood blocking to allow solid anchorage of the soffit material. In some cases, it may be possible to remove the soffit material and reinstall it. However, it is also likely that some or all of the material will need to be replaced, so make sure that it can be matched before it is removed. Short of removing and properly reinstalling the soffit material, testing has shown that the anchorage can be greatly improved by applying a bead of sealant (Figure 3) along the bottom edge of the wall channel to adhere it to the wall surface below followed by applying large dabs of sealant in indentations between the soffit panels and the wall channel at one end (Figure 4) and the fascia flashing at the other end. Surfaces receiving sealant should be cleaned in order to facilitate bonding. Extra resistance can be gained by installing screws that mechanically tie the soffit panels to both the fascia flashing and to the wall channel (Figure 5). Note that use of sealant is a remedial measure only and is not a substitute for proper installation and fastening of soffits in a new installation.

Figure 3. Applying a bead of sealant. (Note: Black sealant was used so that it would be visible in the photograph. Normally a matching sealant color would be used.)

Figure 4. Applying dabs of sealant.

Figure 5. Screws through wall channel.

Figure B.2 25. Practices for minimizing water intrusion through roof vent systems (3) (FEMA 2010)

Wind-driven rain penetration: Currently there is no adequate standard test method to evaluate the potential for wind-driven rain to enter attics through soffit vent openings, such as those shown in Figure 6. To avoid water entry at soffit vents, options include eliminating soffit vents and providing an alternate method for air to enter the attic, or design for an unvented attic. Another approach is to place filter fabric (like that used for heating, ventilation, or cooling [HVAC] system filters) above the vent openings; however, such an approach needs to be custom designed.

Figure 6. Fiber cement soffit with ventilation slots (red arrow).

Fascia cover: Field investigations after Hurricane Ike showed many cases where the aluminum fascia cover (fascia cap) from the fascia board was blown off (Figure 7). The fascia cover normally covers the ends of vinyl and aluminum soffits. When the fascia cover is blown off, the ends of the soffit panels are exposed to wind and wind-driven rain.

Rain screen wall venting: In lieu of providing soffit vents, another method to provide attic air intake is through a pressure-equalized rain screen wall system as discussed in *Siding Installation in High-Wind Regions*, Hurricane Ike Recovery Advisory. This alternative approach eliminates soffit vents and their susceptibility to wind-driven rain entry.

Figure 7. Loss of fascia cover exposes ends of vinyl soffit to direct entry of wind-driven rain.

The IRC currently has no guidelines for the installation of fascia covers. Aluminum fascia covers are typically tucked under the roof drip edge and face-nailed every few feet. More frequent nailing would help secure the fascia cover, but would also inhibit normal thermal movement, which can cause unattractive warping and dimpling of the cover. Vinyl fascia covers are available, which are attached to a continuous strip of utility trim placed underneath the drip edge. This provides a somewhat more secure, continuous attachment and allows for thermal movement. Aluminum fascia covers can also be field notched and installed with utility trim.

Ridge Vents

Key Issues

- Ridge vents are frequently fastened down using ordinary roofing nails since these are normally handy. It is fairly common to find ridge vents dislodged or blown off during a hurricane (Figure 8). Even a partially dislodged ridge vent can begin to act like a scoop that collects wind-driven rain and directs it into the attic.
- Most roofing manufacturers now make ridge vents that have passed wind-driven water tests. They are identified as having passed Florida Building Code's Product Approvals or Testing Application Standard (TAS) 100(A). Typically, they include a baffle in front of the vent tubes that provide the passageway for hot attic gasses to escape. This baffle is intended to trip any flow of wind and water blowing up the surface of the roof and deflect it over the top of the roof ridge.

Figure B.2 26. Practices for minimizing water intrusion through roof vent systems (4) (FEMA 2010)

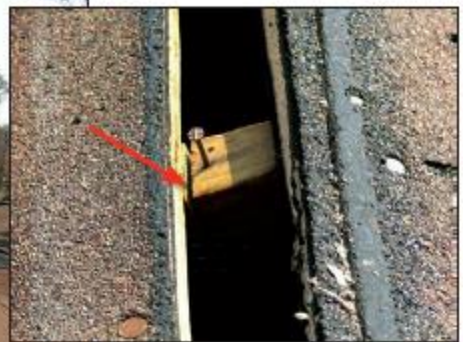


Figure 8. This metal ridge vent was attached with widely spaced roofing nails.

Slotting the Deck

When ridge venting is being added to a roof that previously did not have it, it is necessary to cut a slot through the decking. When doing so, it is important to set the depth of the saw blade so that it only slightly projects below the bottom of the decking. At the residence shown in Figure 8, the saw blade cut approximately 1 1/2 inches into the trusses and cut a portion of the truss plate (red arrow).

Checking Ridge Vents and Their Installation

When they are used, ridge vents are the last part of the roof to be installed. Consequently, the connection is readily accessible and frequently visible without having to pry up the edge of the vent cover top. Check the type and condition of the fasteners. If the fasteners are nails, replacement of the fasteners is in order. If the vent has clear holes or slots without any baffle or trip next to the edge of the vent channels, the vent is probably not one that is resistant to water intrusion and you should consider replacing the ridge vent with one that has passed the wind-driven water intrusion tests.

Remedial Measures

Replace nails with gasketed stainless steel wood screws that are slightly larger than the existing nails and, if possible, try to add fasteners at locations where they will be embedded in the roof structure below and not just into the roof sheathing. Close spacing of fasteners is recommended (e.g., in the range of 3 to 6 inches on center, commensurate with the design wind loads). If the ridge vents are damaged or are one of the older types that are not resistant to water intrusion, they should be replaced with vents that have passed the wind-driven water intrusion tests.

Figure 9. Gable end vent.

Gable End Vents

Key Issues

- Virtually all known gable end vents (Figure 9) will leak when the wall they are mounted on faces into the wind-driven rain. The pressures developed between the outside surface of the wall and the inside of the attic are sufficient to drive water uphill for a number of inches and, if there is much wind flow through the vent, water carried by the wind will be blown considerable distances into the attic.

Figure B.2 27. Practices for minimizing water intrusion through roof vent systems (5) (FEMA 2010)

Remedial Measures

If it is practical and possible to shutter gable end vents from the outside of the house, this is the preferable way to minimize water intrusion through gable end vents (Figure 10). Install permanent anchors in the wood structure around the gable vent and precut, pre-drill, and label plywood or other suitable shutter materials so that they are ready for installation by a qualified person just before a storm approaches. If installation of shutters from the outside is difficult because of the height or other considerations, but there is access through the attic, the gable vent opening can be shuttered from the inside. However, careful attention needs to be paid to sealing around the shutter and making sure that any water that accumulates in the cavity can drain to the outside of the house and not into the wall below.

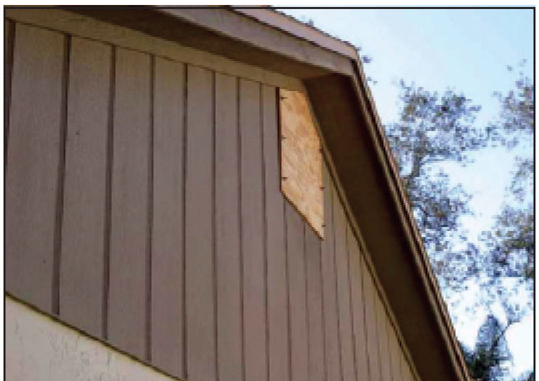


Figure 10. Shuttered gable end vent.

Figure 11. Two off-ridge vents are shown in this photograph. The vent that is covered with roofing felt flipped up and allowed a substantial amount of water to enter the residence. Carpeting, kitchen cabinets, and a large amount of gypsum board had to be replaced because of the water intrusion.

Off-ridge Vents

Key Issues

Poorly anchored off-ridge vents can flip up and become scoops that direct large amounts of wind-driven rain into the attic (Figure 11).

Some vents are also prone to leaking when winds blow from certain directions. This will depend on the location of the vent on the roof surface and the geometry of the roof, as well as the geometry of the particular vent.

Checking Off-Ridge Vent Installations

Off-ridge vents typically have a flange that lies against the top surface of the roof sheathing and is used to anchor the vent to the roof sheathing. Frequently, roofing nails are used to attach the flange to the roof sheathing. The off-ridge vents should be checked to make sure that they are well anchored to the roof sheathing. If they seem loose, or there are not many fasteners holding them down, it could be a weak link in preventing water intrusion when a storm occurs. Since the flange and fasteners are hidden below the roof covering, it is not possible to simply add nails or screws to improve the anchorage as these will create holes through the roof covering.

Remedial Measures

If the off-ridge vent is attached to the roof sheathing with long, thin nails, it may be possible to improve the anchorage by cinching the nails (bending them over against the underside of the roof sheathing). However, if they are short and/or thick, trying to bend them over may cause more harm than good. Some homeowners have had covers made that can be installed from the inside of the attic over the hole where the off-ridge vent is installed. This will be easiest if the vent is larger than the hole and the cover can be attached to the sheathing in an area where the fasteners cannot be driven through the roof covering. Otherwise, it will be important to ensure that the fasteners are short enough that they will not extend through the roof sheathing and damage the roof cover. If the edge of the hole in the roof deck is flush with the inside edge of the vent, it may be possible to install metal straps that are screwed into the walls of the vent and attached with short screws to the bottom surface of the roof sheathing. Again, it is critical to use screws that are short enough that they will not extend through the roof sheathing and damage the roof covering. The strapping should be connected to the walls of the vent with short stainless steel sheet metal screws.

Figure B.2 28. Practices for minimizing water intrusion through roof vent systems (6) (FEMA 2010)

Gable Rake Vents

Key Issues

- Gable rake vents are formed when porous soffit panels or screen vents are installed on the bottom surface of the roof overhang at the gable end and there is a clear path for wind to blow into the attic. This usually happens when the gable overhang is supported by what are called outriggers. Outriggers are typically used when gable overhangs exceed 12 inches. In these cases, the last roof truss or rafter (the gable end truss or rafter) is smaller than the trusses or rafters at the next location inside the attic. Outriggers (2x4s) are installed over top of the last gable truss or rafter, one end is anchored to the second truss or rafter back from the gable end, and the other end sticks out past the gable end wall to support the roof sheathing on the overhang.

