WIND TUNNEL TESTS ON LOOSE-LAID ROOFING SYSTEMS FOR FLAT ROOFS

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In recent years "loose-laid" roofing systems have come into widespread use in North America and Europe. With these systems rigid insulation boards, loose-laid either above or below the water-impermeable membrane, are held in place by a layer of crushed stone or gravel or by a combination of gravel and concrete paving slabs ("pavers"). The pavers are placed in areas of the roof that are prone to gravel scour by wind. In addition to acting as ballast, the gravel and pavers protect the underlying materials from fire and solar radiation. Typically the insulation boards are 2′×4′×2″ thick (0.6m × 1.2m × 5cm) and the paving slabs 2′×2′×2″ thick (0.6m × 0.6m × 5cm).

An alternative approach uses 2′×4′×2″ (0.61m × 1.22m × 51mm) composite insulation boards faced with latex modified concrete, typically ⅜-inch (9.5cm) thick, on the upper surface. These composite boards are tongue-and-grooved along their long edges so that they form an interlocking layer when installed in a staggered array on top of the membrane. With both these approaches the roofing elements are kept in place primarily by gravity. In the case of the composite boards it is advantageous to use counterflashing at the roof edges to hold down the perimeter boards. Sometimes sheet metal bands, or "strapping", are used to interconnect the boards. Strapping can also be used on pavers. In general, direct fastening of boards or pavers to the roof deck is avoided since this would require penetration of the membrane. Figure 1 shows a cross-section through a typical roof system.

These roof systems have been found to be prone to damage in high winds. Unless they are properly designed for wind effects and properly installed, there may be stone scour, overturning of pavers and failure of interlocking layers of composite boards under extreme conditions. It is also possible that loose roofing stone or other roofing elements will be blown from the roof causing damage to nearby building glass or injury to pedestrians. Over the past 10 years a series of investigations has been undertaken at the National Research Council of Canada (NRCC) to arrive at an understanding of the aerodynamic phenomena involved and to provide the essential information for the design of safe systems.[1-7] This work has gone through several stages and further experiments are planned.

The earlier experiments concentrated on the problem of gravel scour and blowoff, and the results have been used to develop a design procedure for roofs that use gravel ballast. A design manual has been published,[3] and the design procedure was outlined at the previous International Symposium.[4]

The present paper reviews more recent experiments which were mainly concerned with wind damage to loose-laid layers of pavers or boards and with behaviour of loose-laid membranes. The experiments showed that pavers and boards are subject to displacement by sufficiently strong winds. In fact the wind speeds which can cause damage can be surprisingly low. For example, 2′ (0.6m) square × 2″ (5cm) thick concrete pavers weighing 100 pounds (445 N) can be dislodged by winds of about 125 mph (200 km/hr) gust speed. The experiments revealed that the mechanism by which boards or pavers are dislodged is altogether different from that involved in gravel scour.

The experimental results[5,7] provide design data for a number of specific configurations, but a general design procedure has not been developed for board or paver installations. Present understanding of the failure mechanism allows some design guidelines to be stated.

EXPERIMENTAL METHODS

Requirements for Valid Experiments

The following paragraphs outline requirements which experiments must meet if they are to give valid results.

A key requirement for experiments is that the roofing system elements (gravel, boards, pavers, etc.) must "see" the same airflow pattern as they would see in an actual installation on the roof of a building. In general, the airflow pattern near the rooftop of a building is significantly different from that in the undisturbed wind upstream of the building. This is because the air must flow over and around the building. In the process large changes in local flow direction, separations, re-attachments and vortices can occur.

The stable pair of vortices formed in winds directed at the corner of a building as depicted in Figure 2 are particularly important. These vortices create strong pressure variations on the rooftop near the corner as seen in Figure 3. As will be discussed later, these strong pressure variations are directly responsible for the failure of paver and board layers. It is essential, therefore, that experimental setups include not only the rooftop but also the building, or at least a substantial portion of the building.

