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Proceedings of the Roof Wind Uplift Testing Workshop

November 8–9, 1989
Oak Ridge, Tennessee

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Proceedings of the Roof Wind Uplift Testing Workshop

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Oak Ridge, Tennessee

November 8–9, 1989

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edited by P. S. Gillis

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Introduction

ROOF WIND UPLIFT TESTING WORKSHOP

G. E. Courville

On November 8-9, 1989, a group of 140 concerned roofing professionals gathered in Oak Ridge, Tennessee to exchange information and to hear discussions on topics dealing with wind's effect on roofs. The roster of attendees starts on page 133. The Workshop was held to address several important issues:

(1) Wind-related roofing problems are a concern to the roofing industry.
(2) There is no comprehensive understanding in the U.S. roofing industry of the dynamics of wind phenomena.
(3) There is inadequate field data on wind's effect on roof performance.
(4) The correlation between field performance and laboratory testing is poor.
(5) Procedures for laboratory testing and field testing are inadequate for many roof systems.
(6) There is little roof uplift resistance research underway in the U.S., and what does exist is poorly coordinated.
(7) Manuals, test procedures, standards, and codes for wind uplift are often inadequate, even confusing and contradictory at times.
(8) Building owners are not well enough informed to commit to the cost of wind uplift technology development or even to the design and construction of stronger roofs.

These concerns led one group, the Single Ply Roofing Institute (SPRI), to commission a study in 1986 to determine the feasibility of an apparatus for testing whole roof assemblies under conditions that closely simulated real roof wind effects. Results from this study were shared with Oak Ridge National Laboratory (ORNL) which has subsequently submitted a review. A major conclusion from the joint talks with ONRL was the importance of avoiding decisions on an individual uplift testing concept with too narrow a focus on wind-related roofing issues. Subsequently, it was decided to schedule a workshop on the topic with the original sponsors being SPRI, ORNL, and the Naval Civil Engineering Laboratories (NCEL). An Organizing Committee was assembled (see inside front cover), additional sponsors joined the original group (again see inside front cover), and the first meeting was held in November 1988.

The Organizing Committee was very aware of the pitfalls that often befall workshops. In particular, if up-front preparation is not included, it is typical for workshops to end with participants only beginning to understand the issues involved. To avoid this, the Committee decided to conduct a two-session workshop. The purpose of the first session was to allow a free-flowing discussion of wind-related roofing issues and to target significant issues for additional study and for specific action recommendations. Subsequently, task groups would be organized to study each of these issues and develop position papers and recommendations for a second workshop session.

This task was completed with the Workshop of November 8-9, 1989. These Proceedings include the text of all prepared materials for the Workshop as well as some reference materials and the following summary section.

WORKSHOP SUMMARY

WIND-RELATED ROOFING ISSUES

1. Laboratory Test Procedures

Existing test procedures (Coursey) are not readily applicable to mechanically fastened roof systems because the onset of failure of these systems is most often identified with component fatigue, a gradual deterioration of uplift resistance, rather than an abrupt loss of adhesion between components or an abrupt loss of cohesion within a component. Existing U.S. procedures do not evaluate roofs for fatigue. On the other hand, extensive testing of roof fatigue has been conducted in Europe, and European standards for roof uplift resistance includes fatigue testing (Gerhardt, Cook, and Paulsen). These procedures are generally collected under the heading of "dynamic test procedures." A recommendation that dynamic testing be incorporated into procedures for testing mechanically fastened roofs in the U.S. was presented to the Workshop (Whelan).

For different reasons, existing U.S. and European procedures fall short of predicting performance for loose-laid ballasted roof systems. Here, uplift resistance is most often related to the air permeance of the roof system, to paver uplift, or to gravel scour. A set of recommendations were presented that define an approach that will provide an improved, research-based procedure for establishing performance requirements of ballasted roofs (Roodvoets).

An important issue not explicitly covered in the materials prepared for the Workshop is that of roof failure originating at the perimeters of roofs (edge effects). A high incidence of problems due to this mechanism was reported by roofing experts who visited the areas damaged by hurricane Hugo. There was some indication during the Workshop that existing testing and experimental apparatus might be applicable for testing of edge effects. It seems necessary, however, that some additional study is required on the mechanisms for edge failure and on test procedures.

2. Full Scale Testing

Several attendees pointed out that the issues highlighted during the Workshop did not include full scale testing. Full scale measuring/testing is vital for a number of reasons:

(a) It provides correlation for and validation of laboratory procedures.
(b) It provides data on wind speed and surface pressure that is useful for developing performance criteria.
(c) It provides the industry with a means of identifying problems.
(d) It is necessary for testing of innovative roof systems.

A range of full-scale test techniques were mentioned at the Workshop:

(a) long-term instrumentation of existing buildings typically in a high wind area;
(b) long-term instrumentation of special test buildings with features for controlling some parameters;
(c) short-term instrumentation of existing buildings, for example, the rapid instrumentation of buildings in the path of a specific hurricane once the weather

bureau is reasonably sure of the storm path; and

(d) simulated wind on full-scale roof test specimens.

The last topic was discussed in some detail in the first session and was reported on in the letter summary of that session distributed earlier to all participants of both sessions.

Quickly, the problem with the procedure is the lack of flexibility in changing the weather parameters and the overall cost of equipment and testing.

In general, the other methods suffer from the same shortcomings. Instrumenting and monitoring buildings is expensive, and, in the sense that one must take the weather as it is, there also can be problems with weather flexibility. Nevertheless, full scale measuring and testing must be considered as an important part of any comprehensive program to develop a better understanding of the behavior of roofs in high wind.

3. Field Information

Somewhat different but complementary to field testing is investigation of roof conditions. This includes surveys of functioning roofs in regions where wind damage can be expected, as well as surveying of failed roofs, for example, roofs that do not survive a hurricane. This can produce information on the efficacy of both design and construction practices. The current lack of field information was treated as an issue in the Workshop (Johnson). Emphasis was placed on establishing response teams to investigate for wind damage to roofs quickly after a storm and on establishing a clearing house for information obtained from field measurements on instrumented buildings and from field investigations.

4. Research Needs

One of the Task Groups formed after the first session of the Workshop was to develop a collection of research items viewed as important to developing better test methods for uplift resistance testing and to develop design and construction practices for building more wind-resistant roofing systems. This Task Group developed the list of 19 topics shown in Table 1 on page 129. Following a discussion of these items during the Workshop, attendees were asked to select the items they considered to be most important. Each attendee was provided with three equal-weight votes that could each go to one of three projects or even all to one project. Votes were tallied and the results are also shown in Table 1 on page 129.

Results of the voting mirror the discussions during the Workshop. Dynamic testing (#9), edge metal problems (#8), and air retarders (#2) received the most votes and were also topics frequently mentioned as important by speakers and attendees during discussions. The topic of air barriers includes research of system air permeability and interior pressure distribution.

SUMMARY

Dynamic testing in Europe (Gerhardt, Cook, and Paulsen) and air barriers/roof air permeability were the two most important technical issues discussed at the Workshop. Regarding the former, the presentations clearly defined the overseas activities and also brought out (but did not resolve) the differences between the proponents of each of the European methods. It is most likely that the U.S. will need to initiate its own research program to determine the procedure that is most applicable to U.S. roofing systems, and it is probably premature to consider development of specific consensus

standards in the U.S. until this work is at least underway.

Hurricane Hugo occurred after the agenda for the Workshop was mostly determined. Nevertheless, many aspects of this natural disaster became part of discussions. Perhaps most significant, when they were asked who had visited hurricane damage sites, about half the attendees indicated they had. The extent of information, however, was apparently very diverse and it was not obvious from the discussion what would be gained by attempting to build a database of this information. Two qualitative ideas that seemed to be consensus views were that much of the roof damage occurred at wind speeds below design values and that many of the failures were initiated by edge problems.

Activity on resolving issues raised at the two sessions of the Roof Wind Uplift Testing Workshop has not ceased with the completion of the Workshop. The importance of encouraging uplift resistance research and monitoring progress toward development of consensus industry standards has been recognized by taking preliminary steps to define a permanent committee, supported by and responsible to the industry, that will meet regularly and report regularly on progress toward these goals. The Building Research Establishment in the United Kingdom is initiating a project to compare the UEAtc method with the BRERWULF method. The above-mentioned committee will follow that work. The committee will work with architects known for their commitment to improved roof systems to develop a strategy that transfers this commitment to others in their profession. It will work with universities that have expressed an interest in establishing a clearing house for roof technical information, it will pursue the concept of a post-failure roofing response team, and it will establish a liaison with the Wind Engineering Research Council, which has recently given roofing issues a high priority on its list of national wind concerns.

The Roof Wind Uplift Testing Workshop was successful on all measurable accounts. The attendance was high, and with few exceptions, key industry individuals and groups were in attendance, invited presentations covered the full scope of the topic and ample time was available for discussion, important issues were identified and comprehensively discussed (thanks to the two-session concept), and, most importantly, follow-up steps are being taken so that this Workshop leaves more of a legacy than just a good discussion of the topic.

ACKNOWLEDGEMENTS

This Workshop would not have been possible without the active support of key sponsors, all of whom have contributed financially in order to keep the workshop fee accessible for wide range of participants, and without the involvement of an industry-wide Organizing Committee whose concern throughout this project has been to produce a workshop that treats roof wind uplift issues objectively and who has been sincerely interested in developing an agenda that not only provides information exchange, but also commits to follow-up.

The logistics of the Workshop have been formidable. The smooth functioning of all activities that so many attendees commented on is a credit to the ORNL staff team assembled to design and implement this program, mainly Pat Love, Sherry Samples, and Kim Grubb, and to the others who assisted them. Thanks also to Bob Wendt and the staff of the DOE Roof Research Center at ORNL for hosting a good tour of the ORNL facilities.

G.E. COURVILLE
Workshop Chairman
November 10, 1989

POSTSCRIPT TO SUMMARY

Nearly three months have passed since the Oak Ridge workshop. This has been a time of reflection upon the issues raised and it has been a time for action on the recommendations. At least two U.S.A. firms are considering importing European technology for dynamic testing, another two organizations are considering having teams systematically inspect roof damage in high storm-risk areas, and ASTM Committee E-6.22 has begun development of a standardized dynamic test procedure.

One consensus recommendation of the workshop is nearing fruition. It was generally agreed that overlying the discussions of important technical issues—including causes of roof wind damage, dynamic testing of roof systems, the importance of sample size in testing, the roles of wind tunnels and air retarders, the need for acceptable procedures for ballasted systems, and field data and response team reports—was the general lack of communication among designers, roofing contractors, and manufacturers about what the problems are, what is being done and should be done to alleviate them, and how effectively information is transferred among those in the roofing industry and to others in the building community. An industry-wide committee was suggested at the workshop to address these matters, and a chairman pro tem (Richard Coursey) was selected to oversee the development of a committee structure. This work is nearly complete, and it is probable that a Committee on Wind Issues formed by and responsive to the needs of the industry will be in place by the time these proceedings are available.

It is gratifying to see these several actions that are being initiated and perhaps even more gratifying to see how they can potentially fit together to move the roofing industry closer to resolving a very difficult issue. The Roof Wind Uplift Testing Workshop provided an opportunity to momentarily put this entire issue into perspective. The duty now is to stay with this perspective as it changes in response to the solving of some problems and the emergence of new ones.

G.E. COURVILLE
February 7, 1990

Keynote Address

PERSPECTIVES ON WIND UPLIFT

Richard L. Fricklas
The Roofing Industry Education Institute
Englewood, Colorado

Revised November 1, 1989

I would like to extend my welcome to you. The hosts for this conference include the Single Ply Roofing Institute (SPRI), the Naval Civil Engineering Laboratory, the Department of Energy, the National Roofing Contractors Association (NRCA), the Roof Consultants Institute (RCI), Dow Chemical, JPS Elastomerics, and Oak Ridge National Laboratory. All of these organizations are concerned with **roof performance**, and it is the objective of this conference to focus on one important aspect of that performance, **wind effects.**

Wind behavior affects every segment of our industry. While much is known about wind dynamics, we lack the comprehensive understanding to apply this knowledge to roof design. Problems include inadequate field data, poor correlation between laboratory and field performance, a lack of appropriate test methods to simulate the loading of single-ply ballasted and mechanically attached roofing systems, and perhaps just as serious, a lack of effective communications between those who have information and those who need it.

The fact that you are here signifies the interest in our subject. The goals of our conference are fairly modest. We won't come up with all the answers, but hopefully we **will** provide direction to our industry, as well as open lines of communication.

In my role as director of the Roofing Institute, part of my job is to assemble technical information in a usable format and to present this information to our seminar attendees. In the next few minutes, I would like to share with you my perceptions of how the roofing industry feels about wind effects, and where the problems lie.

Roofing contractors. The applicator of our roofing systems needs to have attachment requirements completely spelled out in specifications. The philosophy of a contractor is, "Tell me what you want me to do, and I will do it."

It is **not** satisfactory for a roofing specification to simply state "meet Factory Mutual" or "comply with local code." Contractors are generally not licensed to interpret code or to develop roof design. They also are not responsible for all of the components that comprise a wind resistant roof system. As examples, the deck anchorage may belong to the deck installer; the wood blocking and curbing to carpenters; ducts, stacks, and edging to the sheet metal installers; and roof-top units to the HVAC specialists.

When specifications are vague, conscientious contractors are put at a disadvantage during the bidding process. Nowadays there are special requirements for

increased fastener density at edges and perimeters, for more or heavier ballast on ballasted roofs, and for narrower starter sheets on mechanically fastened systems. If these details are not clear in the bidding documents, bids will not be comparable, and the conservative bidder may not get any work.

Contractors are rarely required to conduct pullout tests on existing roof decks. They may not even have access to the pullout testers or know what constitutes adequate pullout resistance. Yet, for some decks that are degraded by moisture, there is really no other way to be sure the attachment is adequate to resist wind forces.

There is a fair amount of confusion on substrates in general. Plywood is being replaced by oriented strand board or wafer board as well as getting thinner. Metal deck gauges are getting thinner. Wet substrates cause fastener corrosion. Fire retardant treated lumber also is reported to accelerate corrosion and to cause plywood to suffer delamination. Low-density insulations may compress in service, resulting in loss of friction to resist lateral movement, as well as fastener backout. All of these items affect the wind uplift resistance of a roof system, and all are beyond the direct control of the roofing contractor.

This conference won't answer many of these contractor questions, but we will be at least looking at a broad variety of possible tests. We must find appropriate test methods if we are ever to resolve these issues.

Architects and engineers. The design profession is really no better off than contractors. There simply aren't adequate resources on wind design. The manuals published by ARMA (Asphalt Roofing Manufacturers Association), NRCA, and SPRI tend to be vague, possibly to avoid liability.

Designers tend to rely on materials manufacturers for guidance, yet the manufacturers do not provide guidelines on air retarders, blocking, or sheet-metal work.

Manufacturers will tend to rely on established tests with which they are familiar, such as the Factory Mutual Class I Category, even when these tests may be inappropriate for a specific situation.

Designers lack an information network. A designer may unknowingly specify a roofing system that is known by the "industry grapevine" to be in trouble, yet the manufacturer of such a system may be reluctant to "pull" such a system from the market, since this may be perceived as an admission of "failure." As a result, the designer has no "early warning system."

In this country, we have no "Good Housekeeping Seal of Roofing," nor an Agrément board to police roof performance like our European brethren.

Our industry has not done a good job of differentiating the behavior of stiff, gravel-surfaced built-up roofs from that of flexible, unsurfaced elastomeric systems. Static tests such as the F.M. test apparatus don't create the oscillations that are particularly harmful to mechanically fastened single-ply systems, so a designer has difficulty anticipating how to compensate for this difference in behavior.

The flutter and billowing of such systems can also draw air and moisture into the roofing system. Flapping single-ply systems have been observed to actually pump water uphill, away from the drains.

Designers also encounter conflicts and contradictions between different parts of building codes. For example, a time-temperature assembly may prohibit the use of wood nailers, whether treated or not. Yet these nailers are critical to wind resistance, and must be installed.

"Air retarders" play an important role in both uplift and condensation problems, yet no U.S. textbook tells us how to create an air retarder and how to seal edges and penetrations. Worse still, we have no test method to evaluate their performance.

Material manufacturers. Even though the material manufacturers generally have more resources at their disposal, they are under both time and money pressures. It is not uncommon to see manufacturers "permit" as few as two fasteners in an insulation board, fully knowing that "one near each corner" will nearly always give a better result.

Manufacturers will not accept responsibility for the behavior of roof decks or wall or edge constructions over which they have little control or about which they have little knowledge, or both. Because of this divided responsibility, there has been no impetus for total systems tests, which include these components.

We as an industry have done a poor job of communicating the data that does exist. Due to lack of manpower and the increased complexity of roofing in general, manufacturers have been observed to have details in their manuals which actually contradict their listings in the F.M. or U.L. (Underwriters Laboratory) approval guides. This is especially common in cases where test agencies have instituted new requirements, calling for extra fastening, half-sheets, or edge securement in their data sheets.

Manufacturers sometimes misinterpret uplift tests and state that their systems will "withstand wind velocities of 120 mph or more," yet in their warranties understate their accountability to "gale force winds" or 50 mph or the like. This indicates either a real lack of comprehension about the effects of pressure coefficients, height, and terrain on uplift, or a lack of understanding about what the market requires to properly design a wind-resistant roof.

Single-ply manufacturers. The single-ply industry does recognize that their flexible membranes are different. They also are aware that many codes have not adequately addressed the single-ply systems, especially the ballasted roof system.

Through SPRI, the industry has developed some engineering data and has lobbied to get code officials to accept these criteria, with some success. The SPRI publications are not yet well known, and guidelines for anchorage of nailers and standardized construction details are slow in coming, as are ASTM recommended practices.

The single-ply industry is also aware that there is a need to simulate flutter, fatigue, and mode of loading of mechanically attached systems. We also need an inexpensive, reproducible test which can simulate ballasted roof performance.