Finding Out if You Have Gable Rake Vents and Whether You Still Need Them

The easiest way to tell if the roof has gable rake vents is to look in the attic on a cool sunny day and see if light is visible in gaps just below the sheathing at the gable end. The presence of the outriggers (2x4s running perpendicular to the gable truss and disappearing into the gable overhang) should also be visible. If there is also a gable end vent or a ridge vent, then the gable rake vent will probably not be needed in order to provide adequate venting for the attic.

Remedial Measures

The best solution if venting provided by the gable rake vents is not needed is to simply plug them up with metal flashing (Figure 12) or pieces of wood that are cut and anchored. They should be well attached and completely seal as many of the openings as possible and particularly those near the gable peak. Sealant can be used to seal around the edges of the metal or wood plugs.

Figure 12. Metal plugs (red arrows) in gable rake vents.

Turbines

Key Issues

- The rotating top portion of many turbines is not designed to withstand high-wind conditions and they are frequently installed with just a friction fit to the short standpipe that provides the venting of the attic. It is possible to find high-wind rated turbines on store shelves in hurricane-prone regions but, in hurricane winds, the turbines will be rotating at tremendous speeds and can be easily damaged by windborne debris.
- The flange on the standpipe that provides the connection of the pipe to the roof sheathing may also be poorly anchored to the roof sheathing.

Checking Turbines and Their Installation

Check any turbines to make sure that the stand pipes are not loose and that the turbine head is anchored to the stand pipe by sheet metal screws and not simply by a friction fit (Figure 13).

Figure 13. This turbine head is attached to the standpipe with dimple punches. Sheet metal screws should be added to strengthen the connection.

Remedial Measures

Loose standpipes should be securely anchored to the roof sheathing. If the standpipe is attached to the roof sheathing with long, thin nails, it may be possible to improve the anchorage by cinching the nails (bending them over against the underside of the roof sheathing). However, if they are short and/or thick, trying to bend them over may cause more harm than good. Some homeowners have had covers made that can be installed from the inside of the attic over the

Figure B.2 29. Practices for minimizing water intrusion through roof vent systems (7) (FEMA 2010)

hole where the standpipe is installed. This will be easiest if the standpipe is larger than the hole and the cover can be attached to the sheathing in an area where the fasteners cannot be driven through the roof cover. Otherwise, it will be important to ensure that the fasteners are short enough that they will not extend through the roof sheathing and damage the roof cover.

If the edge of the hole in the roof deck is flush with the inside edge of the standpipe, it may be possible to install metal straps that are screwed into the walls of the standpipe and attached with short screws to the bottom surface of the roof sheathing. Again, it is critical to use screws that are short enough that they will not extend through the roof sheathing and damage the roof cover. The strapping should be connected to the walls of the standpipe with short stainless steel sheet metal screws.

Beyond any remedial measures taken to anchor the standpipe to the roof sheathing or to plug the hole from the attic side, it is also important to try and seal the standpipe from the outside so that water does not build up in the pipe and leak into the roof sheathing around the hole. The best approach is to have a qualified person remove the top active portion of the turbine vent before the storm and plug the hole at the top of the standpipe. A wooden plug can be used that covers the entire hole and has blocks that rest against the walls of the standpipe where screws can be installed to anchor the plug to the standpipe. Some homeowners have had the entire turbine wrapped in plastic to keep water out during a storm (Figure 14). This can work as long as the turbine or wrapping does not get dislodged. The smaller area provided by removing the turbine top and plugging the hole is considered preferable.

Figure 14. Plastic wrapped turbines.

Figure B.2 30. Practices for minimizing water intrusion through roof vent systems (8) (FEMA 2010)

Metal Roof Systems in High-Wind Regions

HOME BUILDER'S GUIDE TO COASTAL CONSTRUCTION Technical Fact Sheet No. 7.6

Purpose: *To describe practices for designing and installing metal roof systems that will enhance wind resistance in high-wind regions (i.e., greater than 90 miles per hour [mph] basic [gust design] wind speed).*[1]

Key Issues

Damage investigations have revealed that some metal roofing systems have sufficient strength to resist extremely high winds (Figure 1), while other systems have blown off during winds that were well below design wind speeds given in ASCE 7. When metal roofing (or hip, ridge, or rake flashings) blows off during hurricanes, water may enter the building at displaced roofing; blown-off roofing can damage buildings and injure people. Here is general guidance for achieving successful wind performance:

1. Always follow the manufacturer's installation instructions and local building code requirements.
2. Calculate loads on the roof assembly in accordance with ASCE 7 or the local building code, it is recommended to use whichever procedure results in the highest loads.
3. Specify/purchase a metal roof system that has sufficient uplift resistance to meet the design uplift loads.
   - For standing seam metal panel systems, the 2009 International Building Code (IBC) requires test methods UL 580 or ASTM E 1592. For standing seam systems, it is recommended that design professionals specify E 1592 testing, because it gives a better representation of the system's uplift performance capability.
   - For safety factor determination, refer to Chapter F in standard NAS-01, published by the American Iron and Steel Institute.
   - For through-fastened steel panel systems, the IBC allows uplift resistance to be evaluated by testing or by calculations in accordance with standard NAS-01.

Figure 1. This structural standing seam roof system survived Hurricane Andrew (Florida, 1992), but some hip flashings were blown off. The estimated wind speed was 170 mph (peak gust, at 33 feet for Exposure C).

   - For architectural panels with concealed clips, test method UL 580 is commonly used. However, it is recommended that design professionals specify ASTM E 1592 because it gives a better representation of the system's uplift performance capability. When testing architectural panel systems via ASTM E 1592, the deck joints need to be unsealed in order to allow air flow to the underside of the metal panels. Therefore, underlayment should be eliminated from the test specimen, and a 1/8 inch minimum between deck panel side and end joints should be specified.
   - For safety factor determination, refer to Chapter F of the *North American Specification for the Design of Cold-Formed Steel Structural Members* (AISI S100-07).

This fact sheet addresses wind and wind-driven rain issues. For general information on other aspects of metal roof system design and construction (including seam types, metal types, and finishes), see the "Additional Resources" section.

1 The 90 mph speed is based on ASCE 7-05. If ASCE 7-10 is being used, the equivalent wind speed is 116 mph for Risk Category II buildings.

Figure B.2 31. Practices for designing and installing metal roof systems (1) (FEMA 2010)

- For copper roofing testing, see "NRCA analyzes and tests metal," Professional Roofing, May 2003.
- For metal shingles, it is recommended that uplift resistance be based on test method UL 580 or 1897.
- Specify the design uplift loads for field, perimeter, and corners of the roof. Also specify the dimension of the width of the perimeter. (Note: For small roof areas, the corner load can be used throughout the entire roof area.)

4. Suitably design the roof system components (see the "Construction Guidance" section).
5. Obtain the services of a professional roofing contractor to install the roof system.

For observations of metal roofing performance during Hurricanes Charley (2004, Florida), Ivan (2004, Alabama and Florida), and Katrina (Alabama, Louisiana, and Mississippi, 2005), respectively; see Chapter 5 in FEMA MAT reports 488, 489, and 549.

For attachment of corrugated metal panels, see FEMA 55, *Coastal Construction Manual, Appendix K*, available online at: http://www.fema.gov/library/viewRecord.do?id=1671.

An advantage of exposed fastener panels (versus panels with concealed clips) is that, after installation, it is easy to verify that the correct number of fasteners was installed. If fastening was not sufficient, adding exposed fasteners is easy and economical.

Metal Roofing Options

A variety of metal panel systems (including composite foam panels) are available for low-slope (i.e., 3:12 or less) and steep-slope (i.e., greater than 3:12) roofs. Metal shingles are also available for steep-slope roofs. Common metal roofing options are:

Standing-Seam Hydrostatic (i.e., water-barrier) Systems: These panel systems are designed to resist water infiltration under hydrostatic pressure. They have standing seams that raise the joint between panels above the water line. The seam is sealed with sealant tape (or sealant) in case it becomes inundated with water backed up by an ice dam or driven by high wind.

Most hydrostatic systems are structural systems (i.e., the roof panel has sufficient strength to span between purlins or nailers). A hydrostatic architectural panel (which cannot span between supports) may be specified, however, if continuous or closely spaced decking is provided.

Hydrokinetic (i.e., water-shedding) panels: These panel systems are not designed to resist water infiltration under hydrostatic pressure and therefore require a relatively steep slope (typically greater than 3:12) and the use of an underlayment to provide secondary protection against water that infiltrates past the panels. Most hydrokinetic panels are architectural systems, requiring continuous or closely spaced decking to provide support for gravity loads.

Some hydrokinetic panels have standing ribs and concealed clips (Figure 2), while others (such as 5V-crimp panels, R-panels [box-rib] and corrugated panels) are through-fastened (i.e., attached with exposed fasteners). Panels are available that simulate the appearance of tile.

Metal Shingles: Metal shingles are hydrokinetic products and require a relatively steep-slope and the use of an underlayment. Metal shingles are available that simulate the appearance of wood shakes and tiles.

Figure 2. This architectural panel system has concealed clips. The panels unlatched from the clips. The first row of clips (just above the red line) was several inches from the end of the panels. The first row of clips should have been closer to the eave.

Figure B.2 32. Practices for designing and installing metal roof systems (2) (FEMA 2010)

Construction Guidance

- Consult local building code requirements and manufacturer's literature for specific installation requirements. Requirements may vary locally.
- Underlayment: If a robust underlayment system is installed, it can serve as a secondary water barrier if the metal roof panels or shingles are blown off (Figures 2 and 3). For enhanced underlayment recommendations, see Fact Sheet No. 7.2, *Roof Underlayment for Asphalt Shingle Roofs*. Fact Sheet 7.2 pertains to underlayment options for asphalt shingle roofs. For metal panels and tiles, where Fact Sheet 7.2 recommends a Type I (#15) felt, use a Type II (#30) felt because the heavier felt provides greater resistance to puncture by the panels during application. Also, if a self-adhering modified bitumen underlayment is used, specify/purchase a product that is intended for use underneath metal (such products are more resistant to bitumen flow under high temperature).

Figure 3. These architectural panel system have snap-lock seams. One side of the seam is attached with a concealed fastener. Although a large number of panels blew away, the underlayment did not.

