WIND RESISTANCE OF MECHANICALLY-ATTACHED, SINGLE-PLY SYSTEMS FASTENER LOAD, SAFETY CONSIDERATIONS AND OPTIMAL FASTENER PATTERNS

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Wind damage on lightweight roofs of industrial and commercial buildings appears to be quite common in North America. One of the primary reasons for the observed damage is inadequate design against wind uplift. This paper describes the load mechanism and testing methodology of mechanically-attached, single-ply roof membranes and presents a newly designed fastener system incorporating the consequences of the load mechanism.

The new UEAtc approval test, which will be discussed, is based on the observed load mechanism. Using a method to determine the deflection of the roof membrane under wind suction, the reduction in fastener load due to the test apparatus constraint may be calculated. This leads to a correction factor, which will be incorporated in the UEAtc guideline to account for the limited size of the test specimen. The same computational method may be used to calculate the increased load of a fastener, if the neighboring fastener fails. Based on such a calculation, a physically meaningful safety factor has been specified and will be used in the UEAtc guideline. Finally, a design methodology for an optimal attachment system will be described.

KEYWORDS

Approval testing, fastener load, mechanical attachment, single-ply roofs, wind load.

INTRODUCTION

Lightweight roofs of industrial and commercial buildings are increasingly covered with single-ply roof membranes. These roof membrane systems are often attached with mechanical anchors to resist wind uplift forces. The second author has noted an increase in the occurrence of wind damage to these roofs. Investigations of approximately 15 roofs, ranging in size from 3600m² (40,000 ft.²) to 216,000m² (2,400,000 ft.²) indicate that the primary reason for the observed wind damage is inadequate design against wind uplift. Therefore, it can be concluded that designers as well as roof membrane manufacturers need a better understanding of the following:

- Principle of wind load mechanism.
- Knowledge of wind loads (external and internal) acting on the roof and application of the importance of reasonably sized perimeter and corner regions.
- Realistic and reliable wind uplift approval testing.
- Physically reasonable load and safety considerations for fastening elements.

WIND LOAD MECHANISM AND CONSEQUENCES FOR AN OPTIMAL FASTENER DESIGN

In North America design wind pressures on structures are calculated according to the American National Standard Institute's (ANSI) Standard A 58.1 and the National Building Code of Canada, Supplement No. 4, Commentary No. 1. (After submission of the paper the Standard ASCE 7-88 was published, which replaces ANSI A 58.1.) In both documents, the equation to determine the design wind pressure is of the form:

$$p = q\, C_e\, C_G\, C_p$$

with q = wind velocity pressure
C_e = exposure factor
C_G = gust factor
C_p = time average pressure coefficient

The design wind pressures and wind loads calculated are assumed to be static loads. Buildings or building elements of sufficient stiffness that are not sensitive to vibration will react to the wind action as if in the steady state. However, single-ply membranes in general have very little stiffness and, therefore, will deflect almost instantaneously under the fluctuating wind action. This holds true even if an air-retarder is used. Air-retarders are not airtight due to imperfections of the overlaps, the punctuations of the fasteners and other penetrations. Therefore, air will leak into the space between the membrane and thermal insulation. An air-retarder will only "retard" this air-leakage. Tests conducted by the first author demonstrate that it will take approximately 10 to 15 gusts to leak enough air through the air-retarder to establish the building's internal pressure underneath the membrane.

Due to ease of installation, the in-lap (or spot attached) fastening method of roof membranes is most commonly used. Under wind action, the roof membrane will be deflected, leading to a tilting of the load distribution plate of the attachment assembly (Figure 1). The deflection of the roof membrane results in two force components. The normal forces are taken up by the fasteners. The tangential forces are taken up by the load distribution plates in the form of frictional forces. When the friction is not strong enough, an equilibrium of tangential forces may only be accomplished by an additional tangential force in the membrane around the fastener shaft. This leads to a large concentration of membrane stresses with a high potential of roof membrane failures. The most common failure mode (Figures 2 and 3) documented by the authors from field observations over the past 10 years is excessive plate/membrane movement, ultimately resulting in failure of the roof membrane by tearing at the attachment point(s).

Common fastener design inherently harbors another disadvantage, which can be described as a relatively large normal force acting on the screw fastener under wind action. This force is the result of the tilting action of the attachment assembly, the rigid connection between screw/head plate and the screw penetration at the center of the load distribution plate. This unfavorable lever-arm ratio is exerted on the load distribution plate edge by the deflected roof membrane, with a magnitude of approximately 2.5 times the wind uplift force (Figure 1). These relatively large screw forces lead to the following failure modes, also taken from field observations (Figure 4):

- Fastener pull-out from the structural deck.
- Fatigue on the structural deck at the point of fastener penetration.

