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Building Vulnerability to Wind-Driven Rain Entry and Effectiveness of Mitigation Techniques

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ABSTRACT: Previous studies have shown wind-driven rain entry into buildings can lead to large interior and contents damage. A component of IBHS FORTIFIED Home™–Hurricane program includes the integration of a secondary roof sealing strategy to prevent this water entry into the building in the event the roof cover is compromised. The objective of this study was to evaluate and compare the effectiveness of several roof sealing mitigation strategies. For this study, the exterior of a typical full-scale residential structure was constructed. Control tests were run, and each mitigation strategy was evaluated independently. Within the interior of the building, the attic space was partitioned, and a drainage system was installed to collect and direct the water that entered the attic space in each partition into containers placed on load cells. This allowed for different zones to be evaluated independently. The load cells captured a time history of water entry at each roof drainage zone. The weight of water collected at each zone was converted into a volume of water, and then a water entry rate was calculated. Tests were conducted for each mitigation strategy and control case for three wind speed cases, two water intensities, and several building orientations. Results provided in this paper are focused on a subset of these tests. The results indicated that each sealed roof deck strategy noticeably decreased the water entry rates in each roof drainage zone, as compared to control cases where no mitigation strategy was employed. Some strategies were more effective than others in reducing water entry rates. Some drainage zones were more susceptible to water entry than others and possible reasons and solutions to remedy this are suggested.

KEY WORDS: Water-entry; Wind-Driven Rain; Mitigation; Roof Vulnerabilities; Window and Door Vulnerabilities; FORTIFIED Construction.

1 INTRODUCTION

Previous studies have shown that wind-driven rain entry into buildings, particularly from tropical cyclones where the wind-driven rain may last for many hours, can lead to large interior damages beyond any structural or exterior damages [1, 2, 3]. Water entry can occur where it is able to infiltrate through the roof, walls, vents, windows, and/or doors, or at interfaces between these items. Water intrusion can cause extensive damage to interior finishes, furnishings, and other contents, and can lead to ceiling collapse when attic insulation is saturated. When power is lost and/or a building cannot otherwise be dried out within 24–48 hours, additional issues such as mold can develop, potentially extending the period during which the property may not be available for use. An insurance closed claims study for residential properties conducted following Hurricane Charley in 2004 indicated interior losses were 16% of the total loss costs, while contents and additional living expenses were 7% and 4%, respectively [4].

In 2011, Quarles et al. [5] conducted a study at the Insurance Institute for Business & Home Safety's (IBHS) Research Center to measure water entry into the attic space of a residential building through vented soffits and the under-eave area when soffit material was removed, through gable vents, and through a specific sealed- and unsealed-roof deck strategy under wind-driven rain exposures. This study, using a full-scale building, investigated water entry where it was assumed that winds were strong enough to remove the roof covering, but not strong enough to remove roof sheathing, therefore allowing for a direct comparison of selected secondary sealing strategies. A drainage system was developed and installed in the attic space of the test building to capture the water that entered the attic space. Tests were run for different wind speed records and building orientations to quantify differences in performance when the building was subjected to a constant rain rate. Quarles et al. [5] found an increasing rate of water entry through the open eave (soffit material removed) and vented soffits with increasing wind speed. They also found that nearly all water deposited on gable end vents was able to enter the attic space. Additionally, it was found that water entry quantities through the unsealed roof deck were much higher than through any vents or open eaves (under-eave area with soffit material removed), and water entry through the roof deck was noticeably reduced by installing tape along the seams of the sheathing. The current study represents an expansion of this earlier work. While this study had a number of objectives as outlined in Section 2, this paper focuses specifically on water entry through a bare roof deck and in scenarios where mitigation methods were employed specifically to protect the building from water entry through the roof surface in the event the primary roof cover is damaged or lost during a storm. Results for select wind speeds, water rates, and building orientations are discussed for each scenario.

2 STUDY OBJECTIVES

The current study investigated water entry for various roof and vent configurations, as well as different window and door types, on a full-scale (130 m^2) residential structure. The primary goal was to evaluate recommended secondary roof sealing strategies specified in the IBHS FORTIFIED Home™–Hurricane program, a set of engineering and building standards designed to help strengthen new and existing homes through hazard-specific, system-based building upgrades to building code requirements. The entry level (Bronze level) of the FORTIFIED Home–Hurricane program focuses on reducing vulnerabilities to the roof system, including water entry into the attic. Options to achieve a sealed roof deck allowed by the FORTIFIED Home–Hurricane program prior to completion of this study included:

1. Applying a self-adhered polymer-modified bitumen membrane over the entire roof deck.
2. Applying a 101.6-mm-wide self-adhered polymer-modified bitumen flashing tape over all plywood/OSB roof deck seams, and then covering the entire roof deck with a felt underlayment.
3. Applying a high-strength synthetic underlayment over the entire roof deck and sealing all underlayment seams with a compatible adhesive/tape.
4. Applying a qualified closed-cell polyurethane foam adhesive to the underside of the roof deck along both sides of roof framing members and over all joints between roof sheathing.

This study also included an assessment of a new approach where the roof is covered with two layers of high-quality underlayment attached with cap nails. Based on the performance achieved with this system, it has now been added to the FORTIFIED Home–Hurricane program as a fifth option for achieving a sealed roof deck.

In addition to investigating these FORTIFIED Home program sealed roof deck options, water entry at doors and windows was also investigated, as post-storm damage surveys have revealed water can penetrate through and around these components [6, 7, 8, 9]. With all of these goals in mind, water entry was evaluated through the following systems and components:

1. Bare roof deck (control).
2. Bare roof deck with seams taped at sheathing joints. One acrylic and one modified-bitumen tape were used in these experiments.
3. Bare roof deck with a nominal 38.1-mm closed-cell polyurethane foam fillet applied inside the attic space along both sides of the connection between the sheathing and the roof framing members and along horizontal joints between sheathing panels.
4. Roof deck covered with synthetic underlayment and taped underlayment seams.
5. Bare roof deck with underlayment removed and nail holes exposed (control).
6. Bare roof deck with a nominal 76.2-mm closed-cell polyurethane foam fillet applied inside the attic space along both sides of the connection between the sheathing and the roof framing members and along horizontal joints between sheathing panels.
7. Roof deck covered with two layers of ASTM D 226, Type II underlayment lapped according to requirements for underlayment applied for roof slopes between 2:12 and 4:12 and attached following Florida's High Velocity Hurricane Zone (HVHZ) fastening requirements.
8. Roof off-ridge vents on a covered roof.
9. Gable vents on a covered roof.
10. Several configurations of soffit vents at eaves and both vented and sealed gable overhang soffits.
11. Doors, including in-swing, out-swing, sliding, French (one operable and two operable) that were properly installed according to their manufacturers' trade association guidelines including flashing details and caulking.
12. Windows, including single hung (two pressure ratings), double hung, horizontal slider, that were properly installed according to their manufacturers' trade association guidelines, including flashing details and caulking.

The performance differences between the various systems and installations were evaluated to determine the effectiveness of mitigation techniques and proper installation, and to provide guidance on best practices.

3 EXPERIMENT

The distribution of raindrop sizes produced in a wind-driven rain simulation is a critical variable that affects how wind-driven rain interacts with built structures [10, 11, 12, 13, 14, 15]. The wind-driven rain system at the IBHS Research Center was designed to reproduce a raindrop size distribution measured by University of Florida researchers in Hurricane Ike [16] with deposition rates in excess of 203 mm/hr for a horizontal wind speed of 58 m/s. This allows the facility to meet or exceed rain deposition rates adopted in current standardized testing methodologies [12, 13, 14]. The system was designed to produce a consistent raindrop size distribution regardless of flow rate for a range of wind speeds. The distribution was fitted to the Best model [16]. The system has the ability to modulate the wind-driven rain intensity by controlling the discharge rate. This is essentially a mass flux of water through a vertical plane. For the study presented, varying discharge rates were tested and a horizontally mounted array of OTT first-generation Parsivel laser disdrometers was used to investigate the characteristics of the wind-driven rain system. Increasing the discharge rate successfully increased the wind-driven rain intensity and accumulated liquid while there was little effect, as expected, on the raindrop size distribution.

The test building for these experiments featured a gable roof design with 5:12 roof slope, with a smaller section (3.05 m x 6.10 m) added on to the primary structure (9.14 m x 12.19 m), as shown in Figure 1, to create a re-entrant corner and valleys on the roof. During the experiments evaluating the effectiveness of closed-cell polyurethane foam fillets, plywood sheathing was used on one half of the roof (from the ridge to the eave on the re-entrant corner side of the test building) and OSB sheathing was used on the other half of the roof (from the ridge to the eave on the non-re-entrant corner side). For all other tests, OSB sheathing was installed over the entire roof deck. A re-entrant corner is hypothesized to be especially vulnerable to water entry when water collects in the corner at building orientations where the corner faces into the mean wind direction. Valleys may also be susceptible to water entry if they are not flashed appropriately. The test building was constructed by a local building contractor, using typical construction practices, and enhanced to withstand the maximum winds of the test plan. Water entry mitigation strategies for roof decks, such as the addition of tape on roof sheathing joints and closed-cell polyurethane foam in the attic at roof sheathing joints, followed practices outlined in IBHS' FORTIFIED Home–Hurricane program, as well as manufacturers' installation guidelines. The closed-cell foam was installed by a regional contractor. Windows and doors with positive pressure ratings ranging between 1.4 kPa and 2.2 kPa were installed according to guidance from the Fenestration Manufacturers Association (FMA) / American Architectural Manufacturers Association (AAMA) standard practices FMA/AMMA 100-12 [17] and FMA/AMMA/WDMA 300-12 [18]. Water intrusion through windows and doors is a pass/fail criteria with no water entry allowed at pressures less than 11% of the positive design pressure rating. It does not provide any indication of how much water may enter once that threshold is exceeded. Consequently, results of window and door tests conducted as part of this study provide unique quantitative measurements of water intrusion for hurricane-like conditions.