The differences in single-ply behavior have not been well communicated to the construction industry. Instances of floating pitch-pockets have occurred because the pocket was welded to the membrane without the use of a nailer. While that is perfectly fine on a fully adhered built-up roof, an undulating pitch pocket is not going to work on a partially attached single-ply.

Pavers. There seems to be no discernible industry position on roof pavers, and no evidence of cooperation between the competing paver producers. Large scale tests may be needed that will be expensive, and the paver industry should pool its resources to get meaningful results.

Metal roofing industry. This industry is closer to an "engineered" system, perhaps because of its relationship with pre-engineered buildings.

The static UL-90 test is widely used to evaluate metal panel systems. However, if components of the assembly are not all from a single source, there is a good probability that there will be problems. There has not been good correlation between UL rated assemblies and field performance, at least in one government agency report.

Metal roofing is now being heavily promoted for reroofing. It is likely that condensation and corrosion problems will appear, just as they have for other reroofing

systems. Test methods to simulate the effect of inadequate ventilation, air leakage, or failed closures are needed. Also, fastening of base plates and structural components varies widely from manufacturer to manufacturer, with some attempting to anchor into the underlying structural members, while others will just fasten into the old deck. Industry guidelines are badly needed here.

Accessory industry: fasteners and roof vents. The competition for a "better mouse-trap" is fierce, but now we are confused about anticorrosion treatments, non-thermal-bridging, anti-backout, and antirotation designs, as well as plastic vs metal parts. There ought to be some basic principles and tests that apply. What are minimum desirable pullout values for different substrates? What is a minimum practical nailing pattern for insulation or base felts? Is there a laboratory test that can evaluate backout and fatigue? Are plastic plates durable? Do the discs that perforate the insulation board surface reduce pull-through resistance significantly?

Is there a test to establish the function of roof vents? Can they relieve pressures created by wind-uplift? Can they dry out wet material? Do they actually draw moisture into a roof system, increasing fastener corrosion potential?

Roof consultant industry. In the past few years the growth of RCI and other consulting organizations has helped to get technical information into the consultant's hands. However, the lack of in-depth industry information, perhaps out of fear of litigation, hampers the flow of technical data. Communication and mutual trust could help a great deal.

Wind engineering industry. Many of you here today represent this industry. As a layman, I feel that the subject has been made unnecessarily complex. The revised ANSI A-58.1 may be a fine document, but it certainly isn't "user friendly." There is disagreement between ANSI and Factory Mutual on which wind velocity map to use, and this is bound to get the casual user off to a bad start. Also, it is not clear why SPRI chose to use terrain nomenclature that was not consistent with the A-58.1, and why ANSI allowed SPRI's data to be published with these obvious contradictions.

While much engineering has been done on uplift coefficients, why has so little been done on the use of roof "spoilers" to reduce these coefficients? We see both SPRI and FM call for minimum parapet heights with selected systems. Is there an opportunity to aerodynamically reduce our wind problems that's being overlooked? Why also is there no real research on the effects of air retarders? Perhaps your hearing my lamentations (and limitations) will inspire you to address these issues.

Code bodies and insurance agencies. Certainly the insurance industry is in the best position to analyze wind loss history. Perhaps if the history of wind loss performance could be analyzed by a blue-ribbon industry panel, we could then develop laboratory tests which accurately duplicate the predominant failure mechanisms.

Code bodies have done a reasonable job of publishing data where it exists, and of using the research report mode for proprietary systems when coordinated data doesn't exist. However, it is up to us to provide correct criteria so that code approvals fit the job situation.

Building owners. Most owners are not very aware that there is a potential problem. They may tend to select sites and designs that invite disaster. Owners will tend to focus on cost and aesthetics, which they understand, rather than on roofing quality, which they don't understand.

Building occupants are rarely aware of the consequences of displaced ballast, popped fasteners, lost edging metal, or other early warning signs of wind failure. They may not even have a maintenance program or

emergency plan to handle a dramatic roof blowoff such as from our recent hurricane.

Summary. If I can sum up my introduction, we are all in this together.

If we in this room can identify the problems, develop meaningful tests, and make data available in a usable format to those who need it, we will have met our goals.

We need to develop methods, conclusions, and criteria that are not **compromised** to meet economic considerations or **muted** to avoid legal accountability.

Once we have validated the mechanisms of wind attack and convinced industry to adopt appropriate criteria, we will be well on the way to eliminating wind failure of roofing systems. Hopefully this symposium will provide such a beginning.

Dynamic Analysis

ROOFING MEMBRANES—OBSERVED DAMAGE, FAILURE MODES, FAILURE HYPOTHESES AND LABORATORY TESTING

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1. INTRODUCTION

Modern industrial buildings are usually covered with lightweight low-slope roofs. Typical substrates are trapezoidal sheet metal in Europe and trapezoidal sheet metal or plywood in North America. The roof deck is normally covered with a vapor retarder, a thermal insulation layer, and an external roof membrane. Single-ply roofing membranes are increasingly used. There are several possibilities of securing the roof membrane against wind lift-up that will be briefly discussed in this paper. The emphasis will be put on loose-laid mechanically fastened (either with point-fasteners or bars) membranes, since this type of roof fastening seems to be the appropriate and logical arrangement for lightweight roofs. The basis for any realistic proof testing is sufficient knowledge about failures observed on real roofs. An interpretation of the failures has to lead to hypotheses concerning the failure mechanisms. This paper will present a testing procedure that has been developed by WSP consultants based on an extensive study of possible failure modes and failure hypotheses. The test apparatus and the wind load cycle used will be explained. The test procedure described in the draft of the standard wind-uplift test procedure of the UEAtc basic directive is based on this WSP procedure.

2. WIND LOADS ON FLAT ROOFS

Provisions for calculating wind pressures, p, on structures, e.g., low-slope roofs, in North America are described in the American National Standards Institute (ANSI) standard A 58.1 and the National Building Code of Canada, supplement no. 4, commentary no. 1. For both standards the equation to determine the design wind pressure is

$$p = q\, C_e\, C_G\, (C_{p\,int} - C_{p\,ex}) ,$$

where

q = velocity pressure,

C_e = exposure factor,

C_G = gust factor,

$C_{p\,int}$ = coefficient of internal pressure,

$C_{p\,ex}$ = coefficient of external pressure.

It should be noted that the effective velocity pressure q_p is given in A 58.1 by multiplying the basic wind pressure q_{30} = velocity pressure at 30-ft height with the gust factor. Thus, all pressure fluctuations—either caused by wind gusts or the eddying motion of the building flow field—are included in the effective velocity pressure, which may be considered as a gust stagnation pressure. The pressure coefficients given in A 58.1 are based on wind tunnel model studies and are time averaged values. The design wind pressures and wind loads calculated are static loads. Buildings that are not sensitive to vibration (those with a resonant frequency that is less than the frequency of the wind load fluctuations), will in fact react to the wind action as if in the steady state. However, single-ply membranes deflect almost instantaneously under the fluctuating wind action. Therefore, the fastener system is subjected to fluctuating loads and has to be designed accordingly. In particular, the dynamic load action on junctions, which may be sensitive to fatigue behavior, cannot and must not be judged according to equivalent static loads only.

3. SECUREMENT OF SINGLE-PLY MEMBRANES AGAINST WIND UPLIFT

3.1 Ballasted roofs

Loose-laid roofing membranes are commonly secured by means of ballast, e.g., concrete pavers or gravel. Using pavers, their weight has to be adjusted to prevent them from being lifted up due to the wind. The up-lift force on pavers is given by the difference between the external pressure and under-element pressure. The under-element pressure is a function of external pressure and relative paver size. Using the theory of Gerhardt et al. [1] the necessary area weight G/A of the pavers may be calculated in terms of building size and wind conditions.

When using gravel as ballast, scouring due to excessive local wind velocities has to be taken into account. The risk of scouring may be checked using the available information given by Kind [2] and by Gerhardt and Kramer [3].

3.1 Adhered roof systems

Adhered roof systems are very common in Europe. Elastomer or polymer modified bitumen (cold bonding) has been highly recommended by industry and the German roofers association over the past years. The bonding action is due to cohesive forces of the long-chain molecules. When such long-chain molecules are sheared, they will align along the shear direction and thus lose their cohesive strength. This mechanism has to be accounted for, since the wind action will lead to shear stresses in the bonding layer, Fig. 1. The membrane-like deflection of a "bubble" under wind action will lead to a horizontal force component causing shear stresses in the bonding layer. Gerhardt and Kramer [4] have presented further information concerning adhered systems.

3.3 Mechanically attached single-ply membranes

The upper part of Fig. 2 shows the section through a typical roofing system with—from bottom to top—profiled metal deck, thermal insulation layer, and mechanically attached single-ply roofing membrane. Due to the wind load, the membrane will be deformed, leading to membrane tension and loading of the fastener. Since the wind load is varying with time, the fastener experiences fluctuating loads. Two basically different fastener systems are common, namely

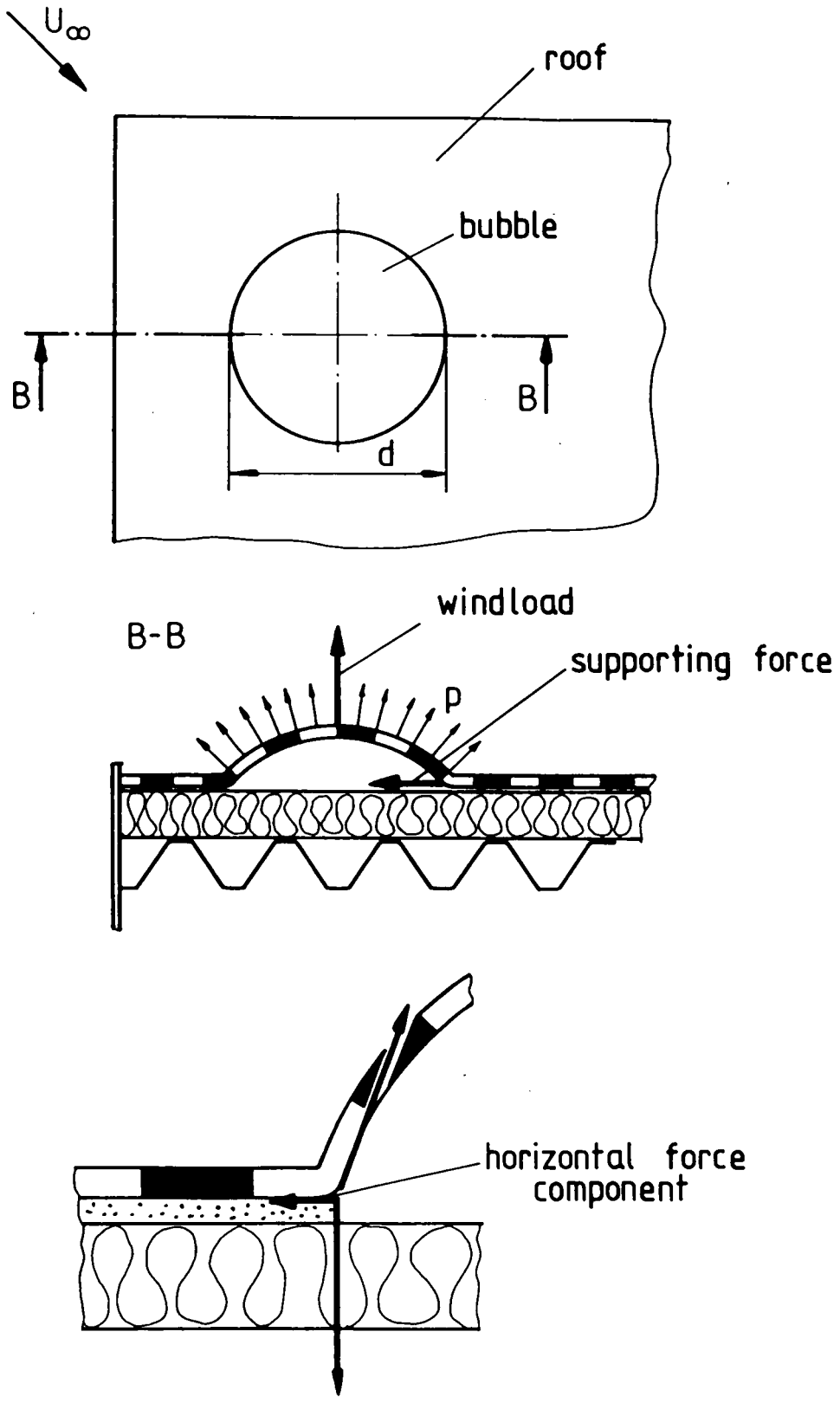
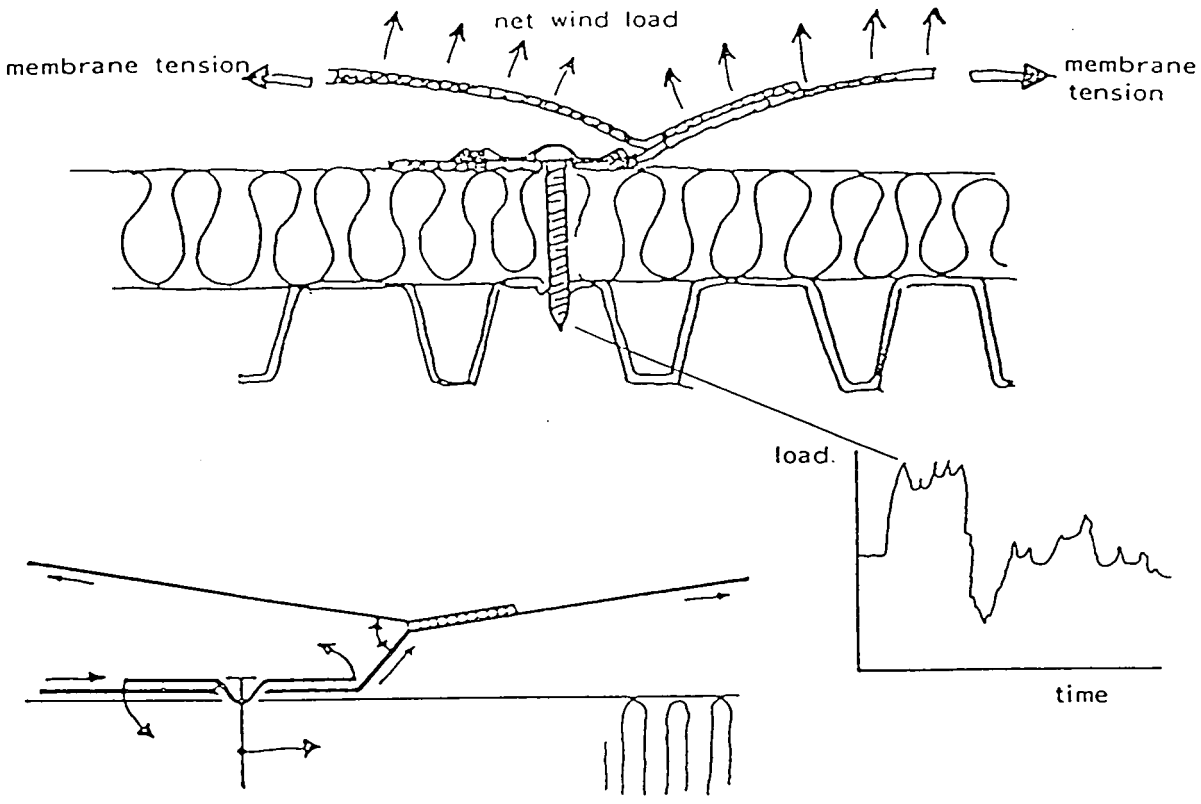
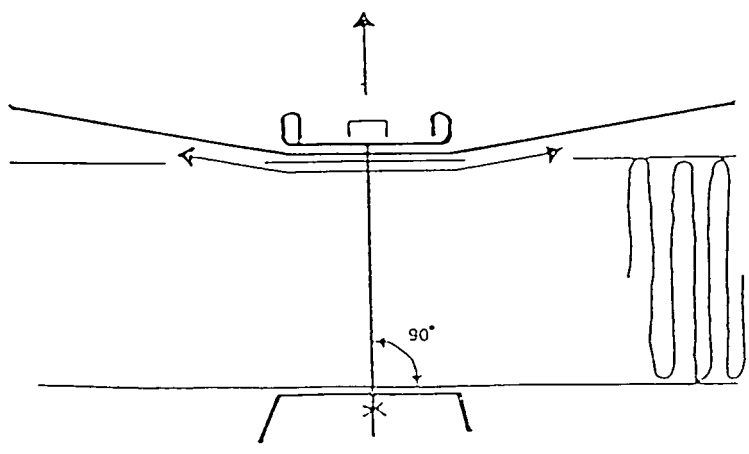


Figure 1. Failure mechanism of adhered roofing sheets.



spot fastener (non symmetrical loading)

note: for determination of max allowable load for fixation system the fluctuating wind pressure has to be taken into account to allow for fatigue behaviour



linear or bar fastener (symmetrical loading)

Figure 2. Mechanical attachment of roof membranes on metal roof deck.

in-lap–spot-fasteners and linear or bar fasteners applied through the membrane sheet (see lower sketches in Fig. 4). The in-lap–spot-fastening system leads to a nonsymmetrical loading and membrane pinching to prevent membrane slippage. The linear fastener gives a symmetrical fastener load.

4. FAILURE MODES AND FAILURE MECHANISMS OF MECHANICALLY ATTACHED SINGLE-PLY MEMBRANES

Field observations were conducted on a series of mechanically attached roof membrane systems. These roofs were attached in-lap based on spacings developed in accordance with Factory Mutual Class I-90 construction. Opening the roof membranes revealed the following deficiencies.

- Slippage of roof membrane from below attachment plates, Fig. 3, leading to loss of compression between roof membrane, insulation substrate, and fastening elements, and ultimately to membrane failure by way of tear spread around the fastener shaft, Fig. 4.
- Fastener backout, Fig. 5.
- Attachment plate deformation, Fig. 6.
- Sheet-metal deformation with fatigue cracks around the bore hole, Fig. 7. The fatigue cracks will ultimately lead to fastener pullout at moderately strong wind velocities (well below design wind velocity).