An optimal solution concerning fastener forces appears to be an attachment system that allows for a largely symmetrical billowing of the roof membrane around the fastener assembly, e.g., by using a continuous bar and cover strip (Figure 5). The same beneficial effect may be obtained with spot-fasteners using the through- membrane attachment method with cover strips. Lately, an attachment method for PVC membranes has been tested with very good success, where the fasteners were provided with PVC washers of diameter d = 180mm (7 in.) to which the pre-welded membrane was bonded. Thus, the membrane will not be penetrated by the fasteners and the billowing wind action will be symmetrical around the fasteners.

In an attempt to combine the advantages of the in-lap and through-membrane attachment methods, WSP Consulting Engineers has developed a securement system that allows for a combination of the described advantages. The deciding feature of this system is a load distribution plate with an off-center position for the screw fastener (Figure 6). Prototype testing has been completed and indicates that this load distribution plate offers the following:

- Remarkable decrease of screw force (normal).
- Increase in frictional forces.
- Reduction of roof membrane stresses at the plate edge.
- Appreciably higher failure loads when compared to currently available attachment systems.

UEATC-METHOD FOR APPROVAL TESTING

A new guideline for approval testing of mechanically-attached roofing membranes has been agreed upon by the relevant commission of the UEAtc. At present, the guideline is being edited and translated in the official UEAtc languages. Publication is anticipated for the end of 1990. Efforts are underway in the United States, in ASTM (Dynamic Testing Mechanically-Attached Single-Ply Membranes ASTM E06.22.04) to form a testing standard similar to the one for the European nations.

The two main test criteria described in the guideline concern the performance and safety aspects of wind uplift and fastener corrosion. The wind uplift test will be discussed briefly. It is based on earlier work by WSP Consulting Engineers described in detail in references 2, 3 and 4. The basic idea of the UEAtc approval test is to determine the allowable load per fastener for a given roof system. This information may be used in combination with the national codes or standards concerning wind loads to calculate the necessary number of fasteners:

$$N_n = p_{design}/W_{allowable}$$

The standard test specimen consists of profiled sheet metal substrate, thermal insulation and a mechanically-attached roof membrane. The thermal insulation layer and the membrane have to be secured against wind uplift. It is explicitly stated that the standard system does not include a vapor check or air-retarder. The allowable load per fastener obtained for such a standard system may also be applied to a system with a vapor check.

The same test procedure may be used for roof systems with concrete, lightweight concrete or wood substrate. The first author has conducted numerous tests with such deckings. Failure loads for otherwise equivalent roof systems indicate that profiled sheet metal decking with standard European sheet metal of thickness 0.75mm (22 ga) are critical for all attachment methods. The standard insulation layer thickness is 100mm. Preliminary tests conducted concerning the influence of the thermal insulation layer thickness indicated this thickness to be critical. For other identical systems, 50mm thick thermal insulation and 200mm thick thermal insulation layers led to larger failure loads.

Wind Load Cycle

The wind load cycle to be used for UEAtc approval tests on mechanically-attached roof membranes consists of a number of sub-cycles, each of which is representative of the accumulated probability distribution of the wind velocity pressures for a five-year return period. The wind load cycle is shown in Figure 7.

The initial higher frequency/low load fluctuations are used to stimulate roof-deck flutter, which may lead to fastener back-out (Figure 8). After having applied four load sub-cycles with a 100 percent load of 300 N/fastener, the 100 percent load for each consecutive cycle will be increased by an increment of 100 N/fastener up to failure. The obtained test load corresponds to the 100 percent load of the load cycle prior to failure. The large number of loadings for loads smaller than the 40 percent load are not considered to shorten the test procedure.

The authors showed[3,4] the validity of this test method comparing laboratory-induced roof failures to field observations of actual roof damage.

This comparative effort identified the following, typical failure modes:

- Plate/membrane movement leading to membrane tearing and ultimately to membrane failure at attachment point.
- Fastener back-out.
- Fastener pull-out.
- Attachment plate deformation.

Test Apparatus and Influence of Test Apparatus Size

A typical test apparatus is shown in Figure 9. It consists of a suction chamber placed on a rigid frame around the test specimen. A fan generates the suction inside the chamber. The gust action is simulated by a control valve. The valve action and the rpm of the fan are controlled by a personal computer to provide the time varying loads according to the load cycle.

The test specimen may be considered a small part of a real roof. However, the membrane deflection is unrealistically constrained along the test rig edges. Part of the wind-induced membrane stresses, which normally have to be taken up by the fasteners, will now be diverted to the test rig edges. Therefore, the smaller the test specimen, the smaller the actual fastener loads under constant suction.

O. Jung[5] developed a program to calculate the actual loads to be taken up by the fasteners of the test specimen, taking into account the test apparatus edge constraint. The two-dimensional, non-linear differential equation describing the deflection of a pre-stressed membrane under wind suction is solved by an iteration method.

