INVESTIGATION OF CHAMBER SIZE FOR UPLIFT PERFORMANCE TESTING OF SINGLE-PLY ROOF SYSTEMS

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The intent of this investigation was to analyze the static uplift performance of two mechanically fastened single-ply membranes. Standard tests were performed using various chamber sizes to determine whether a minimum size could be identified. This minimum size would need to be large enough to eliminate any influence from the perimeter clamping system and produce uplift results comparable to the larger chamber sizes currently being used. The investigation was conducted at Clemson University's Wind Load Test Facility using the BRERWULF system and followed the uplift pressure sequence specified in the Underwriters Laboratories (UL) 1897 and the Factory Mutual (FM) 4470 standardized test protocols. The project was funded by Carlisle SynTec Incorporated, and the testing was conducted by the Civil Engineering Department at Clemson University.

KEYWORDS

BRERWULF, chamber size, fastener load, mechanically fastened, roofing, tributary area, wind uplift tests.

INTRODUCTION

Wind uplift testing of mechanically fastened single-ply roof systems can be conducted by a variety of methods, including either static or dynamic pressure loading. European countries tend to prefer dynamic pressure tests while the United States historically has utilized static pressure test methods. The results of standardized tests are used by roofing manufacturers to establish design values for their systems. Therefore, it is critical that these standardized tests provide a meaningful measure of the absolute performance of roof systems and not simply a relative measure between various roof systems.

Dynamic uplift testing in Europe is conducted following the *UEAtc Supplementary Guide For The Assessment Of Mechanically-Fastened Roof Waterproofing.*[1] This UEAtc procedure consists of first applying 20,000 conditioning cycles with an oscillating load of zero to 100 N (22 pounds) per fastener, then applying a maximum load of 300 N (67 pounds) per fastener over a graduated cycle, and then increasing the maximum cycle load in successive increments of 100 N (22 pounds) per fastener increments until failure occurs. Because fastener loads are not measured, the loading is calculated by assuming a tributary area for a critical fastener and using this area in combination with correction factors and the uplift pressure acting on the membrane to calculate the uplift load per fastener.

One piece of equipment that can be used to apply time-fluctuating air pressure to a test specimen is Building Research Establishment Real-time Wind Uniform Load Follower (BRERWULF). The Building Research Establishment in the United Kingdom developed BRERWULF with the goal of being able to test roof and wall systems under a loading environment more similar to the actual dynamic loading seen in the field. BRERWULF creates either positive or negative pressure in a test chamber and can cycle between these as desired to create a dynamic loading. Although there is no standard loading procedure established for roof systems using BRERWULF, the system can be used to duplicate pressure fluctuations recorded from any wind storm event, wind tunnel study, or any predetermined static or dynamic cycle.

In the United States, wind uplift testing of mechanically fastened single-ply membranes is conducted following the test protocols described in Underwriters Laboratories (UL) 1897[2] or Factory Mutual (FM) 4470[3] test standards. The testing method for both of these protocols consists of pressurizing the underside of the membrane to 1.45 kPa (30 psf) and holding for one minute. If the specimen does not fail, the pressure is increased by 0.72 kPa (15 psf) and again held for one minute. The pressure is increased in increments until failure of the roof system is reached. The difference between the UL and FM test protocols is the specified size of the test chamber. UL requires a 3.0-m by 3.0-m (10-foot by 10-foot) chamber, while FM requires a 3.7-m by 7.3-m (12-foot by 24-foot) chamber. Other chamber sizes have been considered by the industry for the testing of single-ply membrane and other roof systems.

In a 1993 paper, Malpezzi and Gillenwater compared the results of static and dynamic wind uplift performance tests.[4] The main conclusion of their study was that dynamic testing of single-ply membranes did not offer any benefits over static testing because of the elastic behavior of the single-ply membranes. They concluded that the failure load of a dynamic test would be about the same value as the failure load obtained by a much simpler static test. One of their recommendations was to determine the optimum chamber size for static uplift testing to adequately predict the field performance of single-ply roof systems.

This study takes a more complete look at the effect of chamber size on single-ply membrane failure loads. The results suggest that both the chamber size and its shape (or aspect ratio) can greatly influence the uplift pressure at failure. The chamber aspect ratio is defined as the ratio of chamber width to the membrane span length (measured perpendicular to the seam) (see Figure 1). For a specimen with two or more seams, the span length (perpendicular to the width) is defined as the fastener row spacing. For a single-seamed specimen, the span length is the distance between the fastener row and either chamber edge parallel to the seam.

