A NEW FACILITY FOR DYNAMIC WIND PERFORMANCE EVALUATION OF ROOFING SYSTEMS

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Wind-induced effects on roofing systems are dynamic because of the wind's variation with respect to time and space. Through a North American roofing consortium, the Special Interest Group for Dynamic Evaluation of Roofing Systems—SIGDERS, the National Research Council of Canada fabricated and commissioned a North American roofing facility for the dynamic evaluation of roofing systems. Experimental investigations have been carried out on a typical PVC single-ply system. Three types of loading sequences were simulated over the PVC system: Factory Mutual (FM-4470) standard, UEAtc (European Union of Agreement) test procedure and SIGDERS dynamic test protocol. Data from these investigations were compared. Comparison of the applied wind pressures and measured fastener forces, although limited to the tested roof assembly, clearly indicate that they were significantly overestimated under the FM loading sequence. Both UEAtc and SIGDERS loading sequence investigation resulted in similar design parameters. Nevertheless, the SIGDERS loading sequence took less time than that of the UEAtc test procedure. To validate the above findings, the ongoing SIGDERS project will be investigating reinforced EPDM, TPO and modified bitumen single-ply systems.

KEYWORDS

Dynamic evaluation, fastener pullout, loading sequence, membrane tear, roofing system, static testing, wind performance.

INTRODUCTION

Wind performance investigation is critical in the design of durable roofing systems. Design wind pressure varies spatially over the roof. This is demonstrated in Figure 1 which represents typical mean pressure coefficients measured on a PVC single-ply roofing assembly placed in a wind tunnel. The data are for a square-plan building model of 3.2 m x 3.2 m (10 ft. x 10 ft.) exposed to oblique wind direction.[1]

The figure also shows that the pressure coefficients are maximal near the two leading edges; the largest values occur at the corner due to flow vortex. They decrease toward the leeward edge with pressure coefficients moderating in the middle portion of the roof. Also, a line of symmetry exists along the diagonal of the roof. For this roof configuration, a zero pressure coefficient represents the occurrence of flow reattachment. After reattachment, the coefficients are positive. Thus, the wind-induced pressures will vary with respect to space.

The response of the single-ply roofing system for wind-induced pressures is dynamic. In other words, wind-induced loads on the membrane can reach the structural supporting system through two load paths: *pneumatic load path* and *structural load path*. In the pneumatic load path, the load is shared among the layers (membrane, insulation and deck) by differences in pressure across them. In the structural load path, the load passes through the fasteners. If fluctuations of external wind pressures are slower than the membrane response time, the loads are transmitted through membrane tension to the fasteners, i.e., structural load path. For fluctuations faster than the membrane response time, the load will be transmitted through pneumatic actions. Measurements by Cook[2] showed that the higher the applied suction the greater the proportion borne directly by the membrane (structural path). Based on the wind load mechanism for common spot fasteners, Gerhardt and Kramer[3] reported that the fastener force was approximately 2.5 times the wind uplift force.

What arises from the above discussion is that the problem of wind-induced effects on roofs is both time- and space-dependent. This has been found to be true both for the driving force and for the system response. Therefore, a proper three-dimensional and time-dependent (dynamic) analysis is essential for an adequate estimation of wind effects on roofs. Dynamic effects are significant for the roofing system with flexible components such as single-ply membranes. For rigid systems, such as a fully adhered membrane with concrete deck, the dynamic effects may be minimum. This paper presents the development of a roofing facility that makes it possible to perform a dynamic analysis as part of a roofing system investigation. This facility is unique in North America and forms an integral part of the ongoing consortium research

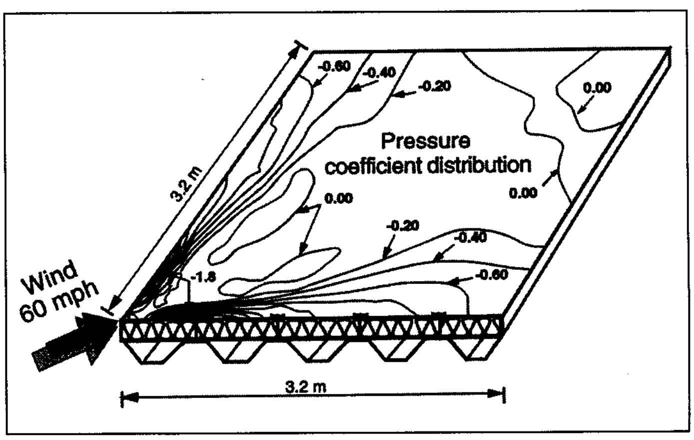

Figure 1. Wind induced mean pressure distribution over a PVC roof.

project entitled *"Special Interest Group for Dynamic Evaluation of Roofing Systems"* (SIGDERS).

This paper has three sections. First, a systematic effort is made to review the existing loading sequences for the evaluation of roofing systems. This includes the two commonly used North American test standards (Factory Mutual [FM] and Underwriters Laboratories [UL]) and two European standard procedures (European Union of Agreement [UEAtc] and Norwegian Wind Standard [NT 305]). The second section of the paper presents measured system responses for a typical PVC single-ply roofing system, which was subjected to two loading sequences—UEAtc, and the new loading sequence developed through SIGDERS research efforts. The system was also subjected to a test similar to the FM load sequence. The third section compares the data from these three investigations. Even though the present findings are limited to the studied system layout, it is clear that the FM loading sequence overestimates the design parameters and yields a different failure mode when compared with the developed dynamic load sequence.

LOAD CYCLES OF THE EXISTING TEST STANDARDS

At present, mainly two test standards are being used in North America to assess wind uplift performance of membrane roof systems. They are the FM 4470 and UL 580 test standards. In Europe, the UEAtc-551 test procedure was developed by Gerhardt and Kramer.[4] It is the only available international standard for fatigue evaluation of roof assemblies. Load sequences for these test standards are summarized in the next four subsections. Detailed descriptions of the test procedures can be found in a review report by Baskaran and Dutt.[5]

Load sequence for the Factory Mutual (FM) 4470 Standard

In the FM load sequence, an initial pressure of 1400 Pa (30 psf) is applied and maintained for one minute. The pressure is then increased at a rate of 700 Pa (15 psf) per minute until failure of the test panel occurs. For example, the windstorm classification (I-90) is obtained when the test assembly successfully passes the 4200 Pa (90 psf) pressure sequence. The FM load cycle is simple in that it takes little time to complete a test. For example, the whole test for an I-120 classification takes less than 10 minutes. However, the FM procedure applies static loading and therefore differs significantly from the wind-induced pressures on roofs, which are shown in Figure 1.

Load sequence for the Underwriters Laboratories (UL) 580 Standard

The UL 580 test procedure applies steady and oscillating negative pressure to the top of a roof assembly and steady positive pressures to the underside. They are applied in five phases. Figure 2 shows a schematic for the UL Class 90 certification.

- The first phase applies a 2330 Pa (48.5 psf) negative pressure for five minutes.
- In the second phase, a 1990 Pa (41.5 psf) positive pressure is added.
- During the third phase, a negative oscillating pressure ranging from 1160 to 2330 Pa (24.2 to 48.5 psf) is applied at a frequency of 10 (2 seconds per cycle for 60 minutes.
- In the fourth phase, a 2710 Pa (56.5 psf) negative pressure is applied for five minutes, while the positive pressure is equal to zero.
- For the fifth and final phase, a 2710 Pa (56.5 psf) negative pressure and a 2330 Pa (48.5 psf) positive pressure are applied for five minutes.