At the fastener locations, the membrane uplift is zero. Using this boundary condition, the membrane stresses, and hence, the forces to be taken up by the fasteners, may be calculated. The deformation is influenced by the modulus of elasticity of the membrane. The modulus has been determined experimentally for non-reinforced and reinforced PVC membranes and for reinforced EPDM membranes. Aside for the material, the modulus of elasticity depends on the strain rate, the stress level and—due to creeping—on the stress exposure time. The estimation of the modulus of elasticity used for the fastener load calculation is quite uncritical for the following reasons:

- The modulus of elasticity influences the calculation of membrane deflection and membrane stresses only mildly. Increasing the modulus by a factor of 10 will change the membrane stresses by a factor of less than 2.
- Only the load reduction due to the edge constraint, i.e., a relative information, is of interest.

The relative information concerning load reductions for reinforced and non-reinforced PVC membranes and reinforced EPDM membranes are very similar. For example, the calculated fastener loads for 1.5mm non-reinforced PVC membranes and 1mm reinforced EPDM membranes under otherwise identical conditions (fastener pattern, applied load) differ by only approximately 5 percent. Therefore, it may be concluded that the data obtained are valid for single-ply roofing membranes independently of the membrane material.

Figure 10 shows a typical plot of calculated membrane deflection for a test specimen of size 6m X 1.5m (19 ft. 6 in. X 4 ft. 10 in.), fastener row separation 0.9m (35 in.) and fastener spacing of 0.25m (9 in.) under a wind suction of p = 1800 N/m² (368 psf). The theoretical fastener load is determined by multiplying the wind pressure "p" by the influence area: A_{infl} = 0/9m X 0.25m = 0.225m² (2.4 sf):

$$W_{th} = p \cdot A_{infl} = 1800 \cdot 0.225 = 405 \text{ N (91 lbs)}.$$

The calculated fastener loads related to the theoretical fastener load are included in Figure 13 (a) small test specimen; without failure. Even the central fastener is loaded by only 78 percent of the theoretical fastener load.

Varying the aspect ratio of the fastener distribution (a/b) and the fastener spacing relative to the test rig width (m/b), a correction factor C_a has been determined to account for the limited size of the test rig (Figure 11). This diagram will be part of the new UEAtc guideline. It allows approval tests to be conducted in test rigs of arbitrary dimensions.

In addition to the correction factor C_a, a statistical correction factor (C_d) will be introduced in the UEAtc guideline. It accounts for the fact that less fasteners will experience high loads in a test rig, when only few fastener rows are present.[6] The correction factor will be C_d = 1, if the test specimen contains at least four fastener rows, C_d = 0.95 for three fastener rows and C_d = 0.85 for two fastener rows.

Safety Factor

The wind loads acting on mechanically-attached single-ply roofing membranes have to be taken up correctly by the fasteners at every part of the roof. Therefore, the wind safety depends strongly on the sufficient amount and on the correct placement of the fasteners. If the fastener density is decreased to its theoretical limit ($N_{min} = p/W_{allowable}$), failure of one fastener will induce the so-called zipper effect, i.e., failure of one fastener will lead to overloading of the neighboring fasteners resulting in larger area damage (Figure 12). To avoid the zipper effect, a safety factor will be introduced in the UEAtc guideline, which appears sufficient to account for the misplacement or failure of individual fasteners at critical locations of the roof.

Two cases have been considered theoretically: A field of 5 X 5 fasteners and a field of 9 X 9 fasteners. Using the calculation method described previously, the fastener load has been determined for all fasteners placed correctly and for failure of the central fastener.

The results are given in Figure 13. For both situations the load of the fasteners next to the failed fastener is approximately 1.4 times the initial load. Therefore, a minimum safety factor of γmin. = 1.5 has been agreed upon by the UEAtc Commission on mechanically-attached roof membranes.

The change in membrane deformation after failure of the central fastener may be seen in Figure 14. The fastener spacing is the same as for the membrane deformation sketch shown in Figure 10. The higher density of the grid lines at the fastener locations II/3 and IV/3 in Figure 14 indicate the higher stresses at those positions leading to the excess wind loads.

Using the above mentioned information, the allowable load per fastener $W_{allowable}$ obtained from UEAtc approval tests is:

$$W_{allowable} = W_{test} \cdot C_a \cdot C_d/\gamma \text{min}.$$

with W_{test} = 100 percent of the load cycle preceding the load cycle in which failure occurred; C_a = correction factor to account for the limited size of the test rig; C_d = statistical correction factor. The safety factor γmin. is a minimum value. Larger safety factors have to be used, if national codes or standards so require.

DESIGN METHODOLOGY

As stated above, an optimal attachment system is achieved if a minimum of fasteners will lead to a sufficient safety of a mechanically-attached, single-ply roofing system. The design of optimal fastener patterns consists of the determination of roof wind loads and the determination of allowable load per fastener for the roof systems chosen.