- Where the basic (design) wind speed is 110 mph[2] or greater, it is recommended that not less than two clips be used along the eaves, ridges, and hips. Place the first eave clip within 2 to 3 inches of the eave, and place the second clip approximately 3 to 4 inches from the first clip. Figures 2 and 4 illustrate ramifications of clips being too far from the eave.
- For copper panel roofs in areas with a basic wind speed greater than 90 mph,[3] it is recommended that Type 304 or 316 stainless steel clips and stainless steel screws be used instead of more malleable copper clips.

Figure 4. These eave clips were too far from the panel ends. The clip at the left was 13" from the edge of the deck. The other clip was 17" from the edge. It would have been prudent to install double clips along the eave.

- When clip or panel fasteners are attached to nailers (Figures 5–7), detail the connection of the nailer to the nailer support (including the detail of where nailers are spliced over a support).

Figure 5. The panels blew off the upper roof and landed on the lower roof of this house. The upper asphalt shingle roof shown had been re-covered with 5V-Crimp panels that were screwed to nailers. The failure was caused by inadequate attachment of the nailers (which had widely-spaced nails) to the sheathing. Note that the hip flashing on the lower roof blew off.

2 The 110 mph speed is based on ASCE 7-05. If ASCE 7-10 is being used, the equivalent wind speed is 142 mph for Risk Category II buildings.

3 The 90 mph speed is based on ASCE 7-05. If ASCE 7-10 is being used, the equivalent wind speed is 116 mph for Risk Category II buildings.

Figure B.2 33. Practices for designing and installing metal roof systems (3) (FEMA 2010)

Figure 6. Blow-off of nailers caused these panels to progressively fail. The nailers were installed directly over the trusses. In an assembly such as this where there is no decking, there is no opportunity to incorporate an underlayment. With loss of the panels, rainwater was free to enter the building.

Figure 7. This residence had metal shingles that simulated the appearance of tile. The shingles typically blew off the battens, but some of the battens were also blown away.

- When clip or panel fasteners are loaded in withdrawal (tension), screws are recommended in lieu of nails.
- For roofs located within 3,000 feet of the ocean line, 300 series stainless steel clips and fasteners are recommended.
- For concealed clips over a solid substrate, it is recommended that chalk lines be specified so that the clips are correctly spaced.
- Hip, ridge, and rake flashings: Because exposed fasteners are more reliable than cleat attachment, it is recommended that hip, ridge, and rake flashings be attached with exposed fasteners. Two rows of fasteners are recommended on either side of the hip/ridge line. Close spacing of fasteners is recommended (e.g., spacing in the range of 3 to 6 inches on center, commensurate with the design wind loads), as shown in Figure 8 in order to avoid flashing blow-off as shown in Figure 9.

Figure 8. The ridge flashing on these corrugated metal panels had two rows of fasteners on each side of the ridge line.

Figure 9. The ridge flashing fasteners were placed too far apart. A significant amount of water leakage can occur when ridge flashings are blown away.

Figure B.2 34. Practices for designing and installing metal roof systems (4) (FEMA 2010)

APPENDIX C: SURVEY QUESTIONNAIRE

Roofing Adhesive Manufacturers

Product General Information

1 State the name of the organization.

2 How long have you been in business (Years)?

3 List your products by name. Please provide the weblink of the product data sheet if available online.

	Product Name	Product data sheet (Weblink)
1		
2		

4 Select the method of application.

	Product Name	Method of Application	Other (Describe)
1			
2			

5 Select the type of adhesive.

	Product Name	Type of Adhesive	Other (Describe)
1			
2			

Product Evaluation under Laboratory Conditions

6 Is the performance evaluated as a product?

	Product Name	Yes/No	Standards and Relevant Information
1			
2			

7 Is the performance evaluated as a product?

	Product Name	Yes/No	Type of Roof Assembly	Standards and Relevant Information
1				
2				

Quality Assurance (QA) Procedures

8 Does your product applied by a certified contractor? (Yes/No)

9 Select the QA procedures implemented for your products. (Select all that apply).

	Visual Inspection	Experimental Techniques	Product Manufacturer Representative Inspection	Other	None
Prior to Installation					
Immediately following Installation					
Periodic					
After an Event (e.g. Damaging wind)					

10 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Visual Inspection*** stated in ***Question 9***.
11 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Experimental Techniques*** stated in ***Question 9***.
12 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Product Manufacturer Representative Inspection*** stated in ***Question 9***.
13 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Other*** stated in ***Question 9***.
14 Do you see the need for performance evaluation of your product under field conditions? (Yes/No)
15 Do you value the access to field performance data of your product? (Yes/No)

Product Warranty

16 Do you provide warranty for your products? (Yes/No)
17 State the warranty period, terms, and conditions.

	Product Name	Period (in years)	Terms & Conditions
1			
2			

18 How do you validate the period and terms of warranty for an adhesive? (Select all that apply).

	Product Testing
	Other, please specify.

19 Provide details of the procedures and/or standards used to validate the warranty terms by ***product testing*** stated in ***Question 18***.
20 State the factors that disqualify your warranty terms.
21 State the amount of each product that you sell per year. (Best estimate).

	Product Name	Amount per year
1		
2		

22 How many warranty claims do you receive during a year (Approximately)?
23 State the nature of warranty claims.
24 State the potential reasons for such claims.

<u>**Roofing Product Manufacturers**</u>

Product General Information

1 State the name of your company.
2 How long have you been in business (Years)?
3 List your products by name. Please provide the weblink of the product data sheet if available online.

	Product Name	Product data sheet (Weblink)
1		
2		

4 Indicate the type of product that you manufacture. (Select all that apply).

	Coatings
	Membranes/Insulation/Roof Coverings/Deck/Other
	Roofing Systems

5 Indicate the type of product by selecting previously stated names form the following pull-down menus.

	Membrane	Insulation	Roof Covering	Deck	Coating	Roofing Systems	Other	Other (Describe)
1								
2								

Questions related to Membranes/Insulation/Roof Coverings/Deck/Other

6 Indicate the type of flat roof that the product is installed in. (Select all that apply).

	Product Name	Asphalt Built Up Roofs	Coal Tar Pitch Build Up Roofs	PVC Roofs	TPO Roofs	EPDM Roofs	Metal Roofs	SPF Roofs	Modified Bituminous Roofs	IRMA Roofs	Other	NA
1												
2												

7 Describe the Other stated in ***Question 6***.

8 Indicate the type of flat roof that the product is installed in. (Select all that apply).

	Product Name	Asphalt Shingle Roofs	Clay tiled Roofs	Concrete Tiled Roofs	Metal Roofs	Wooden Shingle Roofs	Slate Tiled Roofs	NA	Other
1									
2									

9 Describe the Other stated in ***Question 8.***

10 Indicate the method of attachment in the roofing system. (Select all that apply).

	Adhered
	Mechanically attached
	Ballast Held
	Hot applied with asphalt or tar
	Other, please specify

11 Select the product names that utilizes the given method of attachment.

Product name	Adhered	Mechanically attached	Adhered & Mechanically attached	Ballast Held	Hot applied with asphalt or tar	Other	Other (Describe)

12 State the adhesive name(s) used to adhere your products) in a roofing system and select its application methods and type.

Product name	Adhesive Name	Application Method	Describe	Type	Describe

13 Select the mechanical attachment method used for your product.

	Product Name	Attachment Method	Other (Type)
1			
2			

14 Indicate the seam attachment method. (Select all that apply).

	Product Name	Factory applied in-seem Sealant	Welded	Tape	Mechanical Seamer	Manual Application with glue or adhesives	Other	NA
1								
2								

15 Describe ***Other*** in ***Question 14***.

Questions related to Coatings

16 Indicate the type of flat roof that the product is installed in. (Select all that apply).

	Product Name	Asphalt Built Up Roofs	Coal Tar Pitch Build Up Roofs	PVC Roofs	TPO Roofs	EPDM Roofs	Metal Roofs	SPF Roofs	Modified Bituminous Roofs	IRMA Roofs	Other	NA
1												
2												

17 Describe the Other stated in ***Question 16***.

18 Indicate the method of application.

	Product Name	Application Method	Other (Describe)
1			
2			

19 Indicate the type of coating.

	Product Name	Type	Other (Describe)
1			
2			

Product General Information

20 Indicate the location of application in a roof. (Select all that apply)

	Product Name	Over the deck	Over a substrate	Over the insulation	Under the insulation	As the roof covering	Over existing roof	Flashings	Penetrations	Other
1										
2										

21 Describe the Other stated in ***Question 20***.

Product Evaluation under Laboratory Conditions

22 Is the performance evaluated as a product?

	Product Name	Yes/No	Standards and Relevant Information
1			
2			

23 Is the performance evaluated as a product?

	Product Name	Yes/No	Type of Roof Assembly (Flat/Steep Sloped)	Standards and Relevant Information
1				
2				

Quality Assurance (QA) Procedures

24 Does your product applied by a certified contractor? (Yes/No)

25 Select the QA procedures implemented for your products. (Select all that apply)

	Visual Inspection	Experimental Techniques	Product Manufacturer Representative Inspection	Other	None
Prior to Installation					
Immediately following Installation					

Periodic					
After an Event (e.g. Damaging wind)					

26 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Visual Inspection*** stated in ***Question 25***.
27 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Experimental Techniques*** stated in ***Question 25***.
28 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Product Manufacturer Representative Inspection*** stated in ***Question 25***.
29 State the standards, procedures, designation of the personal conducting QA work, and other relevant information related to ***Other*** stated in ***Question 25***.
30 Do you see the need for performance evaluation of your product under field conditions? (Yes/No)
31 Do you value the access to field performance data of your product? (Yes/No)

Product Warranty

32 Do you provide warranty for your products? (Yes/No)
33 Which type of warranty does your company provide?

	Product Warranty
	System Warranty

34 State the warranty period, terms, and conditions.

	Product Name	Type of Warranty (Product/System)	Period (in years)	Terms & Conditions
1				
2				

35 How do you validate the period and terms of warranty for an adhesive? (Select all that apply).

	Product Testing
	Other, please specify.

36 Provide details of the procedures and/or standards used to validate the warranty terms by ***product testing*** stated in ***Question 35***.
37 State the factors that disqualify your warranty terms.
38 State the amount of each product that you sell per year. (Best estimate).