Figures 3 and 4 show several attachment plate contours on the membrane indicating the membrane slippage to be a long-term effect. The fastener backout and the fatigue cracks in the sheet metal must be considered as long-term effects, too. Thus, fastener pullout due to the sheet-metal fatigue and membrane failure by way of tear spread around the fastener shaft are due to material fatigue and <u>not</u> to one-time overloading.

This conclusion is supported by the analysis of wind velocity history indicating a lack of high wind forces. However, the projects investigated are located in areas where wind forces of low magnitude are very common.

It should be concluded from the results of the field observations that approval tests to evacuate the maximum allowable load per fastener element have to be based on a test procedure that takes into account the time varying deformation of the roof membrane and thus simulates the fluctuating wind loads in an appropriate but simple way.

5. TESTING PROCEDURE

5.1 Wind load cycle

The wind loading cycle that will be used in the General Directive of the UEAtc is a modification of the cycle used by Gerhardt and Kramer previously [5]. It is based on the accumulated probability distribution of the wind velocity pressure derived from meteorological data and specified in the CECM-regulations (Comitée Europénne de Construction Métallique), Fig. 8. The wind velocity pressure related to the design wind velocity pressure is plotted vs. the number of occurrences for specified return periods. A load cycle for a five year return period has been developed (see Fig. 9) from the information in Fig. 8. To shorten the test procedure, the great number of loadings for loads smaller than 40% of the design wind load will not be considered. For a 40 year return period the load cycle shown in Fig. 9 has to be used eight times.

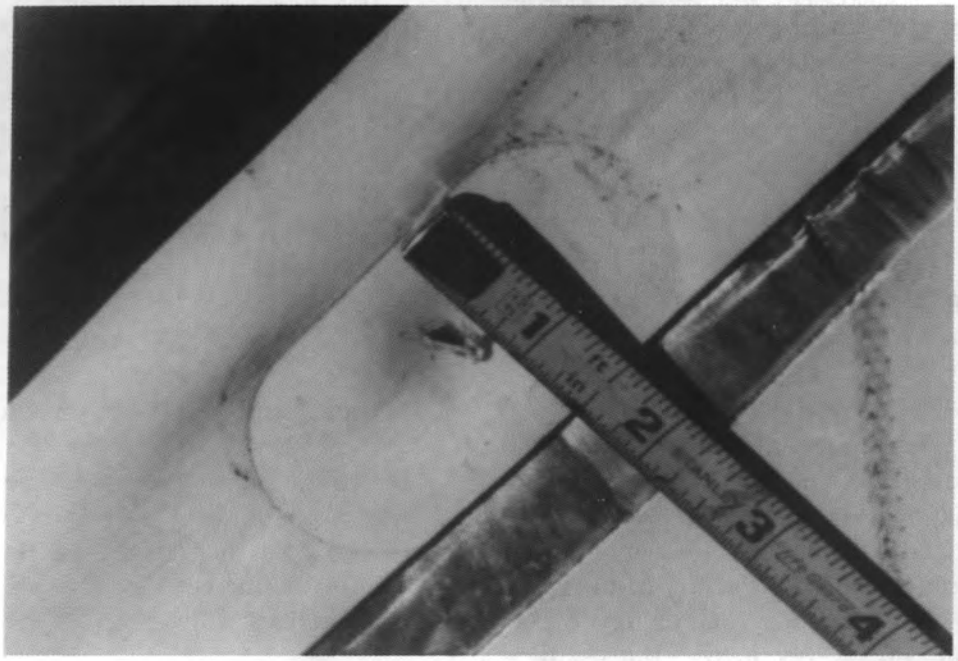


Figure 3. Plate/membrane movement (note enlarged hole).

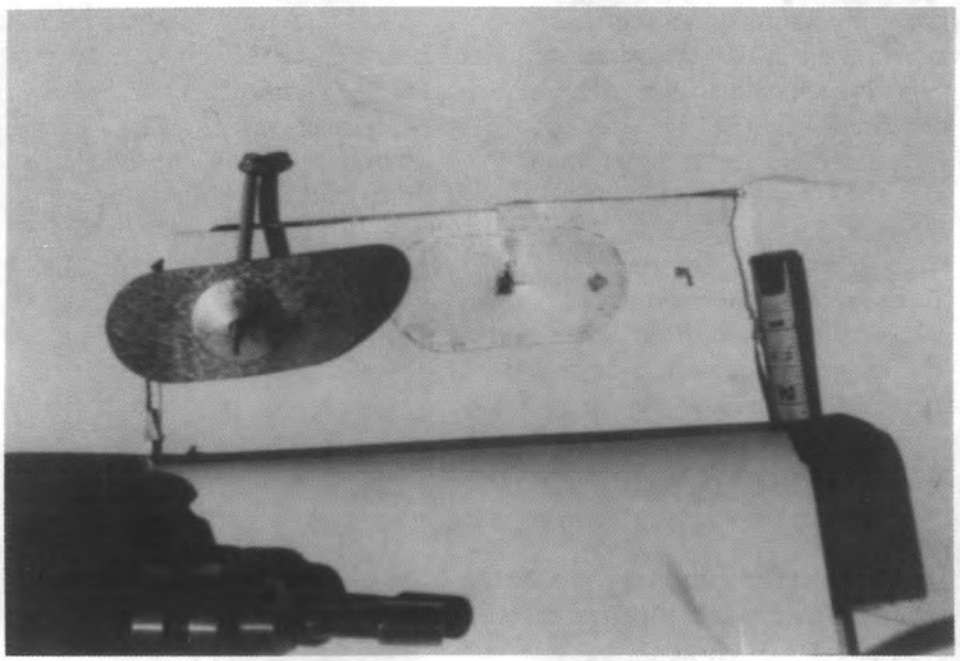


Figure 4. Membrane tear failure at attachment point.

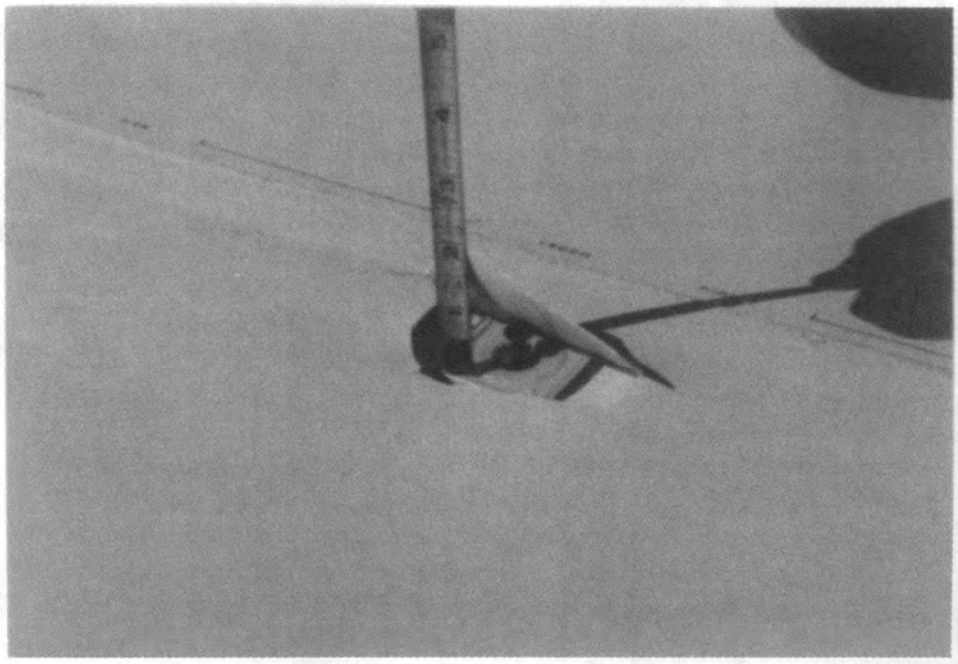


Figure 5. Fastener backout.

Figure 6. Attachment plate deformation.

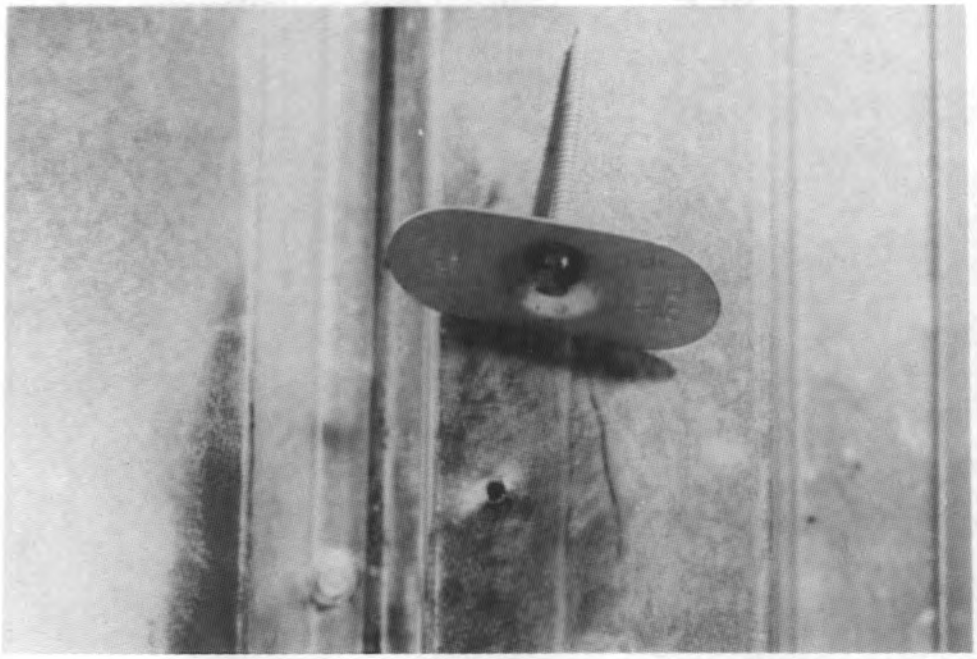


Figure 7. Fastener pullout (note metal deck deformation and fatigue cracks around hole).

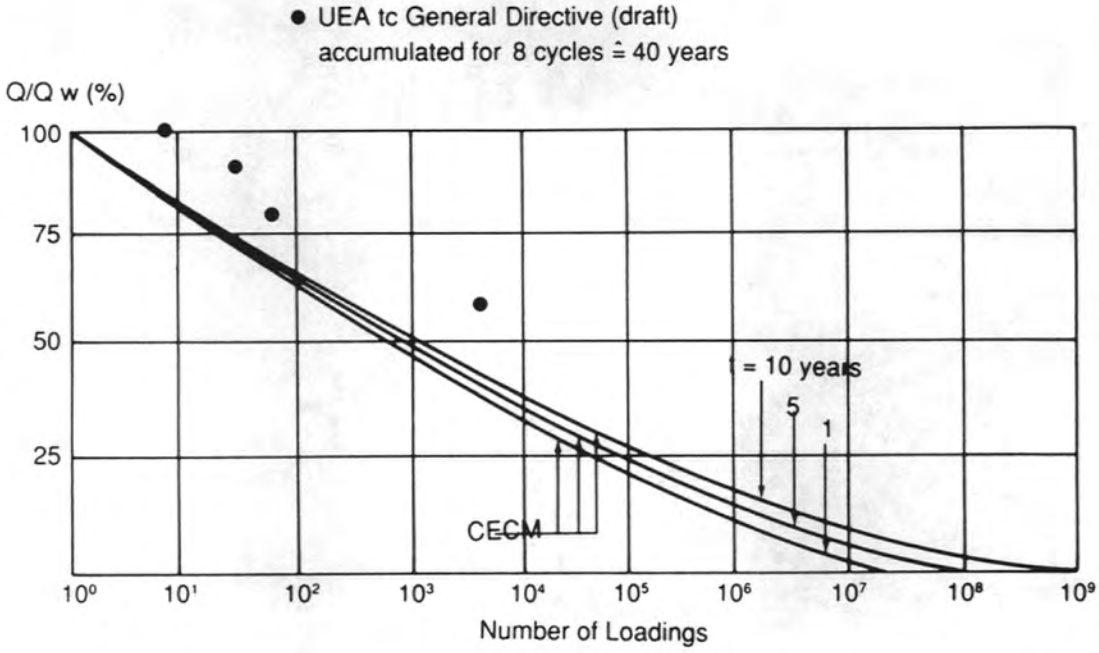


Figure 8. Accumulated probability distribution of wind velocity pressure.

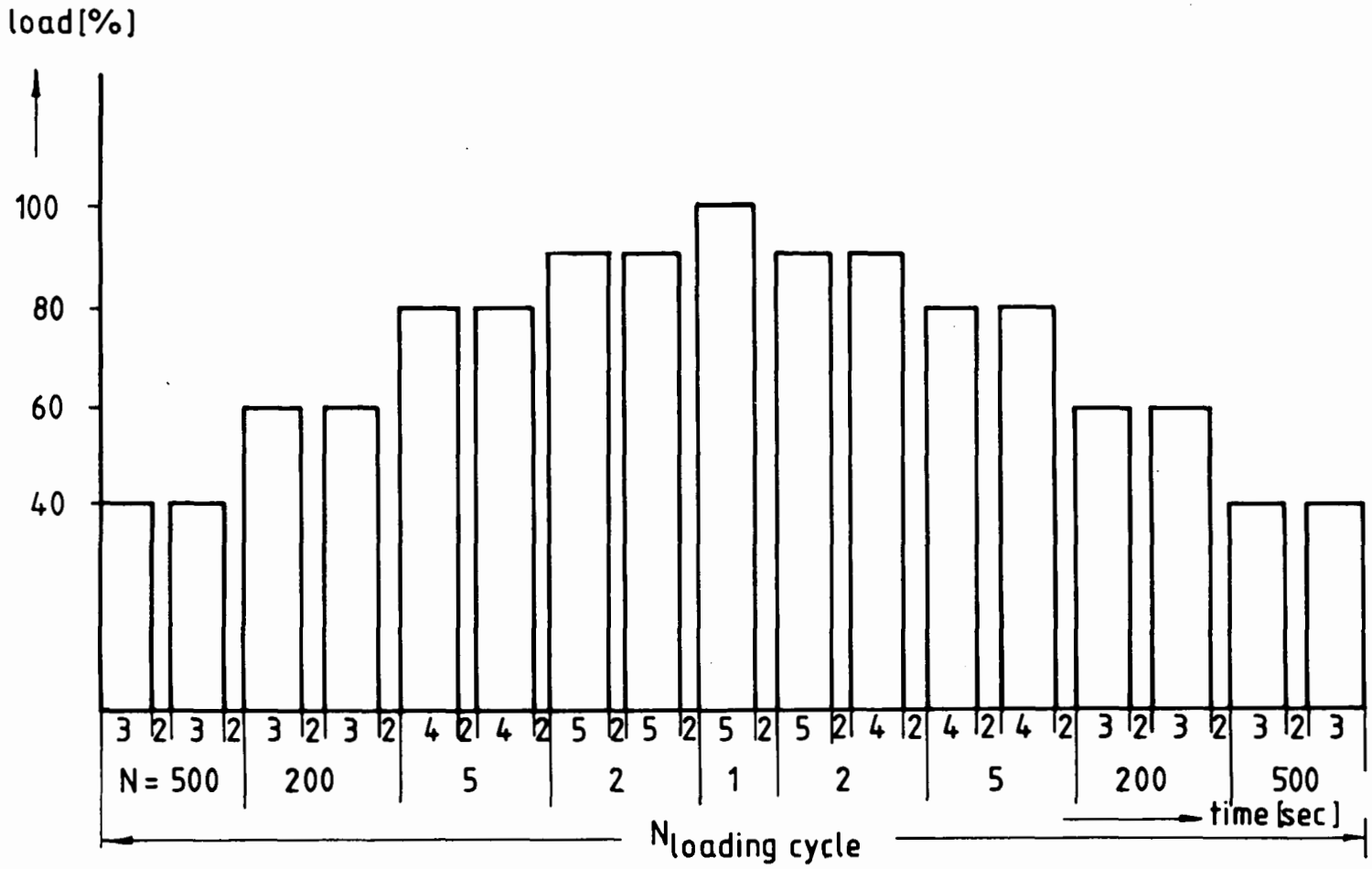


Figure 9. Wind load cycle (5 year return period) based on accumulated probability distribution of Fig. 8.

The proposed wind load cycle is shown in Fig. 10. The initial higher frequency/lower load fluctuations are necessary to determine the risk of fastener backout. After having applied four load cycles (each cycle corresponding to a five year return period with a 100% load of 300 N/fastener) the 100% load for each consecutive cycle will be increased by an increment of 100 N/fastener. The maximum allowable load corresponds to a 100% load of the load cycle prior to failure and has to be decreased according to national safety standards.

5.2 Test Apparatus

The test apparatus is shown in Fig. 11. It consists of a suction chamber placed on a rigid frame around the test specimen. The suction acting on the test roof is achieved in the test chamber by means of a radial fan. Gust action is simulated by way of a control valve. The valve action and the RPM of the fan are controlled by a PC to provide for the various load levels. Realistic loading of the fastening elements is only achieved if the membrane deflection is simulated realistically. This necessitates sufficient dimensions of the test specimen.

A summary of necessary test conditions is given in Table 1. More information concerning the test apparatus and the boundary conditions of realistic tests are presented in reference [6].

6. COMPARISON BETWEEN FIELD OBSERVATIONS AND LABORATORY TEST RESULTS

The validity of the simplified test procedure described in section 5 may best be judged by comparing roof failures of laboratory tests with the field observations. Figures 12 through 16 show failures quite similar to the ones documented in Figs. 3 through 6. The slippages of roof membrane from below attachment plates as given in Figs. 3 and 4 from the field are equivalent to the laboratory test results of Figs. 12 and 13. The fastener backout of Fig. 5 is more pronounced than the one shown in Fig. 14. This may be due to the fact that the fastener of Fig. 5 may have experienced many more low-level load fluctuations. On the other hand, the attachment plate in Fig. 15 is much more bent than the one shown in Fig. 6. Apparently the lab test was more severe. This may be also concluded from the clearly shown fatigue crack in the attachment plate. Finally, the close-up of the bore hole in the sheet metal in Fig. 16 shows stronger fatigue cracks than the ones in Fig. 7.