The roof wind loads given in codes of practice and standards are usually restricted to buildings with basic shapes. Little information is available concerning building planeforms of non-rectangular shape or of building complexes with flat roofs depicting varying height. For larger buildings or building complexes, a wind tunnel study to determine local wind loads leads—in the authors' experience—to substantial savings in roof construction cost.[3,7,8] It was shown that wind tunnel studies to determine the roof wind loads on typical, large industrial complexes lead to a saving of approximately 15 percent of the necessary number of fasteners compared to the design wind loads according to the national standards.

The authors have developed a simple method to obtain areas of the roof subjected to high wind loads. Using the sand erosion technique,[9] the roof zones of high local velocity and thus high local suction may be visualized for complex roof situations. Figure 15 shows an example. The dark areas indicate high wind suction. Lines between areas of different darkness are lines of constant velocity (isotachs) and at the same time lines of constant pressure (isobars). For cornering winds, the windward corners show the isobar lines typical for the conical vortex structures leading to the large local suction in the corner regions. In addition to the roof corner areas, another critical roof area is made visible for wind direction perpendicular to building walls Figure 15. The lower roof deck exhibits a zone of high wind suction near the penetration of the high bay. The pressure measurements conducted were in agreement with the information from the sand erosion pictures. For wind load studies on roofs, WSP Consulting Engineers uses the sand erosion technique regularly to determine the critical roof areas and to adjust the pressure tab density accordingly. This method leads to shorter wind tunnel investigations, and a reduced cost structure.

The majority of roof membrane manufacturers in Europe have completed approval testing as described to determine system specific allowable wind loads. To date, several U.S. manufacturers have completed approval testing or have announced their intent to commence with approval testing. Current testing of U.S. produced roof membrane systems (inclusive of attachment systems) suggests the following:

- Screw/plate design appears insufficient to prevent fastener back-out at lower stress levels.
- Spiked plastic/metal plates do not increase the failure load.
- Fastener spacings appear too optimistic for most roofs, to obtain sufficient wind safety.

Usually, the analysis of the test results will show the weak points of the tested roof systems and will lead subsequently to system improvement. Thus, the dynamic testing of roof systems will lead to safer systems—without increasing the cost.

In the roofing industry, it is quite common to re-cover an existing roof with a single-ply roof membrane system. The airtightness of the existing roofing (typically a built-up roof) may be an important factor in the positional securement of the new single-ply roof membrane and the allowable load per fastening element. Based on the authors' investigation and research, such an endeavor must include airtight perimeter/penetration flashings and uninterrupted continuity of the existing built-up roof to act as an air barrier.

A perfectly airtight vapor check will lead to a redistribution of the loading for the various roof system parts. The membrane and the fasteners securing the membrane will carry less load, but the vapor check/thermal insulation and the fasteners securing those parts will have to carry more. However, vapor checks will normally not be perfectly airtight due to the penetrations by the fasteners, by piping etc., and due to imperfections in the overlap regions of the air-retarder sheets. Such influence parameters may lead to a reduction of fastener loads. They can be and should be investigated in a dynamic test situation as described above, since no generally accepted reduction factors may be given at present.

Wind loads obtained from wind tunnel evaluations, combined with correctly obtained allowable fastener load values, allow the designer to implement optimal solutions with respect to the wind safety of mechanically-attached, single-ply roofing membranes.

REFERENCES

[1] H.J. Gerhardt and C. Kramer, "Befestigungsvorrichtung" Deutsche Patentanmeldung, 40 08 517.1, April 1990.

[2] H.J. Gerhardt and C. Kramer, "Wind induced loading cycles and fatigue testing of lightweight roofing fixations," *Journal of Wind Engineering and Industrial Aerodynamics* 23, pp. 237 - 247, 1986.

[3] H.J. Gerhardt and R.W. Gerbatsch, "Testing Wind Loads on Single-Ply Membranes," *The Construction Specifier*, pp. 61 - 71, November 1989.

[4] H.J. Gerhardt, "Roofing Membranes - Observed Damage, Failure Modes, Failure Hypotheses and Laboratory Testing," Proc. Wind Uplift Testing Workshop, Oak Ridge National Laboratory Conference 891173 pp. 19 - 34, November 1989.

[5] O. Jung, Private communication.

[6] M. Dubois, Private communication.

[7] C. Kramer and H.J. Gerhardt, "Wind Effects on Roofs and Roofing Systems," Proc. 6th U.S. National Conf. on Wind Engineering, Vol. I, B 2-13 ff, University of Houston, Texas, March 1989.

