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# Hail Impact Effects on the Wind Uplift Resistance of Fully Adhered Single-Ply Roof Membranes

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## Abstract

Single-ply roof membranes are an increasingly popular roof covering for low-slope roofing applications. A common installation practice for these types of roof coverings is to fully adhere the membrane to a layer of polyisocyanurate (polyiso) insulation, using an adhesive between the top of the insulation and the underside of the roof membrane to bond these layers to each other.

When a hailstone impacts a fully adhered single-ply roof system, it is possible for the impact force to result in a discrete fracture to the top facer/surface of the polyisocyanurate insulation. Such a fracture may cause a localized disruption in the bond between the membrane and insulation, which in turn, may collectively be suspected of affecting the overall wind uplift resistance of the membrane.

This paper documents an investigation into the effects that hail impacts can have on the wind uplift resistance of single-ply roof membranes fully adhered to polyiso insulation. This effect is analyzed through laboratory testing of fully adhered single-ply roof system mock-ups using a negative pressure vacuum chamber. The tested mock-ups contained varying amounts of bond disruptions simulating the effects of hailstone impacts. The performance of these mock-ups in a negative pressure environment is then used to establish a general characterization of the relationship between the extent of hail-created bond disruption and any reduction in wind uplift resistance of the roof system. This relationship can be used in forensic evaluations of roof systems to aid in the determination of whether or not hail has compromised a roof system.

## Objective and Methodology

The objective of this research was to investigate the effects that hail-impact fractures to the facer of polyiso insulation have on the overall bond to a single-ply membrane, in a fully adhered configuration, under negative (uplift) wind pressure.

The methodology for this investigation consisted of creating test mock-ups of fully adhered roof systems and then testing the performance of the bond between the membrane and insulation in these mock-ups with a negative pressure vacuum chamber. The tested mock-ups were created with varying amounts of debonding (as a percentage of the membrane surface area within the vacuum chamber) simulating the potential debonding effects of hailstone impacts. The tested scenarios are referred to as "debonding scenarios" herein. The tested debonding scenarios were chosen to be representative of debonding resultant of hailstorms with hailstone incidence rates consistent with actual conditions observed in field investigations conducted by the authors.

## Description of Tested Roof Assembly Mock-Ups

The findings presented herein are based on the performance of 14 roof assembly mock-ups, each measuring 6'x6' in area, tested in a vacuum chamber. The general configuration of each mock-up was the same and consisted of the following (from top to bottom):

- 45-mil thermoplastic polyolefin (TPO) membrane;
- 2" thick polyisocyanurate rigid board insulation (4' x 8' panels);
- 22-gauge Type B steel deck.

For each mock-up, the TPO membrane was fully adhered to the polyiso insulation using a TPO bonding adhesive. The polyiso insulation was secured to the metal deck with general purpose roof system fasteners and 3" diameter fastener plates. The mechanical fasteners for the polyiso insulation were installed in a grid pattern providing a tributary area of two square feet to each fastener (equivalent to a total of 16 fasteners per 4'x8' board). A load cell test was performed on the actual screws and metal deck used during testing in accordance with ANSI/SPRI FX-1 (SPRI 2016) and indicated that the fastener pattern had an uplift capacity of at least 240 psf. The steel deck panels were re-used in each mock-up and were mechanically fastened to oriented strand board (OSB) wood panels on a wood frame; however, new TPO membrane, insulation, and fasteners were used in each mock-up.

When constructing each mock-up, bonding adhesive was applied to the topside of the polyiso insulation and the underside of the TPO membrane, per the instructions of the bonding adhesive manufacturer. These materials were then mated per the adhesive manufacturer's instructions. A push broom and a 4" steel roller were used to mate the membrane and insulation.