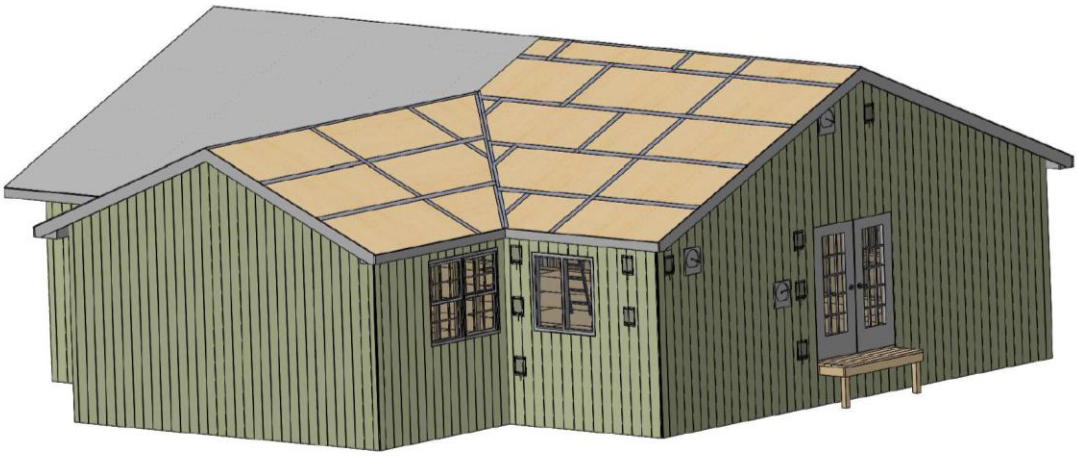

Figure 1. Conceptual drawing for full-scale test building, where half of the roof deck is covered with synthetic underlayment (system and component 1), and half of the roof deck has the seams taped at sheathing joints (system and component 3). Locations of doors, windows, and wind-driven rain gauges are shown for one reentrant corner and one gable end of main building. Main building is 9.14 m x 12.19 m, and smaller attachment is 3.05 m x 6.10 m.

A custom water collection system was designed and installed in the attic space of the test building. The collection system was partitioned into zones to isolate and identify vulnerable points of water entry. Water collection systems were also constructed at doors and windows to collect water that entered at those locations. Wind-driven rain gauges, following Blocken and Carmeliet [12], were attached at selected locations on the exterior walls to evaluate the rain deposition on vertical surfaces.

At each water collection point, the water was funneled into a container placed on a custom scale fitted with a 35 kg load cell. The instrumentation system was designed such that the load cell output was recorded to produce a time-history of water entry over the duration of a test. The data can be matched with associated wind speed time histories used in each test to understand how wind gusts affect the amount of water that enters through various building penetrations.

For each roof system or venting configuration, three wind speed records (low, medium, high) and two water delivery rates (medium, high) were tested, as outlined in Table 1. Tests were generally conducted at eight wind directions (building orientations) at 45° increments relative to the principal axes of the house as indicated in Figure 2. In a few cases, additional tests were conducted at finer increments in wind direction. The flow simulations used for these experiments were designed to model an open country terrain (zo=0.01), matching the mean vertical profile, turbulence, and spectral characteristics found in typical boundary layer winds. Specific details of the flow simulation in the IBHS Research Center can be found in Morrison et al. [19]. Most tests reported in this paper were 10 minutes in duration, and utilized the first 10 minute segment of records 1a, 1b, and 3 from Dixon et al. [20]. Tests for systems and components 1 and 5 (bare roof deck control and bare roof deck with nail holes exposed) reported in this paper were only 2.5 minutes in duration, due to the large quantity of water entering the building. These tests used the first 2.5 minutes of the 10-minute records. Because smaller run times were used for these select cases, mean and peak instantaneous wind speeds were different from the 10-minute tests as indicated in Table 1.

Table 1. Wind speed and water delivery rates tested.

Wind test conditions	Water test conditions	Test duration (s)	Mean wind speed (m/s)	Peak instantaneous wind speed (m/s)
Low	Medium	600	15.7	32.2
Low	High	600	15.7	32.2
Medium	Medium	600	21.0	44.0
Medium	High	600	21.0	44.0
High	Medium	600	25.4	46.3
High	High	600	25.4	46.3
Low	Medium	150	15.0	29.5
Low	High	150	15.0	29.5
Medium	Medium	150	19.5	34.4
Medium	High	150	19.5	34.4
High	Medium	150	24.7	43.1
High	High	150	24.7	43.1

4 ANALYSIS AND RESULTS

The total water volumes collected at each roof drainage zone, door, window, and wind-driven rain gauge were calculated from the measured weights of water. A volume entry (m^3) per unit area of the roof drainage zone (m^2) per unit time (s) was then determined for each measurement location. Results were then converted from a water entry rate in m/s to mm/hr to follow rainfall rate conventions. Variations in accumulation between roof drainage zones were compared both within a single test and across test configurations. These comparisons helped determine systematic roofing system vulnerabilities, as well as those related to particular building orientations, wind angles, and wind speeds.

For the purposes of this paper, water entry was evaluated for systems 1–7 outlined in section 2 above, and for the medium and high wind speed cases with the high water delivery rate. The analysis focused on water entry through roof configurations on the side of the building without the re-entrant corner (quadrants BC and CD) as shown in Figure 2, to eliminate any channeling effects of the valley configurations. Thus, the following building orientations were evaluated: perpendicular to wall C (180°); and 45° quartering angles (225° and 135°) between walls B and C, and C and D, respectively. The roof drainage zones are also shown in Figure 2. Those evaluated for the purposes of this paper were zones 1–18, and the full water entry rates for zones 13–18 were utilized, despite the fact that they span the ridge and thus extend into the A half of the roof. All roof system configurations tested were each installed on half of the roof, with the exception of system 7 (which covered the entire roof), so only the pertinent drainage zones for those systems were included in the analysis. Systems 1–3 were installed on the D side of the roof and water intrusion was evaluated for the CD roof quadrant, while systems 4–6 were installed on the B side of the roof and water intrusion was evaluated for the BC roof quadrant.

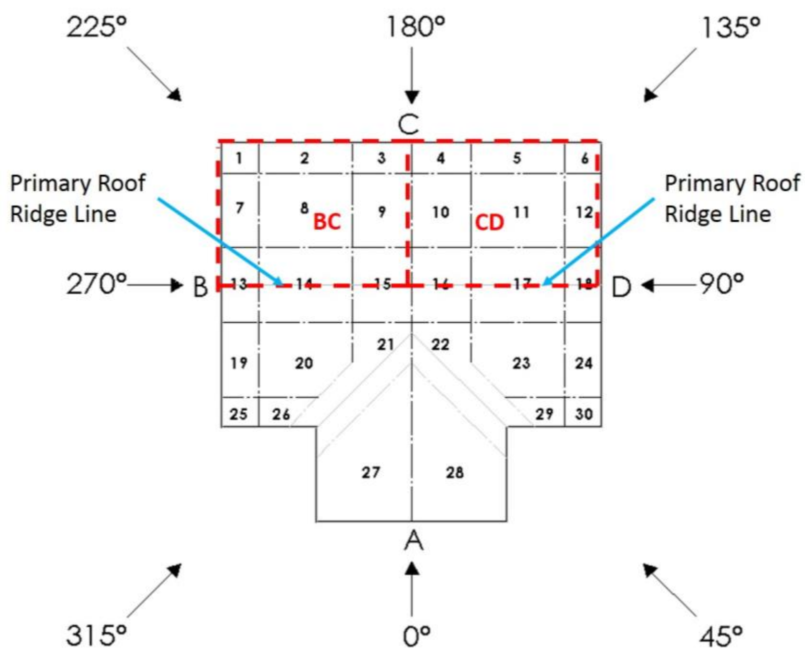

Figure 2. Conceptual drawing for full-scale test building, showing roof drainage zones, quadrants BC and CD, and building orientations.

4.1 Bare roof deck (control)

To evaluate the effect of having no sealed roof deck (i.e., no secondary barrier) for water entry protection, testing was conducted on a bare roof deck where the sheathing seams were open and fully exposed. This simulated a scenario in which the full roof covering material was removed, but no secondary water entry mitigation strategy was employed. This test series served as the control, or baseline, for comparison with prescribed mitigation methods. This scenario was evaluated for the CD quadrant of the building illustrated in Figure 2. Thus, for the purposes of this paper, water entry quantities were evaluated for roof drainage zones 4–6; 10–12; and 16–18. The water quantities collected are shown in Table 2 and Figure 3 for the various building orientations and the medium wind speed record. The total weight of water collected in each drainage zone was converted to a volume, then divided by the drainage area and test duration, so results were consistent and comparable between tests and different drainage zones. The results are presented as a water entry rate in mm/hr.

Table 2. Water entry results for three tested systems, for selected drainage zones and building orientations, for the medium wind speed record.

	Water collection rate (mm/hr)								
	Bare roof deck (control)			Bare roof deck with seams taped at sheathing joints			Bare roof deck with closed-cell polyurethane foam at sheathing joints—nominal 38.1-mm fillet		
	Building orientation			Building orientation			Building orientation		
Drainage partition	135	180	225	135	180	225	135	180	225
4	30.08	19.89	22.04	0.15	1.42	0.20	0.09	2.23	0.18
5	10.79	7.81	13.11	0.10	1.06	0.05	0.07	1.58	0.04
6	4.06	4.19	7.11	0.43	0.45	0.14	3.46	6.08	8.02
10	3.20	3.52	2.64	0.04	0.01	0.07	0.11	0.42	0.15
11	3.01	5.09	4.95	0.03	0.01	0.04	0.11	0.15	0.12
12	0.05	0.54	0.47	0.00	0.00	0.01	0.71	4.14	7.32
16	5.25	14.24	8.77	0.01	0.14	0.05	0.00	0.01	0.00
17	2.08	7.95	5.66	0.02	0.13	0.04	0.02	0.01	0.01
18	0.13	3.90	2.71	0.03	0.05	0.07	0.17	2.38	1.28

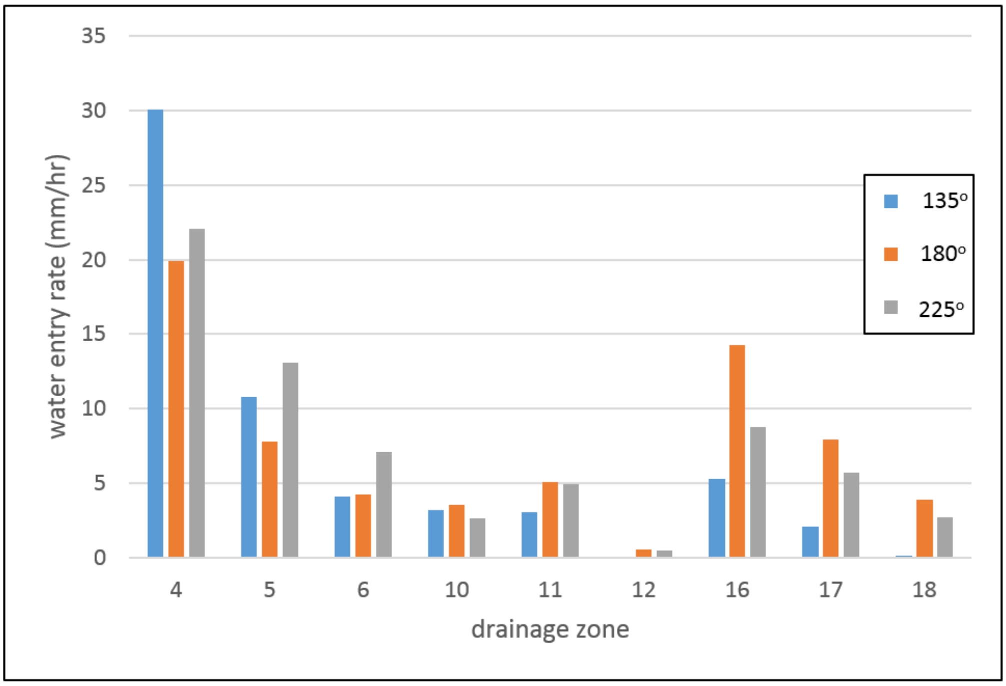

Figure 3. Water entry results for the bare roof deck (control) tests for selected drainage zones and building orientations, for the medium wind speed record.