PROJECT OVERVIEW

A limitation in the current test protocols (UEAtc, FM, and UL) is that they do not provide for the measurement of the actual fastener loads. Instead, the uplift pressure acting on the specimen is multiplied by a calculated tributary area of a fastener to determine this load. The tributary area for a typical interior fastener is a rectangular area with dimensions equal to the fastener spacing along a row and the span length of the fabricated membrane. However, no data is available to verify the relationship between uplift pressure and fastener loads for specimens of various sizes. Therefore, rather than providing an absolute measure of the uplift capacity of a single-ply roof membrane, each protocol only provides a relative measure of performance between specimens tested under the same conditions.

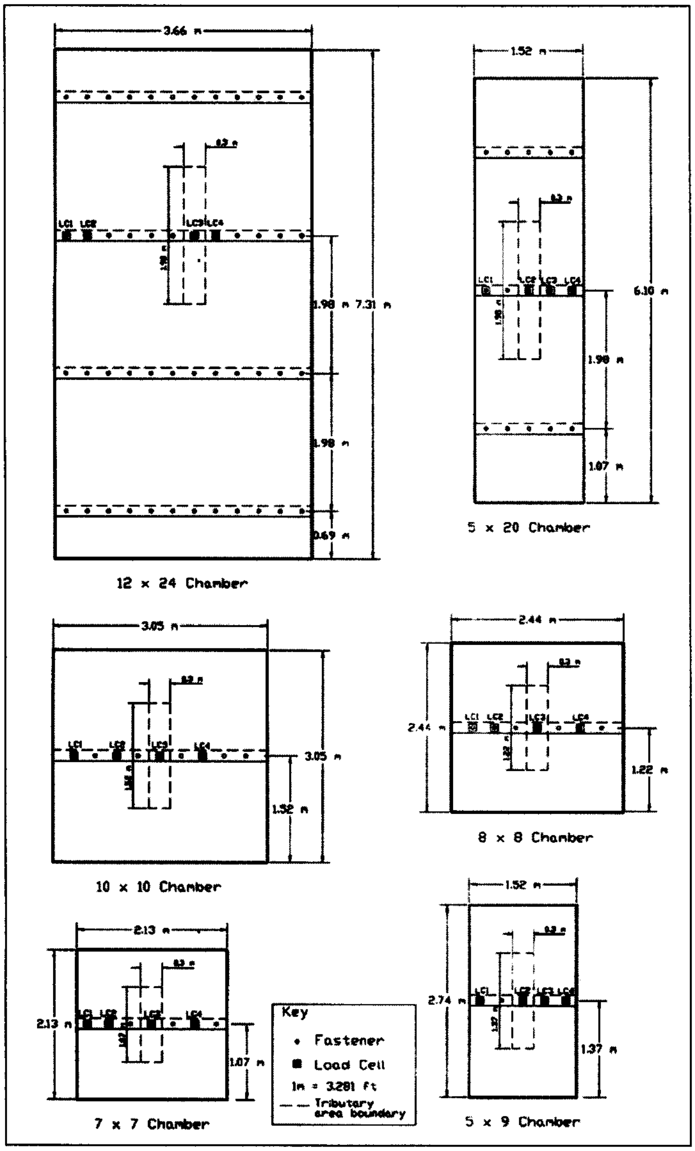

Figure 1. Specimen layouts for evaluated chamber sizes.

The chamber size investigation study was conducted by the Civil Engineering Department of Clemson University using the BRERWULF system connected to a pressure chamber. The project was funded by Carlisle SynTec Incorporated, and testing was conducted in two phases. Phase 1 of the investigation consisted of testing single-ply membranes fabricated from 2.1-meter- (7-foot-) wide reinforced ethylene propylene dienne monomer (EPDM) sheets mechanically fastened to a steel deck. Chamber sizes of 1.5 m by 2.7 m (5 feet by 9 feet), 2.1 m by 2.1 m (7 feet by 7 feet), 2.4 m by 2.4 m (8 feet by 8 feet), 1.5 m by 6.1 m (5 feet by 20 feet), 3.0 m by 3.0 m (10 feet by 10 feet), and 3.7 m by 7.3 m (12 feet by 24 feet) were evaluated.