	Product Name	Amount per year
1		
2		

39 How many warranty claims do you receive during a year (Approximately)?
40 State the nature of warranty claims.
41 State the potential reasons for such claims.

Roofing Contractors

General Information

1 State the name of your company.
2 How long have you been in business (Years)?
3 Are you a certified contractor? (Yes/No)
4 State the certifier agency/agencies. For example, NRCA.
5 Indicate the type of roof your organization is specialized in. (Select all that apply).

	Flat Roofs
	Steep Sloped Roofs

6 Indicate the category of flat roofs installed by your company. (Select all that apply).

	Asphalt Built Up Roofs
	Coal Tar Pitch Build Up Roofs
	PVC Roofs
	TPO Roofs
	EPDM Roofs
	Metal Roofs
	SPF Roofs
	Modified Bituminous Roofs
	IRMA Roofs
	Other, please specify

7 Indicate the category of steep sloped roofs installed by your company. (Select all that apply).

	Asphalt Shingle roofs
	Clay Tiled roofs
	Concrete Tiled Roofs
	Metal Roofs
	Wood Shingle Roofs
	Slate Tiled Roofs
	Other, please specify.

8 Indicate the nature of contracting jobs performed by your company. (Select all that apply).

	New Roof Construction
	Roof Restoration
	Roof Replacement
	Roof Repairs
	Roof Retrofitting
	Roof Recovering
	Preparation of Roof Repair Estimates
	Preventive Maintenance
	Warranty Renewal
	Roof Condition Assessment and Surveys
	Emergency/Disaster Responses
	Roof Maintenance Programs
	Roof Asset Management
	Roof Inspection
	Other, please specify.

9 Do you maintain a database as a part of the roof asset management? (Yes/No/NA)

10 Indicate how you select the individual components for a roofing system. (Select all that apply).

	Client Request
	Consultant Recommendation
	Previous Experience
	Project Budget
	Manufacturer Dictated
	Characteristics of the Facility (Nature of use, duration of use, severity of roof traffic etc.)
	Other, please specify

11 Indicate attributes of a roofing product that you consider, when selecting a product for a roofing job. (Select all that apply).

	Product & Installation Cost
	Life Cycle Cost
	Code Approvals
	Energy Efficiency
	Proven Field Performance
	Warranty Period and Terms
	Physical Properties
	Green Certification/LEED Certification
	Success Rating
	Other, please specify

12 Which of these codes do you consider in product approvals? (Select all that apply).

	UL
	FM
	Miami Dade County
	ICC
	Other, please specify

Roofing Inspection

13 What is the primary purpose(s) of roof inspection?

14 Do you have a standard checklist for roof inspection? (Yes/No)

15 Do you have separate checklists for flat roofs and steep sloped roofs? (Yes/No)

16 Do you have separate checklists for each type of roof? For example-shingled roofs, metal roofs, SPF roofs etc. (Yes/No)

17 If you do not have a standard checklist for roof inspection, briefly describe the implemented procedure.

18 Indicate the main areas of concentration when inspecting a roof. (Select all that apply).

	Roof Traffic
	Contaminants
	Drainage
	Wind Storm Damage
	Moisture Infiltration
	Membrane Seams
	Attachments and Fastenings

	Flashing Details
	Roofing Penetrations
	Rooftop Equipment
	Other, please specify

19 Indicate the method of roof inspection. (Select all that apply)

	Visual Inspection
	Additional Testing
	Other, please specify

20 Do you use special instruments to support ***visual inspection***? (Yes/No)
21 List the instruments used to support ***visual inspection.***
22 Indicate the type of additional testing techniques used for roof evaluation. (Select all that apply)

	Destructive Testing
	Non-Destructive Testing
	Other, please specify

23 Sate the details of the ***Destructive Testing.***
25 State the details of the ***Non-Destructive Testing.***
25 Are you a certified contractor for installing certain type of roofing products? (For example, membrane, insulation, vapor barriers etc.) (Yes/No)
26 State the names of these products that you are certified to install based on the product type.

Roof Board	Insulation	Membrane	Vapor Barriers	Coatings	Adhesives	Deck	Other	Category of Other

Quality Assurance (QA) Procedures

27 Select the QA procedures implemented for your installation. (Select all that apply).

	Visual Inspection	Experimental Techniques	Product Manufacturer Representative Inspection	Other	None
Prior to Installation					
Immediately following Installation					
Periodic					
After an Event (e.g. Damaging wind)					

28 State the standards, procedures, designation of the personal conducting QA work and, other relevant information related to ***Visual Inspection*** stated in ***Question 27***.

29 State the standards, procedures, designation of the personal conducting QA work and, other relevant information related to ***Experimental Techniques*** stated in ***Question 27.***

30 State the standards, procedures, designation of the personal conducting QA work and, other relevant information related to ***Product Manufacturer Representative Inspection*** stated in ***Question 27***.

31 State the standards, procedures, designation of the personal conducting QA work and, other relevant information related to ***Other*** stated in ***Question 27***.

Roofing Performance Issues

32 State the most common roofing performance issue(s) you encountered in field for steep sloped roofs and the recommendations to alleviate such issue(s).

	Performance Issue	Recommendation 1	Recommendation 2	Recommendation 3
1				
2				

33 State the most common roofing performance issue(s) you encountered in field for flat roofs and the recommendations to alleviate such issue(s).

	Performance Issue	Recommendation 1	Recommendation 2	Recommendation 3
1				
2				

Job Guarantee

34 Do you provide guarantee for your jobs? (Yes/No)

35 State the guarantee period, terms, and conditions.

Guarantee Period (s)	
Guarantee Terms and Conditions	

36 How do you validate the guarantee period and terms? (Select all that apply).

37 How many jobs do you sell per year? You can specify this as a number or/and as a square footage.

Number of jobs	Square footage

38 How many guarantee claims do you receive during a year (Approximately)?

39 State the nature of guarantee claims.

40 State the potential reasons for such claims.

<u>Roofing Consultants</u>

All the questions for roofing contractors except Questions 8, 26-31, 34-40 are directed to roofing consultants as well. The following are the questions specific to the consultants.

1 Indicate the nature of consulting jobs performed by your company. (Select all that apply).

	Design Of Roofing Systems
	Architectural Roof Plan Reviews
	Roof Asset Management

	Roof Inspection
	Emergency/Disaster Responses
	Forensic Studies
	Maintenance Programs
	Structural Reviews
	Other, please specify.

APPENDIX D: PRODUCT SPECIFICATION STANDARDS

Table D.1.ASTM Standards on Roofing Product Specifications

Specification Standard		Description
		Adhesives
ASTM D312	Standard Specification for Asphalt Used in Roofing	This specification covers four types of asphalt intended for use in built-up roof construction, construction of some modified bitumen systems, construction of bituminous vapor retarder systems, and for adhering insulation boards used in various types of roof systems. The specification is intended for general classification purposes only, and does not imply restrictions on the slope at which an asphalt must be used.
ASTM D450	Standard Specification for Coal-Tar Pitch Used in Roofing, Dampproofing, and Waterproofing	This specification covers two types of coal-tar pitch suitable for use in the construction of built-up roofing, dampproofing, and membrane waterproofing systems.
ASTM D2939	Standard Test Methods for Emulsified Bitumen Used as Protective Coatings	These test methods cover procedures for sampling and testing emulsified bitumens used in relatively thick films as protective coatings for metals, built-up roofs, and bituminous pavements. The test methods for Sampling, Uniformity, Resistance to Freezing, Weight per Gallon, Residue by Evaporation, Volatiles, Ash Content, Water Content, Flash Point, Drying Time, Resistance to Heat, Resistance to Water, Flexibility, tests used primarily for coatings used over metals and built-up roofs and tests used primarily for coatings used over bituminous pavements.
ASTM D3747	Standard Specification for Emulsified Asphalt Adhesive for Adhering Roof Insulation	This specification covers emulsified asphalt adhesive for use in adhering preformed roof insulation to steel roof decks with inclines up to 33 %. When applied as a continuous film over an acceptable deck surface, the emulsion functions as both an adhesive and a vapor retarder.
ASTM D6753	Standard Specification for Coal Tar Adhesive	This specification covers coal tar adhesive with or without polymer modification suitable for brush, spray, squeegee and trowel application to coal tar built up and coal tar modified bitumen membrane roofings and flashings.
		Coatings
ASTM D449	Standard Specification for Asphalt Used in Dampproofing and Waterproofing	This specification covers three types of asphalt suitable for use as a mopping coat in dampproofing; or as a plying or mopping cement in the construction of membrane waterproofing systems with felts, fabrics, asphalt-impregnated glass mat and with primer.
ASTM D1187	Standard Specification for Asphalt-Base Emulsions for Use as Protective Coatings for Metal	This specification covers emulsified asphalt suitable for application in a relatively thick film as a protective coating for metal surfaces. Performance requirements for two types of emulsified asphalts; Type 1 and Type II, are given.
ASTM D1227	Standard Specification for Emulsified Asphalt Used as a Protective Coating for Roofing	This specification covers emulsified asphalt suitable for use as a protective coating for built-up roofs and other exposed surfaces with inclines of not less than 4 % or 42 mm/m ($^{1}/_{2}$ in./ft). Performance requirements for four types of emulsified asphalts; Type II-Class 1,