The largest water entry rates were generally for the roof drainage zones that were adjacent to the roof eave (4–6) where the vented soffit and other details at the soffit-to-wall joint may have contributed to the water entry rates. There was variation in water entry rates at individual drainage zones with building orientations, but the location of the drainage zone seemed to be the primary factor causing variation in the water entry rate. Figure 3 indicates large water entry rates for most zones, meaning a bare roof deck with no mitigating systems is highly susceptible to water entry, which could cause significant damage to the interior of the building.

Water entry rates through the bare roof deck for the high wind speed record are shown in Table 3 and Figure 4 for the various building orientations. Overall water entry patterns were similar for the high wind speed cases as compared to those of the medium wind speed cases. The largest water entry rates once again generally occurred at the roof drainage zones adjacent to the eave (4–6), and the quantities varied with building orientation. Overall, the water entry rates for the high-speed case were similar to or slightly lower than those for the medium speed case (Figures 3 and 4) for most drainage zones, with the exception of zone 4 for the 135° building orientation. In this case, the water entry at zone 4 was almost twice as high for the medium wind speed test as compared to the high speed test. There was a tendency for water to be blown over or off the roof surface as the wind speeds increased. This resulted in less water draining through cracks between the sheathing during higher wind speed portions of the wind speed time histories.

Table 3. Water entry results for three tested systems, for selected drainage zones and building orientations, for the high wind speed record.

	Water collection rate (mm/hr)								
	Bare roof deck (control)			Bare roof deck with seams taped at sheathing joints			Bare roof deck with closed-cell polyurethane foam at sheathing joints—nominal 38.1-mm fillet		
	Building orientation			Building orientation			Building orientation		
Drainage partition	135	180	225	135	180	225	135	180	225
4	15.52	16.77	10.44	0.86	5.65	0.41	0.26	8.51	0.08
5	10.43	9.39	7.33	0.50	4.25	0.23	0.64	4.93	0.03
6	4.40	4.64	4.40	1.60	1.72	0.14	3.45	5.13	4.27
10	2.14	2.95	1.47	0.09	0.30	0.10	0.09	0.73	0.27
11	2.85	5.07	2.73	0.06	0.25	0.05	0.12	0.30	0.12
12	0.18	0.56	0.35	0.09	0.05	0.01	0.87	3.32	5.65
16	3.70	10.39	5.92	0.05	0.07	0.08	0.01	0.00	0.01
17	1.66	5.91	4.77	0.05	0.10	0.06	0.02	0.01	0.01
18	0.07	3.65	2.73	0.04	0.21	0.04	0.71	1.28	0.93

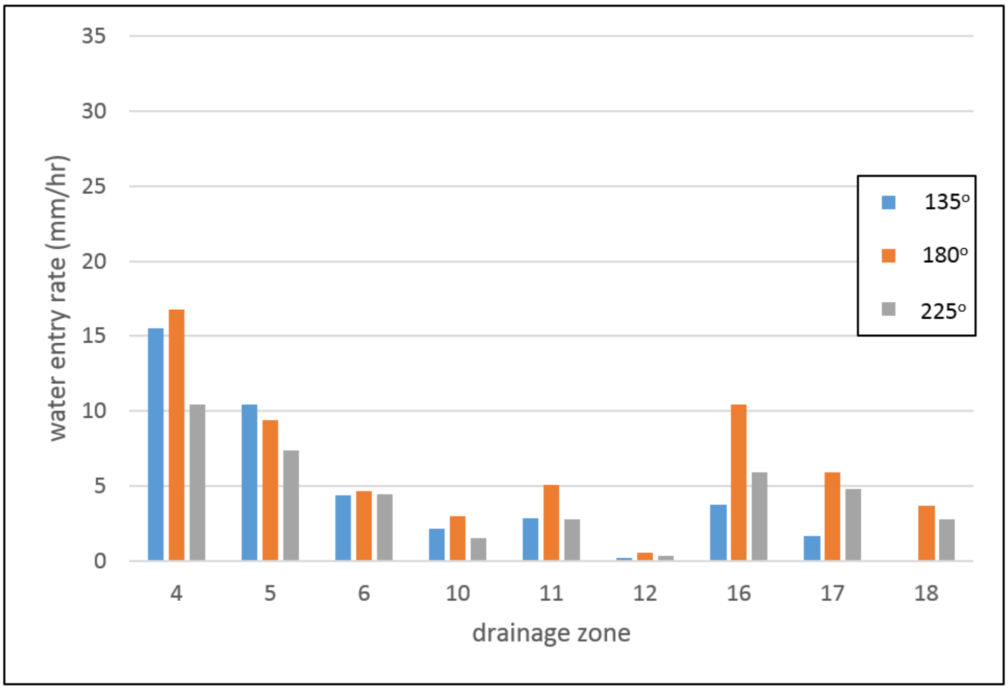

Figure 4. Water entry results for the bare roof deck (control) tests for selected drainage zones and building orientations, for the high wind speed record.

4.2 Bare roof deck with seams taped at sheathing joints

One of the acceptable methods for sealing the roof deck to reduce water entry in the IBHS FORTIFIED Home–Hurricane program is applying a 101.6-mm-wide self-adhered polymer-modified bitumen flashing tape over all OSB roof deck seams, and then covering the entire roof deck with a felt underlayment prior to installing the roof covering. For this series of tests, the tape was installed over the sheathing seams, but the felt underlayment was not installed. This simulated a scenario in which both the roof covering and underlayment were removed by high winds. This scenario was evaluated on the CD quadrant of the building using water entry data for roof drainage zones 4–6; 10–12; and 16–18. The water quantities collected are shown in Table 2 and Figure 5 for the various building orientations and the medium wind speed record.

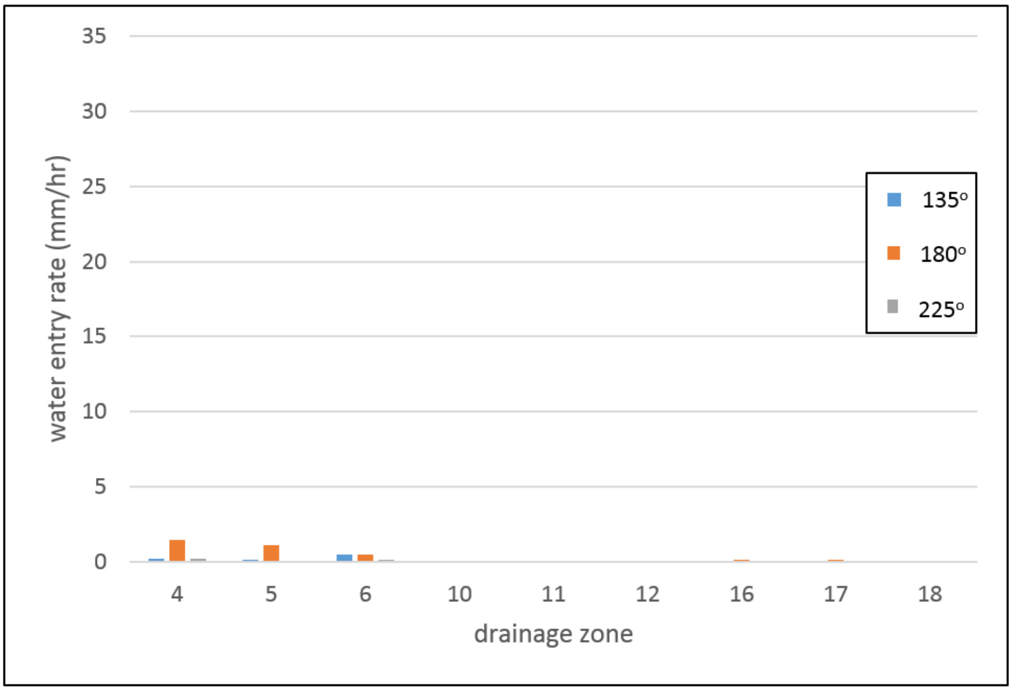

Figure 5. Water entry results for the tests of the bare roof deck with seams taped at sheathing joints for selected drainage zones and building orientations, for the medium wind speed record.

Figure 5 clearly illustrates the positive effects of taped sheathing joints as a water entry mitigation technique. Water entry quantities were reduced by at least 85% for drainage zones 4, 5, and 6 that are affected by water entry through the soffit. Water entry rates were reduced by at least 97% for all other zones (10–12, 16–17) where water entry through the soffit was not a contributor, except for drainage zone 18 where the water entry rate was very small for both the control (bare roof deck) and taped sheathing joint cases. Water entry rates with the tape in place were highest for the 180° (eave perpendicular to the wind) building orientation. Nevertheless, the water entry rates for drainage zones adjacent to the eave were less than 2 mm/hr and water entry rates were less than 0.2 mm/hr in drainage zones away from the eave.

Water entry rates through the bare roof deck with taped seams at sheathing joints for the high wind speed record are shown in Table 3 and Figure 6 for the applicable building orientations. Similar patterns of water entry rates were seen for the high wind speed cases as compared to those of the medium wind speed cases for drainage zones 10–12 and 16–18, with very minimal water entry. The largest water entry rates were measured for the roof drainage zones adjacent to the eave (4–6), and the largest water entry rates tended to occur for the 180° (eave perpendicular to the wind) building orientation. Water entry rates for the roof drainage zones adjacent to the eave (4–6) were substantially larger for the high wind speed cases as compared to the corresponding medium wind speed cases. This is primarily due to the increase in water intrusion through the soffit area as the wind speed increased, a result noted in the earlier pilot studies [5]. Despite the increase in water intrusion through the soffit, the water entry rates in drainage zones 4–6 were less than 6 mm/hr, a reduction of at least 50% when comparing the high wind speed cases with the taped sheathing joints to the corresponding high wind speed cases with no mitigation. Away from the area affected by water intrusion through the soffit, the water entry rates in drainage zones 10–12 and 16–18 were increased slightly in the high wind speed cases compared to the medium wind speed cases, but still remained at or below 0.3 mm/hr.