Also, the building must be immersed in an airstream which is large compared to the building so that the correct flow pattern occurs on the rooftop. It is not satisfactory, for example, to simply install the paver or board layers on the floor of a wind tunnel for testing. Similarly, a flat platform with an airstream directed mainly over its upper surface will not give correct flow patterns. The gustiness or turbulence of natural wind, and the variation of its speed with height above the ground, should also be simulated.

Experiments can be conducted at full scale or at reduced scale with models. Testing at model scale is attractive, because it allows the experiments to be conducted under controlled conditions in a wind tunnel. Certain additional requirements must be met in model experiments. The building and roofing system elements such as stones, insulation boards and pavers must all be geometrically scaled by the same scale ratio. Assuming that the tests are carried out in air at atmospheric pressure and temperature, the density of the model stones, insulation boards and pavers must be the same as that of the prototypes.

Another requirement is that the non-dimensional parameter known as the Reynolds number must not be unduly small. This restricts the minimum size of models. Finally, Froude scaling must be observed. That is, all velocities in the model tests must be factored by the square root of the geometric scale ratio in order to obtain the corresponding full-scale velocities.

If these requirements are met, the motion of stones, pavers, boards etc. in the model experiments will be dynamically similar to those in the full scale situation. Also the non-dimensional pressure coefficients will be equal at corresponding points on the model and on the full-scale rooftop. Reference 5 gives a more detailed discussion of modelling requirements.

Present Experiments

The present experiments were carried out at one-tenth scale in the National Research Council 30′×30′ (9m×9m) wind tunnel. All the requirements outlined in the preceding section were met, although there were some minor compromises.

Buildings, parapets, stones, pavers and insulation boards were all accurately modelled at one-tenth scale, even the tongue-and-groove edges of the concrete faced composite boards. The permeable fabric of some roofing systems was represented in the experiments by a similar fabric of correctly scaled permeability. A thin plastic film was used to model the impermeable membrane. The tensile stiffness of the model membrane was about 10 times greater than strictly required by the modelling rules, but this was judged to be of minor importance. A gusty wind whose velocity varied with height was produced by installing 15-foot (4.6m) spires 65-feet (20m) upstream of the model building, and by covering the intervening tunnel floor with 6-inch (15cm) cube roughness elements. The resulting simulation of natural wind was judged to be satisfactory even though the thickness of the gusty layer was too thin by a factor of about 10.

Two different building models were tested. One represented low-rise building shape (height $\ll$ length, width) with full-scale dimensions of 75′×75′×15′ high (23m×23m×4.6m). The other represented a high-rise shape having full-scale dimensions of 30′×60′×75′ high (9.1m×18.2m×22.9m). Both buildings were tested with a variety of parapets ranging from 4 inches to 96 inches (10cm to 244cm) full-scale height. A variety of roofing system configurations were investigated, and the same model roofing system elements were used on both buildings. The majority of test runs were with a wind directed at a corner of the building (45 degrees to the walls) as in Figure 2, since this was found to be the critical wind direction for roofing system damage. Both buildings were pressure-tapped near the upwind corner of their rooftops. This permitted measurement of pressure distributions underneath the roofing systems, while measurements with a bare rooftop gave the pressure distributions that would exist on the exterior surface of a system.

The experimental procedure for each roofing system and building configuration consisted of slowly increasing the wind speed in the tunnel and noting speeds at which minor and major failure occurred. Pressure distributions were recorded before failure occurred, and roofing system behavior during the failure process was recorded on videotape.

RESULTS

The gust speeds at rooftop level at which failure occurred are listed in Table 1 for a few configurations. As already mentioned, no general design or prediction method has yet been developed for pavers or boards, but the table gives an indication of the wind speeds at which failure can occur. Additional data are available in references 5 and 7. Failure speed depends on many factors, including parapet height, building dimensions, element weight per unit area, and strapping and fastening arrangements around the roofing system perimeter. Wind direction is also important, and the 45-degree direction was found to be the most critical.