It should be mentioned that the observed failures are not necessarily restricted to the types of fasteners shown in the figures. WSP Consultants has tested some 50–80 different types of fastener systems under critical load conditions; the observed failures are quite common to almost all fastener systems investigated thus far.

7. CONCLUSIONS

1. Most roof failures of mechanically attached single-ply membranes are due to material fatigue. A realistic test procedure has to simulate the time varying deformation of the roof membrane caused by the fluctuating wind loads in an appropriate way.
2. A comparison between failures obtained under simulated wind loads, as described in the General Directive of UEAtc, and field observations shows good agreement in failure modes. Therefore, the UEAtc test procedure seems to simulate the wind load action adequately.

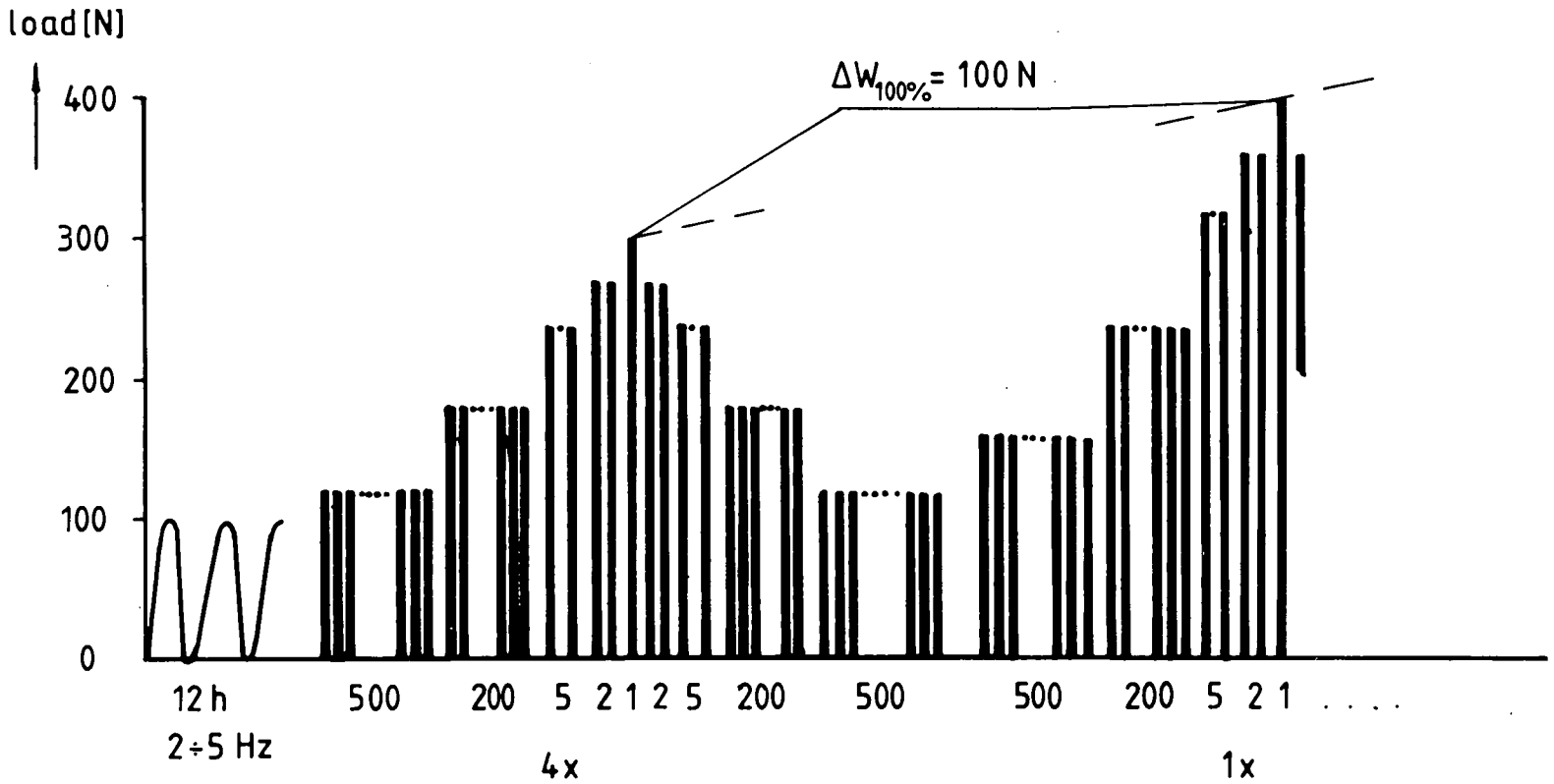


Figure 10. Wind load test cycle (draft of UEAtc General Directive).

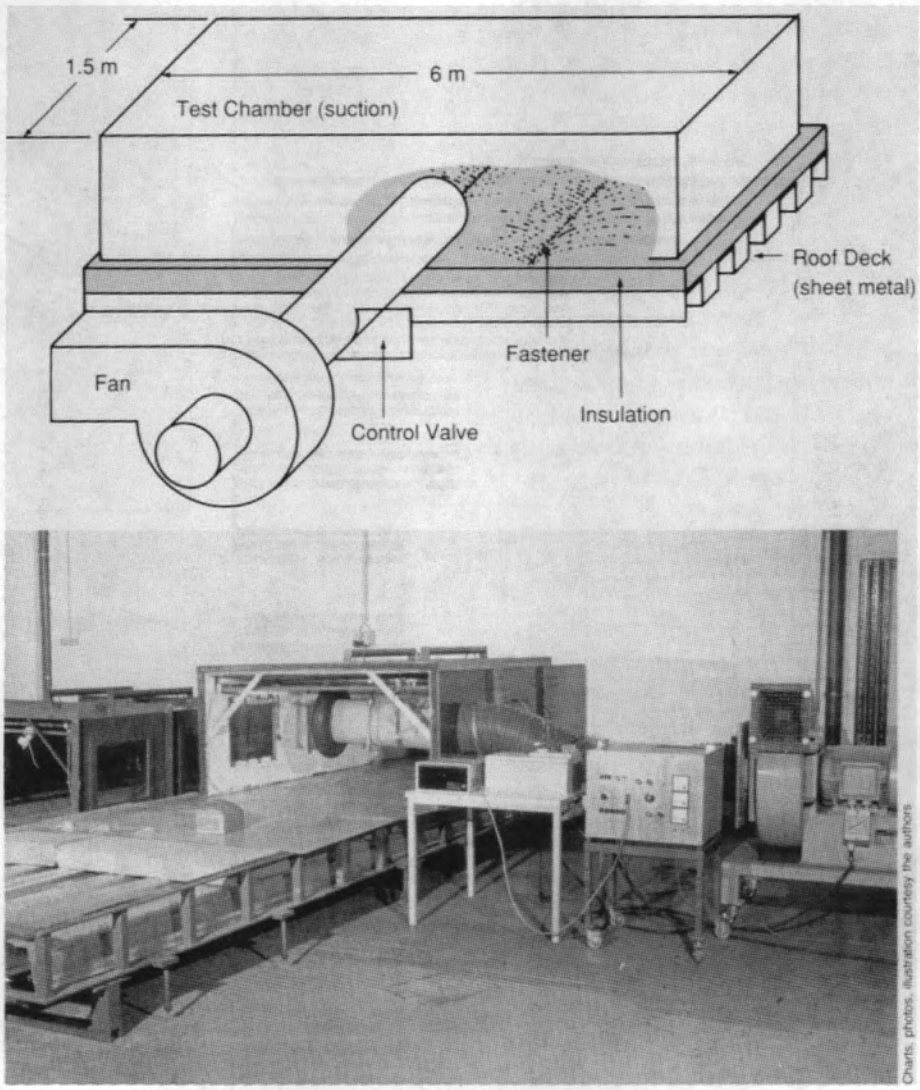


Figure 11. Test apparatus.

Table 1. Summary of necessary testing conditions.

Condition	Reason
1. Minimum size of test specimen/roof tester (4a + 200 mm)* × (4b + 200 mm) with a = fastener spacing b = fastener row spacing	To prevent unrealistic decrease of fastener load (at least for fastener) due to the perimeter fixation and to allow for realistic membrane deformation
2. Wind load cycle	To account for fatigue behavior and to allow for realistic membrane deformation
3. Testing of complete roof systems (roof deck, thermal insulation, membrane, fastener)	Interference of various roof layers is not known
4. Temperature control (important for EPDM, modified bitumen membranes)	To account for decreasing membrane strength with increasing temperature
5. Higher frequency load fluctuations at very low mean load	To test the risk of fastener backout

*1 inch = 25.4 mm

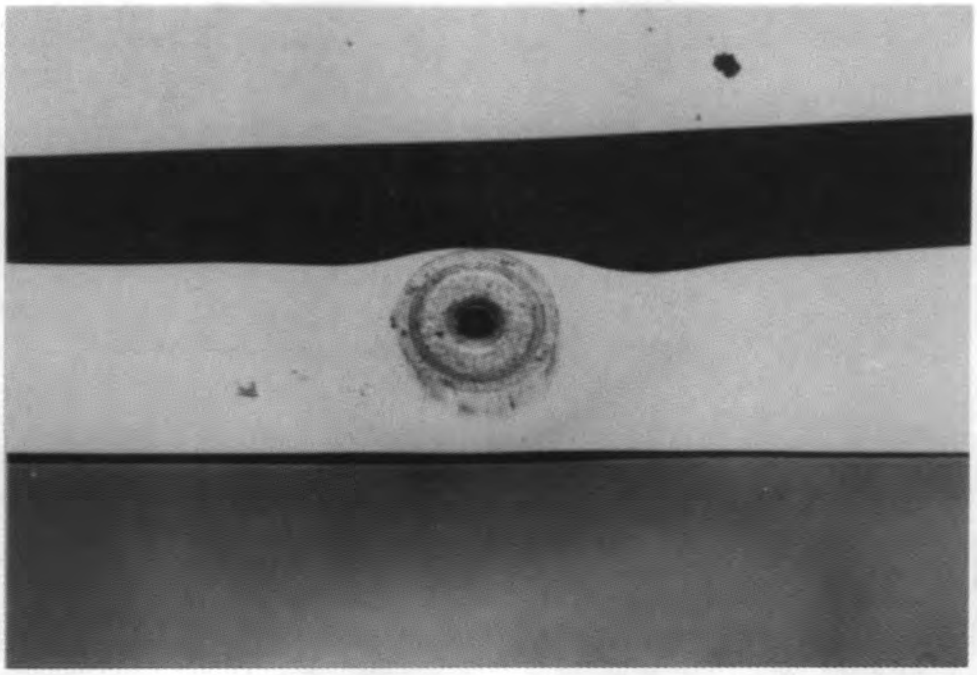


Figure 12. Plate/membrane movement (lab test).

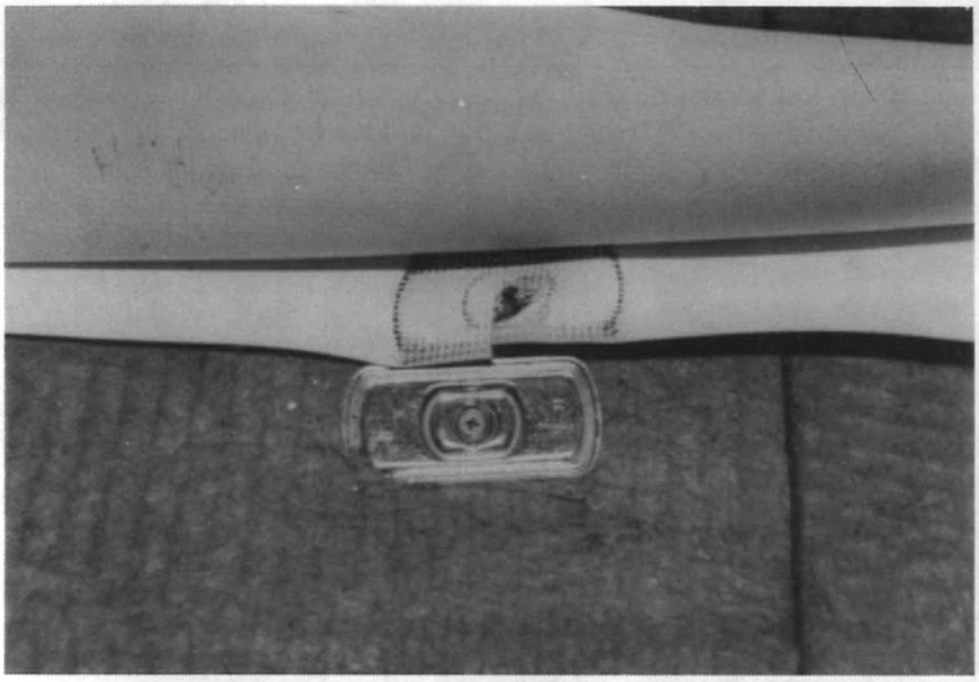


Figure 13. Membrane tear failure at attachment point (lab test).

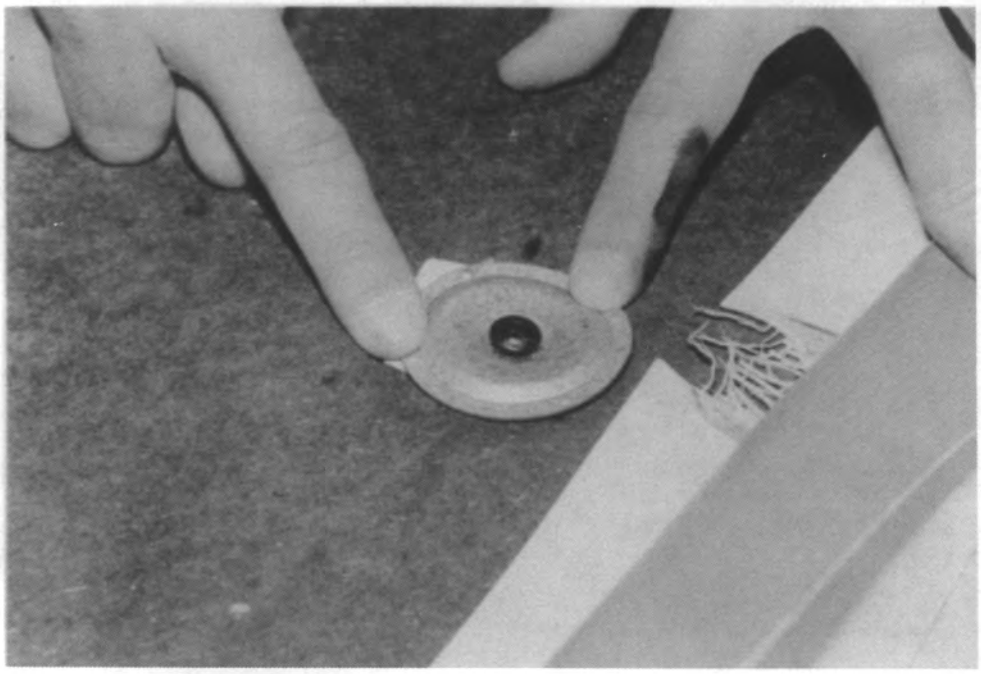


Figure 14. Fastener backout (lab test).

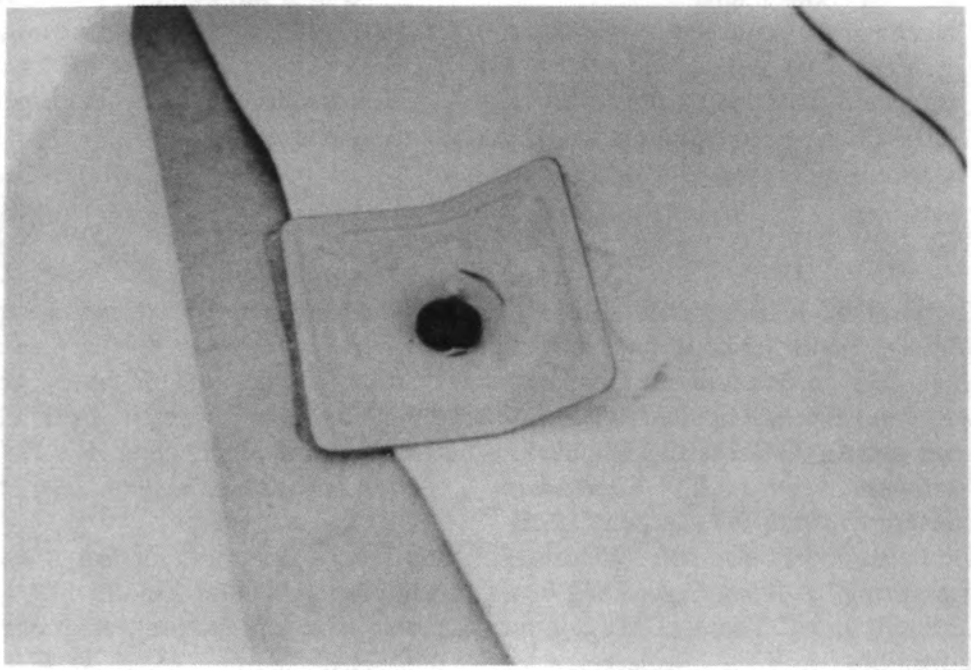


Figure 15. Attachment plate deformation with fatigue crack (lab test).