Phase 2 of the investigation consisted of testing single-ply membranes fabricated from 2.1-m- (7- foot-) wide reinforced thermoplastic olefin (TPO) sheets mechanically fastened to a steel deck. Only chamber sizes of 1.5 m by 2.7 m (5 feet by 9 feet), 2.4 m by 2.4 m (8 feet by 8 feet), and 3.7 m by 7.3 m (12 feet by 24 feet) were considered. The nonstandard 2.4- by 2.4-m (8- by 8-foot) chamber size was considered because it appeared (from the tests on the EPDM specimens) to be the smallest chamber size that allowed for direct comparisons between the membrane uplift pressure and fastener loads at failure. The fabricated specimens for four of the six chamber sizes had a single fastener row aligned with the centerline of the chamber, while the fabricated specimens for the other two chambers had multiple fasteners rows (see Figure 1 for specimen layout of each chamber size). In both phases, the failure pressure and uplift load per fastener for selected fasteners along the center seam of each specimen were recorded.

TEST SETUP

A pressure chamber measuring 4 m by 7.9 m (13 feet by 26 feet) and 380 mm (15 inches) deep was used for all the tests. The 380-mm- (15-inch-) deep steel chamber walls have a predrilled array of holes in the beam webs, which enables the installation of the purlins to support the steel deck. The chamber could be sectioned off to create the smaller subchambers better suited to test the smaller specimens. Cold-formed steel Z-sections, 225 mm (9 inches) in depth, were used for the purlins supporting the steel deck in all chambers except in the 1.5- by 6.1-m (5- by 20-foot) chamber, where 150-mm- (6-inch-) deep hot-rolled steel C-sections were used as purlins.

In all chambers, the roof purlins were spaced 1.5 m(5 feet) on center, onto which a 0.85-mm-thick (22-gauge) trapezoidal profiled steel deck was fastened. The attachment of the roof system to the pressure chamber is shown in Figure 2. A 50-mm- (2-inch-) thick polyisocyanurate insulation layer was installed on the steel deck using manufacturer- recommended fasteners and plates at a minimum coverage of one fastener for every 1.5 m^2 (4 square feet). All fasteners securing the single-ply membrane were fastened to the top flutes of the steel deck. An initial torque was applied to these fasteners (and load cell bolts), which created a clamping force of approximately 140 N to 230 N (30 to 50 pounds) between the fastener plates and the deck. Air/vapor retarders were not used in this setup to allow the single-ply membrane to carry the full pressure within the pressure chamber.

The specimens in Phase 1 were fabricated from 2.1-m- (7-foot-) wide reinforced EPDM sheets that were fastened to the steel deck using threaded fasteners and 50-mm- (2-inch-) diameter nonbarbed metal plates. Threaded fasteners and fastening plates were centered within the 150-mm- (6-inch-) wide field splice and were spaced 300 mm (12 inches) on center (see Figure 3). The field splice was completed using a cleaner and splicing adhesive. EPDM specimens were tested after a minimum cure period of six days had elapsed, to give the adhesive time to attain full strength.

The specimens in Phase 2 were fabricated from 2.1-m- (7-foot-) wide reinforced TPO sheets that were fastened to the steel deck using threaded fasteners and 50-mm- (2-inch-) diameter barbed plastic plates. Threaded fasteners and fastening plates were spaced 300 mm (12 inches) on center near the edge of the bottom sheet, creating a "tab" field splice (see Figure 3). The field splice was completed using heat welding techniques.

The test of each specimen was initiated by subjecting the specimen to a static pressure of 1.45 kPa (30 psf) and holding it for one minute. The pressure was increased in increments of 0.72 kPa (15 psf), each held for one minute, until failure occurred. This loading sequence is the same as the one used in FM 4470 and UL 1897.

Three or four fasteners along a single seam were instrumented during each specimen test. Custom load cells were made to measure the vertical load in a fastener caused by static uplift pressure (see Figure 4). Typically, one load cell was placed at a central fastener location with another load cell adjacent to the first. The third and fourth load cells were placed near the edge of the chamber. This arrangement of load cells provided information about the load distribution along a fastener seam.

The output voltage from each load cell and the chamber pressure transducer was fed through signal conditioners to an A/D board of a PC-based data acquisition system. A sampling frequency of 100 Hz was used, and the mean value for two seconds of data was used to represent the fastener loads and chamber pressure respectively. Data was taken continually for the duration of each test. After each test was complete, a calibration was performed on each load cell using a 440-N (100-pound) spring scale and a commercial load cell.

