STATIC VS. DYNAMIC: A WIND UPLIFT TESTING STUDY

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Wind uplift testing of mechanically fastened single-ply roofing systems in the United States has historically been conducted following the Factory Mutual Research Corporation Standard 4450/4470. Currently, this standard utilizes a 5 ft. by 9 ft. static pressure test table for the uplift evaluation. There has been concern expressed in the industry that static pressure testing does not simulate actual rooftop conditions for mechanically fastened single-plies, and consequently, dynamic uplift testing methods should be followed. Also, the relatively small table size seems to elevate the failure loads, indicating that a large test table is needed to eliminate membrane restraint by the test table frame. This paper discusses a study that was conducted on a reinforced mechanically fastened EPDM system, which was tested for wind uplift resistance following various published test methods both domestically and internationally. Observations, results, comparisons, and conclusions of static vs. dynamic wind uplift testing procedures are presented.

KEYWORDS

Aachen, mechanically fastened, static vs. dynamic, uplift testing, uplift testing comparison.

INTRODUCTION

The most widely used method for testing wind uplift resistance of commercial and industrial roofing systems in the United States is the Factory Mutual Research Corporation 4450/4470 procedure. This testing method has historically utilized a 5 ft. by 9 ft. (5 x 9) static pressure table into which a roofing system is sealed. Compressed air is incrementally introduced below the roofing system until failure occurs. This procedure was developed back in the 1950s for built-up roofing and, although it is not a recognized national standard, it has evolved into being used for wind uplift resistance evaluations for fully adhered and mechanically fastened single-ply designs.

UPLIFT TEST PERFORMANCE

The fully adhered single-ply and built-up roofing systems perform in a similar manner when tested on the 5 x 9 uplift table because both membranes are adhered to a substrate (typically insulation). Because of this adhesive bond, the uplift pressure is carried by the insulation and insulation attachment method. Consequently, membrane movement or inflation, independent from the insulation, does not occur. The membrane used with mechanically fastened single-plies, however, is not adhered to a substrate, but is actually loose between attachment locations. This allows the air to move past the insulation and cause the membrane to inflate, placing all the stress on the membrane and the membrane attachment device.

The validity of the 5 x 9 uplift testing method for mechanically fastened single-plies has been questioned because of this visible performance difference between adhered and mechanically fastened systems. The fact that the membrane is loose on mechanically fastened systems creates questions as to the correlation between membrane movement encountered during testing and membrane movement actually experienced in the field.

UPLIFT TEST CONCERNS

The concern about wind uplift testing of mechanically fastened single-plies has been centered around two points; static vs. dynamic pressure testing and the test table size. The static vs. dynamic pressure issue is created because mechanically fastened systems (as previously mentioned above) are intermittently attached leaving the membrane loose between attachment locations. This loose membrane is free to move or "flutter" as wind blows across the roof. Consequently, the argument is made that this rooftop fluttering and the associated dynamic stresses imparted to the system components are not accounted for in a static pressure testing procedure.

The test table size issue is created because the 5 x 9 dimension limits the membrane width that can be accurately tested. Historically, any fastener row spacing not wider than 8 feet would be tested on the 5 x 9 table, but this practice can create unbalanced forces during the test. These unbalanced forces occur with any fastener row spacing greater than 4 feet because only one full membrane panel (only two field seams) will dimensionally fit on the table. This means that the membrane area between fastener rows is larger than the membrane area between the fastener rows and the ends of the table. Consequently, more stress is applied to the membrane between the rows than between the rows and the ends of the table. In addition, the small table size creates a relatively small test area to perimeter clamping area ratio. This small ratio is known as "edge effect" and results in a large part of the uplift force being carried by the perimeter clamping system. The edge effect reduces the actual stresses imparted to a mechanically fastened roofing system because membrane inflation is restricted. These two conditions, unbalanced forces and edge effect, contribute to higher than expected failure values because the failure load typically exceeds the fastener pullout resistance from the deck and/or the membrane tear strength. Consequently, the argument is made that the 5 x 9 test table is too small for proper testing of certain mechanically fastened single-ply systems.

ALTERNATE UPLIFT TEST METHODS

There are a number of alternate wind uplift testing apparatus/procedures available for use both domestically and internationally. Domestically, Factory Mutual (FM)[1] has a large static pressure table and Underwriters Laboratories (UL)[2] offers one static and one dynamic testing method.