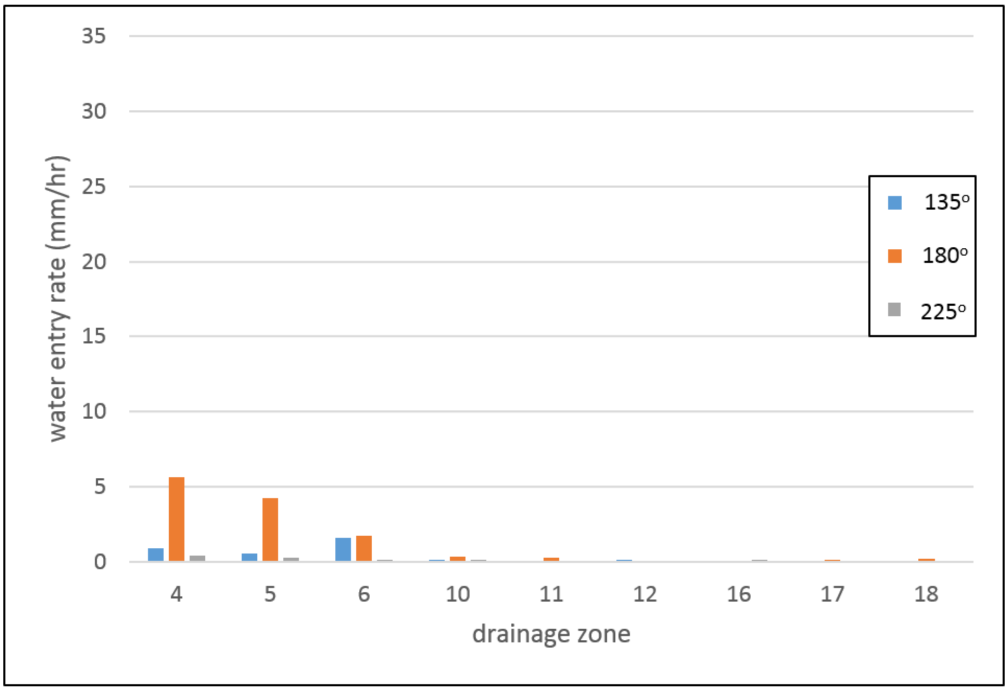

Figure 6. Water entry results for the tests of the bare roof deck with seams taped at sheathing joints for selected drainage zones and building orientations, for the high wind speed record.

4.3 *Bare roof deck with a nominal 38.1-mm closed-cell polyurethane foam fillet applied inside the attic space along sheathing joints*

After tests of sealed roof deck options involving exterior applications of tape, synthetic underlayments, and two layers of high-quality felt were completed, the roof deck was removed and replaced with new material. Plywood was installed on the C-side of the test building and OSB on the A-side of the test building. A closed-cell polyurethane foam adhesive with a density between 30.1-37.6 kg/m^3 was then applied to the underside of the roof deck over all joints between roof sheathing panels and as fillets along both sides of roof framing members. This is also an accepted method for achieving a sealed roof deck in the IBHS FORTIFIED Home–Hurricane program. Because it is applied from within the attic, it is currently the only method available for achieving a sealed roof deck which does not require re-roofing. Closed-cell foam with a nominal 38.1-mm fillet was applied on the D half of the roof while the top surface of the roof deck remained bare. Water entry quantities were evaluated for the CD quadrant of the roof using data from roof drainage zones 4–6; 10–12; and 16–18. The water quantities collected are shown in Table 2 and Figure 7 for the various building orientations and the medium wind speed record.

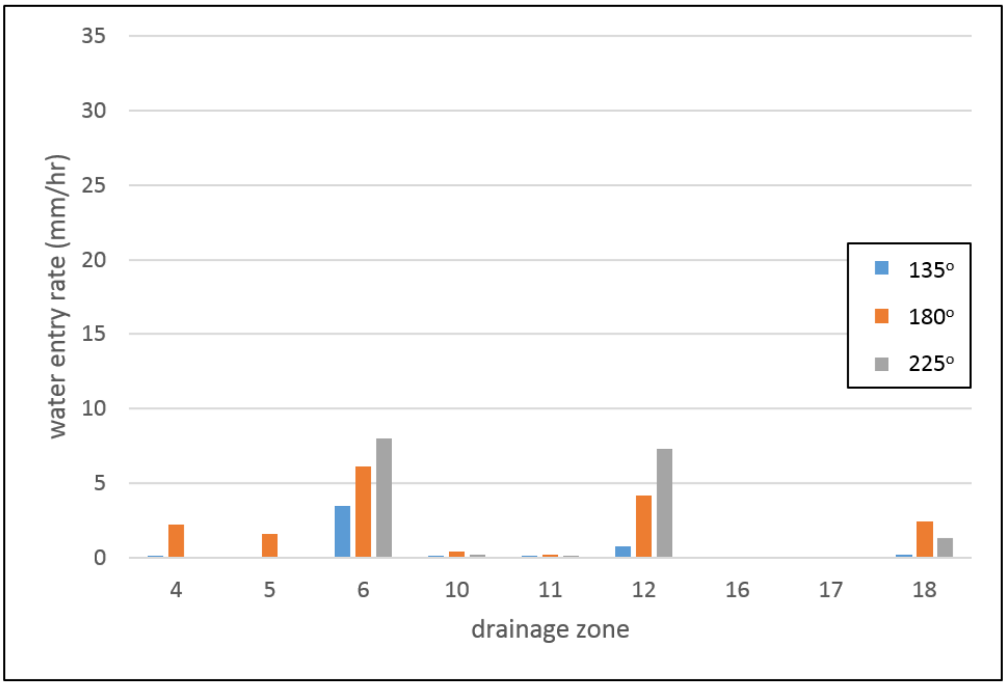

Figure 7. Water entry results for the tests of the bare roof deck with a nominal 38.1-mm closed-cell polyurethane foam in attic over all joints between roof sheathing and as fillets along both sides of roof framing members for selected drainage zones and building orientations, for the medium wind speed record.

Figure 7 shows the water entry rate was reduced for most roof drainage zones when compared to the bare roof deck (Figure 3). However, water entry rates for drainage zones 6 and 12 actually increased and notable water entry rates occurred at two building orientations for drainage zone 18 after the deck was replaced and closed-cell foam was applied. These three drainage zones are adjacent to the gable end wall at D. It is hypothesized that it was more difficult for the foam installers to reach some of the seams near the gable end of the roof—observations made during the experiments confirmed water entry occurred at the truss top-chord-to-sheathing joint closest to the end wall (zone 6). Reductions in water entry rates for most drainage zones were less than the reductions achieved by taping the sheathing joints. However, the total water quantity that entered the building was clearly reduced by adding closed-cell foam in the attic at sheathing panel joints and along framing members.

The water entry rates through the bare roof deck with the nominal 38.1-mm closed-cell foam over all joints between roof sheathing panels and as fillets along both sides of roof framing members for the high wind speed record are shown in Table 3 and Figure 8 for the various building orientations. With the exception of drainage zones 4 and 5 for the 180° building orientation case, all drainage zones with notable water entry rates at the medium wind speed experienced lower water entry rates during the high-speed tests. The largest water quantities were collected at the roof drainage zones adjacent to the eave (4–6), and at zone 12 next to the gable end. Water quantities were generally largest for the 180° (eave perpendicular to the wind) building orientation. Away from the soffit, the water entry rates were reduced by at least 65% and in many cases by much more except for drainage zone 12 when comparing the high wind speed cases for the nominal 38.1-mm foam installation to the cases with no mitigation systems in place. The lack of water entry reduction for zones 6 and 12 again indicated the closed-cell foam installers may have had more difficulty providing effective application of the foam near the gable end.

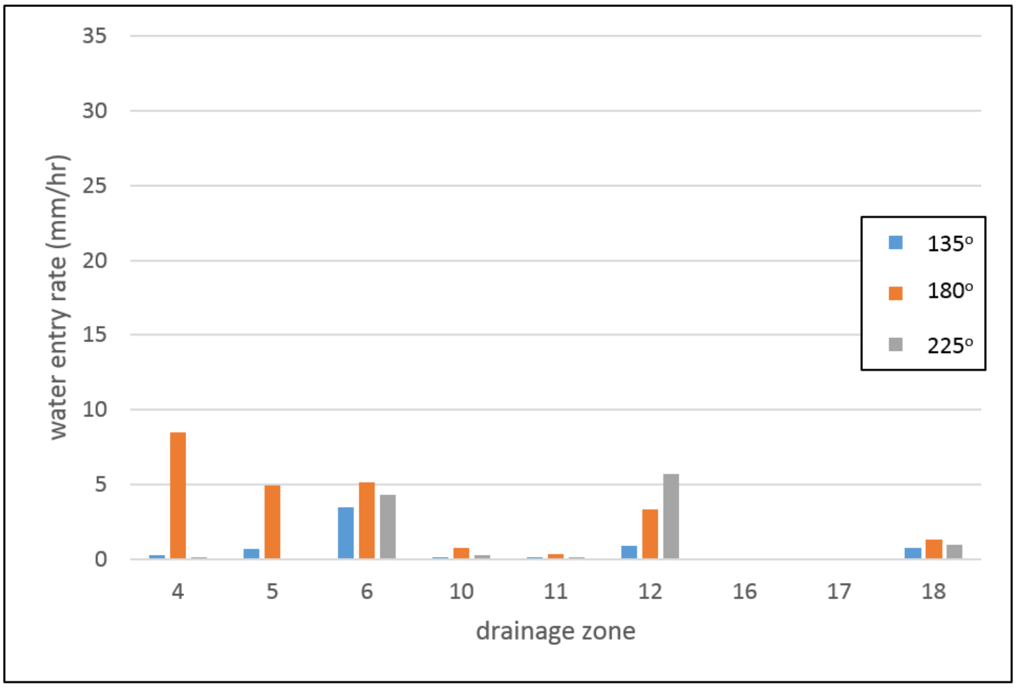

Figure 8. Water entry results for the tests of the bare roof deck with a nominal 38.1-mm closed-cell polyurethane foam fillets at sheathing joints in the attic space for selected drainage zones and building orientations, for the high wind speed record.