As might be expected, some form of interlocking, such as tongue-and-groove or sheet-metal strapping, substantially increased failure speeds. Similarly, using counterflashing to hold down the perimeter boards was very helpful with the composite-board system. Parapet height also had a large influence.

When pavers are not restrained by strapping, initial failure consists of one or more pavers being overturned or otherwise dislodged. As the wind speed increases, progressively more pavers are dislodged and failure proceeds gradually. No pavers were blown off the rooftop in any of the experiments. When pavers or boards are restrained by strapping and/or tongue-and-groove edges the layer behaves in an integrated manner. Failure tends to occur at higher wind speeds and to be rather abrupt. In composite-board systems many boards are often suddenly dislodged and a substantial number are blown off the rooftop.

Membranes bonded to the roof deck by tar or adhesive are normally not susceptible to uplift by wind action. Membranes can also be loose laid on the roof deck. If the deck was leaktight and the membrane was well sealed to the deck around its periphery, no uplift or ballooning of the membrane was observed in the experiments. Also, the membrane had virtually no effect on roofing system behaviour. This is not surprising as it is impossible for the loose-laid membrane to lift up from the roof deck unless air can enter between it and the roof deck. This is precluded by sealing the membrane periphery and by the impermeability of the membrane and the deck. However, if the roof deck is leaky or the membrane is not well sealed around its periphery, ballooning can be expected and was observed in the experiments. The static pressure in the building interior typically exceeds that on the rooftop so that air tends to flow through a leaky roof deck and cause ballooning of a loose-laid membrane. Membrane ballooning can occur at relatively low wind speeds and the resulting damage to the roofing system tends to be extensive.

Pressure distributions above and beneath the roofing systems were an important part of the results. They explain the mechanism responsible for failure of layers of pavers or boards.

DISCUSSION

The mechanism responsible for failure of paver and rigid board systems is revealed by examination of pressure distributions measured above and below the systems. Figure 3 shows a typical pressure distribution on the exterior of a flat roofing system for a wind directed at the corner of a building. Figure 4 shows the pressure distribution measured underneath the insulation boards of a fabric and gravel roofing system which included an array of concrete pavers. The outline of the array is also shown. The building configuration, parapet height and wind direction are the same for Figures 3 and 4. Note that the pressure-contour pattern of Figure 4 bears a substantial resemblance to that of Figure 3. A vee-shaped pattern is evident in both. It should be pointed out that the model pavers in these experiments were machine finished aluminum. All surfaces and edges were accurately flat, smooth and square relative to each other. Furthermore, the pressure-tapped portion of the model roof deck was a smooth flat aluminum plate.

Comparison of Figures 3 and 4 shows that, even with closely fitting pavers, the roof insulation systems tested are sufficiently permeable that the exterior pressure patterns are transmitted in at least recognizable form to the underside of the system. This implies that there is a significant amount of air flow through the joints between system elements and underneath the elements. The pressure distributions underneath the roofing system are similar but not identical to those on the exterior, and in some portions of the rooftop uplifting pressure differentials prevail.

It is believed that this phenomenon occurs in the following manner. Where there are static pressure gradients over the exterior surface of the system there will be pressure variations around the periphery of any given system element (paver or insulation board). This pressure variation evidently causes air to flow under the element from the high pressure portions of the periphery to the low pressure portions. Air enters and leaves the under-element region via the joints between elements. In this way a pressure pattern broadly similar, but not identical, to that on the exterior surface is established underneath the roofing system elements. Because the pressures above and below the system elements tend to equalize, in regions of high suction the pressure differences across the element are substantially lower than those across the roof deck or roof structure. Nevertheless there can be uplifting pressure differentials acting across the elements. In loose-laid systems these must be resisted by the weight of the elements.

The under-element flow is expected to be dominated by frictional resistance. Inertia effects should be small. The pressure under the elements should therefore vary in an approximately linear fashion between the values at the edges of the elements. More precisely, it should satisfy Laplace's equation.