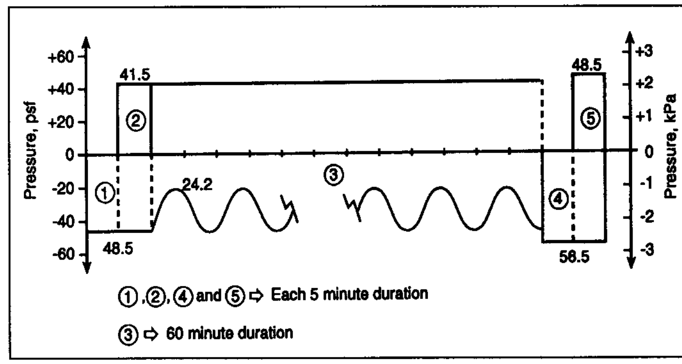

Figure 2. UL 580 - Class 90 load cycle schematic.

Note that the specimen must go through Class 30 and Class 60 test sequences before starting the Class 90 level. The UL procedure takes about four hours to complete the Class 90 test.

Load sequence for the UEAtc Test Procedure

The UEAtc standard wind uplift load cycle was prepared according to a procedure developed by Gerhardt and Kramer.[4] The UEAtc wind load cycle for a five-year return period is shown in Figure 3(a). There are four steps in the UEAtc load cycle.

- Four sets of 1415 gusts with a maximum load of 300 N (67.5 lbf) per fastener are applied. For each gust, the time for loading and unloading is shown in Figure 3(b).
- If the back-out behavior of the fastener is unknown, then the roofing system must be subjected to 200,000 fluctuations with a loading of 100 N (22.5 lbf) per fastener and a frequency not exceeding 10 Hz. This is known as the conditioning cycle and it is applied between the third and fourth loading.
- With a maximum load of 400 N (90 lbf) per fastener, one set of 1415 gusts is applied.
- The maximum load per fastener is increased in increments of 100 N (22.5 lbf) and the test continues with 1415 gusts at each level until failure occurs.

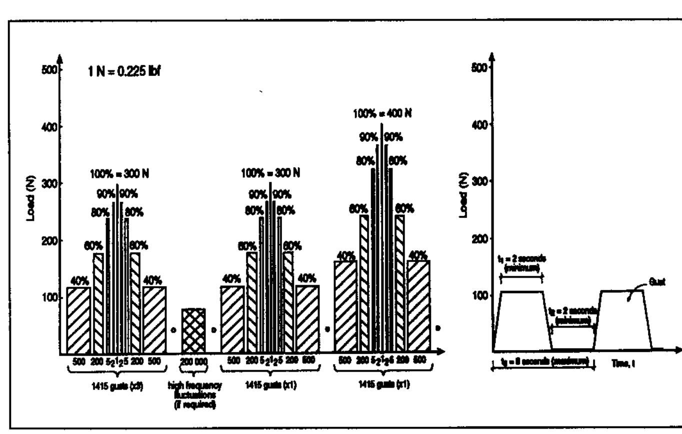

Figure 3. European Union of Agreement (UEAtc) load cycle.

There is one main difference between the UEAtc loading sequence and the FM and UL sequences—the UEAtc procedure calculates the fastener design load for the tested system, whereas FM and UL tests specify a pressure level for the system. However, the North American roofing community has indicated that the UEAtc procedure is too time-consuming.[6] For example, simulating the first set of 1415 gusts takes about three hours, and therefore a typical test takes more than a day. Further observations are listed in Table 1.

Load sequence for the Norwegian Wind Standard
NT BUILD 307 1986-11, "Roof coverings - Wind load resistance" is a standard method being used to test the strength of wind uplift on roof assemblies.[7] It is a static method. In 1987, the Norwegian Building Research Institute (NBI), along with other participants from Scandinavian countries, initiated a study of dynamic load application on mechanically attached roof systems. The dynamic test procedure, *"NBI 162-90 Roof coverings - Dynamic wind load resistance,"* arising from that study is a modified version of NT BUILD 307 static evaluation standard. The apparatus consists of a lower and upper box between which a test specimen is positioned. The lower box applies static suction of 100 Pa (2.1 psf), while the upper box applies pulsating suction as gusts every 15 seconds for one hour. The intensity of the gusts is increased by 200 Pa (4.2 psf) between load intervals until the system fails.

Other test procedures
Smith[8] developed a procedure to test mechanically attached single-ply membranes for fatigue. The number of loading cycles was associated with wind speed increments, by using the Weibull probability distribution. Letchford and Norville[9] proposed a load sequence based on wind pressure records from Texas Tech University's Wind Engineering Research Field Laboratory. They used level-crossing and mean-range count analysis as the cycle-counting methods. This load sequence was also applied in the development of a test standard for determining impact resistance from wind-borne debris.[10] In Australia, Byrne,[11] Morgan and Beck,[12] and Mahendran[13,14] used an experimental setup to apply dynamic loading on sheet-metal roofing. Research findings from this investigation were used to update the Australian Standard (TR 440 - 1978).[15] Recently, Clemson University in the United States acquired the BRERWULF[16] facility for wind testing of building envelopes.

It is clear that the North American roofing community is lagging behind on the advancement of dynamic evaluation compared to their European counterpart. This concern was one of the main outcomes of the 1989 Oak Ridge wind uplift workshop.[17] In addition, several individual studies such as Malpezzi and Gillenwater[18] and Warshaw and Hoher[19] stressed the need to develop a national wind uplift test standard. This is the main thrust of the ongoing SIGDERS consortium project.[20]

DESCRIPTION OF THE SIGDERS FACILITY

Through a consortium effort, a Dynamic Roofing Facility (DRF) was established at NRC for the use of the North American roofing community. This section will present the salient features of the DRF.

Size
The DRF, shown in Figure 4, is 6100 mm (240 in.) long and 2200 mm (86 in.) wide. Its bottom frame of height 800 mm (32 in.) is fixed to the floor, and has a lifting mechanism based on three adjustable jacks in the center. The top chamber, of the same height, is movable. This design allows for the installation and study of roof assemblies of different thicknesses, up to 500 mm (18 in.). This is critical for studying of the effect of insulation thickness on wind performance, as well as for evaluating attachment systems for reroofing conditions. In reroofing situations, it may be necessary to simulate both the existing and the proposed roof assemblies together. The adjustable bottom frame can easily accommodate these conditions. This arrangement can also be utilized to evaluate sloped roofs.

The top chamber has six viewing windows and a gust simulator. The gust simulator consists of a flap valve connected to a stepping motor through a timing belt arrangement. The top chamber is also connected to a suction fan box. The 37 kW (50 HP) fan with a flow rate of 2500 L/sec. (5300 cfm) can produce suction as high as 10 kPa (209 psf) over the roof assembly. The roofing specimen is sandwiched between the top chamber and the bottom frame. Around all the edges, the DRF has snap-on buckles to lock the top chamber together with the bottom frame to form an airtight system.

Operation
The DRF operates on a feedback control system. In other words, the pressure is monitored by a sensitive pressure transducer which sends the pressure signal to the computer, where it is compared with the required pressure. Based on this comparison, a feedback signal is produced from the computer to an AC inverter to accelerate or decelerate the fan speed (rpm). The required pressure level is maintained via this continuous feedback loop. Wind gusts are simulated using the gust simulator. Opening the flap valve bleeds pressure from the chamber, and closing it builds the pressure.