4.4 Synthetic underlayment with taped underlayment seams

Applying a high-strength synthetic underlayment over the entire roof deck and sealing all underlayment seams with a compatible adhesive or tape is another acceptable method for achieving a sealed roof deck in the IBHS FORTIFIED Home–Hurricane program. To evaluate the effectiveness of this method, synthetic underlayment was installed on the B side of the test building and the seams were taped with a modified bitumen tape. Water entry quantities were evaluated for BC quadrant using water entry data from roof drainage zones 1–3; 7–9; and 13–15. These are shown in Table 4 and Figure 9 for the various building orientations and the medium wind speed record.

Table 4. Water entry results for the installation of synthetic underlayment with taped seams, bare roof deck with nail holes exposed, and closed-cell polyurethane foam (nominal 76.2-mm fillet) at sheathing joints, for selected drainage zones and building orientations, for the medium wind speed record.

	Water collection rate (mm/hr)								
	Synthetic underlayment with taped seams			Bare roof deck with nail holes exposed			Bare roof deck with closed-cell polyurethane foam at sheathing joints—nominal 76.2-mm fillet		
	Building orientation			Building orientation			Building orientation		
Drainage partition	135	180	225	135	180	225	135	180	225
1	0.13	0.09	0.32	21.47	18.61	13.15	0.87	0.71	0.64
2	0.08	0.55	0.43	21.61	15.31	18.26	0.06	0.84	0.28
3	0.24	1.07	0.38	29.14	20.38	17.83	0.02	0.82	0.05
7	0.02	0.02	0.01	11.44	8.95	3.37	1.48	2.03	0.04
8	0.03	0.06	0.06	10.57	8.85	7.55	0.10	0.19	0.12
9	0.03	0.01	0.02	10.31	10.53	8.79	0.22	0.34	0.22
13	0.00	0.01	0.01	7.89	9.02	1.36	1.50	2.55	0.49
14	0.00	0.00	0.00	5.17	7.43	3.97	0.03	0.03	0.01
15	0.00	0.01	0.01	6.30	9.09	6.51	0.02	0.02	0.01

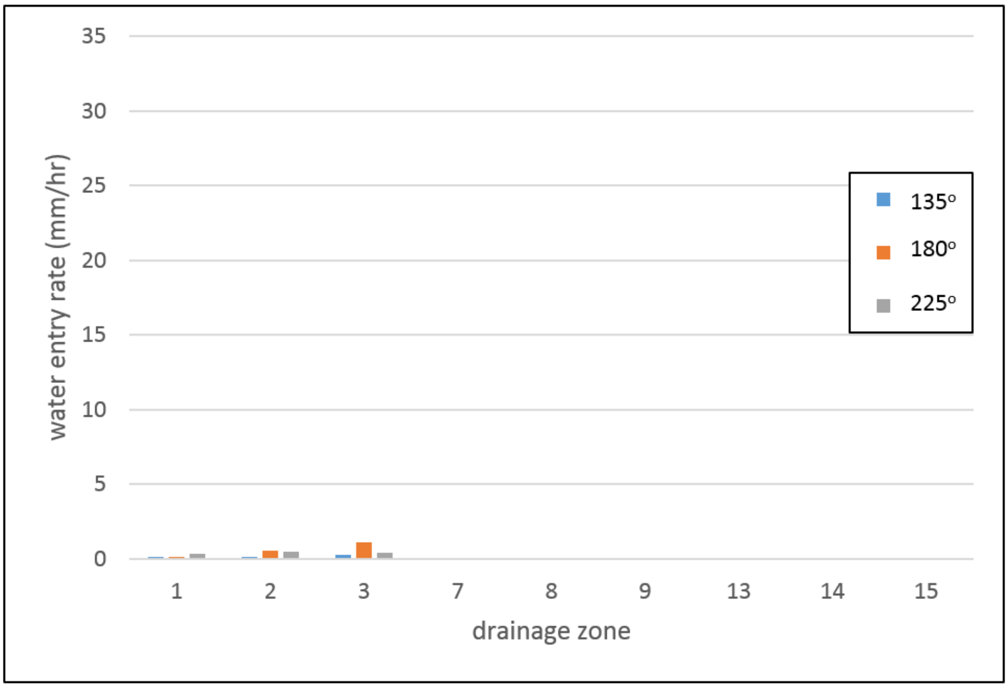

Figure 9. Water entry results for the application of synthetic roof underlayment with taped seams for selected drainage zones and building orientations, for the medium wind speed record.

Figure 9 illustrates the dramatic reduction in water entry for all roof drainage zones when compared to the symmetric zones from the bare roof deck tests (Figure 3). Water entry rates were reduced by at least 93% compared to the corresponding bare roof tests for all drainage zones except 7 in the 135° case, where the water entry rate was very small for both test scenarios. The water entry rate results for this application of synthetic underlayment with taped seams were comparable to that with the taped sheathing joints (Figure 5) and better than the results obtained using the nominal 38.1-mm closed-cell polyurethane foam fillet application (Figure 7). So long as the underlayment was properly installed and did not come loose during high winds, this method reduced the water entry rate to minimal quantities.

The water quantities collected for the high wind speed record for the synthetic underlayment with taped underlayment seams are shown in Table 5 and Figure 10 for the various building orientations. The results showed similar water entry rates for the medium and high wind speed record tests for this mitigation method. The largest quantities entered at the eave drainage zones (1–3), but all quantities were less than 2 mm/hr. The water entry rates were reduced by at least 5 times for all but one relative drainage zones, when comparing the high wind speed cases with the synthetic underlayment installation to the cases with no mitigation systems in place. Similar to the medium wind speed cases, for the high wind speed the synthetic underlayment installation created the least amount of water entry as compared to the previous two mitigation methods discussed in sections 4.2 (taped sheathing seams) and 4.3 (nominal 38.1-mm closed-cell foam fillet) above.

Table 5. Water entry results for the installation of synthetic underlayment with taped seams, bare roof deck with nail holes exposed, and closed-cell polyurethane foam (nominal 76.2-mm fillet) at sheathing joints, for selected drainage zones and building orientations, for the high wind speed record.

	Water collection rate (mm/hr)								
	Synthetic underlayment with taped seams			Bare roof deck with nail holes exposed			Bare roof deck with closed-cell polyurethane foam at sheathing joints—nominal 76.2-mm fillet		
	Building orientation			Building orientation			Building orientation		
Drainage partition	135	180	225	135	180	225	135	180	225
1	0.11	2.05	1.09	12.95	12.89	10.67	0.42	1.54	1.09
2	0.13	3.50	1.33	10.74	11.70	14.40	0.05	4.36	0.90
3	1.43	4.51	1.61	14.56	11.76	11.51	0.01	3.92	0.33
7	0.12	0.09	0.07	5.63	7.18	2.57	0.91	2.50	0.56
8	0.28	0.83	0.41	5.19	7.00	6.24	0.08	0.59	0.12
9	0.27	0.49	0.47	6.58	7.92	6.15	0.18	0.59	0.21
13	0.02	0.02	0.01	6.33	6.35	0.71	1.03	1.56	0.73
14	0.00	0.01	0.01	4.13	5.87	2.40	0.04	0.03	0.00
15	0.01	0.04	0.01	4.77	6.75	4.11	0.01	0.01	0.00

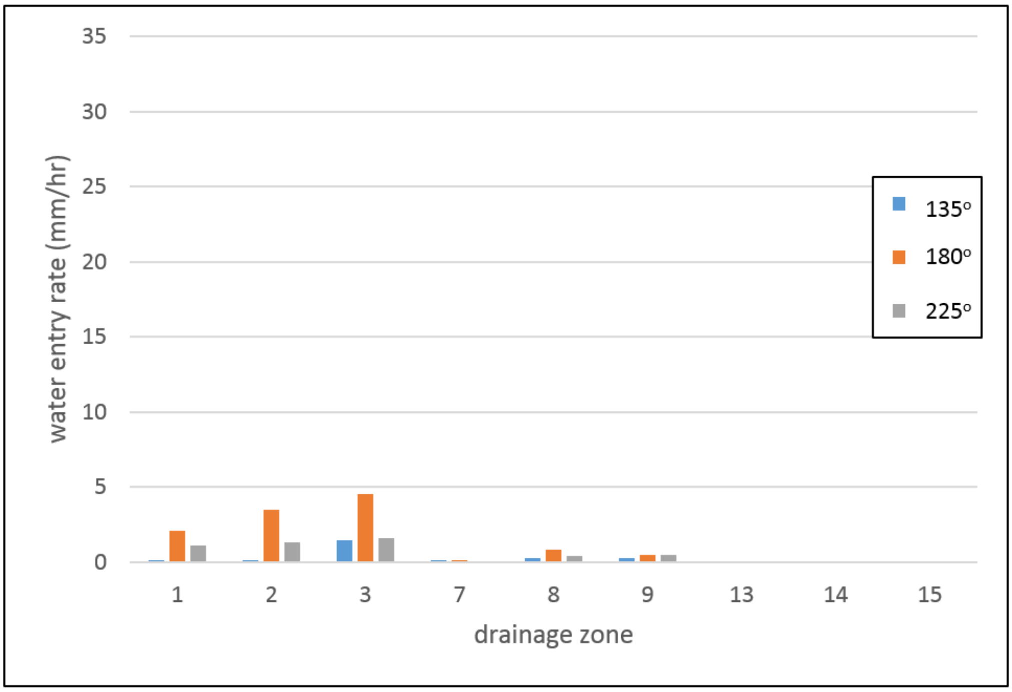

Figure 10. Water entry results for the application of synthetic roof underlayment with taped seams for selected drainage zones and building orientations, for the high wind speed record.

4.5 Bare roof deck with sheathing joints and nail holes exposed

Testing conducted by Quarles et al. [5] indicated nail holes from withdrawn fasteners were susceptible to water entry. Thus, when testing of the synthetic underlayment was complete, the underlayment and associated fasteners were removed, leaving the bare roof deck with sheathing joints and underlayment nail holes exposed. This simulates a situation in which the wind was strong enough and lasted for a long enough duration to remove both the roof covering and underlayment. Water entry rates were again evaluated for the BC quadrant of the roof and results are shown in Table 4 and Figure 11 for various building orientations for the medium wind speed record.