The roofing system elements most prone to blowoff appear to be those over which the exterior surface pressure distribution is most non-linear. The greatest non-linearity does not necessarily occur where the pressure gradients are strongest. The more the exterior pressure distribution departs from linearity, the greater the pressure differences across the element. See Figure 5. High parapets reduce pressure gradients and thus tend to improve resistance to wind damage.

Experiments by Cook[8] confirm that the under-element pressures respond very quickly to fluctuations in the exterior distributions. Consequently, gust speeds are the relevant wind speeds for designing against failure of paver or board systems, as they are for gravel scour and blowoff.

Since pressure differences are responsible for failure of paver and board arrays, and since pressures are proportional to the square of wind speed, the wind speeds to initiate failure should be proportional to the square root of the weight per unit area of the pavers or boards. The experimental data support this conclusion. Therefore if pavers are used to prevent gravel scour in scour-prone areas, they should be sufficiently heavy that they are not dislodged at wind speeds below those required to initiate scour of the gravel.

CONCLUSIONS

Methods which properly simulate the wind flow field over building rooftops are essential if realistic results for gravel scour and wind damage to paver or board arrangements are to be obtained.

Membrane ballooning can be prevented either by adhering the membrane to the roof deck; or by ensuring that the roof deck is leak-tight, and the membrane is well sealed to the deck around its periphery.

Paving slabs and rigid boards can be dislodged by wind action. Failure results from differences in static pressure above and beneath the pavers or boards. Failure is most likely to occur where exterior pressure variations are strong and highly non-linear.

Failure wind speeds depend on many factors, including building proportions, parapet height and wind direction. For pavers and boards, failure speeds are proportional to the square root of element weight per unit area.

Gust speeds at rooftop level are the pertinent wind speeds for design purposes.

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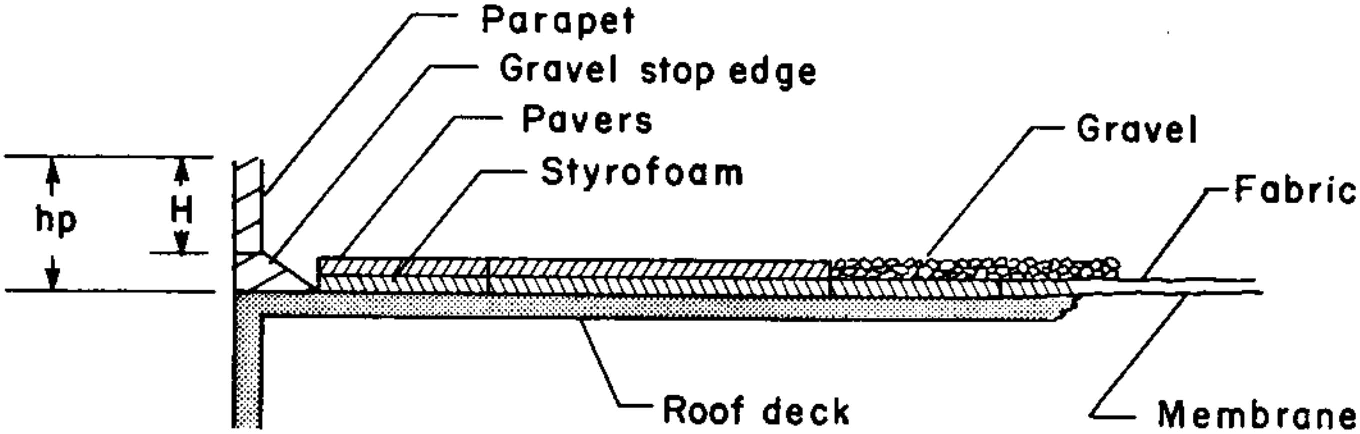