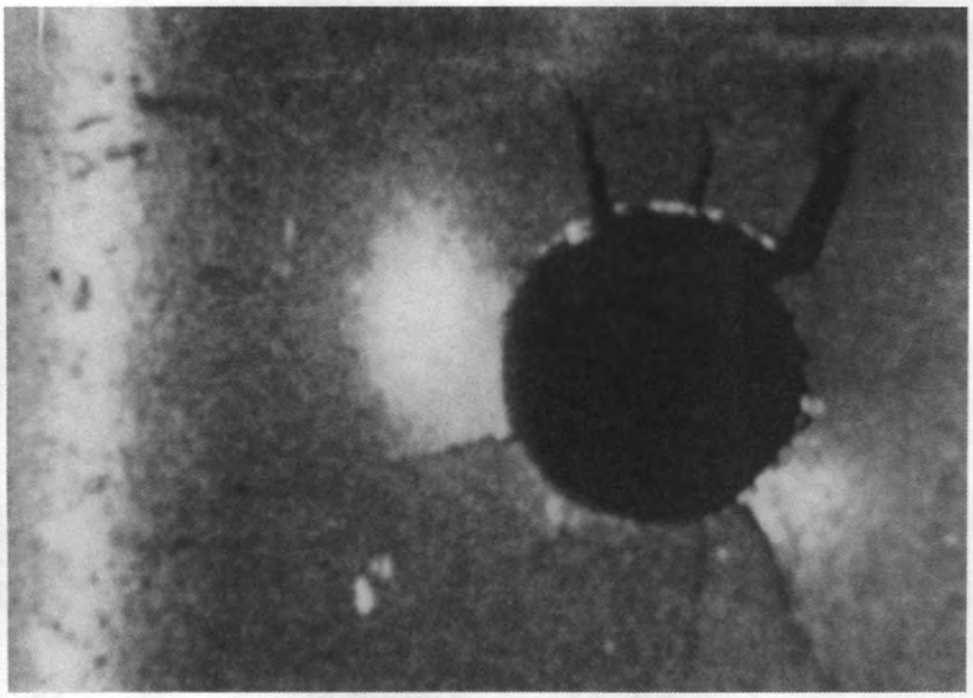


Figure 16. Fastener pullout (lab test).

3. At WSP Consultants some 200 tests of mechanically attached single-ply roof systems have been conducted under simulated wind load. About 50 to 80 different types of fasteners have been tested thus far. Whereas the failure modes observed are similar for most systems, different combinations of systems and fasteners differ greatly in respect to their life expectancy.

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REALISTIC TESTING FOR WIND RESISTANCE

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How can roofs, walls, doors, windows, or similar construction units be tested realistically for their behavior under severe wind loading? The key word is "realistically," for there are current tests using various types of static pressure loading, or regularly fluctuating loading, but these do not reproduce the erratic way in which the wind actually blows.

The UK Building Research Establishment has developed wind-loading test equipment of remarkable versatility. Known as BRERWULF—BRE Real-Time Wind Uniform Load Follower—it can simulate any pattern of loading that you choose on a full-size constructional unit. First developed mainly as a research tool to study the response of multi-layer cladding systems to fluctuations of wind loading, it soon proved to be a suitable test unit for proof testing, performance testing, and fatigue testing of practical structural or cladding systems.

BRERWULF is a computer-controlled test rig that can apply suction or pressure over the range of ±8.5 kilopascals (kPa) to a structural unit. The unit might be, for example, a section of roofing, cladding, or window. This level of suction or pressure is about 1.5 times the highest wind load measured in cyclones. But the rig could readily be modified by using a more powerful fan, if needed, to give higher suctions and pressures.

The mechanical part consists of a pressure box where the test sample is incorporated as one wall. A fan generates air pressure that is transmitted through flexible hose to a specially-designed fast-responding valve. The response is fast enough to take the pressure "from end to end" (full suction to full pressure or the reverse) in one-tenth of a second. The valve is moved by a servomotor under the control of a computer (a Compaq microcomputer) using specially-written software in the "C" language and running under the PC-DOS operating system.

A great advantage is that the whole rig is readily portable—microcomputer, servocontrol box, valve, fan, and piping. The user builds a pressure box of the correct size on site in accordance with the directions supplied for construction, including sealing, and needs only a 7-1/2A, 415V three-phase electrical supply. In an isolated site with no main supply, a portable diesel-driven generator could be sent along with the rig.

So far, the maximum size of an area under test has been 5m^2, but the size could be adjusted to the needs of the user. The pressure range of the fan and its flow rate, which controls the maximum rate of loading and the tolerance to leakage of air through the specimen, could also be changed.

So what can BRERWULF do that other test systems cannot? First, it can

apply any desired pressure within the ±8.5 kPa range, and maintain this pressure despite deflection or leakage of the specimen. Secondly, it can cycle the pressure like other systems, but instead of just cycling between zero and a pressure or a suction, BRERWULF can cycle between any pair of levels—including cycling from a pressure to a standard pattern of test cycles comprised of different numbers at various levels of both pressure and suction. BRERWULF can reproduce this automatically in a single operation, whereas simple cyclic test rigs require adjustment for each level and reconnection of the fan to change from pressure to suction.

Thirdly, and by far most usefully and realistically, is that BRERWULF can reproduce any desired record of wind pressure. The pressure fluctuations produced by real events such as cyclones, hurricanes, or storms taken from meteorological records, or traces of pressures measured in a wind tunnel, can be applied to the specimen. In this way the actual response to realistic wind loads can be observed. In a matter of days, BRERWULF can perform tests that reliably simulate real wind loads on a building for a design life of, say, 50 years. Throughout the test the response of the specimen can be observed and recorded, strains and deflections measured, and the specimen inspected at intervals for deterioration or damage.

Are there any drawbacks? Pressure in the test rig is uniform, but in actual conditions there may be some pressure gradients across the area, tapering off towards the edges. This factor, though detracting a little from realism, probably adds a little to safety and is common to all pressure-box–based systems. There may also be complications if the sample is too porous. For example, the fan may not have enough capacity to allow for the leaks and still develop the required pressure. One option is to use a more powerful fan. But porous material is likely to be used with an impermeable membrane, and the test is actually more realistic if carried out with the porous test sample backed by such a membrane to represent the complete cladding. For example, BRERWULF is a pressure/suction test with no wind flow, so it cannot reproduce problems such as scouring of gravel due to wind, but this is only a minor factor. Most building damage is a direct pressure effect, and the contribution of debris carried by the wind is considered to be a separate problem.

BRERWULF could be of the greatest value for testing constructional units in any area where strong winds cause damage or destruction to buildings. In the UK, in collaboration with the Single Ply Roofing Association, BRERWULF has been successfully applied in testing single-ply polymer-based waterproof roofing membranes as complete systems: membrane, insulation, vapor check, and deck. In fact, the realism of the test proved to be particularly valuable in examining performance of these systems, revealing non-linear interactions between the components that would not have been found by simple cyclic-load tests.

The rig will provide a valuable proof check on the calculations of performance from codes of practice and other sources. For composite systems, where calculation is difficult or impossible, it will provide unique empirical performance information.

BRERWULF is therefore a system that could be of the greatest practical value to building test centers throughout the world, to agreement organizations setting standards, and to R&D laboratories developing new constructional units. Please see the appendix, which consists of a paper originally published in the *Journal of Wind Engineering and Industrial Aerodynamics.*

APPENDIX

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BRERWULF - The Big Bad Wolf

"I'll huff and I'll puff and I'll blow your house down!"

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ABSTRACT

This paper describes the design and performance of a test rig capable of reproducing the fluctuations of surface pressure caused by wind action on areas of buildings and on building components.

INTRODUCTION

Wind engineering research over the past few decades has contributed greatly to our knowledge of the complex characteristics of fluctuating wind loads on buildings. The response of buildings to wind loads is also well understood from the overall level down to major structural components. However, the detail of the mechanisms by which the action of surface pressures is transferred through to the structural members is not understood, particularly when the envelope of the building is composed of multiple layers of differing porosity. When the outermost layer is significantly more porous than the next layer, fluctuations of external pressure will tend to leak through, thereby reducing the wind loads on the outer layer - as with loose-laid insulation boards or paving slabs on flat roofs. When there are two impermeable, but flexible surfaces separated by a nominally sealed void, deflection of the outer surface will change the pressure in the void and transfer load to the inner surface, sharing the load between them - as with double-glazed window units. These are just two of many situations that have pneumatic loading paths in addition to the usual structural paths. These cannot be investigated by the common methods of mechanical loading, but require equipment to generate fluctuations of pressure on areas of building cladding.

In the past several years the UK Building Research Establishment (BRE) has developed such equipment, starting with a simple test rig[1] which enables any value of pressure *or* suction in the range ±8.5 kPa to be applied *suddenly* (within 0.1 s) or *cyclicly* (at rates between 0.1 Hz and 1 Hz) from zero. Similar equipment[2], developed by our hosts here at Aachen, can also superimpose a small high-frequency oscillation onto the main load cycle. However, the restriction that the load cycles between zero and a fixed value was felt to be unrepresentative of real wind loading and unnecessarily onerous. Some thought was given to the design of a control valve that could be cycled between any two given values of pressure. The response of the simple BRE rig was so rapid that it was thought practical to add some sort of servo-control to follow a preset trace and so to reproduce realistic fluctuations of wind loading. The result of this development is BRERWULF - BRE Real-time Wind Uniform Load Follower, otherwise called 'The Big Bad Wolf' in honour of the villain in the 'Three Little Pigs' fable.

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HARDWARE

The principal components of BRERWULF are shown in the flow diagram Figure 1. The test chamber represents the test specimen to be loaded and a cover to contain the controlled pressure. The cover would normally be built to fit each test specimen and must be strong enough to withstand the loading. The operating principle of the pressure control valve (devised by NJC) cannot be revealed here for commercial reasons. The valve mechanism was designed and built at BRE. A centrifugal fan circulates air through the control valve from atmosphere, as indicated by the arrows marked '1'. The pressure in the test chamber may be varied continuously from -8.5 kPa through zero to +8.5 kPa by rotating a shaft through 50°. The valve position - pressure characteristic is very non-linear, which must be accounted for by the control software.

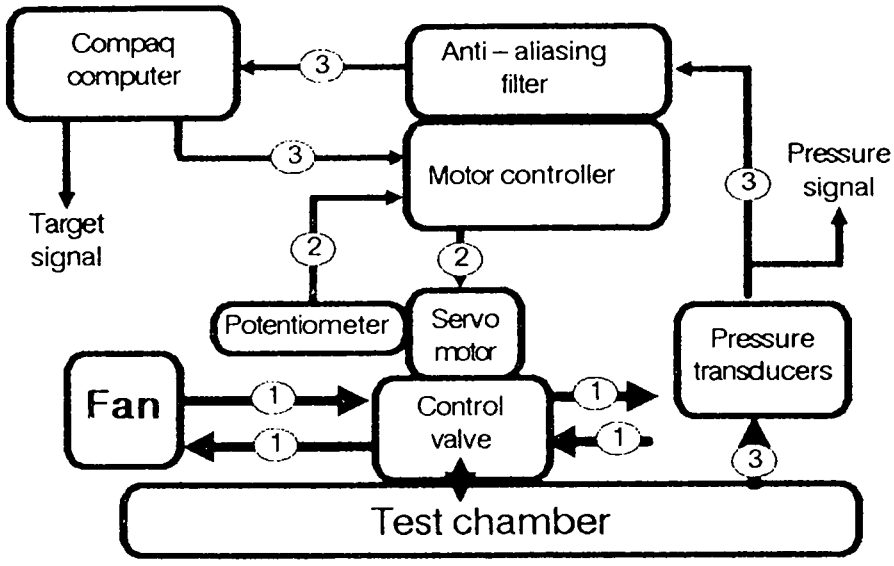


Figure 1 Basic system configuration

The remainder of the system was developed and built by Cambridge Consultants Ltd under contract to BRE. The control shaft of the valve is rotated by a suitably geared DC servo motor and its position is monitored by a potentiometer. The flow does not exert any torque on the control shaft, so that the principal forces on the motor are inertia forces. The motor, controller and potentiometer form a classic servo control loop as indicated by the arrows marked '2'. The command signal to the motor controller is generated by a Compaq microcomputer through a digital-to-analogue converter (DAC) and is calculated by software, depending on the target and current values of pressure in the test chamber. The latter is acquired by two pressure transducers, to allow a choice of position within the test specimen for the feedback signal. Each signal is passed through an anti-aliasing filter and is read by an analogue-to-digital converter (ADC). The pressure feedback loop, indicated by the arrows marked '3', is completed by passing through the servo-motor loop '2' and the air flow loop '1'. Although not strictly part of the control system, a second DAC outputs the target pressure signal which can be compared with the actual pressure

signal to analyse the response.

SOFTWARE

The control software was written in the 'C' language and runs under the PC-DOS operating system. The control program has two main parts: the system control algorithm (written by RKS) and the user control interface (written by APK). There is also a pair of utility programs to assist in the normalisation and checking of the target pressure data traces (written by APK).

System control algorithm

As this controls the performance of the whole system, an algorithm was selected which gave the maximum flexibility for adjustment and would allow new parameters related to the physical system to be included quickly and easily. The algorithm takes due account of the characteristics of all the physical components of the system. The non-linear control valve characteristics were approximated by the linear differential equation:

$$dp / dt + p / T = k\Theta / T \qquad ..(1)$$

where t is time, T is the time constant of the test chamber, k is a constant depending on the configuration of the system, Θ is the valve angle and p is the test chamber pressure. The target pressure is pre-processed, using an inverse model of these system characteristics, to improve the performance by effectively anticipating the system response. To reduce the effects of flow turbulence the algorithm integrates errors. During periods of high control loading, the error sum may become so large that the required valve position exceeds the physical range and this condition would remain until the load requirement falls. This phenomenon, known as 'integral windup' is avoided by a further compensation algorithm.

The system control algorithm comprises the following sequence of operations:

1. Acquire and scale the pressure value;
2. Process the pressure value;
3. Pre-process the current target pressure using the inverse system model;
4. Process the modified target pressure and subtract the processed pressure value to give the error value;
5. Compute the control signal;
6. Apply the anti-windup algorithm to the control signal;
7. Scale the output and send the result to the DAC.

This complete sequence is performed at rates between 30 Hz and 40 Hz.

User control interface

In order that the equipment could be operated by non-specialist staff, it was decided to base the user control interface on the popular concept of 'menus'. Only two levels of menu were needed to satisfy all the required control options, except for the main system function of dynamic control of pressure which requires a third level.

In addition to the menus, a software 'panic button' is provided as a safety precaution. During any control operation, all keys on the Compaq keyboard are disabled until the operation is complete except for the 'escape' key - Esc. Pressing Esc causes the current operation to be interrupted, the valve position immediately restored to the zero pressure position and the appropriate sub-menu redisplayed. This removes the pressure applied to the test chamber within 0.1 s, relieving the load on the specimen as fast as the test chamber time constant allows (very much faster than interrupting the power supply to the fan).

When the program is run, the user is presented with the main menu of five options, represented in Figure 2. Each of the five options invokes a corresponding sub-menu of the operations available for that choice. Control parameters are checked for validity before any operation is allowed. Dismissing any sub-menu returns the user to the main menu, and dismissing the main menu returns the user to the operating system. In Figure 2, the upper row of three sub-menus represent 'housekeeping' functions, while the lower row of two sub-menus are pressure control functions.

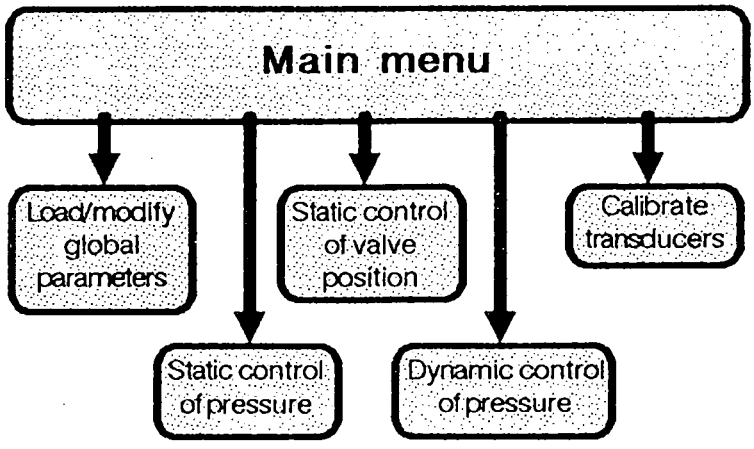


Figure 2 Main menu options

The 'Load/modify global parameters' sub-menu allows the user to specify those parameters used by all the control functions. These include: the angle to which the valve returns when the system is idle; the chamber time constant, T, in the system model equation (1); the files containing the calibration values of the two pressure transducers; the pressure transducer to be used for feedback; and the chamber pressure limits for the positive going and negative going directions. The system will not allow these limits to be breached during operation. If this is attempted the system executes an Esc interrupt.

The 'Static control of valve position' sub-menu allows the system to operate statically without the pressure feedback. The valve position ramps up or down while the ↑ or ↓ keys are depressed, respectively. The valve angle is displayed and the ramp rate can be adjusted.

The 'Calibrate transducers' sub-menu employs the same routines as the previous menu to move the valve. The resulting pressure signals are read by the ADCs and the user is prompted to enter the current pressure (read by a manometer). After this is repeated for a range of pressures, a linear regression is performed on the data from each transducer and the resulting slope (gain) and intercept (zero) is written to disk file.

The 'Static control of pressure' sub-menu allows the user to select any value of pressure or suction in the permitted range. The system maintains this pressure statically against deflection or leakage of the test specimen. Clearly the maximum leakage that can be tolerated depends on the target pressure and the fan characteristics and is typically 0.3 m^3/s. The rate of application of the target pressure is set by the system time constant, T (= 0.1 s minimum). Normally this corresponds to the time constant of the test chamber, but a considerable degree of

latitude is possible which alters the effective damping of the response.

The 'Dynamic control of pressure' sub-menu has four options:

(1) 'Display/modify global parameters' - invokes the earlier 'Load/modify global parameters' sub-menu without going through the main menu. These parameters may need to be changed during a test session and this option is merely a short cut.

(2) 'Run' - invokes the dynamic control of pressure procedure with the current parameters. (See §4.1, below).

(3) 'Display/modify local parameters' - displays the only third level sub-sub-menu. This allows the user to read a target trace of pressure from disk file, to set a single peak pressure value corresponding to the peak value in the file or to read an array of peak pressures, to select the start and stop epoch within the target trace and to select the time increment between values in the trace.