Factory Mutual has developed a large 12 ft. by 24 ft. (12 x 24) table for evaluating specific mechanically fastened systems following the same operating procedures used for the 5 x 9 table. The roofing system is pressurized from below the deck to 30 psf and held for one minute. The pressure is then increased by 15 psf increments, again held for one minute, until failure occurs.

The UL 1897 procedure is a static pressure test method which duplicates the FM procedure with the only difference being that UL uses a 10 ft. by 10 ft. (10 x 10) test table. The UL 580 procedure is a dynamic test which is also conducted on the 10 x 10 table. In addition to pressure from below, the UL 580 apparatus draws a vacuum on the top of the membrane. The vacuum and pressure levels are varied throughout the duration of the test thus creating a dynamic uplift effect.*

International wind uplift evaluations typically involve dynamic testing, especially for mechanically fastened systems. The two most well known international dynamic testing methods are the BRERWULF test rig developed by The Building Research Establishment[3] in the United Kingdom and the fatigue test procedure conducted by WSP in Aachen, Germany.[4] (The German procedure is referred to as the Aachen procedure in this paper, however, this has been included into a UEAtc document titled "UEAtc Supplementary Guide For The Assessment Of Mechanically Fastened Roof Waterproofing.") The BRERWULF machine applies either a pressure or a vacuum, or both, to the roofing system, and can cycle both to create the dynamic effect. There is no standard loading procedure established for roofing materials on the BRERWULF, but the machine can be used to duplicate pressure fluctuations recorded from any wind storm, wind tunnel study, or any predetermined dynamic cycle. The Aachen test table measures approximately 5 ft. by 20 ft. (5 x 20) and uses an oscillating vacuum system above the membrane to create the dynamic effect. The Aachen testing procedure first applies 20,000 conditioning cycles with an oscillating load of zero to 22 pounds per fastener, then applies a 67 pound per fastener load over a defined cycle four times, then increases the maximum cycle load in successive 22 pound per fastener increments until failure occurs. Since the Aachen procedure utilizes pound per fastener load cycles, the psf pressure level is determined by dividing the applied load by the area of membrane held by one fastener.

UPLIFT TEST PROGRAM

In order to determine the effects of various wind uplift testing methods on mechanically fastened single-plies, Carlisle SynTec Systems developed an evaluation program using various established wind uplift testing procedures. Five different uplift tests were conducted on 7 foot wide sheets of reinforced EPDM membrane. The membrane was fastened using 2 inch diameter seam plates and threaded fasteners in the field seams resulting in fastener rows spaced 6½ feet on center. The EPDM membrane was a 45 gauge material reinforced with a 1,000 denier, 9 ft. by 9 ft. (9 x 9) weft inserted weave polyester fabric. The test apparatus used in this study are highlighted below:

Test	Method	Country
FM - 5 x 9 Table	Static	USA
FM - 12 x 24 Table	Static	USA
UL 580 - 10 x 10 Table	Dynamic	USA
UL 1897 - 10 x 10 Table	Static	USA
Aachen - 5 x 20 Table	Dynamic	Germany

Refer to the Appendix for a summary description of each testing procedure.

The assembly tested on each of these machines consisted of a 22 gauge metal deck, an insulation layer, rows of fasteners spaced 6½ feet on center, and fasteners spaced 12 inches on center (see Figure 1). However, due to the configuration of the European deck, the fastener spacing at Aachen was approximately 9.8 inches on center.

UPLIFT TEST RESULTS

The various table sizes and associated membrane layouts create different fastener influence areas. The influence area is determined by the area of membrane being held by a single fastener. Figure 2 shows how the influence area for the four table sizes previously referenced is measured. The shaded area represents the influence area per fastener.

Figure 3 highlights the calculated influence area per fastener, the tested failure load per square foot area, and the corresponding failure load per fastener for the 7 foot mechanically fastened roofing system (MFRS). The influence area per fastener is as measured on Figure 2. The failure pressure is the load per square foot that caused failure on each test apparatus. The failure load is the load per fastener that caused failure, and is calculated by multiplying the influence area by the failure pressure.

Also included in Figure 3 are testing results for a 4.5 foot and a 10 foot wide MFRS (fastener row spacings of 4 feet and 9.5 feet, respectively) which were tested at Aachen and the 10 foot wide MFRS which was tested on the 12 x 24 table. (The fastener layout and splice configuration for these systems was identical to the 7 foot MFRS.)