RESULTS AND DISCUSSION

The only failure mode observed in both phases of the study was membrane tear around the fastening plates (see Figure 5). As expected, the TPO membranes that were fastened by asymmetrically loaded fasteners showed some lateral slippage prior to failure. In general, once failure occurred around a fastening plate (usually the centermost fastener), the membrane subsequently failed around adjacent fastening plates. The time-histories for fastener loads and chamber pressure for the 2.4- by 2.4-m (8- by 8-foot) TPO specimen are shown in Figure 6. These time-histories were similar in form to the time-histories collected from the testing of the other specimens.

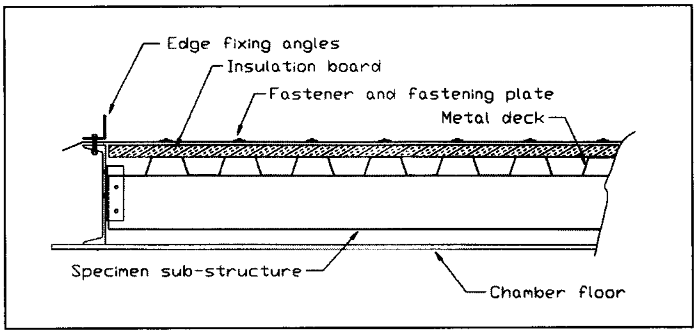

Figure 2. Typical selection through chamber and specimen.

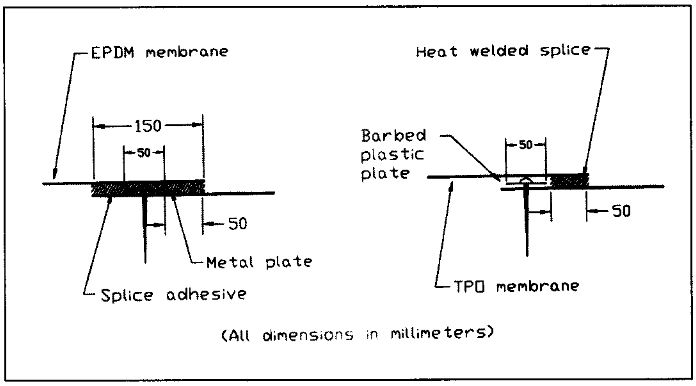

Figure 3. Splice arrangements for EPDM and TPO single-ply membranes.

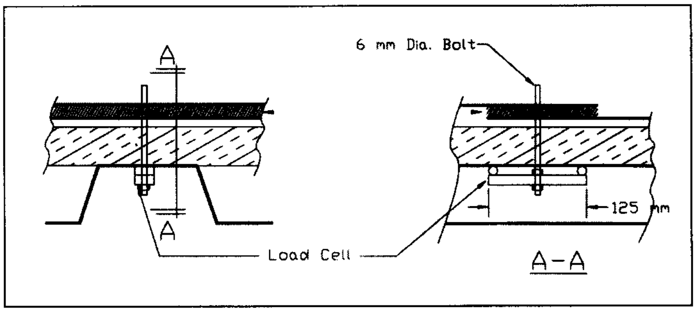

Figure 4. Fastener load cell installation.

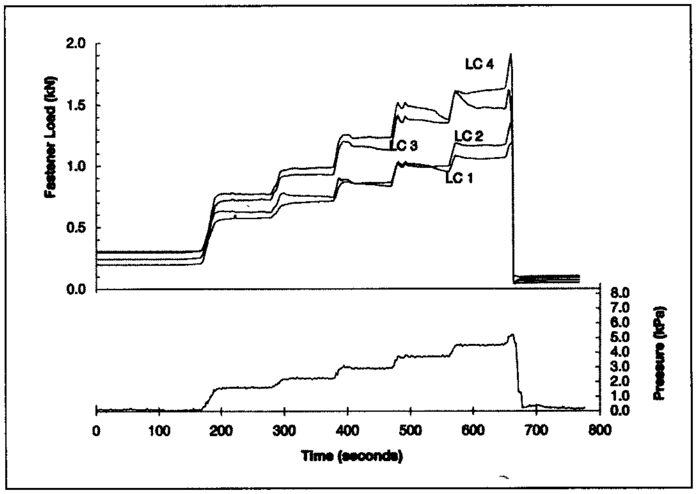

Figure 5. Time-histories from 8x8 TOP specimen test.