For 12 of the 14 constructed mock-ups, discrete circular punctures/voids were created at the top surface of the polyiso insulation, in well-distributed random patterns, prior to the bonding process in order to simulate localized debonding between the roof membrane and polyiso insulation caused by hailstone impacts. For these mock-ups, one of three puncture/void size diameters was utilized (1", 2", or 3" diameter) with the number of installed punctures/voids correlating to a specific surface area percentage (between 0.5% and 5.0%) of debonding relative to the vacuum chamber footprint. The tested debonding scenarios were representative of hail impact distress rates observed in field investigations conducted by the authors. A summary of the tested debonding scenarios is provided in **Table 1**. Observations from the testing confirmed that created punctures/voids created in the top surface of the polyiso insulation successfully resulted in the intended initial debonding (i.e., the membrane and insulation did not adhere to each other on top of the installed punctures/voids after mating the two materials).

**Table 1:** Tested Debonding Scenarios

| Debonding Scenario | Number of Mock-Ups Tested with Scenario |
|---|---|
| Fully bonded (baseline test) | 2 |
| 0.5% debonded (1" diameter areas) | 1 |
| 1.0% debonded (1" diameter areas) | 1 |
| 1.0% debonded (2" diameter areas) | 2 |
| 1.0% debonded (3" diameter areas) | 1 |
| 2.0% debonded (1" diameter areas) | 2 |
| 2.0% debonded (2" diameter areas) | 2 |
| 2.0% debonded (3" diameter areas) | 1 |
| 5.0% debonded (1" diameter areas) | 2 |

Representative photographs showing examples of the tested debonding scenarios are presented in **Figure 1** and **Figure 2**.

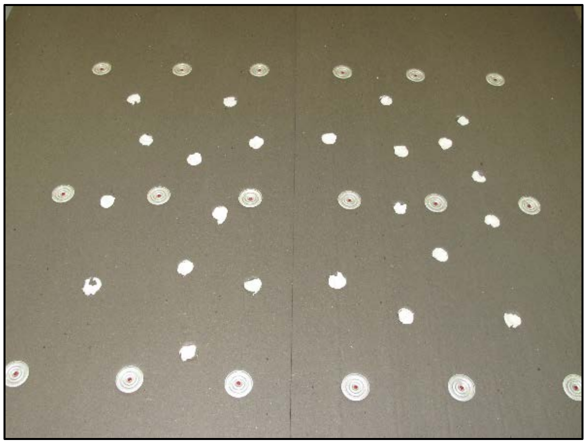

**Figure 1:** Tested debonding scenario of 2.0% debonded (2" diameter areas)

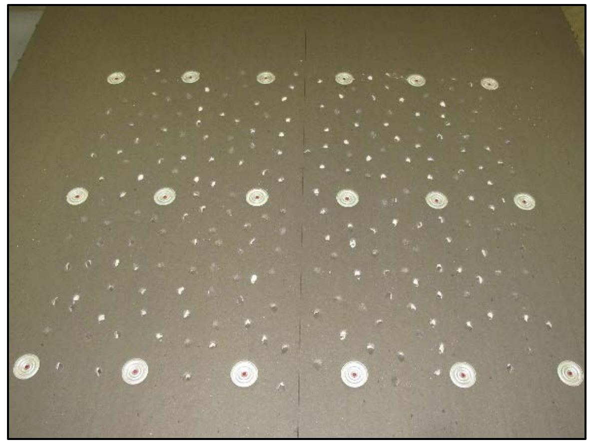

**Figure 2:** Tested debonding scenario of 5.0% debonded (1" diameter areas)

**Description of Vacuum Chamber**

A custom-designed vacuum chamber was used to test the roof mock-ups. The 5' x 5' chamber was designed to withstand negative pressures up to 200 psf and in general accordance with ASTM standard E907 (ASTM International 2004) (**Figure 3**). An elevated bar ("deflection bar") with a laser measurement device mounted to it, which provides distance measurements to the tenth of a millimeter, was used inside of the chamber to measure deflection of the roof mock-ups at the approximate center of the chamber (**Figure 4**). The vacuum (negative) air pressure inside the chamber was created by a vacuum pump connected to the chamber, and the amount of pressure inside the chamber was manually controlled by an opening in the side of the chamber with a gate valve. The amount of pressure inside the chamber was monitored with a digital pressure gauge connected to the chamber that provided readings to the thousandth of a pound-per-square-inch (psi).