Figure 4 identifies the number of cycles that the 7 foot MFRS experienced on each test apparatus as well as the number of cycles that the 4.5 foot and 10 foot MFRS experienced on the Aachen machine.

UPLIFT TEST DISCUSSION

The test data contained in Figure 3 is best analyzed by studying the failure load values. The failure load is an accurate measure of the force necessary to cause failure for a specific table size and a specific membrane system configuration. The 5 x 9 failure load for the 7 foot MFRS appears to be abnormally high (582 lb/fastener) when compared to the other 7 foot failure load test results. This high value is undoubtedly the result of the unbalanced sheet layout as well as the edge effect phenomenon of the 5 x 9 table. The placement of the field splice on the 5 x 9 table as shown in

**Because of the limited number of load cycles in the UL 580 test, some people do not consider this to be a true dynamic test method.*

Figure 2 allows only a short distance (1 foot-3 inches) to the end of the table. The resulting influence area is based on the assumption that half the load applied to the 1 foot-3 inch membrane section is carried by the seam fastening plate and the other half by the perimeter clamping system. In reality, the majority of the load is carried by the clamping system (because of the limited membrane inflation), causing this high failure load value.

In order to further evaluate this edge clamping effect, a separate test was conducted using one splice centered across the 5 foot width of the 5 x 9 table, similar to the UL 10 x 10 table layout. This layout halves the number of fasteners holding the membrane in place from 10 fasteners as shown in Figure 2 (five across each end) to five fasteners across the center of the table. The anticipated failure load using only five fasteners would be approximately half the 150 psf achieved with the 10 fasteners, however, the five fasteners test failed at 135 psf when the metal deck pulled loose from the test table frame (roofing system failure had not occurred). This result indicates that the edge clamping system (edge effect) of the 5 x 9 table greatly influences the failure load values.

It is interesting to note that the four remaining failure loads for the 7 foot MFRS are all very close. Even the UL 10 x 10 table produced similar results without having one seam completely isolated (i.e., having three field seams spaced 6½ feet apart on the table) as occurs on the larger tables. Also, the effect of sheet movement from the dynamic tests did not reduce the failure load of the system. This point is particularly interesting when the length of each test and the number of dynamic cycles is studied (see Figure 4). The 5 x 9, 12 x 24, and the UL 1897 are all static pressure tests (no dynamic cycles), and each takes approximately 10 minutes to complete an I-90 evaluation. The UL 580 is a dynamic test which takes approximately 4 hours to complete if Class 90 is achieved. The 7 foot MFRS failed midway through Class 60, which corresponds to approximately one and one-half hours of testing and 550 cycles of membrane movement. The Aachen procedure also is a dynamic test which can take two days to complete. The 7 foot MFRS test lasted approximately one and one-half days and experienced 25,400 cycles of membrane movement before failure occurred.

Another interesting fact to note is that the same system failure mode was experienced on all tests, specifically, membrane tear around the seam plates. This is especially noteworthy considering that the static 12 x 24 and UL 1897 tests conducted on the 7 foot MFRS produced virtually identical failure loads as did the 550 cycle UL 580 test and the 25,400 cycle Aachen test. It appears that the failure on the dynamic machines is caused by the incremental increase in testing load and not by fatigue. The increasing load exceeds the ultimate strength of the 7 foot MFRS before fatigue from dynamic movement can influence the results. Failure solely from fatigue would require continual cycling using a lower load value than the failure load value. This would require very long test times.

As mentioned earlier, a 4.5 foot and 10 foot wide MFRS was also tested on the Aachen machine. The results obtained are completely opposite of what would be expected. The narrow 4.5 foot MFRS failed at a lower load value than the 7 foot MFRS, and the 7 foot MFRS failed at a lower load value than the 10 foot MFRS. Typically, a larger influence area will cause failure at a low load value because there is more membrane area held by and more stress applied to the attachment location. What appears to be happening with the Aachen test is that it takes longer to complete one cycle with a wide sheet than it does with a narrow sheet. In other words, the Aachen machine takes longer to evacuate the air above a wide membrane than a narrow membrane because of the differences in volumes associated with the varying fastener spacings. Consequently, the narrow sheet can actually be "shocked" by the shorter (quick) cycle time causing premature failure at a low load value. This quick cycle time and low load failure value is further reflected in the number of cycles completed for each of the three sheet widths (see Figure 4). The 10 foot MFRS failed after 35,300 cycles, the 7 foot MFRS failed after 25,400 cycles, and the 4.5 foot MFRS failed after only 9,900 cycles. Again, this is opposite of what would be expected. A narrow sheet should produce a higher failure load and resist more cycles than a wide sheet.