Figure 6. Photograph of EPDM seam failure at end of test.

A summary of the test results is found in Table 1. The tributary area column is the assumed tributary area per fastener for the centermost fastener for each specimen size (see Figure 1 for tributary area of a critical fastener for each specimen). The calculated fastener failure load is determined by multiplying the failure pressure by the tributary area. The measured fastener failure load is the value recorded by the load cell at failure minus the clamping force. The failure load difference is calculated by subtracting the measured fastener load from the calculated fastener failure load and dividing by the measured fastener failure load (given as a percentage).

The column of greatest interest is the failure load difference column. These values indicate how closely the measured fastener failure load can be predicted by the calculated fastener failure load. The larger the fastener load percentage difference, the less accurate the calculated fastener failure load is. The intent of establishing a minimum chamber size is to allow the fastener failure load to be calculated (with a fairly high degree of accuracy) by directly multiplying the static failure pressure by a fastener tributary area.

A quick glance at the EPDM specimens' failure load difference column of Table 1 (also shown by the bar chart given in Figure 7) draws your attention to the 1.5- by 6.1-m (5- by 20-foot) EPDM test specimen value of 69.6 percent. This large percentage difference indicates that this chamber size is not an appropriate size for static uplift testing, if a direct relationship between uplift pressure and fastener load is desired. The reason the 1.5- by 6.1-m (5- by 20-foot) specimen stands out so noticeably appears to be related to the aspect ratio of the ballooning membrane. The ratio of chamber width to fastener row spacing (width to span ratio = 0.77) determines in which perpendicular direction the load is transferred. Because the row spacing exceeds the chamber width, the dominant load transfer direction is parallel to the fastener rows, thus reducing the loads transferred to the fasteners. Therefore, the measured fastener loads are not directly comparable to the calculated fastener loads based on assumed (one-way action) tributary areas.

The next highest failure load difference occurs with the 1.5- by 2.7-m (5- by 9-foot) EPDM specimen. The value of 32.9 percent is dramatically less than the 1.5- by 6.1-m (5- by 20-foot) EPDM specimen, but it is still rather high. In this case, the failure load difference is reduced while the width-to-span ratio increases from 0.77 to 1.11. This suggests that as the width-to-span ratio is increased, load is distributed more towards the fasteners and less to the chamber boundaries perpendicular to the fastener row. Before testing was conducted, it was anticipated that the 1.5- by 2.7-m (5- by 9-foot) specimen would have a very large failure load difference because of previous testing experience by the single-ply roofing industry with this chamber size. It should be noted that 1.5- by 2.7-m (5- by 9-foot) specimens tested previously were fabricated from three sheets requiring two splices. The center sheet was a full 2.1 m (7 feet) in width, and therefore, the two seams were located near the clamping edges. Again, a problem with this layout is that the full center panel transfers more of the load to the chamber edge perpendicular to the fastener row and less to the fasteners. Another concern with this layout is the highly unbalanced load on the fasteners resulting from the difference in the specimen span of each side of a seam.

Looking at the other failure load differences for the TPO specimens in Figure 7, it is apparent that the calculated fastener failure loads from the larger chamber sizes more accurately reflect the measured fastener failure loads. The same trend of small failure load differences is observed here with the larger EPDM specimens. The 1.5- by 2.7- m (5- by 9-foot) TPO specimen had a failure load difference of almost twice that of the similar sized EPDM specimen. This could be attributed to a limited sample size, although it is quite likely that the large failure load difference occurs because of the significant influence from the unbalanced loading along a heat-welded seam. If a 1.5- by 6.1-m (5- by 20-foot) TPO specimen was tested, a large failure load difference would be anticipated.