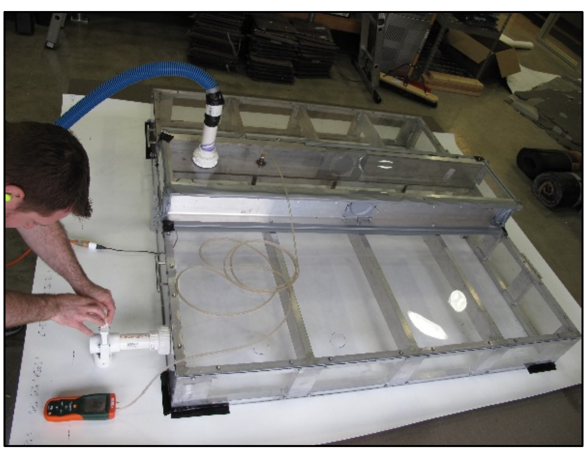

**Figure 3:** Vacuum chamber

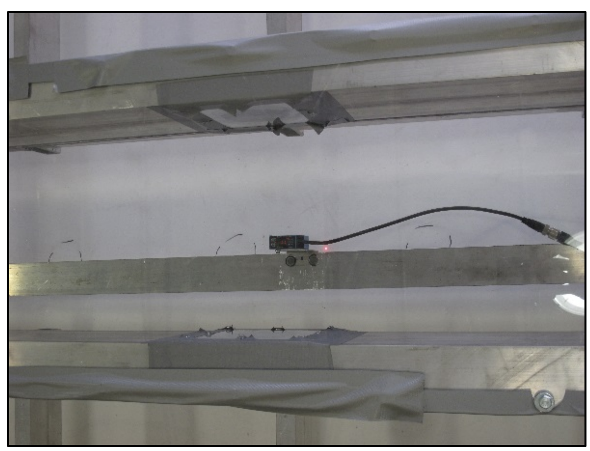

**Figure 4:** Deflection bar inside vacuum chamber

**Laboratory Test Procedure**

Each mock-up was tested with gradually increasing negative pressure in general accordance with the procedures of ASTM E907 (ASTM International 2004). Starting at 0 pounds per square foot (psf), the negative pressure was increased in 7.5 psf (0.052 psi) increments and held for one minute at each step until the ultimate failure criteria was reached, which was selected to occur when any portion of the membrane made contact with the bottom of the deflection bar. For three of the tests, this ultimate failure did not occur; rather, these tests ended because an air leak developed at the chamber that prevented reaching the successive higher pressure step. In each of these three tests, pressures of at least 135 psf were achieved prior to ending the test. Visual observations of the mock-ups were made throughout each test, and deflection readings at the center of the mock-ups were obtained after the 1-minute pause at each pressure step. Initial bond failures were determined for the tests as well, which were defined as the occurrence of widespread areas of membrane bubbling or the presence of any unstable areas of membrane bubbling that continuously expanded under constant pressure.

**Design Wind Pressures for Referenced Model Structure**

To assist in the analysis of the test data/observations, consideration was given to the design uplift wind pressures for the roof system of a model structure. The criteria of this model structure were chosen such that the resultant design uplift pressures would be applicable to, or in excess of, the vast majority of structures within the United States where a fully adhered single-ply thermoplastic membrane roof system may be reasonably utilized. The roof system design pressures of the model structure were determined using Part 1 of Chapter 30 (Wind Loads – Components and Cladding) of ASCE 7-16 (ASCE 2017). The following criteria were chosen for the model structure:

- Partially enclosed building
- Risk category III (i.e., structures with substantial risk to human life)
- Exposure category C (i.e., open terrain with scattered obstructions < 30')
- Flat roof with height of 60'
- Basic wind speed = 140 mph
- Topographic factor Kzt = 1.0 (i.e., no hill, ridge, or escarpment effects)
- Elevation factor Ke = 1.0 (i.e., conservatively at sea-level)

Using the attributes listed above, the design uplift pressure in the field of the roof of the model structure was calculated as approximately 46 psf, and the design uplift pressure in the corners of the roof (the highest for any portion of the roof) was calculated as approximately 94 psf. The closest test pressure step above this corner design value that was utilized in the vacuum chamber testing was 97.5 psf.