		Type II-Class 2, Type III-Class 1 and Type III-Class 2, are given.
ASTM D2823	Standard Specification for Asphalt Roof Coatings, Asbestos Containing	This specification covered asbestos-containing asphalt roof coatings of brushing or spraying consistency.
ASTM D2824	Standard Specification for Aluminum-Pigmented Asphalt Roof Coatings, Nonfibered, and Fibered without Asbestos	This specification covers asphalt-based, aluminum-pigmented roof coatings suitable for application to roofing or masonry surfaces by brush or spray. Test methods to determine the composition and physical requirements of two types of aluminium m pigmented coatings; Type I and Type III, are given.
ASTM D4479	Standard Specification for Asphalt Roof Coatings—Asbestos-Free	This specification covers asbestos-free asphalt roof coatings of brushing or spraying consistency. Test methods to determine the composition and physical requirements of two types of asphalt coatings; Type I and Type II, are given.
ASTM D4586	Standard Specification for Asphalt Roof Cement, Asbestos-Free	This specification covers asbestos-free asphalt roof cement suitable for trowel application to roofings and flashings. Test methods to determine the composition and physical requirements of four types of asphalt coatings; Type I (Class 1 and Class 2) and Type II (Class 1 and Class 2), are given.
ASTM D5643	Standard Specification for Coal Tar Roof Cement, Asbestos Free	This specification covers coal tar roof cement suitable for trowel application in coal tar roofing and flashing systems. Test methods to determine the composition and physical requirements are given.
ASTM D6083	Standard Specification for Liquid Applied Acrylic Coating Used in Roofing	This specification covers liquid-applied water-dispersed acrylic latex elastomeric protective roof coatings. This specification does not provide guidance for application.
ASTM D6694	Standard Specification for Liquid-Applied Silicone Coating Used in Spray Polyurethane Foam Roofing Systems	This specification covers a liquid-applied solvent dispersed elastomeric coating used as a roofing membrane for spray polyurethane foam (SPF) insulation whose principal polymer in the dispersion contains more than 95 % silicone. This specification does not provide guidance for application.
ASTM D6848	Standard Specification for Aluminum Pigmented Emulsified Asphalt Used as a Protective Coating for Roofing	This specification covers aluminum pigmented emulsified asphalt suitable for application as a protective coating for built-up roofs and other exposed surfaces by brush, roller, or spray application. The surfaces to which this product is applied are expected to have positive drainage, as the coating is not anticipated for use where ponding conditions exist. The product is suitable for use on sheet metal and smooth or granule surfaced emulsion, conventional BUR, and modified bitumen systems.
ASTM D6878	Standard Specification for Thermoplastic Polyolefin Based Sheet Roofing	This specification covers flexible sheet made from thermoplastic polyolefin (TPO) as the principal polymer, intended for use in single-ply roofing membranes exposed to the weather. The sheet shall contain reinforcing fabrics or scrims. The tests and property limits used to characterize the sheet are values intended to ensure minimum quality for the intended purpose. In-place roof system design criteria, such as fire resistance, field seaming strength, material compatibility, and uplift resistance, among others, are factors, which

		should be considered but are beyond the scope of this specification.
ASTM D6947	Standard Specification for Liquid Applied Moisture Cured Polyurethane Coating Used in Spray Polyurethane Foam Roofing System	This specification covers a single component, moisture cured, elastomeric urethane polymer coating used as a protective coating for spray polyurethane foam roofing systems. This specification does not provide guidance for application. Test methods for viscosity, elongation and Tensile Strength , Accelerated Weathering, Permeance, Water Absorption, Adhesion to Specified Substrate, Tear Resistance and Low Temperature Flexibility are discussed.
Sealants		
ASTM D3019	Standard Specification for Lap Cement Used with Asphalt Roll Roofing, Non-Fibered, and Fibered	This specification covers lap cement consisting of asphalt dissolved in a volatile petroleum solvent with or without mineral or other stabilizers, or both, for use with roll roofing. The fibered version of these cements excludes the use of asbestos fibers. The test methods to determine composition and the physical requirements of three types of lap cement; Type 1-Grade 1, Type 1-Grade 2 and Type III, are given.
SPF roofs		
ASTM D7425	Standard Specification for Spray Polyurethane Foam Used for Roofing Applications	This specification covers the types and physical property requirements of spray polyurethane foam (SPF) for use in SPF roofing applications.
Roof membranes		
ASTM C836	Standard Specification for High Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane for Use with Separate Wearing Course	This specification describes the required properties and test methods for a cold liquid-applied elastomeric-type membrane, one- or two-component, for waterproofing building decks and walls subject to hydrostatic pressure in building areas to be occupied by personnel, vehicles, or equipment.
ASTM C957	Standard Specification for High-Solids Content, Cold Liquid-Applied Elastomeric Waterproofing Membrane With Integral Wearing Surface	This specification describes the required properties and test methods for a cold liquid-applied elastomeric membrane for waterproofing building decks not subject to hydrostatic pressure. The specification applies only to a membrane system that has an integral wearing surface. This specification does not include specific requirements for skid resistance or fire retardance, although both may be important in specific uses.
ASTM D146	Standard Test Methods for Sampling and Testing Bitumen-Saturated Felts and Woven Fabrics for Roofing and Waterproofing	These test methods cover the sampling and examination of felts or woven fabrics, saturated or impregnated but not coated with asphaltic or coal-tar materials, for use in waterproofing or for the construction of built-up roof coverings.
ASTM D226	Standard Specification for Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing	This specification covers asphalt-saturated organic felts, with or without perforations, intended to be used with asphalts in the construction of built-up roofs, and water proofing systems. The physical property requirements of two types of asphalt-saturated felts; Type 1 and Type II and the test procedures to determine them are given.

ASTM D227	Standard Specification for Coal-Tar-Saturated Organic Felt Used in Roofing and Waterproofing	This specification covers coal-tar-saturated organic felt intended to be used with coal-tar pitches in the construction of built-up roofs and in the construction of waterproofing systems. The physical property requirements of Coal-Tar-Saturated Organic Felt and the test procedures to determine them are given.
ASTM D1327	Standard Specification for Bitumen-Saturated Woven Burlap Fabrics Used in Roofing and Waterproofing	This specification covers woven burlap fabrics, saturated with either asphalt or refined coal-tar, as specified by the purchaser, for use in the membrane system of roofing or waterproofing or as specified by the manufacturer.
ASTM D1668	Standard Specification for Glass Fabrics (Woven and Treated) for Roofing and Waterproofing	This specification covers finished treated (coated) woven-glass fabrics coated with either asphalt, coal-tar pitch or an organic resin compatible with the roofing, waterproofing, or other usage as specified by the purchaser.
ASTM D2178	Standard Specification for Asphalt Glass Felt Used in Roofing and Waterproofing	This specification covers glass felts impregnated to varying degrees with asphalt; Types IV and VI, intended to be used in the construction of built-up roofs, and in the construction of waterproofing systems.
ASTM D2626	Standard Specification for Asphalt-Saturated and Coated Organic Felt Base Sheet Used in Roofing	This specification covers the required physical properties of asphalt-saturated and coated organic felt base sheet with mineral surfacing on the top side, with or without perforations, for use as the first ply of a built-up roof. When not perforated, this sheet is suitable for use as a vapor retarder, with a solid mopping of asphaltic material, under roof insulation or between multiple layers of roof insulation.
ASTM D3468	Standard Specification for Liquid-Applied Neoprene and Chlorosulfonated Polyethylene Used in Roofing and Waterproofing	This specification covers required physical properties of two types neoprene and chlorosulfonated polyethylene synthetic rubber; Type 1-Grade 1, Type II-Grade 2 and Type II, suitable for use in roofing and waterproofing.
ASTM D3909	Standard Specification for Asphalt Roll Roofing (Glass Felt) Surfaced With Mineral Granules	This specification covers asphalt-impregnated and coated glass felt roll roofing surfaced on the weather side with mineral granules, for use as a cap sheet in the construction of built-up roofs.
ASTM D4434	Standard Specification for Poly(Vinyl Chloride) Sheet Roofing	This specification covers flexible sheet made from poly(vinyl chloride) resin as the primary polymer intended for use in single-ply roofing membranes exposed to the weather. The sheet shall contain reinforcing fibers or reinforcing fabrics. The tests and property limits used to characterize the sheet are intended to ensure minimum quality for the intended purpose.
ASTM D4601	Standard Specification for Asphalt-Coated Glass Fiber Base Sheet Used in Roofing	This specification covers asphalt impregnated and coated glass fiber base sheet, with or without perforations, for use as the first ply of the built-up roofing. When not perforated, this sheet is suitable for use as a vapor retarder, with a solid mopping of asphaltic material, under roof insulation or between multiple layers of roof insulation.

ASTM D4637	Standard Specification for EPDM Sheet Used In Single-Ply Roof Membrane	This specification covers flexible sheet made from ethylene-propylene-diene terpolymer (EPDM) intended for use in single-ply roofing membranes exposed to the weather. The tests and property limits are defined to ensure minimum quality for the intended use. The sheet may be non-reinforced, fabric- or scrim-reinforced, or fabric-backed vulcanized rubber sheet.
ASTM D4897	Standard Specification for Asphalt-Coated Glass-Fiber Venting Base Sheet Used in Roofing	This specification covers asphalt-impregnated and coated glass-fiber base sheet with mineral surfacing on the top side and coarse mineral granules on the bottom side for use as the first ply of a roofing membrane. These base sheets provide for the lateral release of pressure in roofing systems because they are not solidly attached and the coarse granular surface provides an open, porous channel in the horizontal plane beneath the membrane. The base sheets shall be permitted to be with or without perforations or embossings.
ASTM D4811	Standard Specification for Nonvulcanized (Uncured) Rubber Sheet Used as Roof Flashing	This specification covers nonvulcanized (uncured) rubber sheet made of EPDM (ethylene-propylene-diene terpolymer) or CR (polychloroprene) intended for use as watertight roof flashing exposed to the weather. The tests and property limits used to characterize these flashing materials are minimum values to make the product fit for its intended purpose.
ASTM D4990	Standard Specification for Coal Tar Glass Felt Used in Roofing and Waterproofing	This specification covers glass felt impregnated with coal tar intended to be used with coal tar pitch in construction of built-up roofs and in the construction waterproofing systems.
ASTM D5019	Standard Specification for Reinforced CSM (Chlorosulfonated Polyethylene) Sheet Used in Single-Ply Roof Membrane	This specification covers reinforced non-vulcanized polymeric sheet made from chlorosulfonated polyethylene (CSM) intended for use as a single-ply roof membrane exposed to the weather. The sheet shall be reinforced with fiber or fabric.
ASTM D5665	Standard Specification for Thermoplastic Fabrics Used in Cold-Applied Roofing and Waterproofing	This specification covers thermoplastic fabrics such as polyester, polyester/polyamide bicomponent, or composites with fiberglass or polyester scrims that can be used during the construction of cold-applied roofing and waterproofing. This specification is intended as a material specification. The specified tests and property values used to characterize the respective fabrics are intended to establish minimum properties.
ASTM D5726	Standard Specification for Thermoplastic Fabrics Used in Hot-Applied Roofing and Waterproofing	This specification covers thermoplastic fabrics such as polyester, polyester/polyamide bicomponent, or composites with fiber glass or polyester scrims that can be used during the construction of hot-applied roofing and waterproofing. This specification is intended as a material specification. The specified tests and property values used to characterize the respective fabrics are intended to establish minimum properties.
ASTM D6134	Standard Specification for Vulcanized Rubber Sheets Used in Waterproofing Systems	This specification covers unreinforced vulcanized rubber sheets made from ethylene propylene diene terpolymer (EPDM) or butyl (IIR), intended for use in preventing water under hydrostatic pressure from entering a structure.
ASTM	Standard Specification for Styrene	This specification covers prefabricated modified bituminous sheet materials reinforced with