[8] H.J. Gerhardt and C. Kramer, "Mechanisch befestigte Dachabdichtungen unter Windeinwirkung" in: Sealing with Plastic and Rubber Sheets - A European Task, 4th International Sealing Congress, Darmstadt, Technical Association for Plastic and Rubber Sheeting (TAKK), April 1990.

[9] W.J. Beranek and H. van Koten, "Visual Techniques for the Determination of Wind Environment," Proc. of the 3rd Colloquium on Industrial Aerodynamics, Part 3, pp. 1-15, Aachen, 1978.

[10] H. Wieland, Statik und Dynamik der Befestigungen von Dachabdichtungsbahnen, Vortrag anläßlich des SFS-Seminars, 1985.

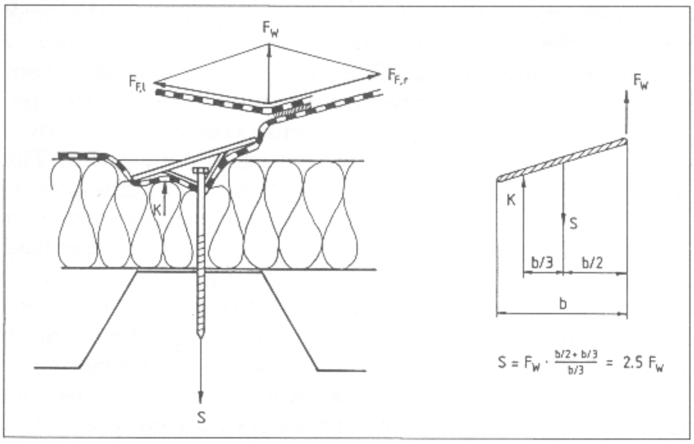


Figure 1 *Schematic drawing of load distribution at an attachment assembly under wind action (after (10)).*

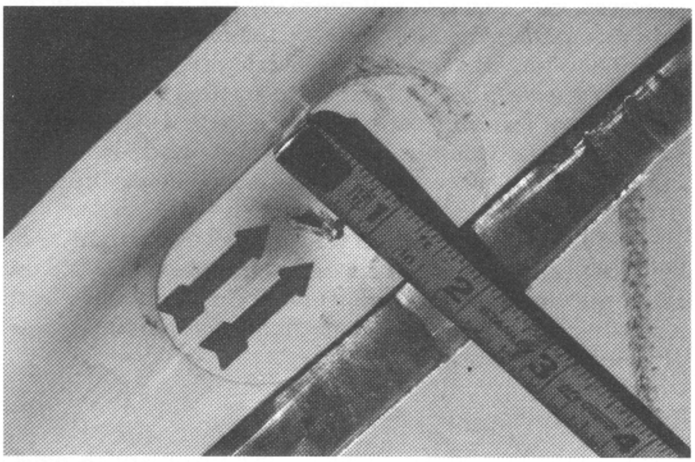


Figure 2 *Field observations of a mechanically-attached, single-ply roof showing membrane tear.*

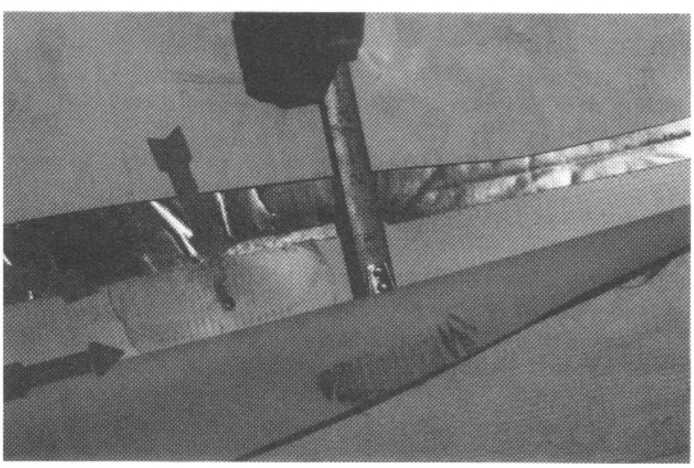


Figure 3 *Field observations of a mechanically-attached, single-ply roof showing fastener/plate movement that has led to excessive membrane tear.*