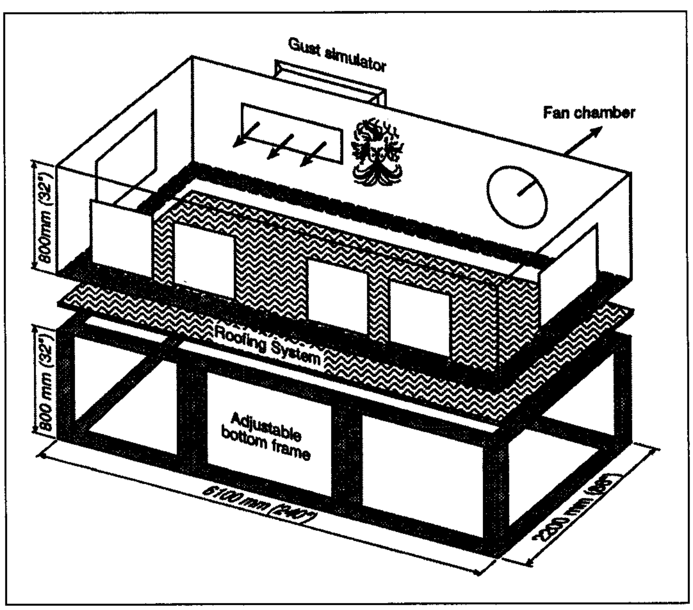

Figure 4. Dimensions of the SIGDERS dynamic roofing facility.

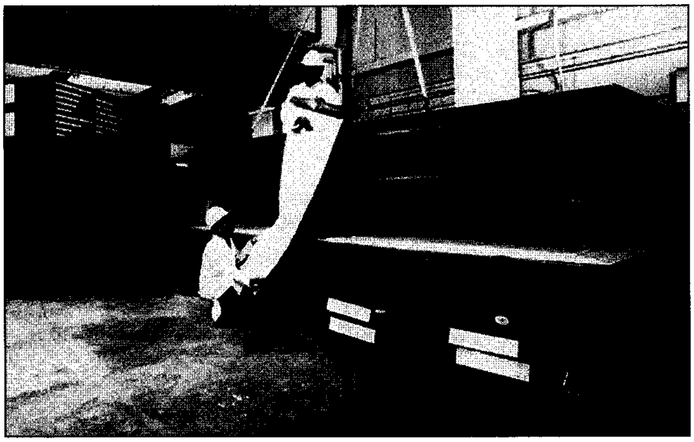

Figure 5. Photograph of the SIGDERS dynamic roofing facility.

The timing of the flap valve operation is controlled by another feedback signal loop connected to the same computer through a controller. At present, the DRF can simulate wind gusts up to 2 Hz in frequency.

Instrumentation

More instrumentation is added onto the facility to measure the dynamic response of the roofing system. As shown in Figure 6, there are 32 pressure sensors to measure the pressures at various locations; one eddy-current deflection sensor to measure the deck movement of the system; eight bi-directional load cells to measure the forces acting on roofing fasteners; and ten ultrasonic-deflection sensors to measure the deflection of the membrane. All signals are monitored by an HP mainframe system.

Commissioning of DRF

Several quality assurance requirements were carried out for commissioning the DRF. The following two features are pertinent to assess roofing systems for the UEAtc test protocol.

Gust simulation

As represented in Figure 3, the UEAtc test procedure applies 1415 gusts for each cycle. Each gust should be simulated as shown in Figure 7(a). The constant t_1, during which the roofing system is subjected to loading, should be at least two seconds in duration. Similarly, t_2 represents the unloading time, and should also be at least two seconds. For each gust, the total gusting time t_3 should not exceed eight seconds. Figure 7(b) shows a simulated gust at the DRF. As shown in the figure, the DRF takes only 6.6 seconds to simulate a gust while satisfying the minimum requirement for the other two time constants. Based on these time constants, one cycle (1415 gusts) of the UEAtc test procedure takes about three hours in the DRF. This has been found to be true for various pressure levels.

Pressure requirement

Equally important is maintaining a constant pressure at the required level throughout each loading time (t_1). This is demonstrated in Figure 8.

For this particular gust, the required pressure is 215 Pa (4.5 psf), shown by the dotted line. The simulated pressure curve is shown along with the monitored data from the feedback control (refer to **Size**). A typical example in calculating

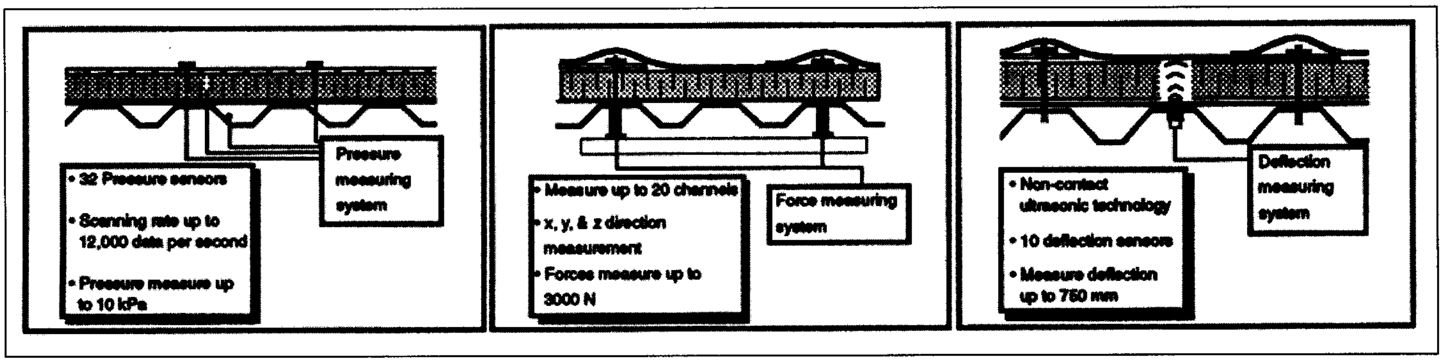

Figure 6. Instrumentation details of the SIGDERS facility.

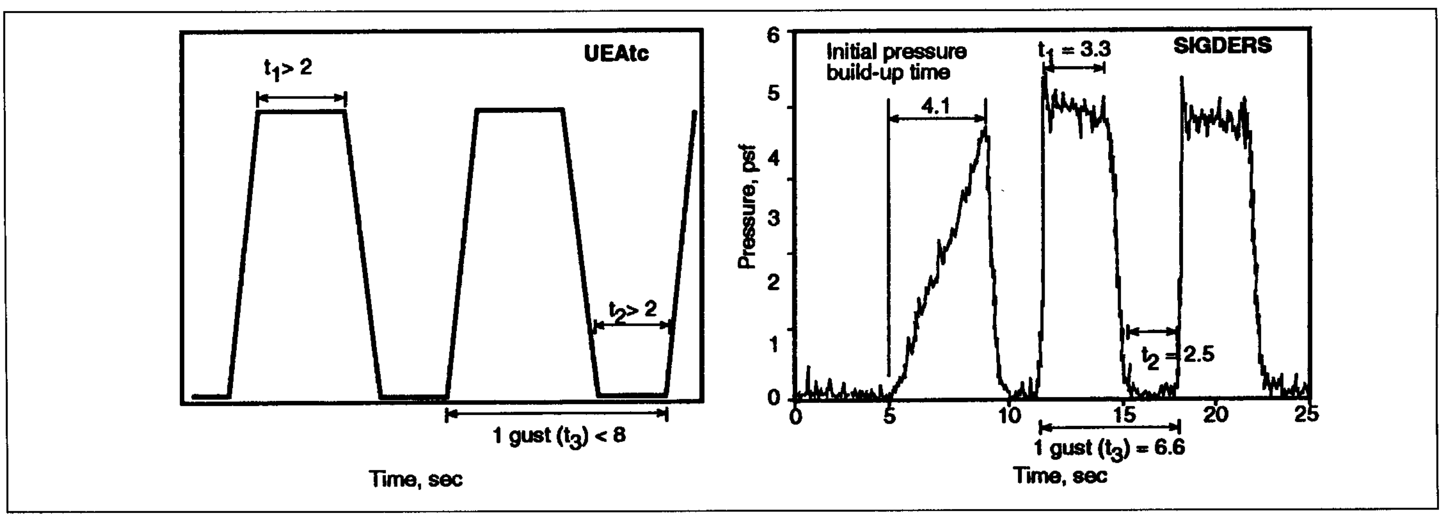

Figure 7. Commissioning of the SIGDERS facility for UEAtc load cycle - time requirement.