An interesting observation from Table 1 is a comparison

	Fastener Tributary Area		Static Failure Pressure		Calc. Fastener Failure Load		Meas. Fastener Failure Load		Failure Load Difference
Specimen	(m^2)	(ft^2)	(kPa)	(psf)	(kN)	(lbs)	(kN)	(lbs)	(%)
12x24 EPDM	0.61	6.50	3.30	69	2.0	449	2.0	455	-1.4
10X10 EPDM	0.46	5.00	4.02	84	1.9	420	1.9	432	-2.8
8X8 EPDM	0.37	4.00	5.03	105	1.9	420	1.8	401	4.7
7X7 EPDM	0.33	3.50	5.08	106	1.7	371	1.8	409	-9.3
5X20 EPDM	0.60	6.50	5.12	107	3.1	696	1.8	410	69.6
5X9 EPDM	0.42	4.50	5.70	119	2.4	536	1.8	403	32.9
12X24 TPO	0.61	6.60	2.73	57	1.7	376	1.8	393	-4.3
8X8 TPO	0.37	4.00	5.17	108	1.9	432	1.8	413	4.6
5X9 TPO	0.42	4.50	5.03	105	2.1	493	1.0	220	114.8

Table 1. Summary of failure pressures and fastener loads.

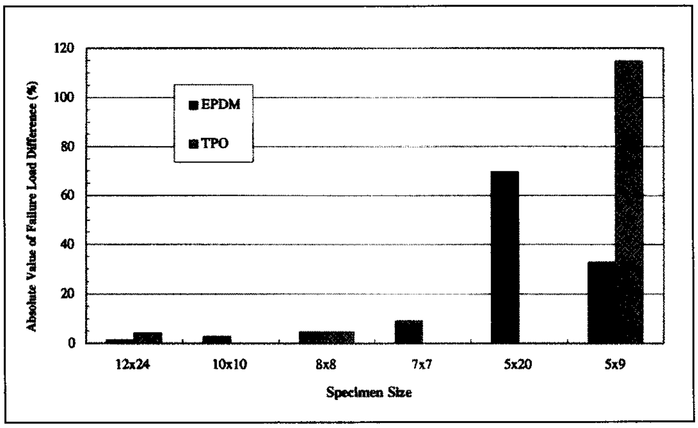

Figure 7. Difference between calculated and measured fastener failure loads.

between the failure pressure for the three largest [3.7- by 7.3-m (12- by 24-foot), 3.0- by 3.0-m (10- by 10-foot), and 2.4- by 2.4-m (8- by 8-foot)] EPDM specimen sizes. The pressures range from a low of 3.30 kPa (69 psf) to a high of 5.03 kPa (105 psf) for the same material. However, the calculated fastener failure load for the three is nearly identical (as it should be). This indicates that the failure load of the material and the failure mode has been identified, and the actual width of the membrane is irrelevant. Knowing the failure load per fastener (and assigning an appropriate factor of safety) allows a designer to customize the fastener and fastener row spacings of a mechanically fastened system to satisfy the wind uplift requirements for a particular building location.

CONCLUSIONS AND RECOMMENDATIONS

The test series reported here involved the static testing of one specimen for each chamber size and material type. On occasion, more than one test was performed to confirm results. Although few samples were tested, the results provide confidence because each sample had installed three, four,—and in one case—five load cells, which considerably improves repeatability and confidence in using the results as guidelines for the industry. The experiments covered a wide range of chamber sizes and two primary material products in common use. The sheet width was held constant to observe the effect of chamber sizes. The results presented in this paper lead to the following conclusions and recommendations:

- A static uplift chamber with minimum dimensions of 2.4 m by 2.4 m (8 feet by 8 feet) appears to be sufficient to allow the calculated fastener load to reasonably approximate the actual fastener failure load, as the failure load difference for this chamber size is less than 5 percent. A five percent difference is within the tolerance of the measuring device.
- The minimum width of a rectangular wind uplift chamber should be at least 1.5 times the fastener row spacing (giving an aspect ratio of at least 1.5). This will ensure that the center fastener along a seam will have a rectangular tributary area resulting in a calculated fastener load representative of the actual fastener load. If a smaller aspect ratio is used, then a tributary area correction factor is needed to properly calculate the fastener load at failure. In the case of the UEAtc test, such a correction factor is provided because the aspect ratios of specimens are typically less than 1.5.
- The failure pressure values currently obtained by UL or FM testing procedures are not meaningful value by themselves, but must be supported with descriptions of test chamber size related to sheet width. It is suggested that using an appropriate chamber size (described previously) allows fastener failure load to be calculated (using the failure pressure), which characterizes the material and fastening device being evaluated. Membrane width is then no longer important; only the fastener tributary area associated with the system layout on a particular building is relevant. The roof system designer can then specify a fastener arrangement that is most appropriate for the expected loads and for variable sheet width configurations.

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