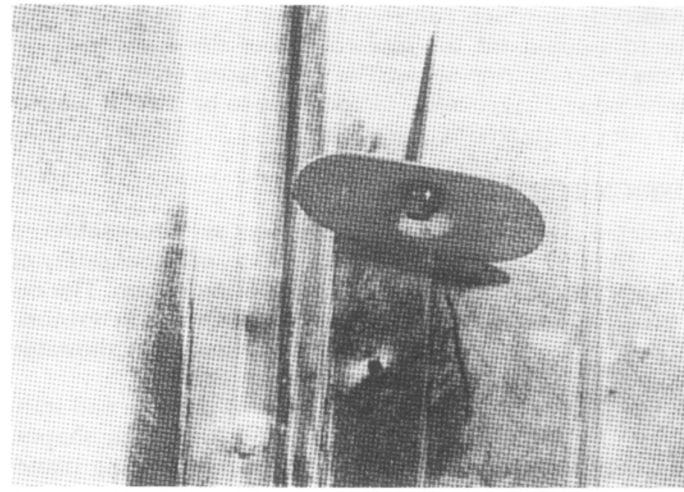


Figure 4 *Field observation of a roof failure showing fastener pull-out.*

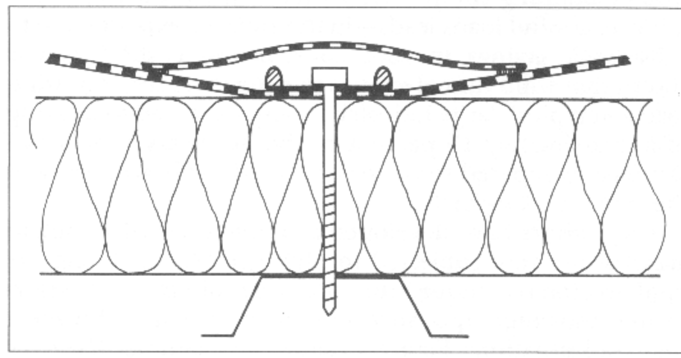


Figure 5 *Section view of a continuous bar fastening system with cover strip.*

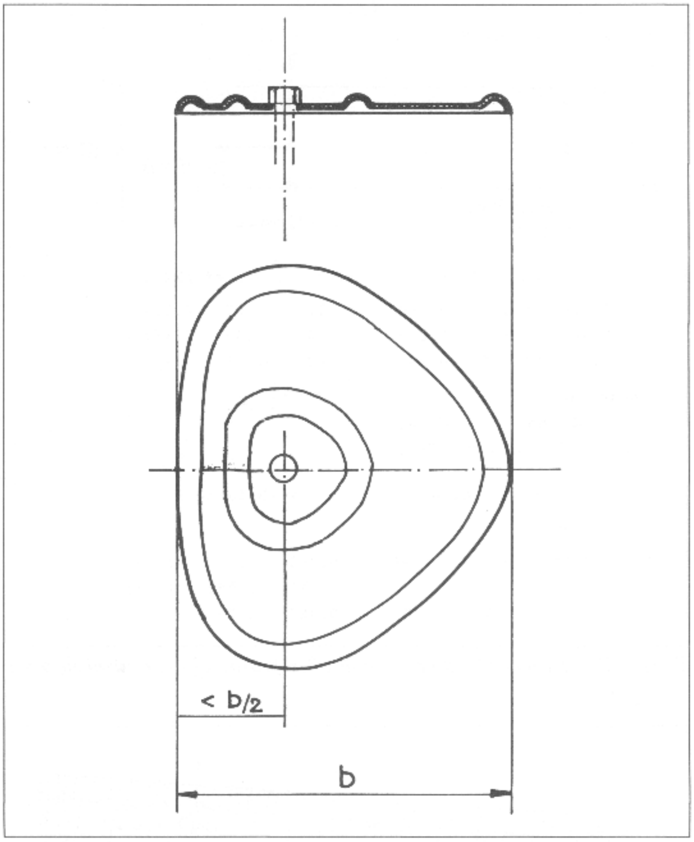


Figure 6 *Section and plane view of a prototype fastener plate.*

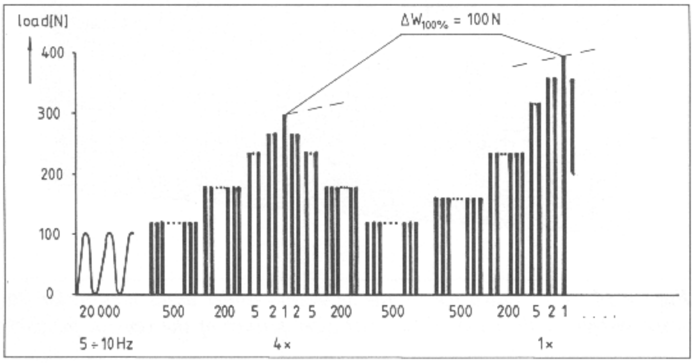


Figure 7 *UEAtc wind load test cycle.*

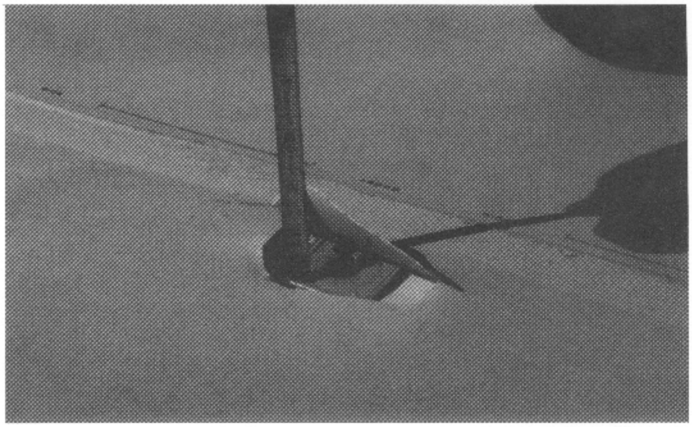


Figure 8 *Field observation of fastener back-out caused by high-frequency, low-load fluctuations.*