D6162	Butadiene Styrene (SBS) Modified Bituminous Sheet Materials Using a Combination of Polyester and Glass Fiber Reinforcements	a combination of polyester fabric and glass fiber, with or without granules, which use styrene butadiene styrene (SBS) thermoplastic elastomer as the primary modifier and are intended for use in the fabrication of multiple ply roofing and waterproofing membranes. This specification is intended as a material specification only. The specified tests and property limits used to characterize the sheet materials are intended to establish minimum properties.
ASTM D6163	Standard Specification for Styrene Butadiene Styrene (SBS) Modified Bituminous Sheet Materials Using Glass Fiber Reinforcements	This specification covers prefabricated modified bituminous sheet materials with glass fiber reinforcement, with or without granules, that use styrene butadiene styrene (SBS) thermoplastic elastomer as the primary modifier and are intended for use in the fabrication of multiple ply roofing and waterproofing membranes. This specification is intended as a material specification only. The specified tests and property limits used to characterize the sheet materials are intended to establish minimum properties.
ASTM D6164	Standard Specification for Styrene Butadiene Styrene (SBS) Modified Bituminous Sheet Materials Using Polyester Reinforcements	This specification covers prefabricated modified bituminous sheet materials reinforced with polyester fabric as the primary reinforcement, with or without granules, which use styrene butadiene styrene (SBS) thermoplastic elastomer as the primary modifier and are intended for use in the fabrication of multiple ply roofing and waterproofing membranes. This specification is intended as a material specification only. The specified tests and property limits used to characterize the sheet materials are intended to establish minimum properties.
ASTM D6221	Standard Specification for Reinforced Bituminous Flashing Sheets for Roofing and Waterproofing	This specification covers factory prepared reinforced bituminous sheet used in flashing. The bitumen used may be asphalt, coal-tar pitch, or polymer modified bitumen. The reinforcement may include any one or a combination of organic (wood fiber), polyester, or glass fiber felts, woven fabrics, or thermoplastic films. Fine mineral powders, granules, or metal foils may be used as surfacing. The criteria listed in this specification are based on round robin testing of materials that, if correctly installed, can be used as the primary material for flashing membranes.
ASTM D6222	Standard Specification for Atactic Polypropylene (APP) Modified Bituminous Sheet Materials Using Polyester Reinforcements	This specification covers prefabricated modified bituminous sheet materials reinforced with polyester fabric, with or without granules that use atactic polypropylene (APP) as the primary modifier and are intended for use in the fabrication of multiple ply roofing and waterproofing membranes. This specification is intended as a material specification only. The specified tests and property limits used to characterize the sheet materials are intended to establish minimum properties.
ASTM D6223	Standard Specification for Atactic Polypropylene (APP) Modified Bituminous Sheet Materials Using a Combination of Polyester and Glass Fiber Reinforcements	This specification covers prefabricated modified bituminous sheet materials reinforced with a combination of polyester fabric and glass fiber, with or without granules, that use atactic polypropylene (APP) as the primary modifier and are intended for use in the fabrication of multiple ply roofing and waterproofing membranes.

ASTM D6298	Standard Specification for Fiberglass Reinforced Styrene-Butadiene-Styrene (SBS) Modified Bituminous Sheets with a Factory Applied Metal Surface	This specification covers fiberglass reinforced modified bituminous sheet materials that use styrene-butadiene-styrene (SBS) thermoplastic elastomer as the primary modifier and are surfaced with a factory applied continuous metal foil. These materials are intended for use in the fabrication of multiple ply roofing and waterproofing membranes and flashings.
ASTM D6509	Standard Specification for Atactic Polypropylene (APP) Modified Bituminous Base Sheet Materials Using Glass Fiber Reinforcements	This specification covers prefabricated modified bituminous sheet materials with glass fiber reinforcement, which use atactic polypropylene (APP) as the primary modifier and which are intended for use as a base sheet in the fabrication of multiple ply roofing and waterproofing membranes.
ASTM D6754	Standard Specification for Ketone Ethylene Ester Based Sheet Roofing	This specification covers flexible sheet made from ketone ethylene ester (KEE) as the primary polymer intended for use in single ply roofing membrane exposed to the weather. The sheet shall be reinforced with fabric.
ASTM D6878	Standard Specification for Thermoplastic Polyolefin Based Sheet Roofing	This specification covers flexible sheet made from thermoplastic polyolefin (TPO) as the principal polymer, intended for use in single-ply roofing membranes exposed to the weather. The sheet shall contain reinforcing fabrics or scrims.
ASTM D7067	Standard Specification for Reinforced White PIB Sheet Used in Roofing Membrane	This specification covers white reinforced non-vulcanized polymeric sheet made from polyisobutylene (PIB) intended for use as a single-ply roof membrane exposed to the weather. The sheet shall be reinforced with fiber or fabric. The polymers used in these sheets have thermoplastic characteristics at time of installation. The tests and property limits used to characterize these sheets are minimum values.
ASTM D7311	Standard Specification for Liquid-Applied, Single-Pack, Moisture-Triggered, Aliphatic Polyurethane Roofing Membrane	This specification covers in-situ applied, single-pack, moisture-triggered, aliphatic polyurethanes intended to form an elastomeric single-ply membrane, once cured. The cured membrane may or may not contain a reinforcing material. Single-pack, moisture-triggered, aliphatic polyurethanes are characterized by their ability to use moisture to trigger the curing process only.
		Insulation and Cover boards
ASTM C208	Standard Specification for Cellulosic Fiber Insulation Board	This specification covers the principal cellulosic fiber insulating board types, grades, and sizes. Requirements are specified for composition, construction, physical properties, tolerances, sampling procedures, and test methods.
ASTM C552	Standard Specification for Cellular Glass Thermal Insulation	This specification covers the composition, sizes, dimensions, and physical properties of cellular glass thermal insulation intended for use on surfaces operating at temperatures between −450 and 800°F (−268 and 427°C).
ASTM C578	Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation	This specification covers the types, physical properties, and dimensions of cellular polystyrene boards with or without facings or coatings made by molding (EPS) or extrusion (XPS) of expandable polystyrene. Products manufactured to this specification are intended for use as thermal insulation for temperatures from —65 to +165°F (—53.9 to +73.9°C).

		This specification does not apply to laminated products manufactured with any type of rigid board facer including fiberboard, perlite board, gypsum board, or oriented strand board.
ASTM C726	Standard Specification for Mineral Fiber Roof Insulation Board	This specification covers the composition and physical properties of mineral wool insulation board used above structural roof decks in building construction. The mineral wool roof insulation acts as a base for systems such as single-ply, polymer-modified bitumen and built-up roof. This specification also covers mineral wool insulation boards that incorporate a fibrous high density upper layer on the top surface.
ASTM C728	Standard Specification for Perlite Thermal Insulation Board	This specification covers the composition and physical properties for perlite thermal insulation board used principally above structural roof decks and as a base for built-up, modified, and elastomeric membrane roofing in building construction.
ASTM C1177	Standard Specification for Glass Mat Gypsum Substrate for Use as Sheathing	This specification covers glass mat gypsum substrate, which is designed to be used as an exterior substrate for a weather barrier.
ASTM C1278	Standard Specification for Fiber-Reinforced Gypsum Panel	This specification covers fiber-reinforced gypsum panels. Exterior Fiber-Reinforced Gypsum Soffit Panels are designed for use on exterior soffits and carport ceilings that are completely protected from contact with liquid water.
ASTM C1289	Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board	This specification covers the general requirements for faced thermal insulation boards composed of rigid cellular polyisocyanurate surfaced with other materials. The insulation boards are intended for use at temperatures between −40 and 200°F (−40 and 93°C). This standard is intended to apply to rigid cellular polyurethane-modified polyisocyanurate thermal insulation board products that are commercially acceptable as non-structural panels useful in building construction. The term polyisocyanurate encompasses the term polyurethane.
ASTM C1484	Standard Specification for Vacuum Insulation Panels	This specification covers the general requirements for Vacuum Insulation Panels (VIP). These panels have been used wherever high thermal resistance is desired in confined space applications. This specification applies to composite panels whose center-of-panel apparent thermal resistivity typically range from 87 to 870 m·K/W at 24°C mean, and whose intended service temperature boundaries range from —70 to 480°C.
ASTM D6506	Standard Specification for Asphalt Based Protection Board for Below-Grade Waterproofing	This specification covers an asphalt based protection board used for protecting the integrity of below grade or below wearing surface waterproofing. The protection board protects the waterproofing system from backfill, surfacing, construction activities, and weathering conditions prior to backfilling or applying surfacing.