(4) 'Return to main menu' - returns the user to the main menu.

The operation and performance of this main dynamic control function is described in detail in §4.1 below.

Utility programs

There are two utility programs for pre-processing files of pressure trace data. The main dynamic control function requires a trace of pressure to follow which has been pre-digitised as an array of integer values in the range ±2048 and stored as a file on disk. One utility program reads a file of up to 32767 raw numbers in ASCII format corresponding to the desired pressure trace, p, digitised at equal intervals of time, normalises the values so that the *absolute* peak value, $|\hat{p}|$, becomes 2048 and all the others are adjusted in proportion, thus:

$$I = \text{Int}\,(\,2048 * p \,/\, |\hat{p}|\,) \qquad ..(2)$$

ie each value retains its original sign, and writes a new file of the normalised integer values, I. The other utility program reads through a file and assesses the severity of the data, listing the most negative and most positive values in the file (in a normalised file one must correspond to ±2048), and the fifteen largest transitions of pressure (the difference between two consecutive values) with the corresponding absolute values and locations within the file.

DYNAMIC CONTROL OF PRESSURE

Operation

The target pressure trace may be derived in many ways: directly from a full-scale experiment; from the wind tunnel, with the appropriate scale factors applied; from the anemometer record of a storm, converted to dynamic pressure and multiplied by a suitable pressure coefficient assuming quasi-steady response; or synthesised in some artificial manner, such as sine wave, swept-sine (chirp) or filtered white noise. However the target trace is obtained, the system requires it to be digitised as an array of up to 32767 values at equal intervals of time (0.1 s minimum).

In order to make the operation as flexible as possible, the target data trace is normalised by Eqn (2), using the utility program described earlier. BRERWULF can then reproduce any selected portion of this trace at any time interval $\Delta t \geq 0.1$ s between the values, with the peak value corresponding to any desired value in the range ±8.5 kPa. The normalised trace is *algebraically* scaled to the target peak value, thus:

$$p = \hat{p} * I \,/\, 2048 \qquad ..(3)$$

so that specifying a negative target peak value inverts the target signal. The program interpolates values between the target values and issues the command signal to the motor controller at sub-intervals between 25 ms and 30 ms.

eg four 25 ms sub-intervals for a 100 ms interval, seven 27 ms sub-intervals for a 189 ms interval, etc.

To reproduce the original trace exactly the user specifies the *absolute* original peak value. Take as an example an original trace with a negative peak value (suction) of say $\hat{p}$ = -2 kPa. As the trace is normalised by $|\hat{p}|$ in Eqn (2) this value becomes I = -2048, *ie* it retains its original sign. Specifying $\hat{p}$ = 2 kPa as the target peak value in Eqn (3) reproduces the original signal, but specifying $\hat{p}$ = -2 kPa inverts the target signal making the peak value a positive pressure.

Instead of specifying a single target peak value, the user may specify an array of up to 2000 peak values stored in a file (using any suitable text editor). In this case, BRERWULF repeats the selected portion of the target trace scaled to each peak value, sequentially. If, for example, the target trace represents a period of one hour, the array of peak values could correspond to the peak values in consecutive hours to synthesise the passage of a storm. Alternatively the array of peak values could correspond to the *N*-highest expected peaks in the design lifetime of the test structure to investigate the long-term fatigue performance.

Performance

The system performance is dependent on the volume and flexibility of the test chamber. The maximum pressure of 8.5 kPa corresponds to about 1/12 of atmospheric pressure, so approximately 1/12 of the volume of air in the test chamber must be moved to make this change. On the other hand, all the air displaced by the test specimen as it deflects must be moved. Thus flexibility is at least an order of magnitude more onerous than volume.

The system performance with no test chamber attached was with a 5 m by 5 m roof panel in a 4.25 m^3 test chamber. The roof panel consisted of a corrugated steel deck on 5 m-long cold-rolled steel purlins at 1.5 m centres. The design pressure for the roof was -1 kPa, but a peak test pressure of -2 kPa was used at which the roof deflected 130 mm in the centre, displacing about 1.5 m^3 of air (corresponding to 1/3 of the volume, compared with 1/50 of the volume for the pressure change alone). The test trace was derived from the region of high suction at the periphery of a low-pitch roof at model scale in the BRE boundary layer wind tunnel, digitised at intervals equivalent to Δt = 0.5 s in full scale.

Figure 3 shows the transfer function gain and phase between the target and actual pressure when the trace was reproduced at 0.1 s intervals (real time * 5). The system response without the test chamber is good (-3dB) to about 2 Hz. The 5 m by 5 m roof reduces the response to about 0.2 Hz with an indication of a possible damped (Helmholtz?) resonance at 0.08 Hz, owing to the very high flexibility. This conventional transfer function approach is not strictly appropriate because the system is non-linear. The limitation is on the rate of loading, rather than the frequency response, and this is best demonstrated in the time domain.

Figure 4 shows the target and response traces for three cases, each including the target peak value $\hat{p}$ = -2.0 kPa near the middle of the trace. (Note that the signal is largely negative, but that a small positive pressure excursion occurs shortly before the peak value. This would not be possible to reproduce in a system that applies either pressure or suction from a datum of atmospheric pressure.) Trace (a) was obtained with no test chamber in real time (0.5 s intervals) and shows that the response follows the target trace faithfully, except that sharp peaks are rounded off by the loss of very high-frequency components so that the peak response is 7% lower than the target peak. The corresponding real time response of the 5 m by 5 m roof in trace (b) follows only the low-frequency components of the target trace. (Note that the response trace is delayed relative to the target trace by the time constant of the roof.) Consider the response to the target trace to the rapid drop in pressure approaching the peak target value which exceeds the maximum rate of loading possible with the valve fully open.

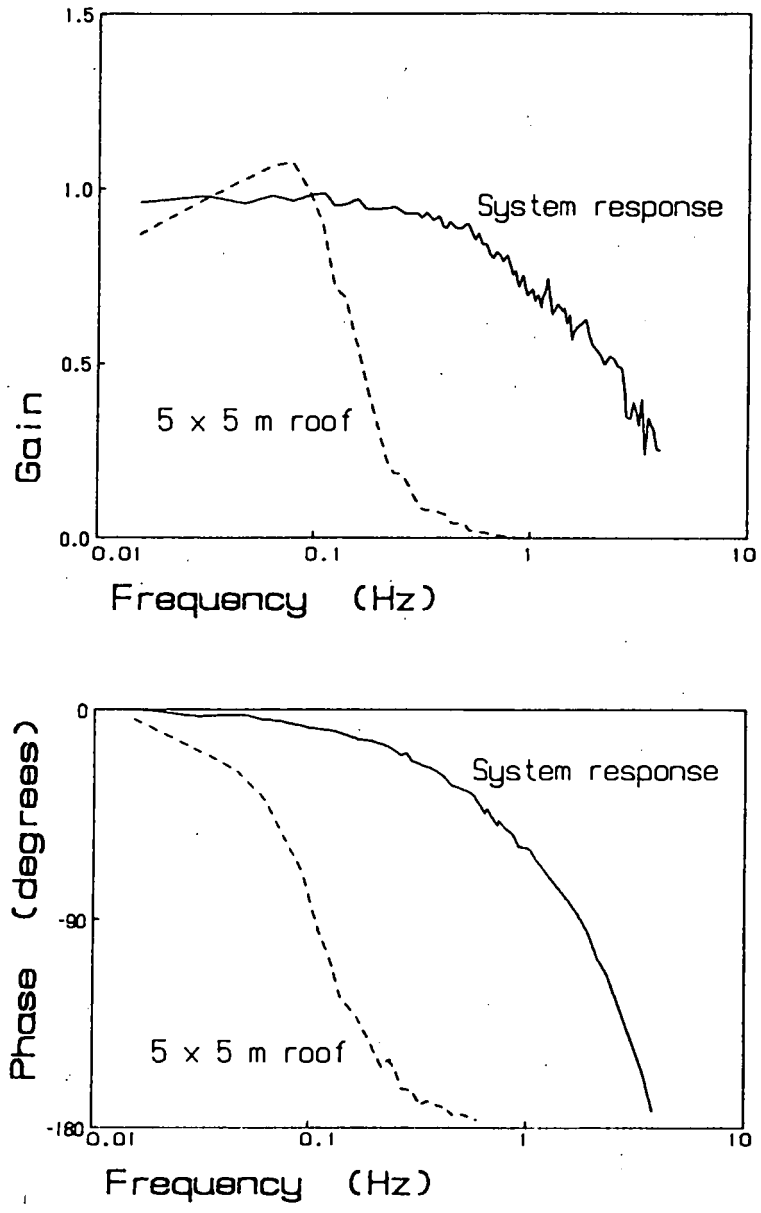
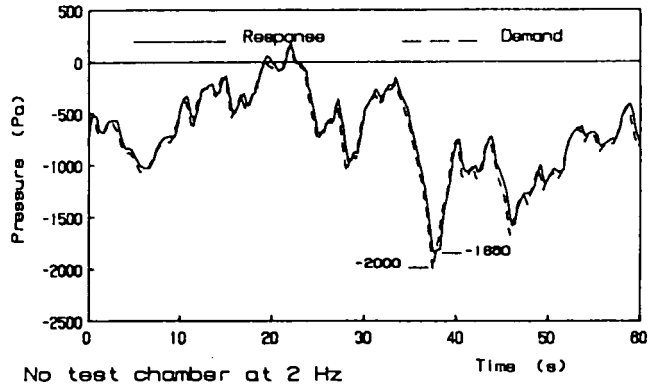
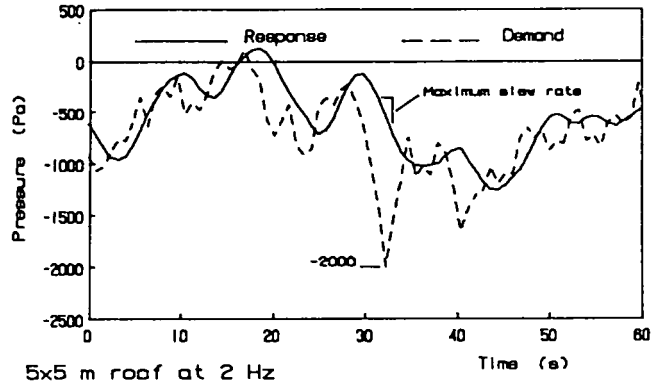


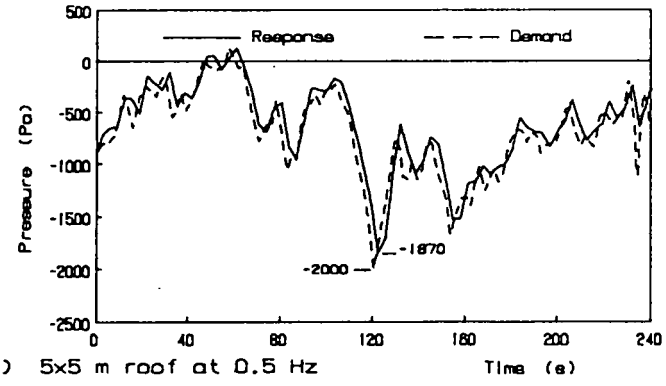
Figure 3 Transfer function



(a) No test chamber at 2 Hz



(b) 5x5 m roof at 2 Hz



(c) 5x5 m roof at 0.5 Hz

Figure 4 Typical loading traces

The control demand exceeds the physical range of the value, but the anti-windup algorithm holds the valve fully open only until the target pressure rises again to meet the response pressure. The maximum slew rate of the response in trace (b) is a little more than half the target rate. Increasing the time interval between values reduces the target slew rate in proportion and brings it within the achievable range. Trace (c) is the corresponding response when the target trace was reproduced four times slower (2 s intervals), showing that the peak is now reproduced marginally better than in trace (a).

Application

The prototype BREWULF was developed principally as a research tool to study the response of multi-layer cladding systems to fluctuations of wind loading. The ±8.5 kPa range of pressure is about three times greater than the maximum cladding loads predicted by the UK Code of Practice[3] anywhere in the United Kingdom. It is also greater than loads predicted in tropical cyclones. This range makes BRERWULF a suitable test apparatus for proof testing actual structural or cladding systems. The roof used to illustrate the performance of BRERWULF provides a very onerous test. Most practical cladding systems will be much less flexible, enabling the full response of the system to be exploited.

It is the intention of BRE to compile a collection of target pressure traces typical of various building forms and locations from full-scale and model-scale tests. Sufficient meterological data presently exist to synthesise peak pressure arrays which represent the population of storms expected in the design life of a structure. This will enable realistic agrément procedures to be devised. Agrément and proof-testing applications are commonly performed by mechanical or dead-weight loading techniques. The realism of the loading offered by BRERWULF is likely to be a major advantage.

A new application, not previously attempted in this field, is 'forensic' investigations: that is the reconstruction in the laboratory of wind loading events that have occurred in the field from meteorological records of the event. The cause of a specific failure could be investigated and new proposals could be compared with the result. The nearest existing analogue to this process is probably the reproduction of past earthquake events using shaking tables.

ACKNOWLEDGEMENT

BRERWULF was developed as part of the research programme of the Building Research Establishment of the Department of the Environment of the United Kingdom and this paper is published with the permission of the Director.

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NBI ROOF WIND UPLIFT STRENGTH TEST FACILITY AND LOAD PROGRAMS

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Trondheim Division, Norway

INTRODUCTION

The Norwegian Building Research Institute (NBI), Trondheim Division, has been engaged in roofing research from its establishment in the 1950s.

For low-slope roofs with flexible roofing, field investigation techniques were originally used as a basis for subsequent revision of recommended codes of practice.

At the beginning of the 1970s, the need for laboratory testing and evaluation became more evident. Backed by the industry, NBI set out to build a multifunction roof-testing apparatus with test programs for:

- wind uplift strength (pressure and temperature),
- simulated aging (temperature and moisture), and
- accelerated aging (IR lamps and UV tubes).

The apparatus and the results of the initial research were presented at the International Symposium on Roofing Research (ISRR), Brighton, in 1974 [2].

During the 1970s, the apparatus was extensively used for wind-uplift strength research and commercial testing. The standard method for testing the wind-uplift strength of roof assemblies was proposed as a Nordtest Method and finally approved as NT BUILD 307 in 1986 [4].

In 1987, NBI initiated a project with participants from the four Scandinavian countries and cosupported by the Nordic Fund for Technology and Industrial Development to study dynamic load application on mechanically fixed roof systems.

This paper concentrates primarily on giving a short description of the apparatus and loading conditions. More detailed information has been published in various NBI publications.

Results of the initial research testing using dynamic load application on mechanically fixed light roof membranes is due to be published as an NBI report.

MEMBRANE ASSEMBLY TEST

Standard wind load (NT BUILD 307)

A section of the roof is placed in a steel frame and mounted between the upper and lower box. The membrane is held in position between the flanges of the steel frame and a steel profile surrounding the apparatus and held down by the weight of the upper box.

Load is applied as static pressure in the lower box and as pulsating suction in the upper box, as shown in Fig. 2. Each load interval represents a testing time of 25 minutes with 5 minutes static load and 20 minutes pulsating load. The intensity of loading is increased in increments as shown in Fig. 3.

The membrane temperature can be controlled during testing using the air cooling arrangements. For Norwegian conditions the recommended test temperature is ±0 °C.

The mode of failure is determined on the basis of breakage of the membrane or fastening system or any permanent deformation that may cause premature reduction in the service life of the membrane waterproofing function. The associated total load is given as the capacity at failure for the assembly.

In the case of mechanically fixed systems, the design capacity is based on at least two assembly tests. Usually this means one assembly with a low number of fasteners and one with a high number of fasteners. In this way, the major effects from fastener geometry and load increments are eliminated. The average capacity at failure is reduced with a safety factor bearing in mind that national codes for design of structures may use the loadfactor approach. NBI Design Sheet A 544.206 (attached as an appendix to this paper) shows how to find the required numbers of fasteners from a given code for wind load and capacities found by testing according to NT BUILD 306 and 307.

Dynamic load

The apparatus for dynamic wind load applications is shown in Fig. 1. It is basically the same apparatus as for standard wind load testing, but with the following additions:

- a steel tank of 11 m^3 to store air at low pressure,
- a 50-cm diam. release valve,
- an air intake slit positioned between rows of fasteners and connected to the main air duct by flexible tubes,
- a 20-cm wide section without insulation in the roof assembly under the air intake slit and between rows of fasteners, and
- pressure equalizing between load applications.

The load is applied as dynamic suction in a 30-mm wide slit positioned above the roof membrane and between the rows of fasteners where the insulation has been removed. The membrane under the air slit is lifted up first, with the result that a non-axial load is transmitted to the fasteners.

The following load programs have so far been defined and used in the research testing:

1. Load intervals with increasing intensity.

   (a) Dynamic load (Fig. 4). Suction applied as gusts every 15 sec. for one hour per load interval. The intensity of the gust is increased in increments of 200 Pa from one load interval to the other.
   (b) Static + dynamic load (Fig. 5). A static suction is applied in the upper box to lift the membrane from the base. Gusts of suction are the same as for *(a)*.