## Observations and Data

During the uplift tests, visual observations were conducted. After the end of each test, a post-test visual evaluation was performed, which included pulling the membrane off the insulation to observe the conditions of the tested mock-up components. The general observations from the tests included the following:

- As negative pressure was increased during the testing, the membrane would bubble over several of the insulation fastener plates (**Figure 5**).
- Membrane bubbles over fastener plates gradually increased in size with the increasing negative pressures, but typically remained stable during the pause at each pressure step. At negative pressures of 120 psf and greater, some areas of bubbling over fastener plates expanded into widespread areas of debonding and eventually became unstable resulting in continuous expansion under constant pressure and ultimate failure (**Figure 6**).
- Membrane bubbling occurred directly over a portion of the created 2" and 3" diameter punctures/voids during testing. These bubbles were closely confined to the approximate diameter of the respective voids at pressures less than the model structure design (97.5 psf). Above the model structure design pressures, these bubbles gradually increased in size, but did not become unstable, expand into widespread areas of membrane debonding, or result in ultimate failure for any tested debonding scenario.
- Until ultimate failure, deflection of the roof system was greatest at the center of the test area and was predominately the result of upward deflection of the insulation and decking, not separation of the membrane from the insulation.
- For each test where ultimate failure occurred, failure was the result of the membrane separating from the insulation surface in an area originating from a fastener plate location (most common) or originating from differential deflection across the butt joint of the polyiso insulation boards.
- The fastener plates nearest the center of the test area were typically deformed upward due to deflection of the polyiso insulation.
- During several of the tests, the polyiso insulation fractured or pulled through the fasteners nearest to the center of the test area (**Figure 7**).
- No insulation fasteners pulled out of the roof deck during testing.

- At areas where the membrane was separated from the insulation, the failure did not always delaminate or tear the insulation facer from the polyiso core, but in multiple instances the insulation facer was wrinkled at an area where separation occurred (**Figure 8**).