APPENDIX E: PRODUCT PERFORMANCE EVALUATION STANDARDS

Table E.1.Roofing Product Performance Evaluation Standards

Standard	Test method	Description
ASTM C1250	Standard Test Method for Nonvolatile Content of Cold Liquid-Applied Elastomeric Waterproofing Membranes	Provides a laboratory procedure for determining the average nonvolatile content for one- and two-component cold liquid-applied elastomeric waterproofing membranes. This method can be useful for determining application coverage rates.
ASTM C1305	Standard Test Method for Crack Bridging Ability of Liquid-Applied Waterproofing Membrane	This test method is used to indicate a waterproofing membrane's ability to maintain its integrity while bridging a preexisting crack in the substrate at low ambient temperatures, when the membrane is least likely to be flexible.
ASTM C1306	Standard Test Method for Hydrostatic Pressure Resistance of a Liquid-Applied Waterproofing Membrane	This test method is used as a screening tool to determine the hydrostatic pressure to which a liquid-applied waterproofing membrane may be subjected without failing when stretched over a crack in the substrate. This test method discriminates between a membrane that is very resistant to hydrostatic pressure and one that is not. No prediction of durability at lower hydrostatic pressures can be made when using the results of this test method.
ASTM C1522	Standard Test Method for Extensibility After Heat Aging of Cold Liquid-Applied Elastomeric Waterproofing Membranes	This test method describes a laboratory procedure for determining extensibility for one- or two-component cold liquid-applied elastomeric waterproofing membranes. This test method is used to determine a membrane's ability to bridge a crack that forms after the membrane has been applied and allowed to cure.
ASTM C1549	Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer	Provides a procedure for use with a portable measuring device with an integral light source suitable for laboratory and field readings from small-area samples. This procedure is suitable for use with flat opaque materials.
ASTM D4	Standard Test Method for Bitumen Content	This test method covers the determination of bitumen content in materials containing at least 25 % bitumen.
ASTM D6	Standard Test Method for Loss on Heating of Oil and Asphaltic Compounds	This test method is useful in characterizing certain petroleum products by the determination of their loss of mass upon heating under standardized conditions.
ASTM D36	Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus	This test method covers the determination of the softening point of bitumen in the range from 30 to 157°C [86 to 315°F] using the ring-and-ball apparatus immersed in distilled water [30 to 80°C] or USP glycerin (above 80 to 157°C). The softening point is useful in the classification of bitumen and is indicative of the tendency of the material to flow at elevated temperatures encountered in service.
ASTM D146	Standard Test Methods for Sampling and Testing Bitumen-Saturated Felts and Woven Fabrics for Roofing and Waterproofing	These test methods cover the sampling and examination of felts or woven fabrics, saturated or impregnated but not coated with asphaltic or coal-tar materials, for use in waterproofing or for the construction of built-up roof coverings.
ASTM	Standard Test Methods for Sampling, Testing,	These test methods include procedures for sampling, examination, physical

D228	and Analysis of Asphalt Roll Roofing, Cap Sheets, and Shingles Used in Roofing and Waterproofing	testing, and analyses of asphalt roll roofing, cap sheets, and shingles used in roofing and waterproofing. Other components of these materials are allowed to include, but are not limited to, felts, mats, films, foils, mineral stabilizers, papers, and mineral surfacing.
ASTM D1864	Standard Test Method for Moisture in Mineral Aggregate Used on Built-Up Roofs	This test method covers the determination of moisture in mineral aggregate for use on built-up roofs.
ASTM D1865	Standard Test Method for Hardness of Mineral Aggregate Used on Built-Up Roofs	This test method measures the resistance to physical breakdown in handling of built-up roofing aggregates.
ASTM D3105	Standard Index of Methods for Testing Elastomeric and Plastomeric Roofing and Waterproofing Materials	This index is provided for reference to aid in the selection of procedures and test methods used in the evaluation of sheet and liquid roofing materials, as appropriate.
ASTM D3409	Standard Test Method for Adhesion of Asphalt-Roof Cement to Damp, Wet, or Underwater Surfaces	This test method offers a means of evaluating the adhesive properties of asphalt roofing cements used to repair roofs under adverse conditions.
ASTM D3746	Standard Test Method for Impact Resistance of Bituminous Roofing Systems	This test method provides a means of evaluating roofing systems for resistance of bituminous roofing systems to impact loads of many kinds.
ASTM D4073	Standard Test Method for Tensile-Tear Strength of Bituminous Roofing Membranes	This test method covers the determination of the tensile-tear strength of bituminous roofing membranes. Determining the tensile-tear strength of laboratory and field samples of roofing membranes should be useful in developing performance criteria, and as one basis for comparison of different materials and systems.
ASTM D4074	Standard Test Method for Bitumen and Aggregate Content of Bitumen-Aggregate Mixtures From Roofing Samples	This test method covers the determination of the bitumen content of adhered aggregate surfacing on a roof, and the approximate mass per unit area of the flood coat and adhered aggregate.
ASTM D4402	Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer	This test method is used to measure the apparent viscosity of asphalts at handling, mixing, or application temperatures.
ASTM D4830	Standard Test Methods for Characterizing Thermoplastic Fabrics Used in Roofing and Waterproofing	These test methods cover the procedures for characterizing thermoplastic fabrics (for example polyester, polyamide, polypropylene, and so forth) used in prefabricated roofing and waterproofing membranes. The test procedures to determine unit mass, thickness, breaking load, elongation, work to break, trapezoidal tearing strength, puncture strength, static heat stability and dynamic heat stability are described.
ASTM D4932	Standard Test Method for Fastener Rupture and Tear Resistance of Roofing and Waterproofing Sheets, Roll Roofing, and	This test method covers the determination of the force needed to pull a fastener through any type of roofing or waterproofing ply sheet, roll roofing, or shingle, or to cause fastener failure under specified laboratory conditions. Test values for the

	Shingles	resistance of specific ply sheets, roll roofing, or shingles to selected fastener pull-through may assist in the determination of appropriate fastener spacing. The relative behavior of different fasteners and fasteners with and without caps may be evaluated.
ASTM D4977	Standard Test Method for Granule Adhesion to Mineral Surfaced Roofing by Abrasion	The test provides a quantitative measure of the quality of mineral granule surfacing retention of mineral granule-surfaced roofing materials such as asphalt shingles, asphalt roll roofing and polymer-modified bitumen cap sheets.
ASTM D4989	Standard Test Method for Apparent Viscosity (Flow) of Roofing Bitumens Using the Parallel Plate Plastometer	This test method covers the measurement of apparent viscosity of roofing bitumen by means of a parallel plate plastometer.
ASTM D5076	Standard Test Method for Measuring Voids in Roofing and Waterproofing Membranes	This laboratory test method can be used on multi-ply roofing and waterproofing systems to measure, classify, and count the voids between felt plies, between insulation layers, and between the membrane and insulation layers. Voids between the felt plies or between the membrane and insulation layer in multi-ply systems can be the seeds for future blisters. In one-ply systems, this test method can be used to count and measure the voids in the adhesive in laps and, in adhered systems, in the adhesive between the membrane and the insulation.
ASTM D5081	Standard Test Method for Aggregate Layer Hiding Power	One of the functions of a roofing aggregate is to shield the roofing membrane from sunlight that may be destructive to the roofing membrane. This test method measures the quantity of gravel needed to exclude light under arbitrary laboratory conditions.
ASTM D5100	Standard Test Method for Adhesion of Mineral Aggregate to Hot Bitumen	Mineral aggregate shields bituminous membranes from solar radiation. Unadhered mineral aggregate can be displaced by wind, water, and traffic, exposing the bitumen. This test method provides a laboratory means of determining and recording the mass of aggregate that adheres to a bituminous pour coat of hot bitumen on a roof membrane.
ASTM D5147	Standard Test Methods for Sampling and Testing Modified Bituminous Sheet Material	These test methods cover procedures for sampling and testing prefabricated, reinforced, polymer-modified bituminous sheet materials designed for single- or multiple-ply application in roofing and waterproofing membranes.
ASTM D5385	Standard Test Method for Hydrostatic Pressure Resistance of Waterproofing Membranes	This test method tests the hydrostatic resistance of a waterproofing membrane and can be used to compare the hydrostatic resistance of waterproofing membranes.
ASTM D5405	Standard Test Method for Conducting Time-to-Failure (Creep-Rupture) Tests of Joints Fabricated from Nonbituminous Organic Roof Membrane Material	An important factor affecting the performance of joints of nonbituminous membranes is their ability to remain bonded over the membrane's expected service life. Time-to-failure tests provide a means of characterizing the behavior of joints under constant load over time. This test method covers laboratory

		determination of the time-to-failure (creep-rupture) of joints fabricated from nonbituminous organic roof membrane material.
ASTM D5602	Standard Test Method for Static Puncture Resistance of Roofing Membrane Specimens	This test method covers evaluation of the maximum static puncture load that roofing membrane specimens can withstand without allowing the passage of water. Roof membrane specimens to which the test method is applicable include bituminous built up, polymer-modified bitumens, vulcanized rubbers, non-vulcanized polymeric, and thermoplastic materials. This test method is not applicable to aggregate-surfaced membrane specimens, but it is applicable to specimens having factory-applied granules.
ASTM D5635	Standard Test Method for Dynamic Puncture Resistance of Roofing Membrane Specimens	This test method covers the evaluation of the dynamic puncture energy that roofing membrane specimens can withstand, without allowing the passage of water, when subjected to impact from a rigid object having a sharp edge. Roof membrane specimens to which the test method is applicable include bituminous built-up, polymer-modified bitumens, vulcanized rubbers, non-vulcanized polymeric, and thermoplastic materials. This test method is not applicable to aggregate-surfaced membrane specimens; however, it is applicable to specimens having factory-applied granules.
ASTM D5636	Standard Test Method for Low Temperature Unrolling of Felt or Sheet Roofing and Waterproofing Materials	Unrolling capabilities are important during application, and the temperature at the time of unrolling is believed to affect the performance of roofing and waterproofing membranes. This test method enables a researcher to measure the relative behavior of low temperature unrolling of roofing and waterproofing felt or sheet materials under laboratory conditions.
ASTM D5683	Standard Test Method for Flexibility of Roofing and Waterproofing Materials and Membranes	Membrane flexibility is important during application, and changes in flexibility are believed to be linked to the performance of roofing and waterproofing membranes, but the actual link between test data and performance is unknown and is dependent on the materials and exposure. This test method measures the flexibility of roofing or waterproofing sheet materials or membranes by bending the test material over a block containing arcs of specific radii at a standard temperature.
ASTM D5849	Standard Test Method for Evaluating Resistance of Modified Bituminous Roofing Membrane to Cyclic Fatigue (Joint Displacement)	In this test method, a relatively low travel rate of cycling is used and the material is tested for a specified number of cycles under conditions of increased amplitude or lower temperature. This test method is applicable to testing specimens consisting of a single ply of the polymer-modified bitumen material or a multiple-ply composite that includes the polymer-modified bitumen material.
ASTM D6136	Standard Test Method for Kerosene Number of Unsaturated (Dry) Felt by Vacuum Method	The kerosene number is used in calculating saturation efficiency. The ability to absorb kerosene is an indication of the ability to absorb hot asphalt. This test