This observation is further supported by examining the failure load of the 10 foot MFRS tested on the 12 x 24 table. The 12 x 24 table result of 427 pounds per fastener closely duplicates the 7 foot MFRS results on the 12 x 24, UL 1897, and UL 580, which is what should be expected. The only difference in the membranes is the width, so it makes sense that the failure loads for the same material would be similar. The influence area and failure pressure may vary depending upon table size and membrane layout, however the failure load should remain fairly constant. The Aachen result of 540 pounds per fastener appears to be overly high because of the long dynamic cycle time.

FASTENER BACKOUT CONCERNS

One additional reason sometimes mentioned for conducting dynamic testing on mechanically fastened single-plies is the evaluation of a fasteners resistance to backout forces. Fastener backout occasionally occurs on the roof because of membrane movement, deck and building vibration, insulation shrinkage or creep, or a combination of any of these. Backout was not experienced on the two dynamic test machines utilized under this study because an anti-backout plate and fastener attachment system was utilized. However, the use of these two dynamic test machines creates a vertical uplift cycling load which creates very little, if any, lateral movement. Evaluations separate from this study have shown that lateral movement causes backout and that a small scale lateral movement test can very quickly identify the backout resistance of a fastening system. The two dynamic uplift test methods evaluated in this study (Aachen and UL 580) are probably not sufficient to completely evaluate fastener backout potential on their own because of their inability to apply lateral forces. It should be noted however, that fastener backout has reportedly been observed on the Aachen test in the past, but it is not a typical occurrence.

OBSERVATIONS

The fact that similar failure loads were obtained for the 7 foot MFRS when tested on the three largest table sizes indicates that there is an optimum table size which could be used to evaluate the ultimate performance of a roofing system, while keeping the amount of materials and required costs to a minimum. The 5 x 9 appears to be too small because of the unbalanced forces and the edge effect as previously explained. Both the 10 x 10 and the Aachen (5 x 20) test tables are the next smallest size measuring 100 feet^2 each. The 10 x 10 did not allow for the isolation of one splice, but it still produced similar results to the 12 x 24 table. The Aachen table is narrow (5 feet, the same as the 5 x 9), but it too produced results similar to those on the 12 x 24. This indicates that there are probably minimum table dimensions that can be used to produce consistent results. Additional research is needed to determine these minimum dimensions. Once the table size is determined it may be possible to test a particular system once, determine the failure mode and associated load, and mathematically calculate the allowable fastener spacing and membrane width (distance between fastener rows) which could be used to resist specified rooftop uplift values.

CONCLUSIONS/RECOMMENDATIONS

The test data presented in this paper leads to the following conclusions and recommendations:

- The 5 x 9 uplift table produces very high test results because of either an unbalanced sheet layout or the edge effect phenomena, or both. It therefore does not appear to be an appropriate test method for mechanically fastened single-plies.
- The use of dynamic testing does not appear to offer any advantages over a sufficiently large static pressure test method, especially considering the length of test time and the complexity of the test equipment. Additional testing is needed to confirm that this observation is true for other membrane materials and systems other than evaluated under this study.
- The current dynamic test procedures do not appear to completely and absolutely evaluate a fasteners ability to resist backout forces. A separate small scale fastener backout evaluation test method should be developed to be used in conjunction with static wind uplift testing.
- Additional testing needs to be conducted to determine the optimum table size for evaluating the ultimate uplift strength of both reinforced and non-reinforced mechanically fastened single-ply systems.
- The United States roofing industry needs to develop a national wind uplift test standard for evaluating the performance of all roofing systems, but especially for mechanically fastened designs. This will eliminate confusion generated by the use of various U.S. test methods and table sizes. It is hoped that this paper will help stimulate a move in that direction.

REFERENCES

[1] Factory Mutual Research Corporation, 1151 Boston-Providence Turnpike, P.O. Box 9102, Norwood, Mass. 02062-9988, USA.

[2] Underwriters Laboratories, Incorporated, 333 Pfingsten Road, Northbrook, Ill. 60062, USA.

[3] Building Research Establishment, Garston, Watford WD2 7JR, United Kingdom.

[4] Ingenieurgeneinschaft WSP, Walkenrather Strabe 120, D-5100, Aachen, Germany.