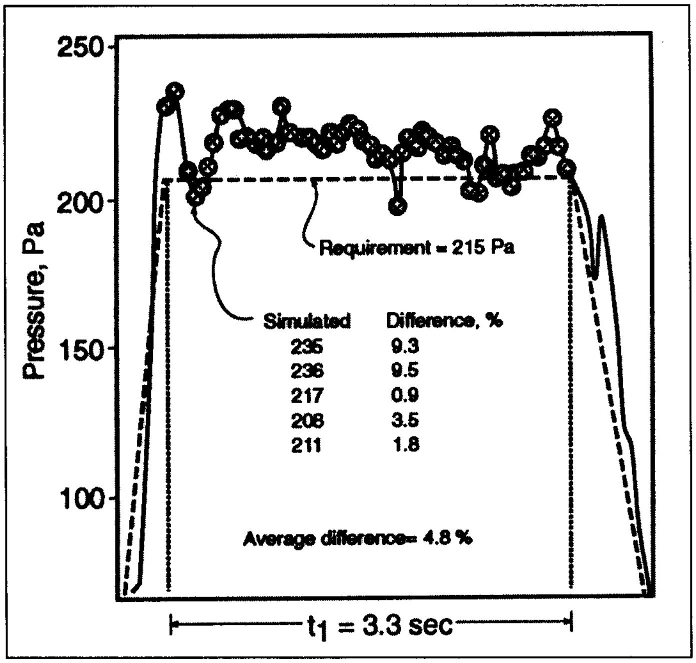

Figure 8. Commissioning of the SIGDERS facility for UEAtc load cycle - error estimation.

the percentage difference between the required pressure and the actual pressure is also inserted in the figure. It is clear that the loading time is 3.3 seconds and the pressure required by the UEAtc test procedure is maintained within a margin of 5 percent. Similar requirement verifications are also made at high pressure levels.

SIGDERS load cycle development

Approach

For the ongoing SIGDERS research project, a dynamic load sequence has been developed based on wind tunnel pressure records on a full-scale single-ply PVC roofing system of 3048 mm x 3048 mm (10 ft. x 10 ft.) in size. The wind tunnel tests were carried out in the 9000 mm x 9000 mm (30 ft. x 30 ft.) NRC wind tunnel. Figure 9 shows a photograph of the roofing model in the wind tunnel. Eighty-one pressure taps were fitted in the membrane to measure the unsteady pressure loads induced on it. Additional information on the wind tunnel investigations has been reported by Savage et al.[21]

Load sequence

The methodology followed for the development of the load cycle is documented by Baskaran, Chen and Savage[22] and Baskaran and Chen.[23] The load sequence developed based on SIGDERS research at NRC is presented in Figure 10.

The load sequence is divided into two groups: Group 1 with a zero minimum value and Group 2 in which the cycles are applied over a constant static component. Group 1 can be viewed as wind-induced suction over the roof assembly. Group 2 may reflect the combination of exterior fluctuations with a constant interior pressure on a building.[24] The cycles applied over a mean component in the Group 2 loading sequence are aimed to simulate membrane flutter. During loading sequences 5, 6, 7 and 8, the membrane is lifted due to the mean component so that tension is exerted at the attachments. Membrane flutter is a commonly observed

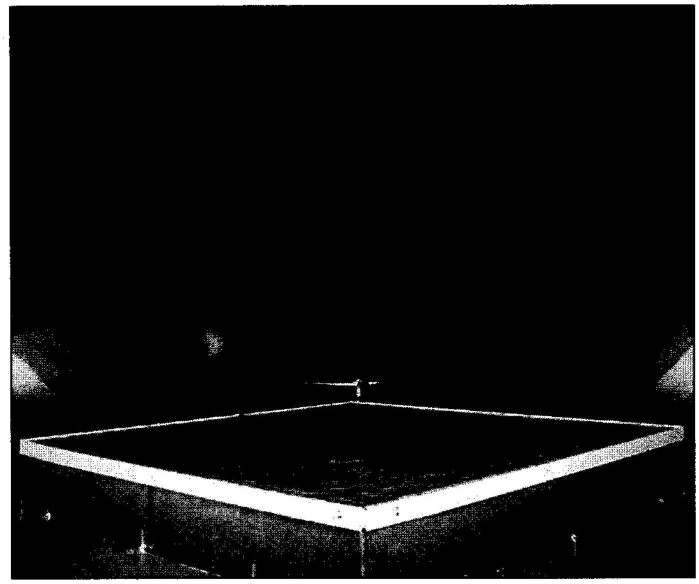

Figure 9. Photograph of a 3 m x 3 m PVC roof assembly tested at NRC's 9 m x 9 m wind tunnel.

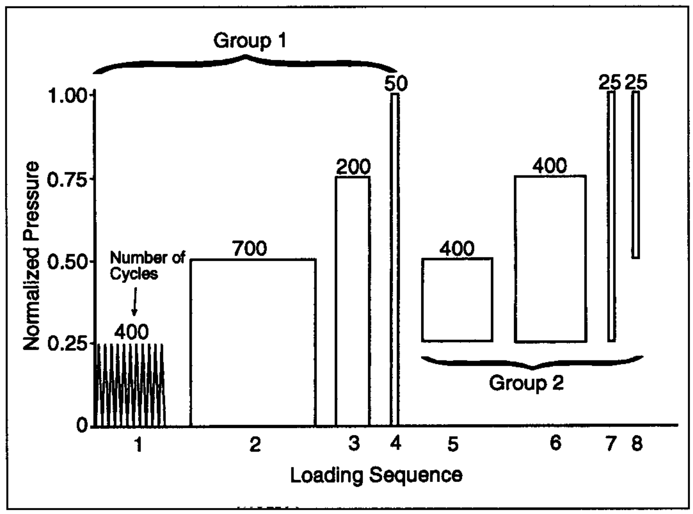

Figure 10. SIGDERS load cycle for PVC investigation.

event[7,25] and is one of the main causes of fatigue at attachment locations.

The developed dynamic wind load cycle has 2200 gusts in total. Load cycle pressure ratios are presented in the y-axis. They can be converted into test pressures by using design pressures calculated in accordance with the local building code or wind standards. Design pressures account for building height, local wind conditions, roof slope and other factors.

RESULTS AND DISCUSSION

Roofing system layout

Common features of the roofing system under investigation (refer to Figure 11) are as follows:

- Deck: 0.76 mm (22-Ga) steel deck with a profile height of 38 mm (1.5 in.) and a flute width of 150 mm (5.9 in.). The steel deck was fastened to the wood frame with size-10 round-head screws.