Figure 1 Typical inverted roof system

Description of Building and Roofing System	Gust Speed at Rooftop Level		Remarks
	mph	(km/hr)	
1. low-rise, 15 feet (4.5m) high; 6-inch (15cm) parapets; fabric and gravel system with concrete pavers			
(a) lightweight concrete (15 psf; 715 N/m²)	95	(155)	2 pavers dislodged
(b) normal concrete (26 psf; 1240 N/m²)	125	(200)	2 pavers dislodged
2. low-rise, 15 feet (4.5m) high; 6-inch (15cm) parapets; tongue-and-grooved composite boards (4.6 psf; 215 N/m²)			
(a) edge boards loose	75	(120)	4 boards dislodged
(b) edge boards held down by counter-flashing	165	(270)	sudden major failure
3. high-rise, 30 feet (9m) wide; tongue-and-grooved composite boards (4.6 psf; 215 N/m²) peripheral boards strapped			
(a) 12-inch (30cm) parapets	85	(135)	≅ 10 boards dislodged, some blown off rooftop
(b) 36-inch (90cm) parapets	155	(250)	abrupt major failure; boards dislodged from ≅ 30% of rooftop

Table 1 Some gust speeds for failure (45 degree wind direction; bonded membrane)

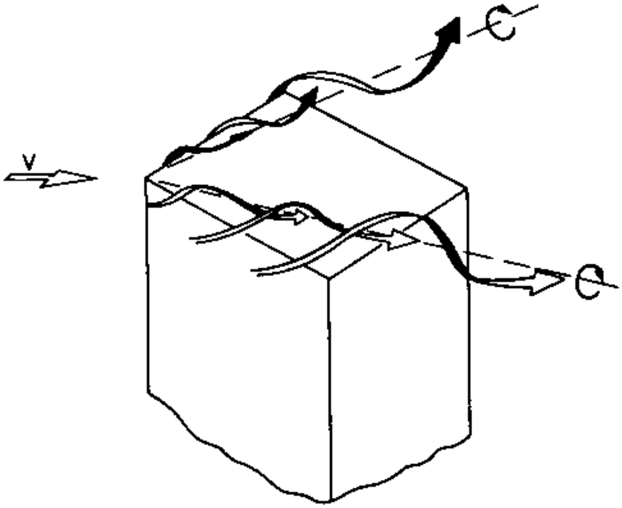

Figure 2 Roof vortex formation for wind at 45 degrees to building walls

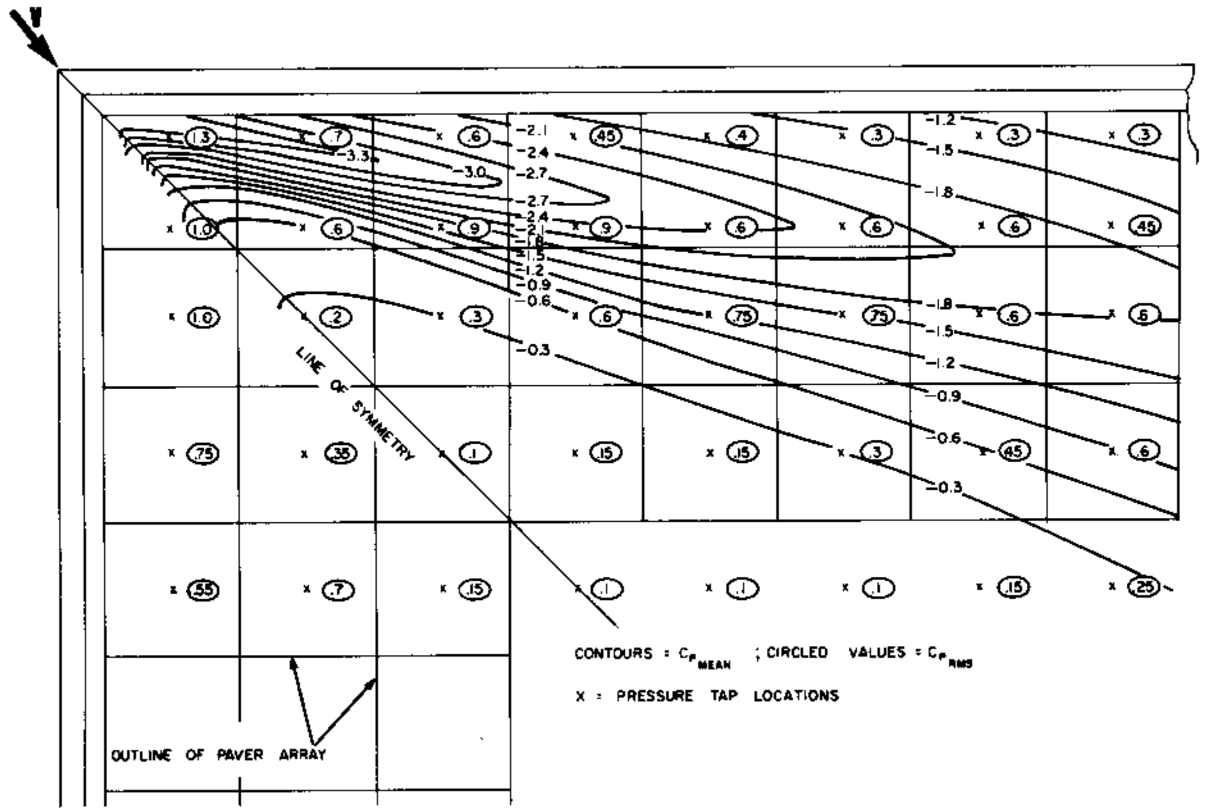

Figure 3 Pressure distribution on roofing system exterior for a square planform low-rise building, wind angle 45 degrees, parapet height 6-inches (0.15m)