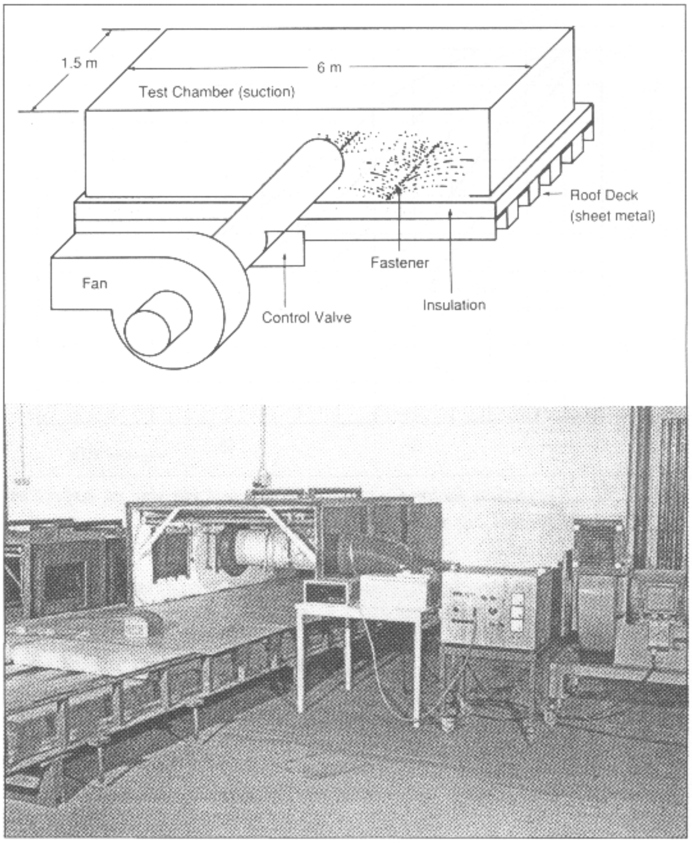


Figure 9 *Test apparatus for dynamic testing.*

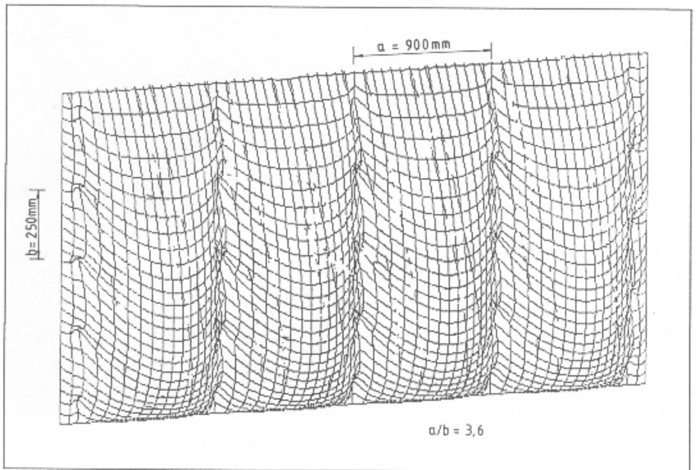


Figure 10 *Calculated membrane deflection under wind suction.*

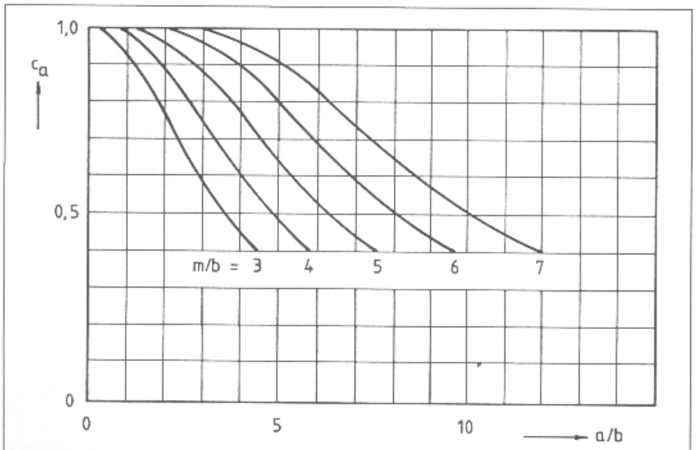


Figure 11 *Correction factor C_a to account for test rig size vs. aspect ration a/b (m/b = test rig width/fastener spacing).*