APPENDIX

FM 4450/4470 - 5 x 9 Table
FM 4450/4470 - 12 x 24 Table
UL 1897 - 10 x 10 Table

Pressure Level,* psf	Time, Min.
30	1
45	1
60	1
75	1
90	1
105	1
120	1
135	1
150	1

* Resisting 60 psf for one minute achieves I-60 rating.
Resisting 90 psf for one minute achieves I-90 rating.
Test continued until failure occurs.

Table 1

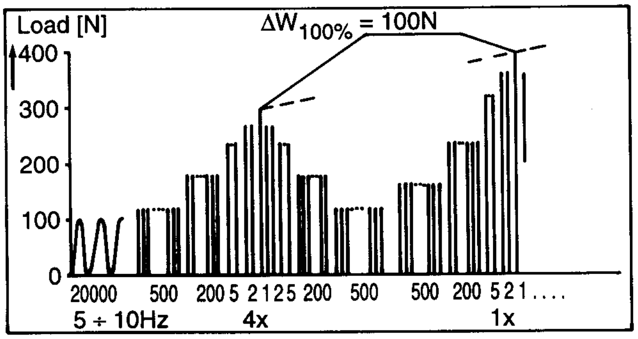
UL 580 - 10 x 10 Table

Rating	Time, Min.	Pressure Level,* psf		
		Neg.	Pos.	Total
Class - 30	5	16	0	16
	5	16	14	30
	60	8-27	14	22-41
	5	24	0	24
	5	24	20	44
Class - 60	5	32	0	32
	5	32	27	59
	60	16-55	27	43-82
	5	40	0	40
	5	40	34	74
Class - 90	5	48	0	48
	5	48	41	89
	60	24-48	41	65-89
	5	56	0	56
	5	56	48	104

* Testing terminated after failure or after completion of Class 90 cycle, whichever occurs first.

Table 2

Aachen - 5 x 20 Table



Note:
- 20,000 cycles of 0 to 100 Newton load (0 to 22 pounds) is applied first.
- A 300 Newton load (67 pounds) is then applied in the percent increments and number of cycles shown. Four cycles are conducted at this level.
- The load is successively increased by 100 Newton (22 pound) increments until failure occurs. Only one cycle is conducted at each load level.