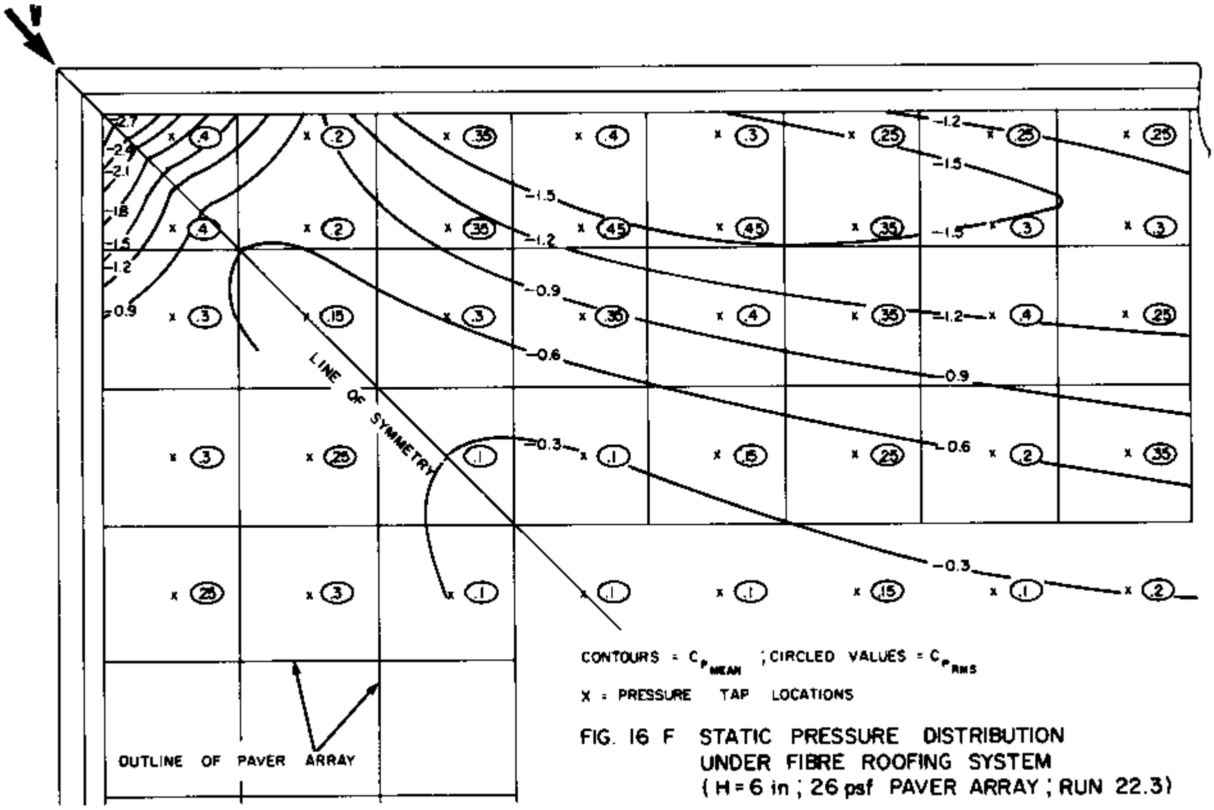

Figure 4 Pressure distribution under fabric and gravel roofing system with 26 lb/ft² (125 kN/m²) paver array for a square planform low-rise building, wind angle 45 degrees, parapet height 6 inches (0.15m)