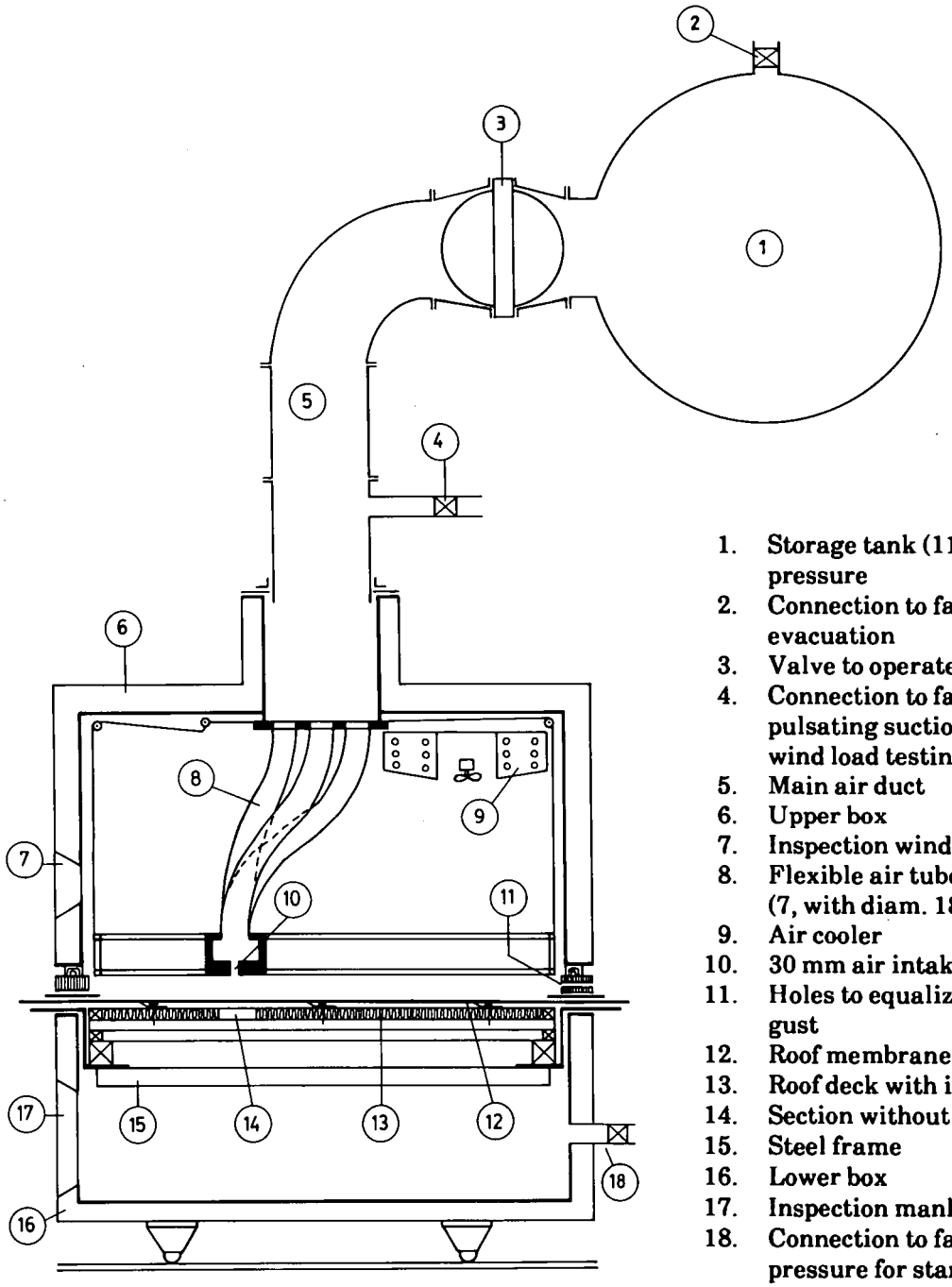
2. Load with fixed intensity (Fig. 6).

   Gusts of suction applied continuously every 15 sec., with fixed intensity.

The intensity of suction quoted is instantaneous pressure measured at the air intake slit above the roof membrane.

SIMPLIFIED MEMBRANE TEST

To reduce the cost of testing, NBI has developed a method of testing the membrane



1. Storage tank (11 m^3) for air at low pressure
2. Connection to fan for air evacuation
3. Valve to operate dynamic suction
4. Connection to fan operating pulsating suction for standard wind load testing (NT BUILD 307)
5. Main air duct
6. Upper box
7. Inspection window
8. Flexible air tubes (7, with diam. 18 cm)
9. Air cooler
10. 30 mm air intake slit
11. Holes to equalize pressure after gust
12. Roof membrane with fasteners
13. Roof deck with insulation
14. Section without insulation
15. Steel frame
16. Lower box
17. Inspection manhole
18. Connection to fan operating static pressure for standard wind load testing (NT BUILD 307).

Figure 1. Roof testing apparatus.

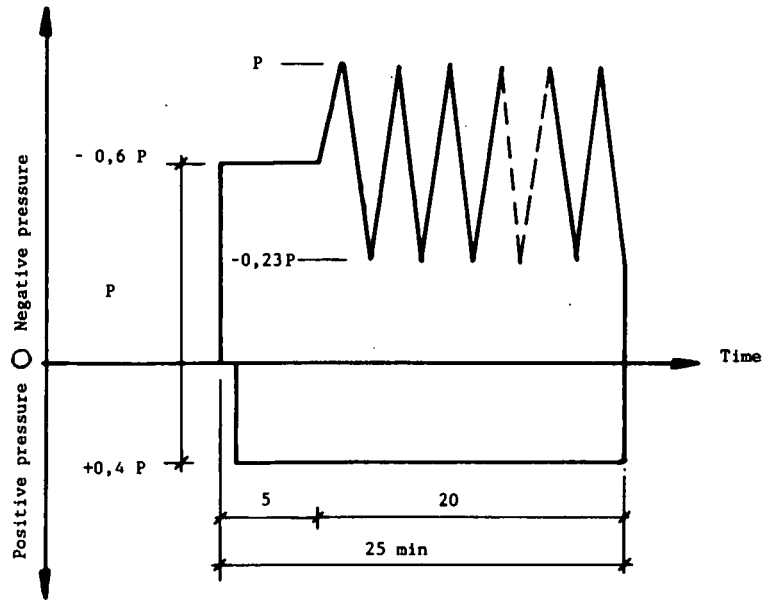


Figure 2. Standard wind load (NT BUILD 307), pulsating pressure.

Total load (Pa)	700	1400	2100	2800	3500	4200	4900	5500
Static load (Pa)	500	1000	1500	2000	2500	3000	3500	4000
Load interval	1	2	3	4	5	6	7	8

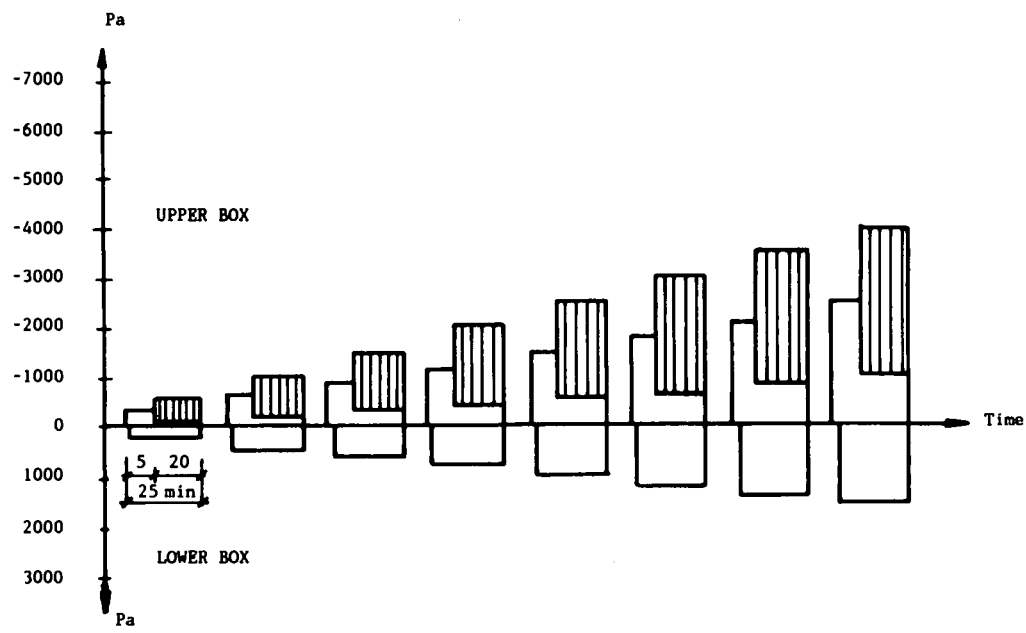


Figure 3. Standard wind load (NT BUILD 307), intervals with increasing intensity.

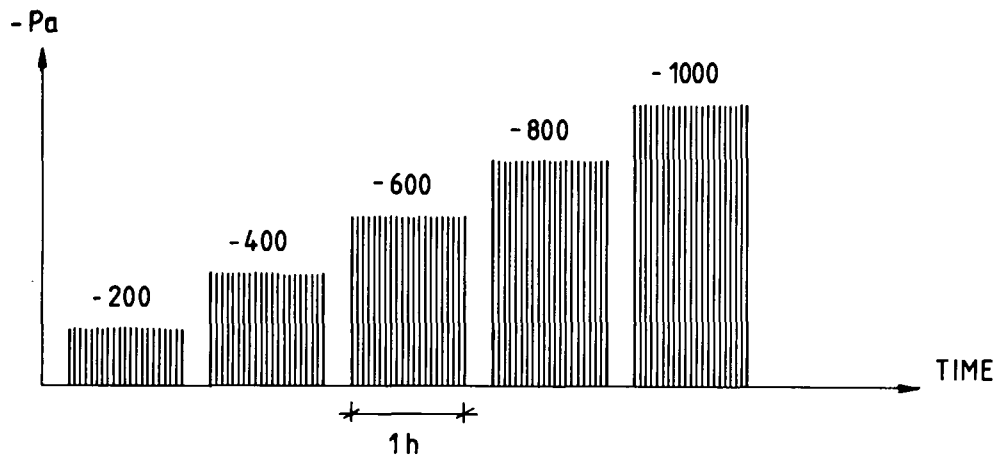


Figure 4. Dynamic load, intervals with increasing intensity.

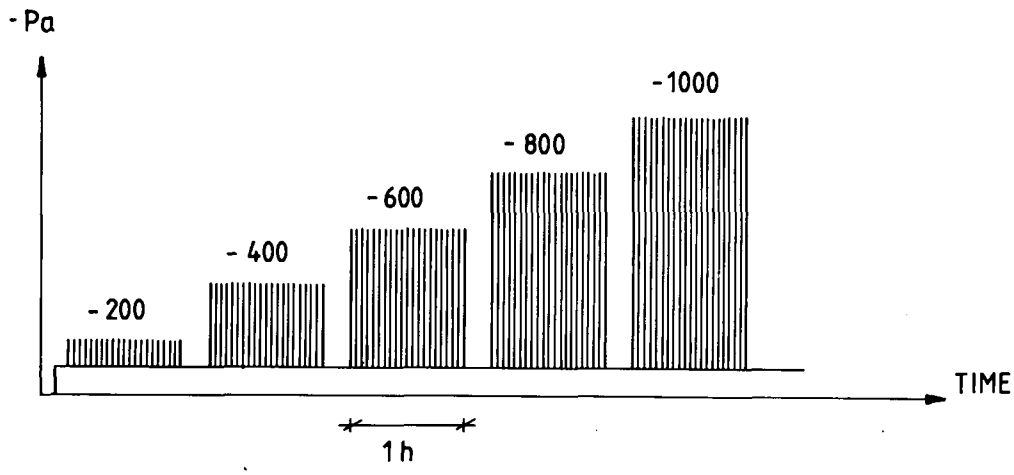


Figure 5. Static plus dynamic load, intervals with increasing intensity.

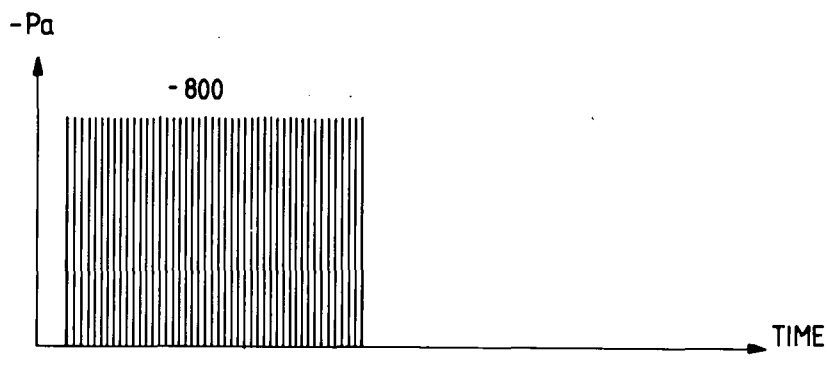


Figure 6. Dynamic load, fixed intensity.

strength of individual fasteners.

The membrane is fixed between two steel frames with a free area of 400 mm by 400 mm. The fastener is installed in two ways:

(a) through the membrane, or
(b) through an underlying flap or membrane edge and prestressed against a piece of insulation.

The pullout strength is determined in a tensile machine using a constant speed of deformation of 50 mm/min. The correlation between capacity at failure for the assembly test and simplified test can be established on an individual basis and used for comparative testing and assessing of possibilities during product development.

FASTENER STRENGTH TEST *(NT BUILD 306)*

NBI has developed a test method using pulsating load application on individual fasteners that was accepted as Nordtest Method in 1986. Detailed instructions are given for installing fasteners to be tested in concrete, aerated concrete, and steel decks.

The testing procedure is as follows. The static pullout strength must be tested first. The fastener and the base material in which it is mounted are secured in the test machine in such a manner that any effects of bending are as far as possible avoided. The machine is to be operated at a speed of 5 mm/min.

Testing with pulsating load is to be carried out at load intervals with increments increasing by one fifth of the average capacity for static load, but rounded off to the nearest whole 100 N. The minimum increment is 100 N, the maximum increment 500 N. In each interval, 200 load cycles (loading and unloading) are to be applied. The load is increased by intervals in the defined load region until breakage occurs. Deformation speed is 50 mm/min. If elastic deformation occurs, the speed is increased at interval 3 and succeeding intervals. An attempt is made to maintain the same total testing time as in interval 2. Deformations at each load interval are recorded.

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APPENDIX

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Roofing

Mechanical fastening of bituminous and polymeric membranes

Design Sheet
Building Details
A 544.206
Spring 1988

Published in cooperation with
the Norwegian Roofing Research Group, Høgskoleringen 7, 7034 Trondheim – NTH

0 General

01 Contents

This pamphlet shows how insulation and roofing membranes can be mechanically fastened to withstand wind loads, using plugs, selfdrilling screws, nails or staples.

The pamphlet also describes the method employed for calculating the design wind load for the roofing membrane. NS 3479 gives information about cases which this pamphlet does not cover. It is recommended that a civil engineering consultant carries out the calculations.

02 Principles for fastening

Three methods for fastening insulation and roofing membrane can be distinguished:

- fastening into loosely laid roofing membrane
- fastening through roofing membrane which has been bonded to insulation
- fastening only through the insulation with bonded membrane.

When design calculations are being made, it has to be decided what is the weakest link in the construction. Breaks may occur at:

- the fastening point to the substratum
- the fastening plug itself (stem or stress plate)
- the fastening point to the roofing membrane and insulation.

03 Reference

Norwegian Standard:
NS 3479 Dimensjonerende laster (Design loads)

NBI Design Sheets:

A 525.203 Kompakte tak med isolasjon av ekspandert polystyren (Solid roofs insulated with expanded polystyrene)

A 544.202 Tekking med folier. (Roofing with polymeric membranes)

A 544.203 Tekking med asfalt takbelegg (takpapp). Metoder og tekkebetingelser (Roofing with roofing felt. Methods and prerequisites for roofing work)

A 544.204 Tekking med asfalt takbelegg (takpapp) og takfolier. Detaljløsninger (Roofing with roofing felt and polymeric membrane. Detailed methods)

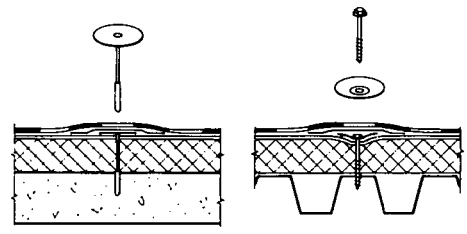

Fig. 11
Examples of fastening assemblies
a. Using a plug or bolt for fastening into concrete
b. Using a screw for fastening into steel plate decks

1 Materials

11 Fastening assemblies using plugs or self-drilling screws

Figure 11 shows examples of mechanical fasteners for concrete roofs and steel decks employing, respectively, plugs and self-drilling screws. The fastener must be sufficiently strong to withstand stresses incurred during installation and be able to transmit dynamic load from roofing to substratum. Load transmission can be symmetrical about an axis, as when a stiff element is being fastened down, but asymmetrical loading must also be considered, e.g. when fastening into the edge of a breadth of felt or into a flap (fig. 311).

111 *Corrosion protection* of the mechanical fasteners must be documented and assessed in relation to the assumed stresses to which the roof will be exposed. These can be divided into three main groups.

Category K:
Risk of condensation on the lower side of the roofing membrane, but only for relatively short periods.
Good opportunities for drying out to room climate.

Examples:

- Steel deck roof whithout vapour barrier
- The stress plate on the fastening assembly is covered or embedded

Category KL:
Great risk of long periods when condensation is standing on the fastening assembly due to high relative humidity in the air between the roofing membrane and an impervious substratum.

UDC 69.024.15 SfB (47) Key words: roofing, fastening assemblies © All rights reserved

Norwegian Building Research Institute. Tel. (02) 46 98 80 P.O.Box 123 Blindern, 0314 Oslo 3, Norway

Poor opportunities for drying out.
Examples:

- Steel deck roof with vapour barrier
- Concrete deck roof
- Re-roofed roofs
- Stress plate on the fastening assembly exposed at the edge of the roofing membrane

Category KLA:
Condensation as in category KL, but with aggressive substances in the insulation or on existing roofing material in the case of re-roofing.
Examples:

- Corrosion-promoting phenol compounds in the insulation
- Re-roofing in areas experiencing corrosion-promoting fallout from industry, acid precipitation or sea spray

112 A DIN 50018 Kesternich Chamber using 2.0 l SO_2 is employed to test procedure itself has been modified in accordance with Factory Mutual Standard 4470, where maximum 15 % of the surface may be attacked by red rust when the sample is subjected to a prescribed number of cycles. The temperature-humidity stability of organic coatings is tested for 300 hours at 90 °C and 100 % RH and the coatings should not peel off or show any blistering.