Table 3

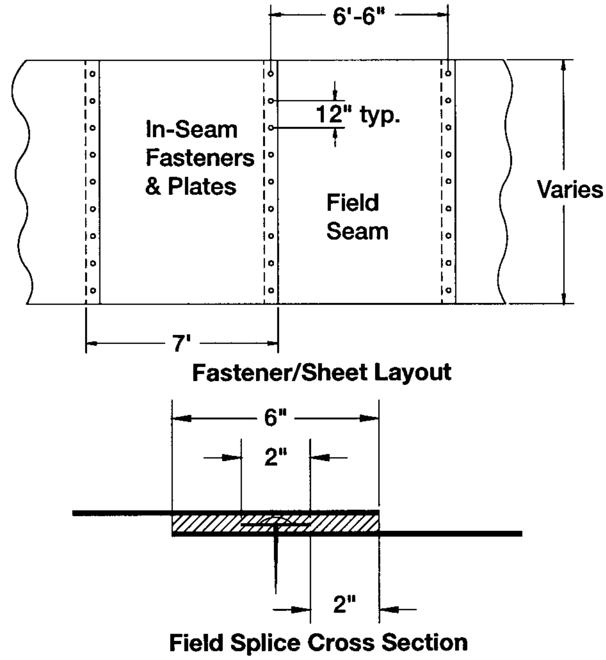


Figure 1 *System layout.*

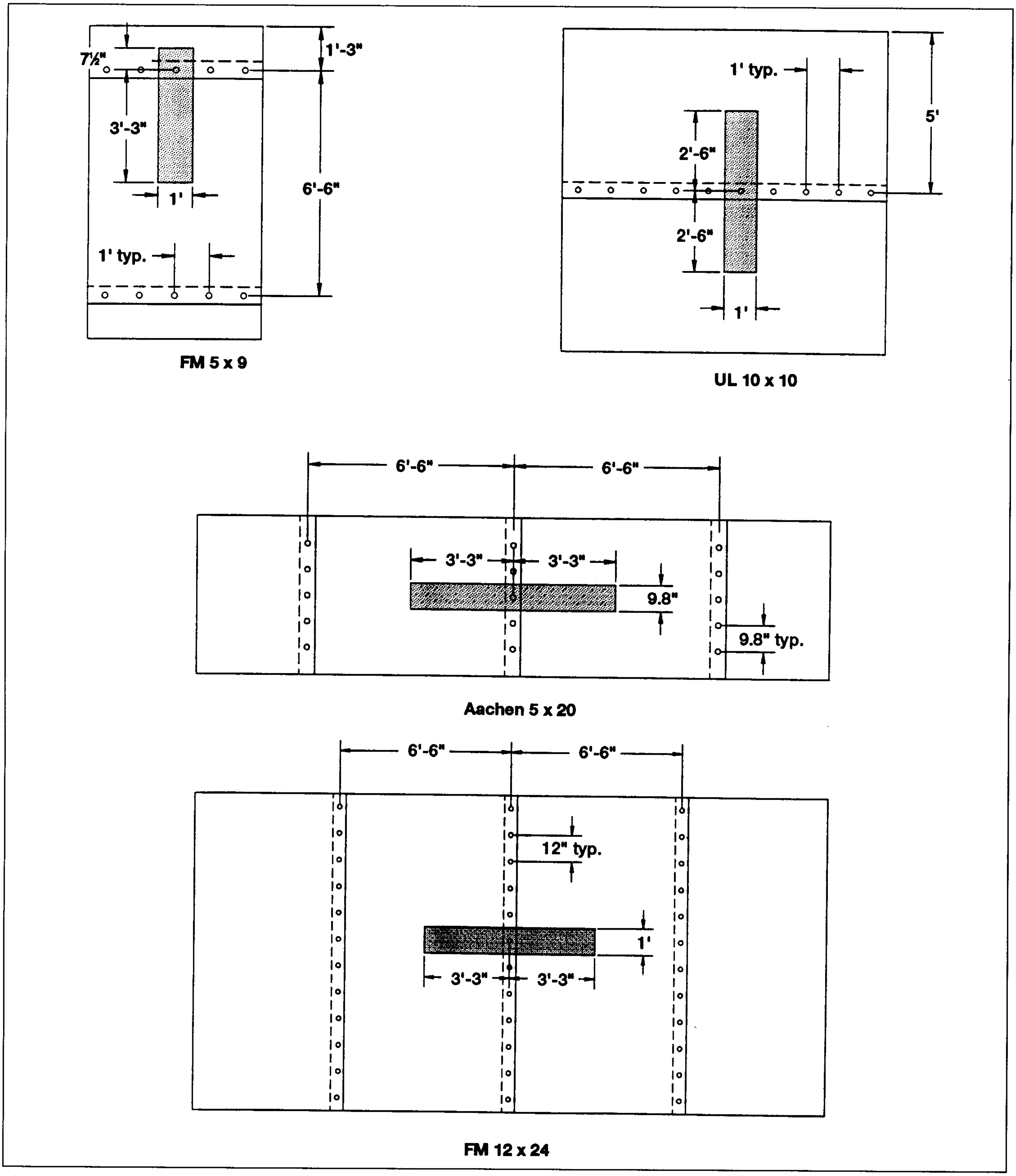


Figure 2 Influence area.

Influence Area (sq. ft./ fast)					
System	FM 5 x 9	FM 12 x 24	UL 1897	UL 580	Aachen
4.5	—	—	—	—	3.27
7.0	3.88	6.5	5.0	5.0	5.31
10.0	—	9.5	—	—	7.76
Failure Pressure (psf)					
System	FM 5 x 9	FM 12 x 24	UL 1897	UL 580	Aachen
4.5	—	—	—	—	41
7.0	150	57	75	83	72
10.0	—	45	—	—	70
Failure Load (lb./fast)					
System	FM 5 x 9	FM 12 x 24	UL 1897	UL 580	Aachen
4.5	—	—	—	—	135
7.0	582	371	375	415	382
10.0	—	427	—	—	540

Figure 3 *Test results.*

Test method	Number of Cycles
FM - 5 x 9	0
FM - 12 x 24	0
UL - 1897	0
UL - 580	550
Aachen - 4.5 Foot MFRS	9,900
Aachen - 7 Foot MFRS	25,400[1]
Aachen - 10 Foot MFRS	35,300[1]

[1] The number of cycles does not include the 20,000 initial conditioning cycles.

Figure 4 *Dynamic test cycles.*