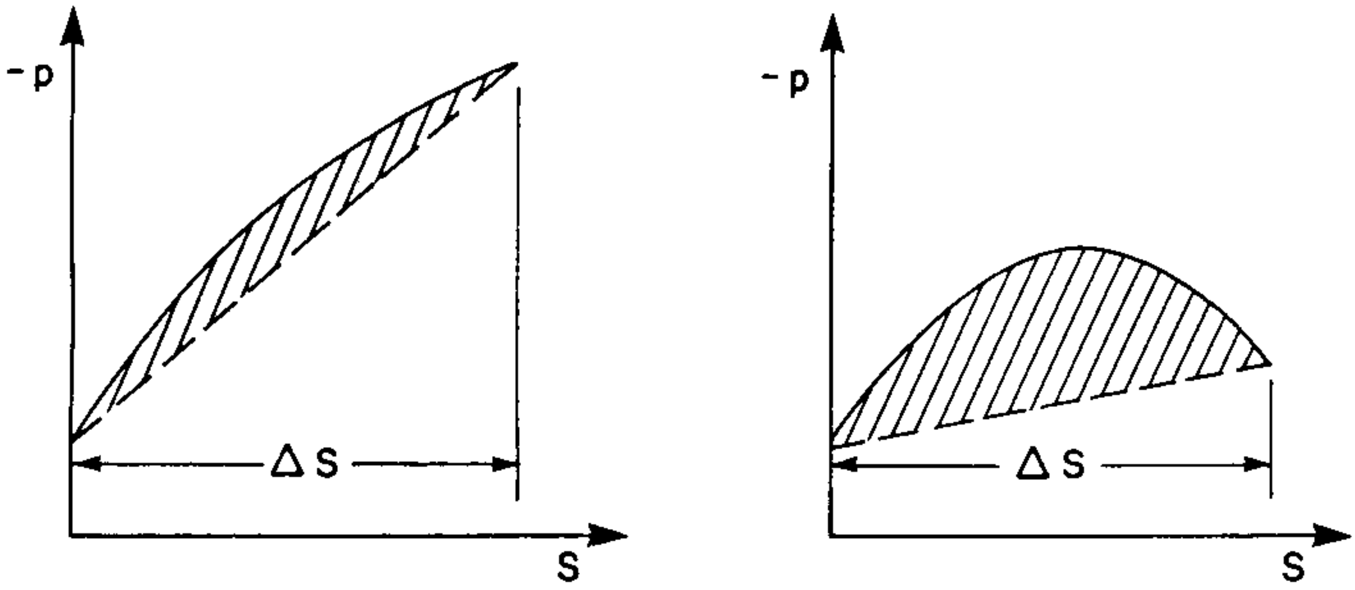

Figure 5 Effect of upper surface pressure distribution on the uplift force on a roof element

Uplift force ∝ to hatched area
——*Upper surface pressure distribution*
- - - -*Lower surface pressure distribution*
ΔS = Element width