		method covers the determination of the relative saturating capacity of unsaturated (dry) felt papers used in roofing.
ASTM D6225	Standard Test Method for Granule Cover of Mineral Surfaced Roofing	The test is used primarily after an abrasion test has been conducted, to determine the portion of asphaltic compound that has been exposed as a result of the abrasion test. This test method is used to determine the extent of coverage of the granular surfacing over the asphaltic coating in a sample of mineral surfaced roofing. This test method applies to both "as manufactured" material and material that has weathered or undergone other types of exposure.
ASTM D6294	Standard Test Method for Corrosion Resistance of Ferrous Metal Fastener Assemblies Used in Roofing and Waterproofing	This test method evaluates relative corrosion resistance of the components by determination of percentage of rust or white rust. It is important to evaluate the corrosion resistance of ferrous metal components used in low-slope roofing and waterproofing because they provide integrity and securement of other system components, such as insulation and membranes. This test method applies primarily to evaluating the effectiveness of barrier coatings to provide general corrosion protection under test conditions.
ASTM D6356	Standard Test Method for Hydrogen Gas Generation of Aluminum Emulsified Asphalt Used as a Protective Coating for Roofing	There is the possibility of water reacting with aluminum pigment to generate hydrogen gas, which should be avoided. This procedure measures the amount of hydrogen gas generation potential of aluminized emulsion roof coating.
ASTM D6511	Standard Test Methods for Solvent Bearing Bituminous Compounds	Provides procedures for sampling and testing of physical and performance properties of solvent-bearing bituminous materials used in roofing and waterproofing. The properties determined are uniformity, weight per gallon, nonvolatile content, solubility, ash content, water content, consistency, behavior at 60°C, Pliability at —0°C, alluminium content, reflectance of alluminium roof coatings, strength of laps of rolled roofing adhered with roof adhesive, adhesion to damp, wet, or underwater surfaces, mineral stabilizers and bitumen, mineral matter and volatile organic content.
ASTM D7051	Standard Test Method for Cyclic Thermal Shock of SBS-Modified Bituminous Roofing Sheets with Factory-Applied Metal Surface	This test method is used to determine the dimensional changes and physical stability of the product upon exposure to specified cyclic thermal conditions. It is also useful in determining the integrity of the bond between the metal foil and the SBS-modified bituminous compound.
ASTM D7052	Standard Test Method for Determining Impact Resistance of New Low Slope Roof Membranes Using Steel Balls	This test method covers the determination of impact resistance of new low slope roof membranes when applied directly over rigid insulation or cover board, or structural concrete, lightweight insulating concrete, gypsum, cementitious wood fiber or wood roof decks. The method evaluates new roof membranes when first applied and also after simulated deterioration caused by the ultraviolet radiation and moisture.

ASTM D7105	Standard Test Method for Determining the Adhesive and Cohesive Strength Between Materials in Roofing or Waterproofing Membranes and Systems	This test method is useful to define the force needed to cause separation of the roofing or waterproofing system or components perpendicular to the plane of the system, and to define the weakest plane in the system. The separation may be adhesive at the weakest bond, or cohesive within the weakest material. If the failure is cohesive, the adhesive strength is greater than the cohesive strength.
ASTM D7281	Standard Test Method for Determining Water Migration Resistance Through Roof Membranes	This test method provides a means of evaluating roof membranes including built-up roof membranes, modified bitumen, and single ply roof membranes, seams, and laps for resistance to water migration from standing water on the roof. This test method evaluates roof membranes when first applied and also after simulated deterioration caused by the ultraviolet energy of the sun.
ASTM D7349	Standard Test Method for Determining the Capability of Roofing and Waterproofing Materials to Seal around Fasteners	The capability of asphalt-based roofing or waterproofing materials to seal around a penetrating fastener and prevent the passage of liquid water at the fastener/material interface is determined by penetrating the material with a fastener, erecting a water column over that penetration, and monitoring the assembly for water passage for a period of time. The test method includes protocols that establish levels for the test method parameters.
ASTM D7379	Standard Test Methods for Strength of Modified Bitumen Sheet Material Laps Using Cold Process Adhesive	These test methods cover the procedure for sampling and testing the strength of laps formed with adhesive used with polymer-modified bituminous sheet materials. These tests are useful in sampling and testing combinations of modified bitumen sheet materials used with cold applied adhesives.
ASTM D7586	Standard Test Method for Quantification of Air Intrusion in Low-Sloped Mechanically Attached Membrane Roof Assemblies	This test method can be useful in understanding the response of low-sloped mechanically attached membrane roofing assemblies to air pressure differences induced across the assembly. This test method is intended to measure only air intrusion associated with the opaque roof assembly free from penetrations such as those associated with mechanical devices, roof junctions, and terminations. The results are intended to be used for comparison purposes and may not represent the field installed performance of the roof assembly.
ASTM D7635	Standard Test Method for Measurement of Thickness of Coatings Over Fabric Reinforcement	This test method covers measuring the thickness of the coating over fiber backing or reinforcing fabric. The thickness of coating material over fiber, fabric, or scrim can be measured with a standard or digital optical or reflectance microscope.
ASTM D8052	Standard Test Method for Quantification of Air Leakage in Low-Sloped Membrane Roof Assemblies	This test method is intended to measure air leakage of a roof assembly with rooftop penetrations. This test method can be useful in understanding the response of low-sloped membrane roof assemblies and role of different roofing components to air pressure differences induced across the assembly. The results are intended to be used for comparison purposes and likely do not represent the

		field installed performance of the roof assembly.
ASTM D8154	Standard Test Methods for [1]H-NMR Determination of Ketone-Ethylene-Ester and Polyvinyl Chloride Contents in KEE-PVC Roofing Fabrics	This test method pertains to the determination of the relative contents of Ketone-Ethylene-Ester (KEE) and Polyvinyl Chloride (PVC) after their extraction from reinforced roofing membranes, or fabrics. Based on Proton Nuclear Magnetic Resonance Spectroscopy (H-NMR), the method allows for the quantification of PVC with respect to an internal standard. The KEE content is then obtained by difference. The test method is not applicable to membranes or blends that contain high molecular weight polymers other than PVC and KEE.
ASTM E108	Standard Test Methods for Fire Tests of Roof Coverings	Provides procedures for testing the performance of roof assemblies exposed to gas flame and burning pieces of wood. Roof coverings are tested and rated as part of an assembly. The available classifications, in order from most fire-resistant to least fire-resistant, are Class A, Class B and Class C.
ASTM E907	Standard Test Method for Field Testing Uplift Resistance of Adhered Membrane Roofing Systems	Provides a procedure for field-testing roof assemblies' resistance to uplift pressures.
ASTM E1592	Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Differences	Refer Section 2.7.1.2
ASTM E1918	Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field	This test method covers the measurement of solar reflectance of various horizontal and low-sloped surfaces and materials in the field, using a pyranometer. Solar reflectance is an important factor affecting surface and near-surface ambient air temperature. Surfaces with low solar reflectance (typically 30 % or lower), absorb a high fraction of the incoming solar energy which is either conducted into buildings or convected to air (leading to higher air temperatures). The test method described here measures the solar reflectance of surfaces in the field.
ASTM E1980	Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces	This practice covers the calculation of the Solar Reflectance Index (SRI) of horizontal and low-sloped opaque surfaces at standard conditions. The method is intended to calculate SRI for surfaces with emissivity greater than 0.1.
FM 4450	Approval Standard for Class 1 Insulated Steel Deck Roofs	The requirements of this standard is used to measure and describe the performance of Class 1 Insulated Steel Deck Roofs in response to exposure from heat, wind, live load resistance, corrosion of metal parts and fatigue of plastic parts under controlled laboratory conditions.
FM 4451	Approval Standard for Profiled Steel Panels for Use as Decking in Class 1 Insulated Roof	This standard is used to evaluate a roof deck for its performance as it relates to allowable love load deflection, combustibility from below the deck, wind uplift

	Construction	resistance, foot traffic resistance of insulation, bearing capacity of insulation and corrosion resistance.
FM 4454	Approval Standard for Lightweight Insulating Concrete for use in Class 1 and Noncombustible Roof constructions	This standard is used to evaluate the potential for fire spread, corrosion resistance and to obtain satisfactory wind uplift performance of lightweight insulating concrete.
FM 4470	Approval Standard for Single-Ply, Polymer-Modified Bitumen Sheet, Built-Up Roof (BUR) and Liquid Applied Roof Assemblies for Use in Class 1 and Noncombustible Roof Deck Construction	This standard evaluates single ply, polymer modified bitumen sheet, BUR and liquid applied roof assemblies for their performance in regard to fire from above and below the structural deck, simulated wind uplift, susceptibility to hail storm damage, water leakage, foot traffic, corrosion of metal parts, susceptibility to heat damage, puncture resistance, and solar reflectance.
FM 4472	Approval Standard for Cementitious Panel Roof Decks	This standard is intended to evaluate each cementitious panel roof deck for its performance as it relates to allowable live load deflection, combustibility from below the deck, wind uplift resistance, ability to maintain an adequate securement of the above deck components and to obtain satisfactory performance of the cementitious panel roof covering systems as a whole.
FM 4473	Specification Test Standard for Impact Resistance Testing of Rigid Roofing Materials by Impacting with Freezer Ice Balls	This test standard states test requirements and procedures for the assessment of impact resistance of new rigid roofing materials.
FM 4474	Evaluating the Simulated Wind Uplift Resistance of Roof Assemblies using Static Positive and / or Negative Differential Pressures	Refer Section 2.7.1.1
FM 1-52	Field Verification of Roof Wind Uplift Resistance	Refer Section 2.7.2.1
UL 580	Field Tests for Uplift Resistance of Roof Assemblies	Refer Section 2.7.1.3
UL 1897	Uplift Tests for Roof Covering Systems	Refer Section 2.7.1.4
NT Build 307	Roof Coverings Dynamic Wind Load Resistance (Static Pressure Test, Pulsating Pressure Test and Dynamic Test Protocol)	Refer Sections 2.7.1.5 and 2.7.1.6
ETAG 006	Guideline for European Technical Approval of Systems of Mechanically Fastened Flexible Roof Waterproofing Membranes	Refer Section 2.7.1.7
CSA A123.21	Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane Roofing systems by Canadian Standards Association	Refer Section 2.7.1.8