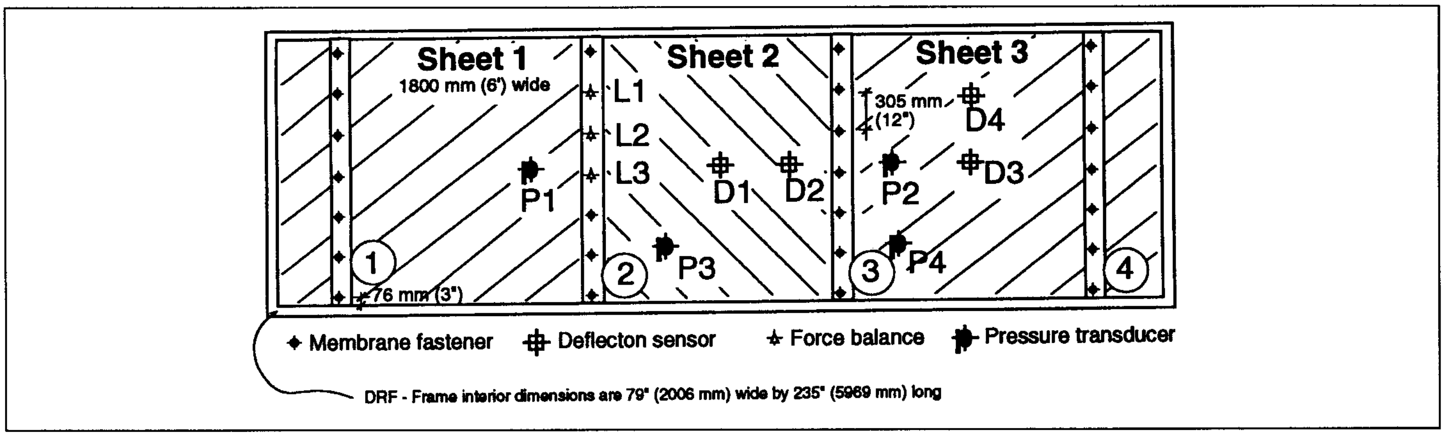

Figure 11. PVC membrane layout and fastening arrangement.

- Insulation: 100 mm x 1500 mm x 3000 mm (4 in. thick x 4 ft. x 8 ft.) polyisocyanurate (ISO) boards mechanically attached to the deck with six fasteners per board. Fasteners were 127 mm (5 in.) long with a plastic disc 76 mm (3 in.) in diameter.
- Membrane: Reinforced PVC membrane sheets of 1800 mm (6 ft.) wide. Three full-width sheets were installed, with two dummies at the ends. Fasteners 127 mm (5 in.) long with a plastic disc of 51 mm (2 in.) in diameter were used to attach the membrane to the deck along four seams.

Figure 12 shows two details for the installed PVC roofing system. Figure 12(a) shows how the membrane overlaps at seams. As shown, all seams had a 127 mm (5 in.) overlap in which the membrane fastener was installed 38 mm (1.5 in.) to the right of the seam.

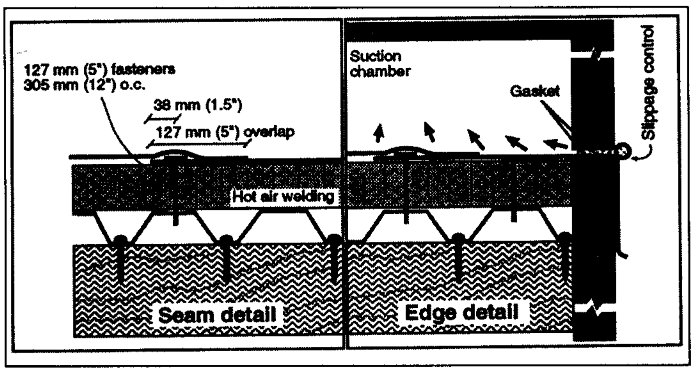

Figure 12. Edge and seam details of the PVC system.

Hot-air welding process was done on the rest of the seam (89 mm - 3.5 in.). Welded portion ranges from 38 mm to 45 mm (1.5 in. to 1.75 in.). One such edge detail is shown in Figure 12(b). To ensure airtightness, gaskets were used both at the top and bottom of the DRF frame. Outside the DRF frame, solid wood pieces 76 mm (3 in.) in diameter were welded to the membrane at several locations along the edges to prevent possible membrane slippage during the testing.

Investigation based on UEAtc load sequence

Figure 13 shows the typical measured response of a roofing system subjected to the UEAtc loading sequence. It is presented in the form of time histories corresponding to the cycle prior to system failure (in this case, Cycle 18). Note that the system failed during Cycle 19. The three curves represent, respectively, the pressure difference across the membrane at location P1, induced loads on the central fastener L3, and the membrane deflection at location D1. The simulated pressure satisfies the UEAtc requirement (refer to Figure 3) and induces a similar loading pattern on the fastener. The pressures for the 40 percent, 60 percent, 80 percent and 90 percent loading rates were 1187 Pa (24.8 psf), 1781 Pa (37.2 psf), 2374 Pa (49.6 psf), and 2648 Pa (55.3 psf), respectively.

During the 18th cycle, a maximum suction pressure of 2969 Pa (62 psf) was applied at Step 5. This represents the

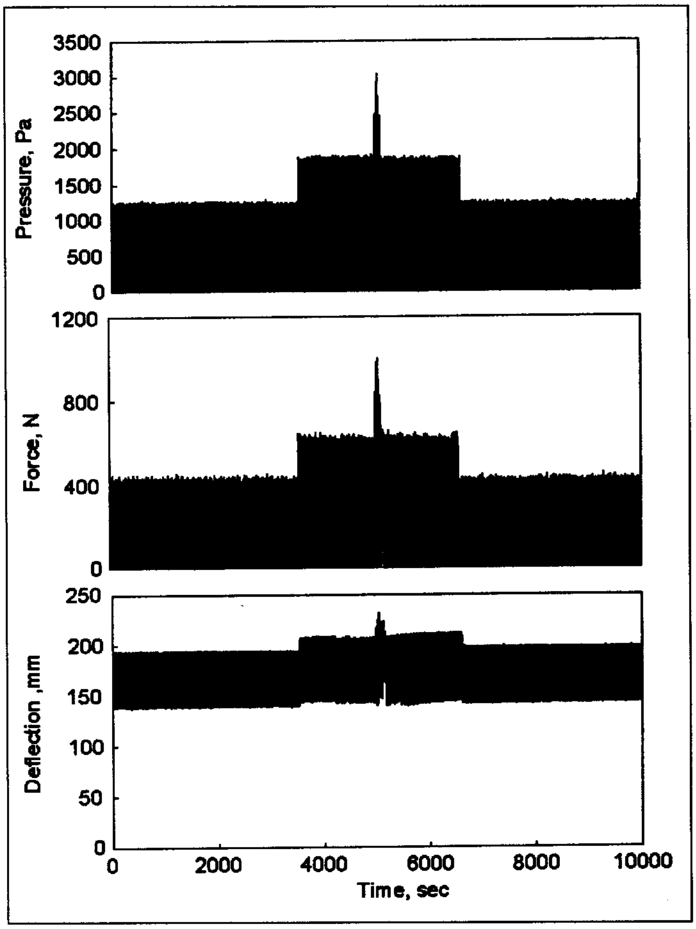

Figure 13. Typical pressure, force and deflection time histories from UEAtc testing, cycle 18.

100 percent loading rate, at which a force of 964 N (217 lbf) developed on the central fastener. (Even though force and deflection measurements are not required for UEAtc certification, they were carried out by the present study in order to get an in-depth understanding of the system behavior.)

For each cycle, mean, minimum and maximum values were calculated from time histories. Figure 14 shows the maximum deflection values at various loading rates for loading Cycles 10 to 18. An increase from 40 to 100 percent of the loading causes an increase in the membrane deflection. This was found to be true irrespective of the cycle number. Similar membrane responses were also noticed for deflections monitored at locations D2, D3 and D4 (refer to Figure 11).