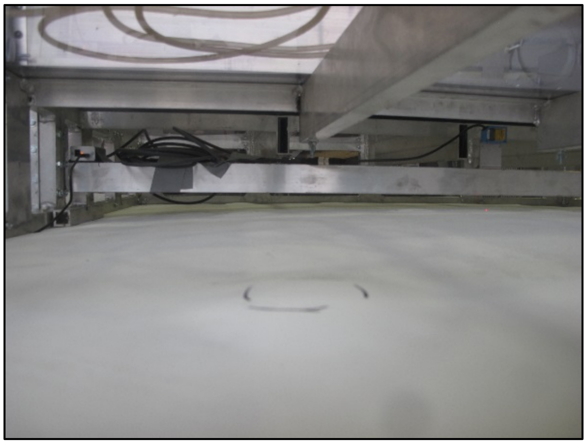

**Figure 5:** Membrane bubbling over insulation fastener locations at 105.0 psf

**Figure 6:** Expanding debonding area over a fastener location at 127.5 psf

**Figure 7:** Polyiso insulation fractured at fastener

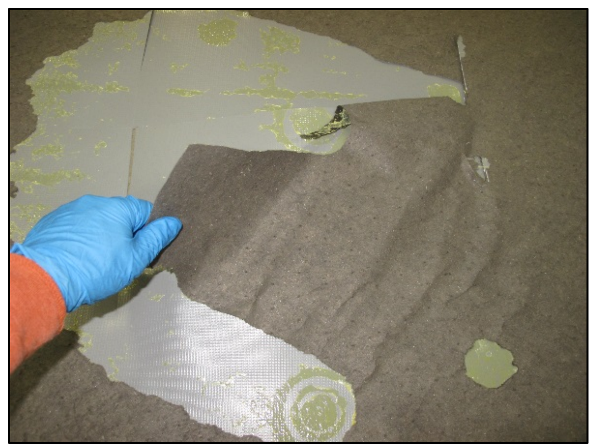

**Figure 8:** Underside of membrane at area where membrane separated from insulation

**Table 2** provides a summary of when initial bond failure and ultimate bond failure occurred for each tested debonding scenario.

**Table 2:** Summary of Test Failures

| Debonding Scenario | Test 1 | | Test 2 | |
|---|---|---|---|---|
| | Initial Bond Failure | Ultimate Test Failure | Initial Bond Failure | Ultimate Test Failure |
| Fully bonded (baseline test) | N/A* | 142.5 psf** | 127.5 psf | 135.0 psf |
| 0.5% debonded (1" diameter voids) | 127.5 psf | 135.0 psf | | |
| 1.0% debonded (1" diameter voids) | 135.0 psf | 142.5 psf | | |
| 1.0% debonded (2" diameter voids) | 120.0 psf | 135.0 psf | N/A* | 135.0 psf** |
| 1.0% debonded (3" diameter voids) | 135.0 psf | 142.5 psf | | |
| 2.0% debonded (1" diameter voids) | 135.0 psf | 142.5 psf | 127.5 psf | 127.5 psf |
| 2.0% debonded (2" diameter voids) | 127.5 psf | 142.5 psf | 142.5 psf | 142.5 psf |
| 2.0% debonded (3" diameter voids) | 157.5 psf | 165.0 psf | | |
| 5.0% debonded (1" diameter voids) | 127.5 psf | 135.0 psf | N/A* | 150.0 psf** |

* No bond failure occurred for this test

** Ultimate test failure pressure listed indicates last pressure step before an air leak prevented reaching the next step

## Analysis

The referenced model structure represents a conservative exemplar building, which would have design pressures higher than or equal to the vast majority of structures in the United States that may utilize a fully adhered single-ply membrane roof system. This model structure has a 94 psf design uplift pressure for the roof's highest wind pressure zones. Therefore, the performance of the test mock-ups up to the 97.5 psf pressure step is a good indicator of the influence of the tested debonding scenarios within typical design conditions. None of the test mock-ups exhibited bond failure between the membrane and polyiso insulation at or below this step (**Figure 9** and **Figure 10**).