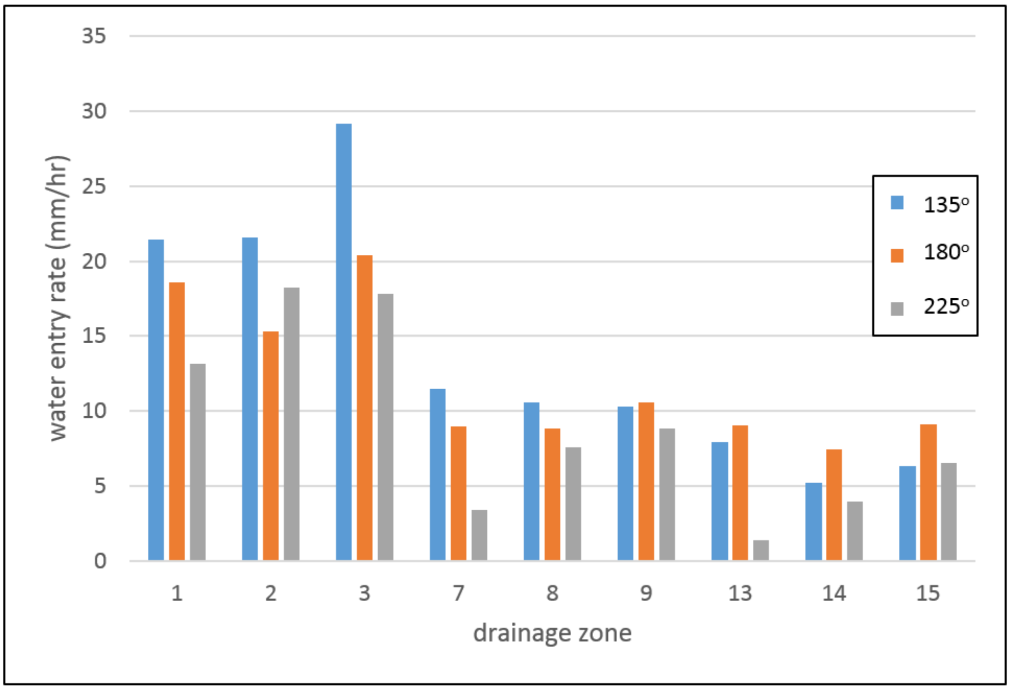

Figure 11. Water entry results for selected drainage zones and building orientations for the medium wind speed record when the synthetic roof underlayment was removed, leaving the sheathing joints and nail holes exposed.

The results in Figure 11 indicate that a large amount of water entered in various zones of the roof when there was no mitigation method employed and when the underlayment nails were removed to simulate withdrawn fasteners. The water entry rates were dramatically higher than when the underlayment was in place. Using building symmetry to compare data from this test series to the bare roof deck (control) tests shown in Figure 3, drainage zones 1, 2 and 3 in Figure 11 correspond to drainage zones 6, 5 and 4, respectively; drainage zones 7, 8 and 9 correspond to drainage zones 12, 11 and 10, respectively; and drainage zones 13, 14 and 15 correspond to drainage zones 18, 17 and 16, respectively. Similarly, building orientation 225° in Figure 11 corresponds to 135° in Figure 3, and 135° in Figure 11 corresponds to 225° in Figure 3. Zone 3 in Figure 11 experienced roughly similar water entry rates to zone 4 in Figure 3, although the highest water entry rates both occurred for a direction of 135° as opposed to the expected mirroring of results. Drainage zones 1, 2, 7, 8 and 9 for the case with the synthetic underlayment removed (Figure 11) all experienced significantly higher water entry rates than their corresponding drainage zones for the bare roof control case (Figure 3). The increased water entry rates may be due to the exposed nail holes or to more water being blown farther into the attic because of the difference in soffit ventilation configuration. Differences in water entry through various soffit venting configurations will be examined using additional data from experiments in this project, but results are outside the scope of this paper. Water entry rates for drainage zones 13, 14 and 15 in Figure 11 are of similar magnitude to the water entry rates for zones 16, 17 and 18 in Figure 3, except that the water entry rates are more uniform in Figure 11 while they decrease from 16 through 18 in Figure 3.

For the high wind speed record, the water entry rates measured for the bare roof deck with exposed nail holes are shown in Table 5 and Figure 12 for the various building orientations. The results show consistently lower water entry rates than for the medium wind speed tests for this scenario. This is consistent with the results observed for the bare roof deck (control) tests. A comparison of water entry rates shown in Figure 12 with those for the corresponding drainage zones for the bare roof deck in Figure 4 show similar trends to that described above for the medium speed tests. The largest increases in water entry rates occurred for drainage zones 7–9 in Figure 12 as compared with drainage zones 10–12 in Figure 4.

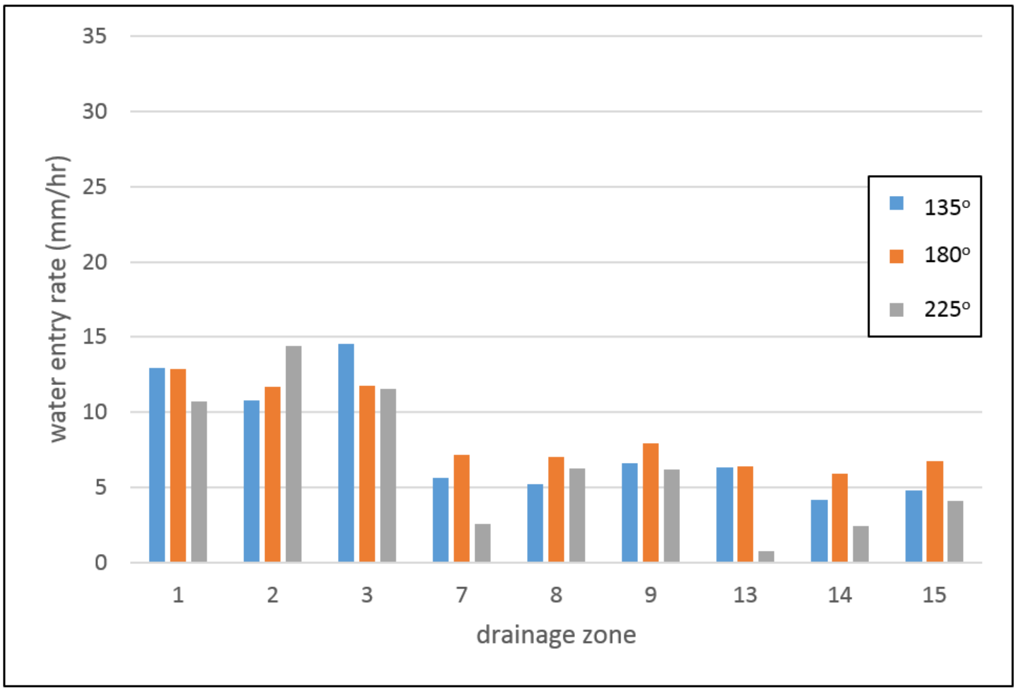

Figure 12. Water entry results for selected drainage zones and building orientations for the high wind speed record when the synthetic roof underlayment was removed, leaving the sheathing joints and nail holes exposed.

4.6 Bare roof deck with a nominal 76.2-mm closed-cell polyurethane foam fillet applied inside the attic space along sheathing joints

To evaluate the water entry mitigation performance for a thicker and wider application of closed-cell polyurethane foam, a nominal 76.2-mm layer of foam was applied over all joints between roof sheathing panels and as fillets along both sides of roof framing members from inside the attic space on the B half of the roof. Water entry rates were evaluated for the BC quadrant using data for roof drainage zones 1–3; 7–9, and 13–15. These values are shown in Table 4 and Figure 13 for various building orientations for the medium wind speed record.

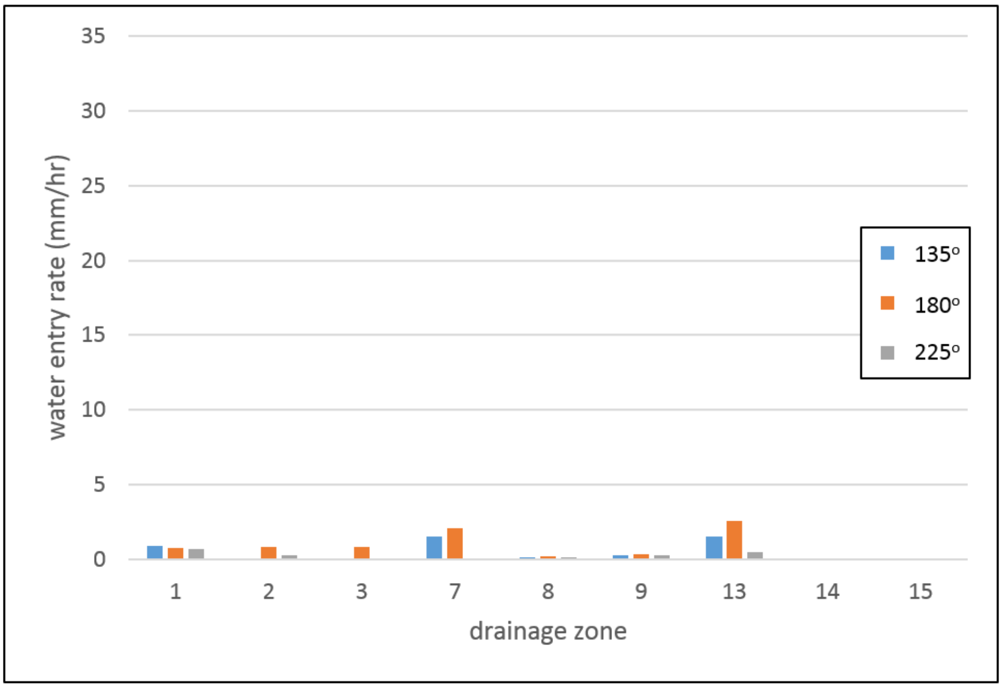

Figure 13. Water entry results for the tests of the bare roof deck with a nominal 76.2-mm closed-cell polyurethane foam in attic over all joints between roof sheathing and as fillets along both sides of roof framing members for selected drainage zones and building orientations, for the medium wind speed record.

Figure 13 shows a dramatic reduction in water entry rates when compared to the bare roof case (Figure 3), and water entry rates are less than 3 mm/hr for all drainage zones and all building orientations. Similar to the 38.1-mm application of foam, the largest water entry rates occurred in drainage zones next to the gable end. However, water entry rates at the roof corner (drainage zone 1) were very low compared to the rates observed for the 38.1-mm foam installation (drainage zone 6 in Figure 8). Water entry rates in the field (7) and ridge zone (13) were also substantially lower for the thicker foam application. In general, the water entry rates for the thicker (nominal 76.2-mm) closed-cell foam installations at the medium wind speed were substantially reduced, though not to the same degree of effectiveness as the methods of taped sheathing joints or application of synthetic underlayment with taped seams.