Membrane fastener forces at locations L1, L2 and L3 are shown in Figure 15 for 40 and 80 percent loading. This represents the induced vertical force component on the fasteners. The load increases as the cycle number increases because of the increase in the applied pressure. However, due to membrane deflection, the load does not increase linearly; that is, doubling the applied pressure does not double the force induced on the fastener. This is the case at all locations for all cycles. Notice that L2 is equidistant from L1 and L3 (refer to Figure 11), but the difference between the forces induced on L1 and L2 is smaller than the difference between

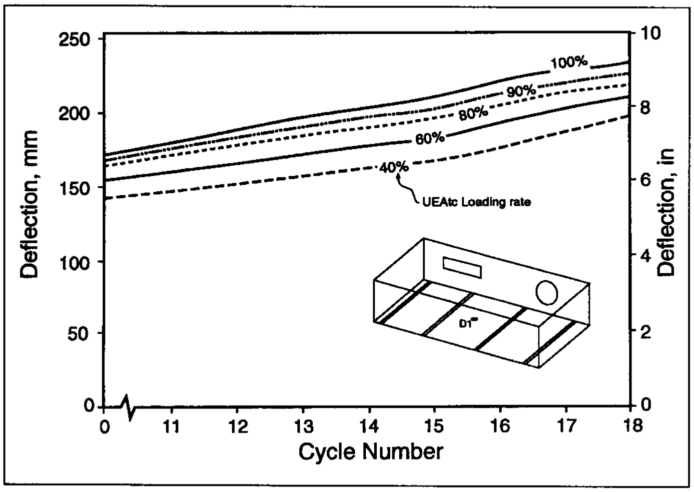

Figure 14. Measured membrane deflection during UEAtc testing.

L2 and L3. The smaller load observed at L1 may be due to edge effect.

Investigation based on SIGDERS load sequence

A second system, with an identical fastener and instrumentation layout to that shown in Figure 11, was investigated by subjecting it to the loading sequence developed by the SIGDERS research project (refer to Figure 10). The UEAtc loading sequence software was modified to accommodate the new load cycle sequence.[26] This section presents the experimental data obtained from the SIGDERS loading sequence investigation.

In Figure 16, the solid line represents the pressure difference across the membrane, whereas the dotted line represents the pressure drop across the insulation. If a seam were to open due to poor welding or if the membrane were to lose its airtightness due to the development of pin holes, a pressure drop would be created across the insulation. Otherwise, the membrane is expected to experience the full applied pressure. As shown in Figure 16, this has been found to be true. This monitoring procedure, developed by the current study, identifies any membrane tear or seam failure during the testing. During the system investigation, the membrane experienced all the applied suction. This instrumentation procedure has eliminated the need to stop the test at intermediate levels to examine the airtightness of the membrane. This not only saves testing time, but also helps to maintain continuity in the testing process from one loading sequence to the next. Figure 16 also displays the pressure requirement for the loading sequence 2 and 3. The difference between the applied pressure and the required pressure is, in fact, minimal.

Figure 17 shows the membrane deflection at three different locations, D1, D2 and D4 (refer to Figure 11), presented as time histories. It is clear that the testing was completed in less than three hours. The central location, D1, has the maximum deflections of 200 mm (7.9 in.) during loading sequence 4. D2, being closer to the fastener attachment, has less deflection than D1. Deflection at D4 is further restrained due to the edge effect and is minimal for all three loading sequences.

Figure 18 shows the measured forces on the fasteners. Horizontal (Fx) and vertical (Fz) forces are shown for four dif-

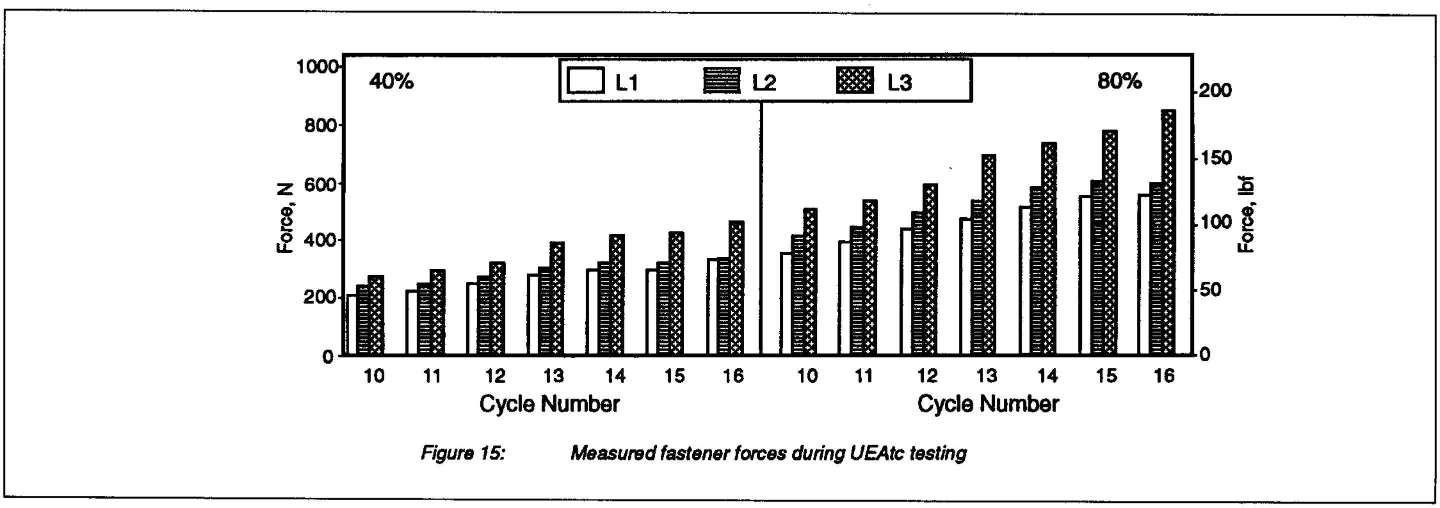

Figure 15. Measured fastener forces during UEAtc testing.

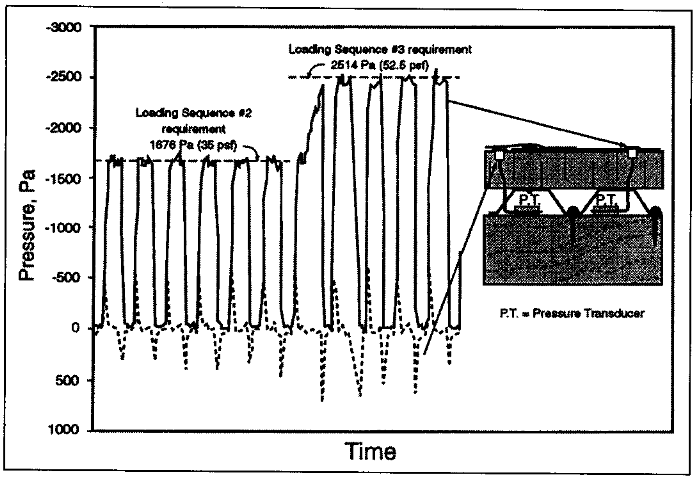

Figure 16. Monitored pressure difference across the membrane and insulation, SIGDERS load cycle.