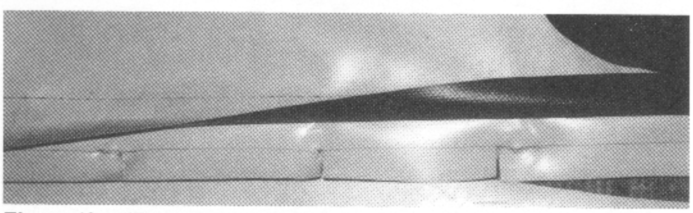
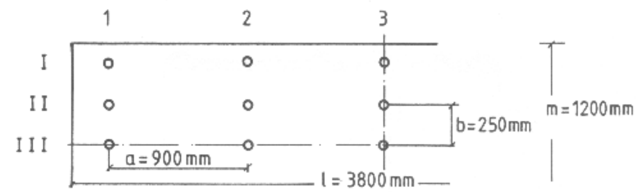


Figure 12 *"Zipper effect" (failure of one fastener may result in progressive failure).*

a) Small Test Specimen



without failure			with failure of III/3		
0.114	0.118	0.190	0.116	0.193	0.198
0.306	0.627	0.630	0.314	0.649	0.857
0.358	0.778	0.780	0.343	0.746	./.

b) Extended Roof Area
(a = 500 mm; b = 250 mm;
l = 4670 mm; m = 2250 mm)

	without failure			with failure		
	3	4	5			
III	0.993	0.993	0.993	0.993	1.0	1.033
IV	1	1	1	1.013	1.053	1.375
V	1	1	1	0.980	1.05	./.

Figure 13 *Fastener load before and after failure of the central fastener.*

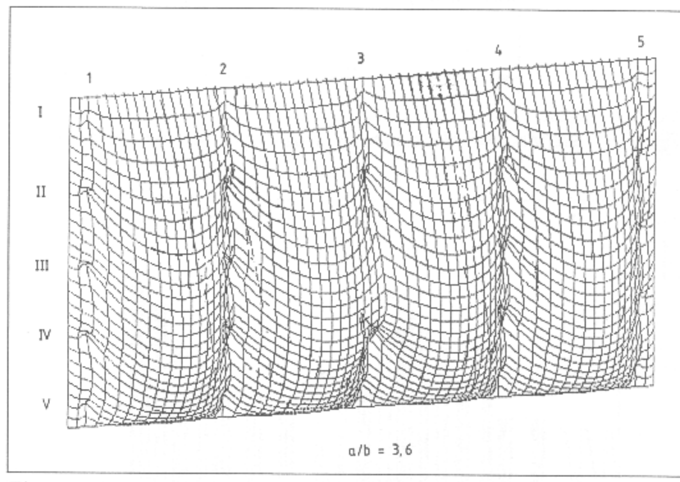


Figure 14 *Calculated membrane deflection under wind suction for the same system as shown in Figure 10 after failure of the central fastener.*

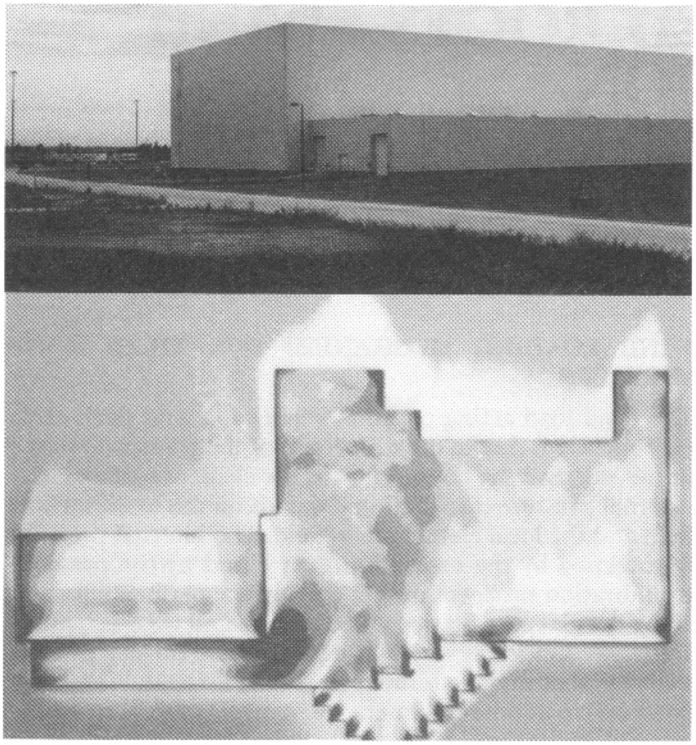


Figure 15 *Sand erosion picture (lower) of building shown (upper) to determine areas of high suction.*