The water entry rates measured for the bare roof deck with a nominal 76.2-mm closed-cell foam attic application for the high wind speed records are shown in Table 5 and Figure 14 for the various building orientations. For most roof drainage zones, the higher wind speed record resulted in slightly higher water entry rates for the 180° building orientation case than the rates measured for the medium wind speed tests for this mitigation method. The largest water quantities entered at the eave drainage zones (1–3) and along the gable end in zone 7. Water entry rates were substantially reduced when compared to the high wind speed cases with the bare roof deck (control, Figure 4) cases. As was the case with the medium wind speed record, the application of a nominal 76.2-mm closed-cell foam fillet reduced water entry, though not quite as much as taped sheathing seams or the application of synthetic underlayment with taped seams. The total amount of water entry was generally less for the thicker foam application.

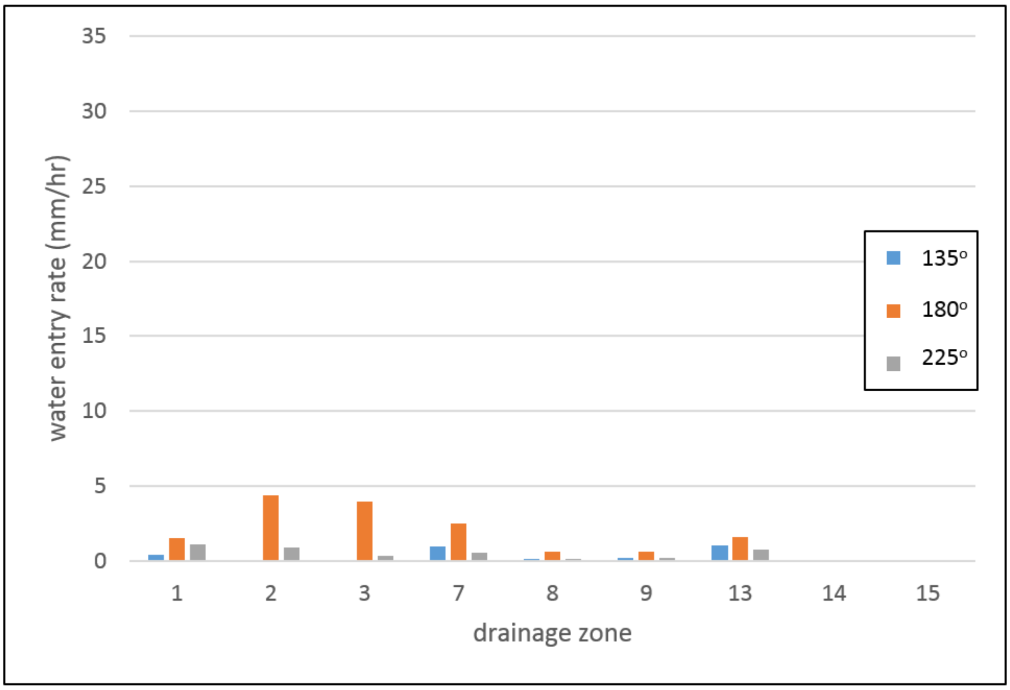

Figure 14. Water entry results for the tests of the bare roof deck with a nominal 76.2-mm closed-cell polyurethane foam in attic over all joints between roof sheathing and as fillets along both sides of roof framing members for selected drainage zones and building orientations, for the high wind speed record.

4.7 Roof deck covered with two layers of ASTM D 226, Type II underlayment lapped according to requirements for 2:12 through 4:12 roof slopes and attached following Florida's HVHZ fastening requirements

Although not included in the list of acceptable methods originally developed for achieving a sealed roof deck in the IBHS FORTIFIED Home–Hurricane program, applying two layers of underlayment is a well-established method for roofs with slopes between 2:12 and 4:12. At the recommendation of a roofing expert, two layers of ASTM D 226, Type II underlayment was applied following these lower slope requirements and attached following the fastener spacing requirements of Florida's HVHZ guidance, according to Section 1518.2.1 of the Florida Building Code-Building [21] and Section R4402.7.2.1 of the 2010 Florida Building Code-Residential [22]. This method was evaluated during this testing program to compare to sealed roof deck methods accepted by the FORTIFIED Home–Hurricane program, and to evaluate whether it should be added to the list of approved methods. This application was applied to both halves of the roof, thus all drainage zones 1–18 were evaluated, and data are provided in Table 6 and Figure 15 for the medium wind speed cases. Data for the high wind speed cases are also shown in Table 6 and in Figure 16. On the B half of the roof, conventional plastic button cap nails were used to fasten the underlayment, while the D half of the roof used tin caps and ring shank nails meeting the requirements of Florida's HVHZ according to Section 1517.5 of the Florida Building Code-Building [21] and Section R4402.6.5 of the 2010 Florida Building Code-Residential [22] to fasten the underlayment. Neither side suffered underlayment loss during the tests.

Table 6. Water entry results for the installation of two layers of ASTM D 226, Type II underlayment lapped according to requirements for 2:12 through 4:12 roof slopes and attached following Florida's HVHZ fastening requirements, for selected drainage zones and building orientations, for the medium wind speed record.

	Water collection rate (mm/hr)					
	Medium wind speed			High wind speed		
	Building orientations			Building orientations		
Drainage partition	135	180	225	135	180	225
1	0.02	0.21	0.45	1.38	2.06	0.04
2	0.00	0.77	0.50	1.47	3.48	0.05
3	0.01	0.71	0.19	0.80	3.43	0.09
4	0.02	1.79	0.11	0.19	6.39	0.23
5	0.01	1.73	0.04	0.02	5.55	0.41
6	0.09	0.64	0.02	0.02	2.21	1.81
7	0.00	0.01	0.01	0.01	0.03	0.01
8	0.00	0.00	0.00	0.07	0.18	0.00
9	0.02	0.01	0.01	0.00	0.10	0.01
10	0.00	0.00	0.01	0.02	0.09	0.01
11	0.01	0.00	0.00	0.00	0.24	0.02
12	0.01	0.00	0.00	0.01	0.02	0.04
13	0.00	0.00	0.05	0.01	0.00	0.01
14	0.00	0.00	0.00	0.00	0.02	0.00
15	0.00	0.00	0.01	0.01	0.01	0.01
16	0.01	0.01	0.02	0.02	0.01	0.01
17	0.01	0.00	0.01	0.00	0.01	0.00
18	0.00	0.01	0.01	0.01	0.00	0.01

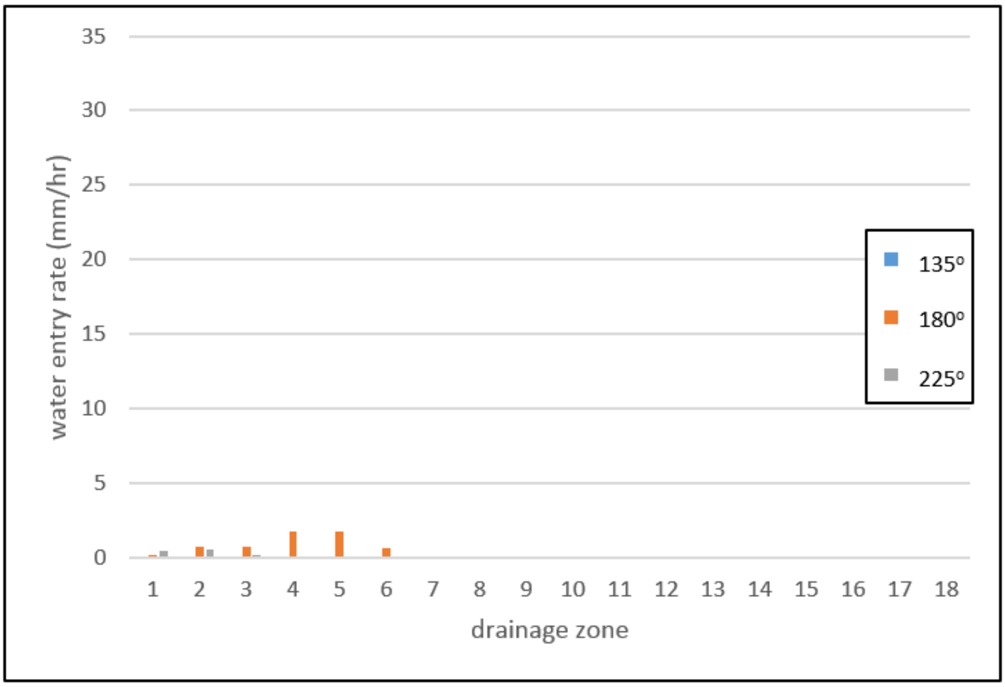

Figure 15. Water entry results for tests of two layers of ASTM D 226 Type II underlayment for selected drainage zones and building orientations, for the medium wind speed record.

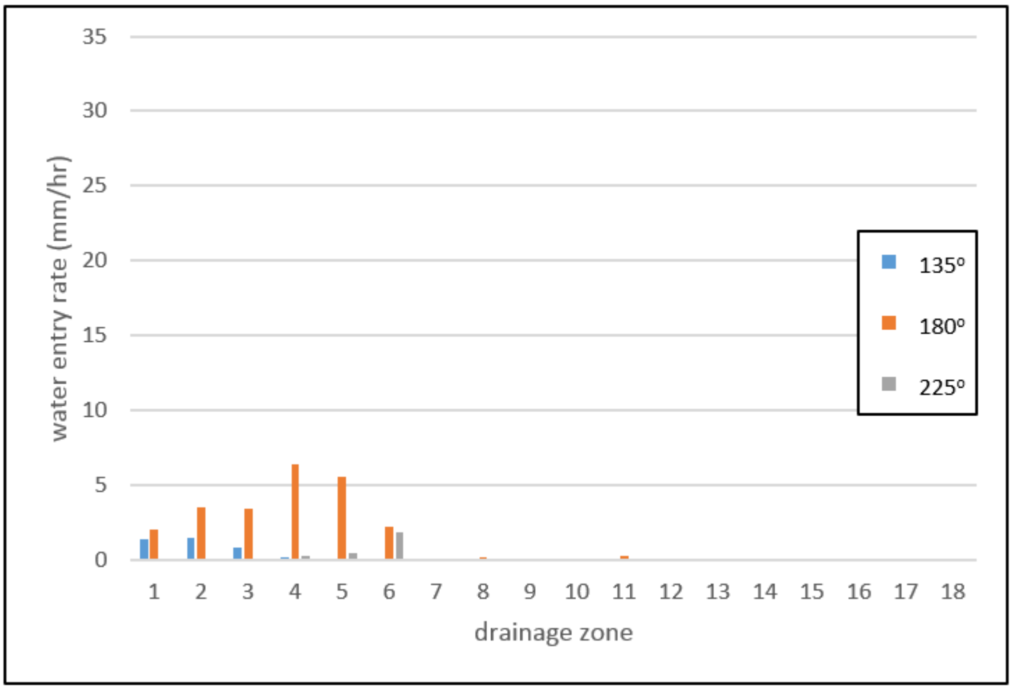

Figure 16. Water entry results for tests of two layers of ASTM D 226 Type II underlayment for selected drainage zones and building orientations, for the high wind speed record.