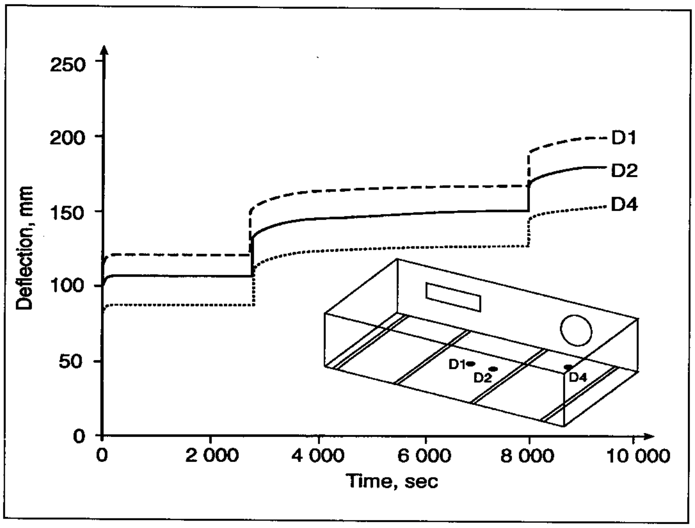

Figure 17. Typical deflection time histories from SIGDERS investigation.

ferent loading sequences. For the SIGDERS load sequences 1, 2 and 3, the maximum applied pressures are respectively 838 Pa, 1676 Pa and 2514 Pa (17.5, 35 and 52.5 psf). The system failed during the application of 3352 Pa (70 psf), during loading sequence 4. From Figure 18, one can deduce that:

- Fx is significantly lower than the Fz, irrespective of the loading sequences and location.
- An increase in the applied pressure increases the fastener forces non-linearly. In other words, even though the applied suction is doubled from loading sequence 1 to 2, the induced forces corresponding to loading sequence 2 are not twice that of loading sequence 1. This is true for both Fx and Fz. This response is similar to one measured under UEAtc, as shown in Figure 15.
- Location L3, at the central fastener, had the maximum induced force, irrespective of the loading sequence. A load of 773 N (174 lbf) was measured for loading sequence 3, and when the system failed, a maximum load of 1022 N (230 lbf) was recorded.

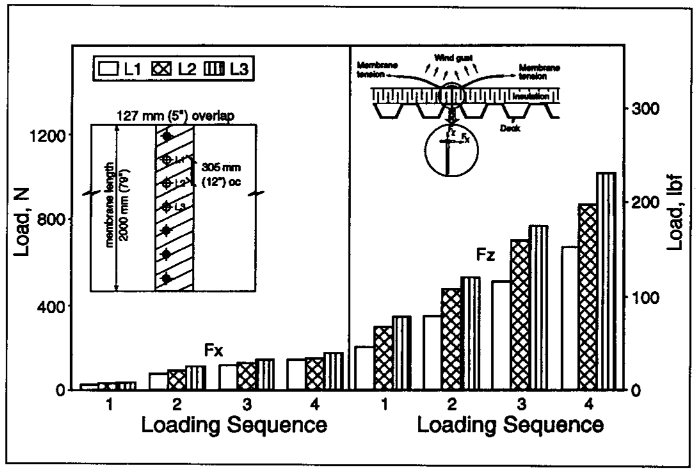

Figure 18. Measured fastener forces during SIGDERS investigation.

EFFECT OF LOADING SEQUENCE ON ROOFING SYSTEM RESPONSE

This section presents the effects of different loading sequences on the roofing system performance. The focus here is on a comparison of the existing fatigue loading sequence (UEAtc) and the proposed dynamic loading sequence (SIGDERS). First, general features between them are compared in Table 1.

Source data

The development of the UEAtc test protocol was based on wind climatic data accumulated over a five-year return peri-

Parameter	UEAtc	SIGDERS
Source data	Wind climatic records	Roof pressure time histories
Relationship with wind speed	No	Yes
Relationship with code	No	Yes
Internal pressure	No	Yes
Low pressure fluctuations	Yes	No
Membrane flutter	No	Yes
Testing time	48 hours	2.8 hours
Maximum number of gusts	No	2200
Low-intensity gusts (<40 %)	71% per cycle	18%
Medium-intensity gusts (40 to 75 %)	28% per cycle	68%
High-intensity gusts	1% per cycle	14%
Correction for temperature	Yes	No
Correction for specimen size	Yes	No
End product	Fastener design load	Dynamic evaluation

Table 1. Comparison of UEAtc and SIGDERS loading sequence.

od.[4] The development of the SIGDERS loading sequence, however, was based on unsteady-pressures measurements taken on full-scale roof components in the wind tunnel. The latter facilitates the establishment of the relationship between the wind speed, local building code or wind standards, and variation in internal pressure.

Testing
If fastener back-out design is unknown, then the UEAtc sequence has the option of applying a high-frequency conditioning cycle (refer to Figure 3). Simulating a constant suction in Group 2 of the SIGDERS sequence creates membrane lifting and the superimposed cycles mimic the effect of membrane fluttering (refer to Figure 10). The time required to complete the UEAtc procedure depends on the number of cycles that a particular system can sustain. In the example discussed here, the system sustained 18 cycles, which took about 48 hours of testing time. When tested using the SIGDERS procedure, the system failed after 2.8 hours of testing. Even application of all 2200 cycles of the SIGDERS sequence can take only about four hours of testing time. The major difference in testing time is the application of the low intensity gusts by the UEAtc procedure. As shown in the table, each cycle of the UEAtc sequence consists of about 71 percent low-intensity gusts, and applies only a single gust at the maximum load. SIGDERS applies about 68 percent medium-intensity gusts to accelerate the fatigue on the attachment system.

Other
The existing UEAtc protocol includes a correction to account for temperature variations and membrane size, whereas in the SIGDERS procedure these factors have not yet been addressed. At the end of UEAtc testing, fastener design loads are obtained. In SIGDERS, attempts have also been made to correlate the test pressure selection with the local building code or wind standards by setting the maximum test pressure equal to the design pressure. Thus the latter provides a complete insight into the dynamic performance of a roofing system.

Comparison between static and dynamic evaluation
Measured fastener forces from UEAtc and SIGDERS tests are compared in Figure 19 for various simulated pressures. More data points at different loading rates have been collected during the application of low intensity gusts for the UEAtc. The three data points from SIGDERS correspond to the maximum load measured for loading sequences 1, 2 and 3. Both UEAtc and SIGDERS induce similar forces on fasteners for various applied pressures. This is true for all three locations. Nevertheless, at location L1, forces measured under the SIGDERS sequence were about 5 percent less than those under UEAtc sequence. As shown in Figure 11, L1 is closer to the edge, which may affect the induced forces on the fasteners.

To compare the above findings with the existing FM 4470 standard, a third roofing system was tested using a load cycle similar to FM 4470 standard. Tables 2 and 3 compare all the design parameters (pressure, forces and deflection) obtained from the above three investigations. The response parameters which the roofing system sustained are given in Table 2. In other words, these parameters correspond to conditions under which the roofing system passed the required number of cycles under the three loading sequences. The system withstood 3591 Pa (75 psf) suction during FM static investigation.

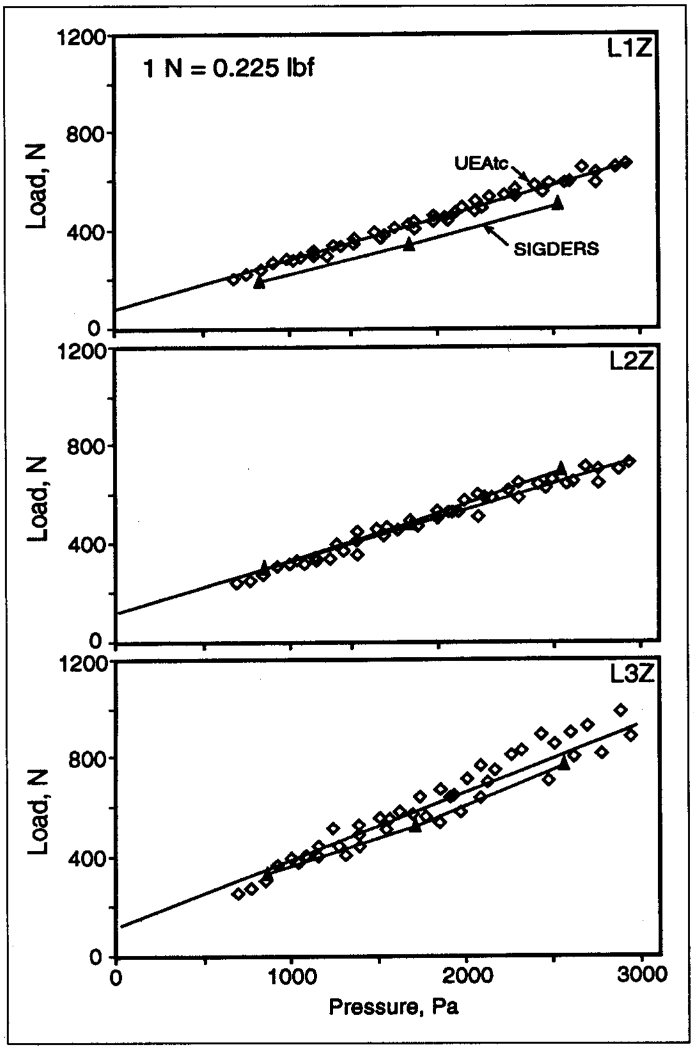

Figure 19. Comparison of measured forces from the UEAtc and SIGDERS investigation.