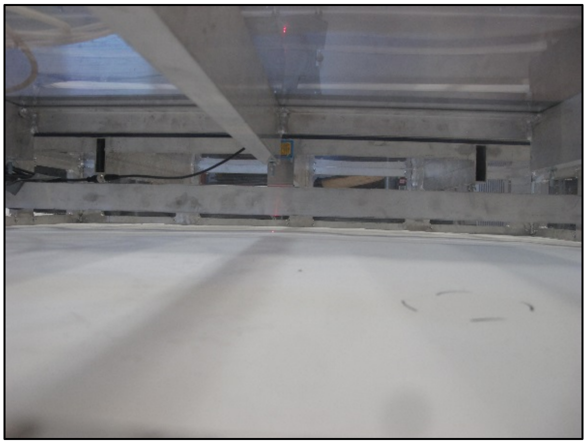

**Figure 9:** View across membrane for 2.0% debonded (2" diameter fractures) test at 97.5 psf uplift pressure

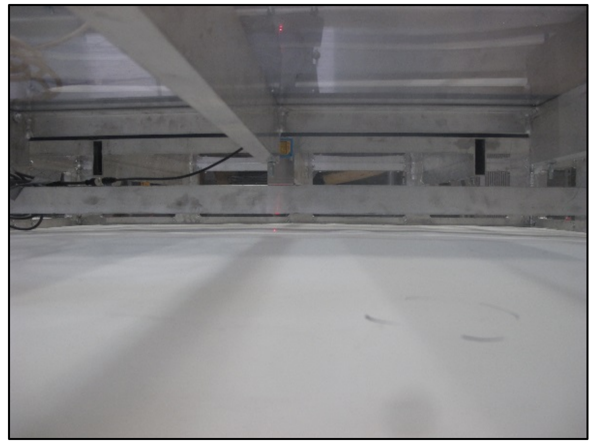

**Figure 10:** View across membrane for 5.0% debonded (1" diameter fractures) test at 97.5 psf uplift pressure

The testing revealed that membrane bubbling occurs as a gradual and progressive condition with increasing negative pressures. These bubbles most commonly occurred directly over insulation fastener plates with every test mock-up exhibiting bubbling over several fastener plates. For a portion of the tests, some areas of bubbling were observed to occur over areas of differential deflection across the polyiso board joint and/or over isolated 2" or 3" diameter installed punctures/voids. During the majority of the testing duration, bubbled areas were limited in extent, closely matching the size of the fastener plate, area of differential deflection, or installed puncture/void below. At uplift pressures of 120 psf and greater, areas of bubbling were observed to become widespread or unstable (continuously expanding under constant pressure) and qualified as bond failure; however, these bond failures never originated from bubbling over an installed puncture/void in the polyiso insulation. Furthermore, there was no discernible relationship between when bond failure occurred and the size or percentage of installed debonding in the tested scenarios. Therefore, for the tested scenarios, bond failure was controlled by the insulation fastener plates, general workmanship, and/or differential deflection across polyiso board joints, and was not a function of the localized debonding over installed punctures/voids in the polyiso insulation.

Although deflection measurements were obtained at each pressure step for each test, the measurements were found to hold no relevance to the performance of the bond between the membrane and insulation because the bond failures never occurred directly at the location where deflection measurements were taken. Thus, the deflection readings were representative of the overall deflection of the entire roof system, including the insulation and decking deflections, and did not specifically capture when bond failure occurred or the extent of separation between the membrane and insulation. Based on the findings from this testing, roof system deflection measurements are not a reliable indicator of bond failure for these types of fully adhered single-ply roof membranes.

## Conclusions

Scenarios were tested that included debonding areas individually up to 3" in diameter and collectively up to 5% of the roof surface area. The tested scenarios are representative of debonding resultant of hailstorms with hailstone incidence rates consistent with actual conditions observed in field investigations conducted by the authors. This testing indicated that the simulated hail impact debonding (i.e., fractures to the facer of polyiso insulation) was inconsequential to the overall bond between the membrane and insulation. Scenarios of more severe/extensive hail impact debonding are either unlikely to be the result of a singular storm event, or would be expected to cause direct membrane failure (e.g., punctures), which would make evaluation of the wind uplift resistance of the roof system unnecessary.

For further interpretation of the testing results, consideration was given to the design uplift wind pressures for the roof system of a model structure. The design criteria for this model structure were chosen such that the resultant design uplift pressures would be applicable to, or in excess of, the vast majority of structures within the United States where a fully adhered single-ply thermoplastic membrane roof system may be reasonably utilized. Bond failure between the membrane and polyiso insulation did not occur in any of the tested scenarios while test pressures were within the range of design pressures of this model structure.

Considering the scenarios tested, membrane bubbling under uplift pressure is a gradual and progressive condition. At uplift pressures of approximately 120 psf and above, such bubbling may become widespread or unstable (continuously expanding under constant pressure) resulting in overall bond failure between the membrane and insulation. However, bond failure between the membrane and insulation was controlled by membrane bubbling that originated over fastener plates and/or differential deflection across polyiso board joints.

The testing also revealed that deflection measurements from inside of a vacuum chamber test, such as ASTM E907, do not reliably capture bond failure between the membrane and substrates as these measurements are most reflective of total roof assembly deflection (including insulation and decking deflections) rather than separation between the membrane and the layers below.

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