The largest water entry rates for the medium wind speed record occurred at the eave edges of the roof in drainage zones 1–6, and all entry quantities were less than 2 mm/hr. Largest water entry rates occurred for the perpendicular building orientation of 180°. Water entry rates were significantly reduced compared to the bare roof deck (control, Figure 3). Water entry rates for this application were similar to those of the taped sheathing joints and synthetic underlayment with taped seams applications. Water entry rates for the two layers of felt were smaller than those of the closed-cell polyurethane foam installations inside the attic space.

More water entered the roof for the high wind speed tests than for the medium wind speed tests for the system with two layers of felt. Largest water quantities were captured along the eave edge of the roof, and values ranged from 2–7 mm/hr for these zones when the wind was perpendicular (180°). These data indicated the effectiveness of this mitigation method.

5 SUMMARY AND FUTURE WORK

Water entry rates were evaluated for many roof system configurations under several wind conditions and impinging water rates. The results are summarized in Figures 17 and 18 for the medium and high wind speed cases, respectively. These show the total water entry rate for the windward-facing portion of the roof for each of the mitigation strategies as compared to the control case (bare roof deck). This was calculated by summing the total volume of water that entered the roof in a given test, and dividing it by the total square area of all drainage zones and the duration of the test. From these comparisons, it is apparent that each mitigation method was effective in reducing the total water entry rate for the windward half of the roof. Water entry rates were at least 70% lower or more when one of the mitigation methods was installed. For most mitigation measures, the total water entry rates were slightly higher for the high wind speed records.

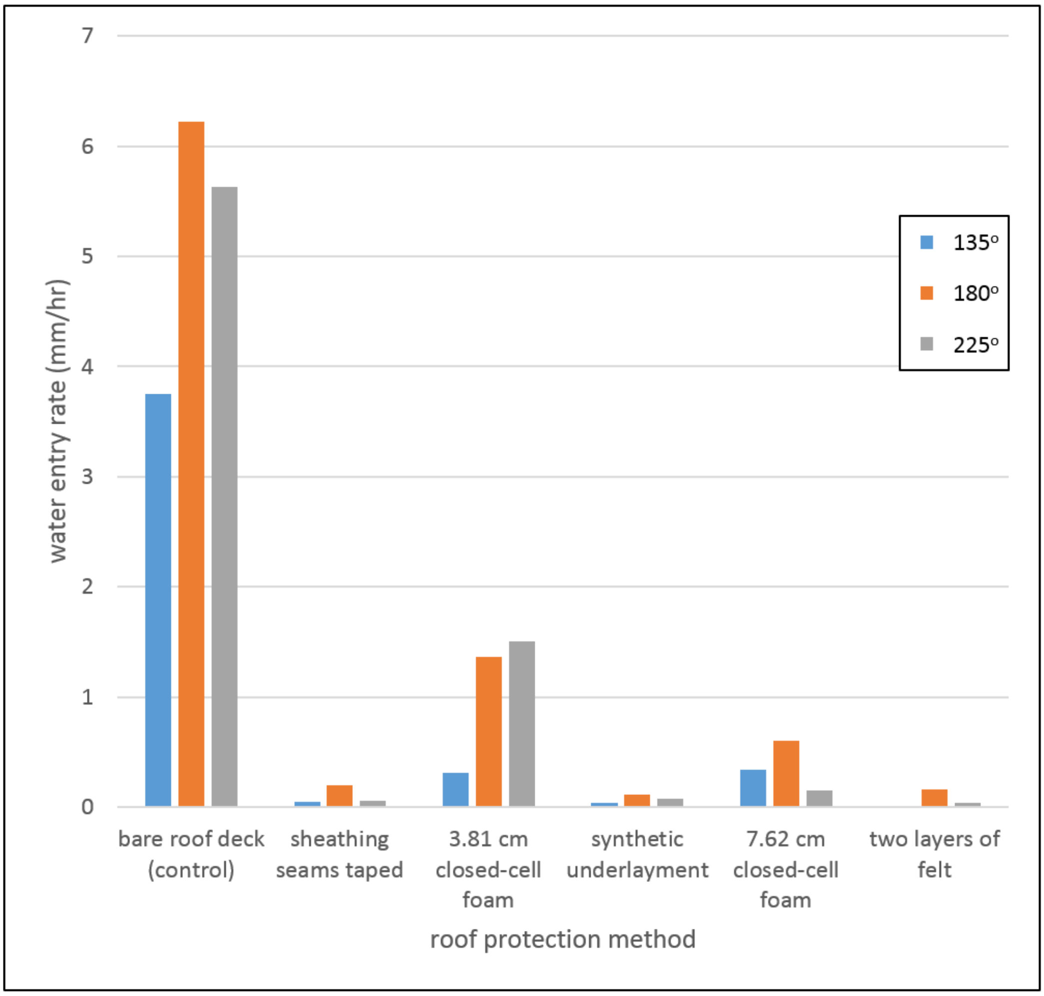

Figure 17. Total water entry rates for the windward-facing portions of the roof for each mitigation strategy and the control test for select building orientations, for the medium wind speed record.

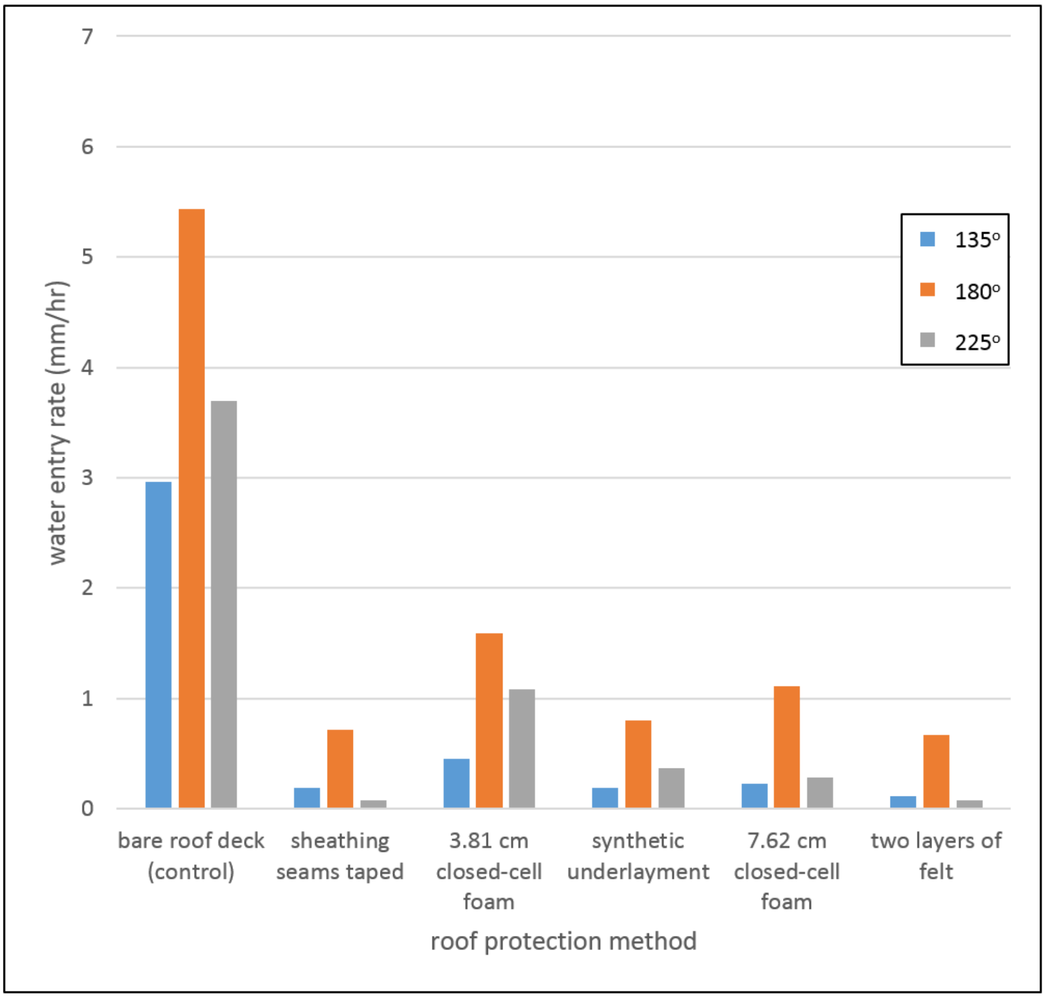

Figure 18. Total water entry rates for the windward-facing portions of the roof for each mitigation strategy and the control test for select building orientations, for the high wind speed record.

The key results are summarized as follows:

1. When no mitigation actions were taken, water entry rates were large. The largest quantities entered in portions of the roof adjacent to the eave for the building orientations evaluated.
2. There were generally not large differences in water entry rates as a function of building orientation, although when differences were seen, water entry was usually greatest at the 180° perpendicular direction.
3. For some test scenarios, water entry in some portions of the attic was greatest for the medium wind speed record, while for others it was greatest for the high wind speed record.
4. All sealed roof deck mitigation methods reduced the amount of water entry into the attic space by 70% or more. If the drainage zones where soffit water entry may have occurred were not considered, the water entry rates in many cases could be reduced even further.
5. From this dataset, the reduction in water entry was greatest for (a) taped sheathing joints; (b) synthetic underlayment with taped seams; and (c) two layers of ASTM D 226 Type II underlayment.
6. Mean water entry rates were not much reduced in the corner roof zones (1 and 6) for the 38.1-mm fillet closed-cell polyurethane foam mitigation method. It is hypothesized that application in this area of the roof may have been difficult for the installers due to the small amount of working space. Therefore, when this water entry mitigation method is selected, extra care should be taken in corners and other tight spaces to ensure adequate foam coverage and protection.

As a result of the testing, the IBHS FORTIFIED Home requirements for a sealed roof deck have been updated to include the two-layer application of ASTM D 226 Type II felt system. The next steps of this study will involve investigating the water entry rates for additional building orientations, wind speed, and water quantity rates. Water entry on the other half of the building will also be evaluated to determine the effects of treatments in the valleys. The water entry rates for the various doors and windows will also be evaluated to determine which systems are most vulnerable to wind-driven water entry.

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