Parameter	UEAtc	SIGDERS	FM
Pressure Pa (psf)	 2969 (62)	 2514 (52.5)	 3591 (75)
Force N (lbf)	 964 (217)	 773 (174)	 1316 (296)
Deflection mm (in.)	 231 (9.1)	 202 (7.9)	 233 (9.2)

Table 2. Comparison of the design parameters measured from different load cycles—System sustained.

This is about 43 percent* higher than the pressure it withstood under SIGDERS dynamic evaluation. Fastener loads under the FM sequence yield 1316 N (296 lbf). This again is significantly higher than the measured loads derived from the UEAtc (964 N - 217 lbf) and SIGDERS (773 N - 174 lbf) loading sequences.

Table 3 presents data for conditions under which the roof-

* *(3591 - 2514)/2514, 1077/2514 = 0.429, 0.429*100 = 43%.*

Parameter	UEAtc	SIGDERS	FM
Pressure Pa (psf)	3227 (67)	3352 (70)	4309 (90)
Force N (lbf)	960 (216)	1022 (230)	1586 (350)
Deflection mm (in.)	269 (10.6)	260 (10.2)	319 (12.6)
Failure Mode	Tear and delamination	Tear and delamination	Fastener pull-out

Table 3. *Comparison of the design parameters measured from different load cycles— System failed.*

ing system failed. Under the UEAtc sequence, the system failed at Cycle 19, loading step 5, during the application of 3227 Pa (66 psf) pressure. The maximum measured fastener force was 906 N (216 lbf). Similarly, under the SIGDERS sequence, the system failed at loading sequence 4 during the application of 3352 Pa (70 psf) pressure. SIGDERS loading sequence 4 (refer to Figure 11) has 50 cycles, and the failure occurred at Cycle 34.

On the other hand, in the FM test, the system withstood the application of 3591 Pa (75 psf) for one minute. The system failure occurred after two seconds during the build-up of 4309 Pa (90 psf) pressure. When the system failed due to fastener pull out, the measured load on the central fastener was 1556 N (350 lbf). This is, again, about 52 percent† higher than the force measured for the same fastener under the SIGDERS sequence.An equally important observation from the comparison is the failure mode during the above three investigations. Typical failure modes from the FM, UEAtc and SIGDERS investigations are shown in Figures 20, 21 and 22, respectively. In the FM tests, the failure resulted due to fastener pull out from the deck. Neither the membrane nor the seams were damaged.

By contrast, for UEAtc and SIGDERS testing, membrane tearing and delamination of the membrane fabric coat occurred at the seams. On the welded portion of the seams, delamination initiated during the middle of the testing sequence and progressed. The membrane tear at fastener locations caused the system failure. None of the fasteners lost its engagement with the deck. This type of failure mode is in agreement with several field observations made during high-wind events.[27] Nevertheless, further study is necessary to validate differences in failure modes.

Figure 20. *Photograph of the fastener pull out during FM testing.*

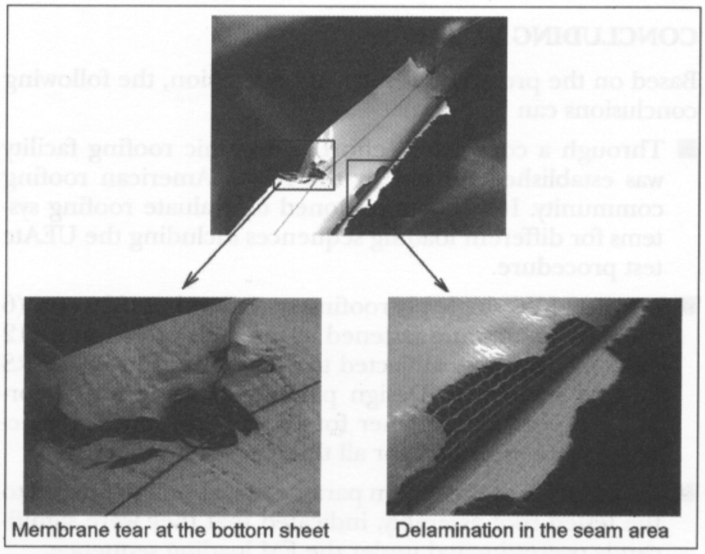

Figure 21. *Photograph of the membrane tear and delamination during UEAtc testing.*

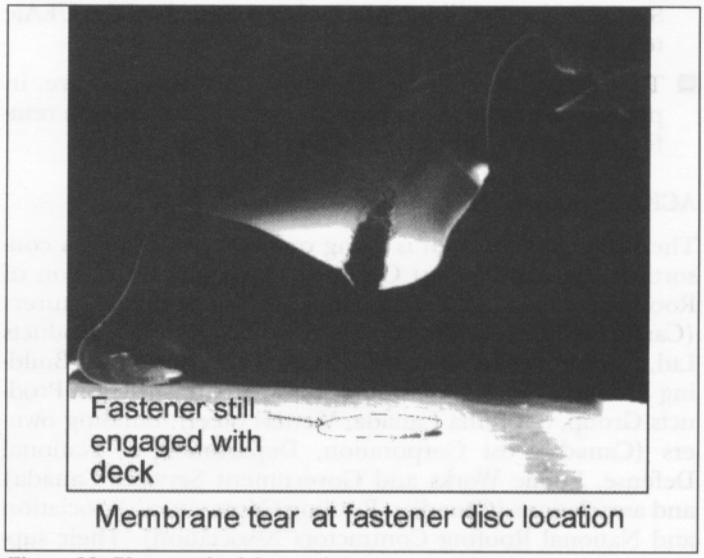

Figure 22. *Photograph of the membrane tear and disc engagement during SIGDERS investigation.*

† (1556 - 1022)/1022, 534/1022 = 0.523*100 = 52%.

CONCLUDING REMARKS

Based on the presented results and discussion, the following conclusions can be drawn:

- Through a consortium effort, a dynamic roofing facility was established for use by the North American roofing community. It was commissioned to evaluate roofing systems for different loading sequences including the UEAtc test procedure.
- A typical PVC single-ply roofing system with a 1829 mm (6 ft.) wide membrane fastened at intervals of 305 mm (12 in.) on center was subjected to FM, UEAtc and SIGDERS loading sequences. Design parameters for wind performance (pressure, fastener forces and membrane deflections) were measured for all three loading sequences.
- Comparison of the design parameters, although limited to the tested roof assembly, indicated that they were significantly overestimated under the FM loading sequence.
- Both UEAtc and SIGDERS load sequence investigations resulted in similar design parameters. Nevertheless, the SIGDERS loading sequence took less time than the UEAtc test procedure.
- To validate the above findings, investigations are in progress using various single-ply systems, including a reinforced EPDM, TPO and modified bitumen.

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