113 Using as a basis the stresses listed in section 111, the following minimum demands for protection against corrosion are stipulated, given in Kesternich cycles:

2 cycles for category K
8 cycles for category KL
15 cycles for category KLA

Table 113 gives the types of coating and materials which provide satisfactory protection against corrosion.

Table 113
Types of roof and recommended protection against corrosion

Category	Roof construction	Types of coating and materials for mechanical fastening essemblies		
		Stem	Stress plate	
			Covered or embedded	Exposed
K	Steel sheet deck Vithout vapour barrier	10–15µ El Zn	20µ Zn	20µ Al Zn Stainless steel Al Plastic
Kl	Steel sheet deck w/vapour barrier Concrete Re-roofing	Special coating Stainless steel Al Plastic	20µ Zn	20µ Al Zn Stainless steel Al Plastic
KLA	As for KL, but the stem on the fastening assembly is exposed to aggressive substances	Special coating Stainless steel Al Plastic	20µ Zn	20µ Al Zn Stainless steel Al Plastic

114 *Galvanic corrosion.* Table 114 shows what risk there is of galvanic corrosion occurring when stress plates and screws made of different kinds of material are used together.

Table 114
Combinations of different materials in the fastening assembly

Category stem	Category stress plates	K	KL			
		Hot-dipped galvanised (Zn)	Hot-hardened Zn polymer	AlZn	AL	Stainless
K KL	ElZn Hot-hardended Zn polymer	• •	•	•	0	0
KLA	ElZn • Polymer	•	•	•	0	0
	Stainless Acid resistant	•	0	0	0	•

• Material combinations without risk of galvanic corrosion
0 Combinations which are good, provided corrosion-promoting substances are not introduced from the indoor climate. If this is the case, the use of steel constructions should be carefully considered.

12 Nails for roofing felt

The pamphlet presupposes the use of 28/25 hot-dipped galvanised clout nails.

13 Staples

Staples having the correct angle between crosspiece and leg should be used (fig. 13). They must be galvanised and be 20-25 mm broad. When they are being put in, arched staples will cut down into the roofing material damaging it and resulting in inadequate grip. There have been some cases of damage due to this.
Staples must be inserted at the same position as clout nails (see NBI Design Sheet A 544.203).

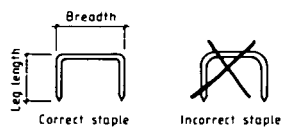

Fig. 13
The angle between leg and crosspiece on staples must form a right angle.

Table 13
Dimensions of staples

Shape of the wire	Breadth mm	Wire dimension (b × t) mm
Rectangular	24.0 22.0	2.0 × 1.0 2.4 × 0.9
Approximately round	26.5 26.0 24.0	1.6 × 1.4 1.8 × 1.3 1.6 × 1.4

2 Wind loads and calculations

Rules for calculating wind loads are given in NS 3479.

21 Dynamic pressure

Wind velocity and dynamic pressure depend upon the height and position of the building. Figure 21 illustrates the relationship between these factors. After wind velocity and dynamic pressure have been read off, the wind load is determined on the drawing with the help of form factors.

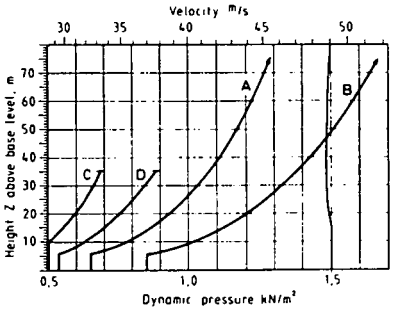

Fig. 21
How wind velocity and dynamic pressure vary with height above base level
Curve A: For districts not suffering hard weather, e.g. lowland areas inland
Curve B: For exposed districts, e.g. coastal areas
In particularly exposed places, e.g. outer coastal districts, the wind velocity must be assessed specially.
Curve C: For constructions in built-up areas in districts not exposed to hard weather
Curve D: For constructions in built-up areas in exposed districts

211 *The height of the building* is reckoned as its height above the base level of the terrain. In the case of buildings standing on local elevations in the terrain, e.g. on a ridge, the height is to be calculated from the foot of the hillside (fig. 211).

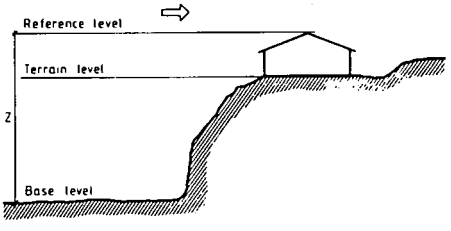

Fig. 211
Base level and terrain level

212 The location of the individual building is assessed on the basis of knowledge of local conditions as regards stresses caused by wind. Locally, where extreme wind speeds are experienced, it may be necessary to calculate with still greater wind loads than those given for exposed districts. Building sites that are extremely exposed can also be found in places otherwise looked upon as being in districts which are not exposed.

22 Form factors for external load

Form factors (μ_e) for external load depend upon roof shape and the secion of the roof concerned (table 22). Since roof surfaces along edges of roofs are exposed to greater wind suction than the rest of the roof, the roof is subdivided into three areas, illustrated in figures 22 a and b when determinations of external load and suction are being made. When the parapet is low, the fastener at the edge must be dimensioned according to form factor 4.

Table 22
Form factors (μ_e) for external load on flat roofs p· 6

Roof shape	Form factor (μ_e)		
	Corner area	Edge area	Central area
Roof with internal drain	2.5 3.0	2.0 2.0	1.0 1.0
Double pitched roof	High 4.0	2.0	1.0
Single pitched roof	Low 3.0		

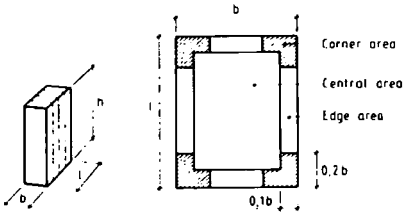

Fig. 22 a
Roof areas for high buildings, h > b 3, with flat roofs

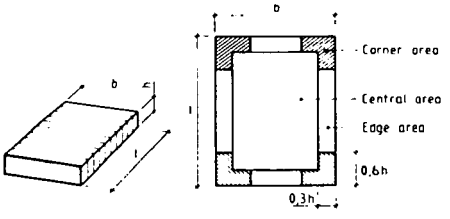

Fig. 22 b
Roof areas for low buildings, h < b·3, with flat roofs

23 The efficiency of external load

The transmission of load to the mechanical fastener depends upon the roofing membrane being deformed to a certain extent. The membrane will bend up between fastening points, and its volume will increase on its lower surface. Depending on how impervious the substratum is, negative pressure will then become operative, which can be deducted from the suction on the upper surface (fig. 23).

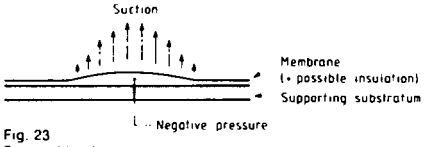

Fig. 23
External load

Table 23 gives factors for the efficiency of external load, depending upon the supporting construction.

Table 23
Factors affecting efficiency of external load

Factor f_3	Supporting construction
0.6	Impervious supporting construction – in situ cast concrete – concrete and lightweight concrete units with impervious joints – roof deck made of sheets with welts
0.8	Partially impervious supporting construction – concrete and lightweight concrete units with open joints – roof deck made of sheets without welts
1.0	Open supporting construction – profiled steel sheets, with or without acoustic perforations on ribs – roof deck made of rough boarding

24 Form factors for internal load

The manometric pressure in the building is of interest since it may form an additional load on the membrane and influence the required strength of fastener (fig. 24).

Form factors (μ_1) for internal load depend upon the imperviousness of the building and can be given as:

μ_1 = 0.2 for normally impervious buildings
μ_1 = 0.7 for open buildings, e.g. open warehouses.

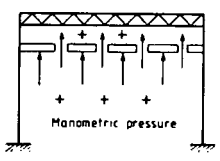

Fig. 24
Internal load

25 The efficiency of internal load

If the roof deck is sufficiently impervious and strong, it will hinder transmission of load to the fastener. Table 25 gives the factors for transmission of internal load, depending upon the supporting construction.

Table 25
Factors affecting efficiency of internal load

Factor f_4	Supporting construction
0	Impervious supporting construction – in situ cast concrete – concrete and lightweight concrete units with impervious joints
0.5	Partially impervious supporting construction – concrete and lightweight concrete units with open joints – profiled steel sheets without acoustic perforations
1.0	Open supporting construction – profiled steel sheets with acoustic perforations

26 Calculating the design wind load

The design load for individual sections of the roof can be calculated on the basis of the following formula:

$P_d = 1.6 \cdot 0.9 \cdot q\,(f_3 \cdot \mu_e + f_4 \cdot \mu_i)$

where

1.6 = the wind load factor
0.9 = the life-time factor (from return periode of 50 years to 20 years)
q = the dynamic pressure (N/m²) (fig. 21)
μ_e = the form factor for external load (table 22)
μ_i = the form factor for internal load (section 24)
f_3 = the factor for the efficiency of external load (table 23)
f_4 = the factor for the efficiency of internal load (table 25)

If we make the space between rows of fasteners = a, and the space between fasteners in a row = b, the load of those that are connected to the roofing membrane (including ballast) can be incorporated in the following manner when the distribution of the load on the individual fastening points is being calculated:

$p_d = (P_d - E)\,a \cdot b$

where

p_d = the design load per fastening point
E = the load of the roofing membrane itself, or of the roofing membrane and the insulation when these are bonded together, along with ballast

27 Calculating the design capacity of the fastening assembly

Fastening into the substratum:

a. On the basis of tests using a static load (this is looked upon as a test which is not particularly representative):
   – plugs and screws $X_d = 0.5^{*} + 0.9\,(X_m - k \cdot s)$
   – clout nails and staples $X_d = 0.5^{*} + X_m$

*) when pullout tests are being made on the individual building, this factor can be increased to 0.75

where

X_d the design capacity
X_m the mean value of the capacity of failure under tests
k the factor for the number of tests, as shown in table 27
s the standard deviation

b. On the basis of tests using pulsating load in accordance with NBI method 129/83 (NT-BUILD 306):
   – plugs and screws $X_d = 0.9\,(X_m - k \cdot s)$
   – clout nails and staples $X_d = 0.70\,X_m$

Fastening into roofing membrane and insulation:

a. Static load $X_d = 0.5\,X_m$
b. Pulsating load in accordance with NBI method 92/85 (NT-BUILD 307) «Taktekningers styrke mot vindlast» («The capacity of roofing membranes to withstand wind load»)
   $X_d = 0.70\,X_m$

Table 27
Factor (k) for the number of test values (n)

n	5	6	7	8	9	10	..>30
k	1.96	1.85	1.79	1.74	1.70	1.67	..

3 Fastening methods, workmanship and capacities

31 Fastening into roofing membrane and insulation

311 *Fastening into loosely laid roofing membrane* (fig. 311 a – i). The mechanical fastener is inserted after a layer of bituminous roofing felt or polymeric membrane has been laid loosely on the insulation or the roof deck. When the fastener is going through the insulatin into the supporting construction, a fastening assembly comprising a plug or self- drilling screw is used. When fastening directly into a wooden roof deck, clout nails or staples are used.

If there are several layers of bituminous roofing felt, the layer which is laid out before the mechanical fastener is installed should be strong enough to take up the wind load alone; an underlay of polyester-based reinforced bituminous felt can, for example, be used. The roofing must otherwise withstand the wind load without suffering permanent deformation which may lead to folds and, later, cracks forming if snow or ice come onto the roof. Non- symmetrical strain on the fastening assembly may result in decreased strength. Stapling and nailing must take place normal to the roof surface to ensure that heads do not form an oblique angle with the roofing membrane, perhaps leading to the fastener cutting down into the membrane giving reduced grip.

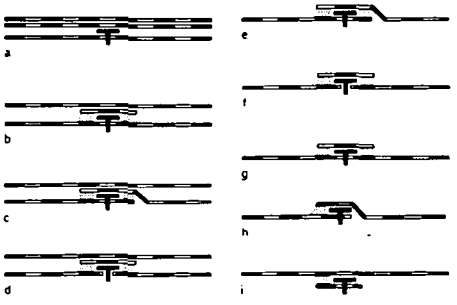

Fig. 311
Methods of fastening in loosely laid roofing membrane
a) Three-ply bituminous roofing felt
b) Two-ply bituminous roofing felt with extra felt covering the fastener
c) Two-ply bituminous roofing felt with the fastener centrally placed in a bonded overlap
d) Two-ply bituminous roofing felt with the fastener through the overlap of the first layer and a patch covering the joint
e) Single ply bituminous roofing felt with the fastener centrally placed in the bonded overlap
f) Single ply bituminous roofing felt with the fastener in the joint between the breadths of felt and a strip covering the joint
g) Fastener installed through membrane with extra cover
h) Fastener installed in the edge of the membrane felt
i) Fastener installed in the underlying membrane flap

312 *Fastening through bituminous roofing felt which is bonded to insulation* (fig. 312). The fastener is installed through the first layer of felt, which is bonded to the insulation.

If the fastening assembly is being installed in the joint betweeen panels it has to be remembered that panels with ship lap require precise placing of the fastener to ensure that both insulation panels are held fast.

313 *Suppliers give the design capacity* for fastening assemblies into roofing membranes and insulation. This must comply with documented tests, e.g. NBI Design Certificate.

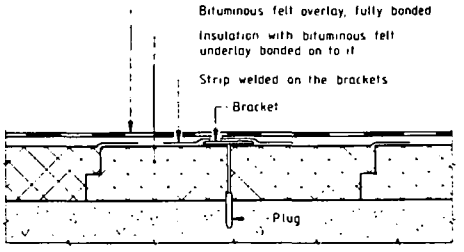

Fig. 312
Fastening through bituminous felt underlay bonded to insulation (doubled sheets)
Fastening assembly; brackets with plugs or screws

32 Fastening into the substratum

321 *Fastening into steel plate decks.* Plates thinner than 0.7 mm should not be used.

Steel plates are subject to strong vibrations during wind loading, and any slack in the attachment between the supporting construction and the plug can produce noise which may be annoying. As corrosion protection on the steel plates is easily weakened at each fastening point if the indoor climate is particularly damp or encourages corrosion in other ways, the attachment into the steel plates should be considered especially carefully.

Cold bridges may develop at every fastening point if the screw is inserted into the joint between sheets of insulation, or if the insulation is in any other way impaired. This may lead to condensation forming on the stem of the fastening assembly, and water can be led straight down to the attachment into the steel plate.

322 *Fastening into concrete and lightweight concrete.* It is very important to reach the correct depth when installing. There must be sufficient space for the plug after possible drilling dust has fallen into the hole. If the deck is drilled all the way through, fragments of concrete are usually broken off the lower surface. This is generally only an aesthetic problem, but it may also be difficult to achieve a good grip if the break is too big relative to the length of the plug. This is especially likely if deck thicknesses less than 50 mm are being used.

323 *Fastening into wood.* Table 323 shows the design capacities. Roof decks made of wooden planks have numerous joints, cracks and knots, and if installation is done carelessly with nails and staples being put into these, the strength may be impaired. Grip will also be reduced if the wood is particularly damp and dries out after the nailing or stapling.

Mechanical nailing (or stapling) may give satisfactory results, but requires awareness of variations in the substratum.

Table 323
The design capacity X_d (N) when fastning with nails or staples which go through the roof deck

Substratum for roofing membrane	Dry materials			Damp material (Not protected against precipitation)		
	Nails 28/25	Staples		Nails 28/25	Staples	
		Round in section	Rectangular in section		Round in section	Rectangular in section
12 mm plywood	160	80	80	145	55	55
15 mm rough board	110	85	95	100	60	65

If the roof deck is not protected from precipitation prior to the roofing work being carried out, the design capacities for fastening into damp materials must be used. These are reduced by 10 % for clout nails and 30 % for staples.

33 Number of fasteners

To work out the number of fasteners required, the design wind load is divided by the design capacity for attachment into the substratum or roofing membrane. In addition, the minimum number of fasteners must be considered in relation to the construction.
Critical factors may be:

- movement in the insulation. In the case of loosely laid roofing membrane and insulation, there must be sufficient fasteners per insulation panel to prevent panels becoming displaced beneath the roofing membrane.
- movement in the roofing membrane. Flutter can lead to fatigue at the fastener or produce noise.
  Noise may also occur when light roofing membrane is placed on a hard substratum.

In the case of loosely laid roofing membrane and insulation, the number of plugs or self-drilling screws should be at least:

- 1 per insulation panel
- 1 per m²

The maximum space between fasteners and rows of fasterners must not exceed 1,0 m.
If it is desired to reduce the number of fastening points below this, or to increase the space between rows of fasteners, this must be documented specially.

34 Vapour barrier

In constructions above rooms that have high relative humidity (RH) it may be disadvantageous to use mechanical fastening assemblies that pass through the vapour barrier, and this must be carefully considered. In the case of solid roofs, ballasted systems provides the best chance for good vapour barrier performance.

4 Example of design calculations

Information about the building and roofing is given in fig. 4 a.

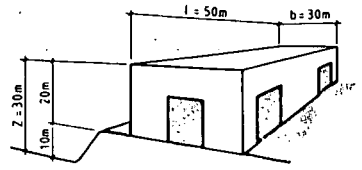

Fig. 4 a
The building has openings towards the wind, a low parapet and is located in an exposed district.
- 0,8 mm steel sheets with acoustic perforation
- 100 mm insulation, loosely laid
- bituminous roofing felt reinforced with 180 g/m² polyester which is loosely laid and has bonded joints
- self-drilling screws with 70 mm diameter stress plates
- strips bonded over the fasteners
- fully bonded bituminous felt overlay

Design capacities:

- fastening into steel plate decks, 820 N each
- fastening into roofing membrane, 1500 N each

Fastening into steel plate deck will be decisive using 820 N per fastener. The design wind load is calculated as explained in section 26; this is illustrated in fig. 4 b.

Number of tests: Central area $\frac{3\,280}{820} = 4$ per m²

Edge area $\frac{5\,210}{820} = 6$ per m²

Corner area $\frac{6\,170}{820} = 8$ per m²

$$P_d = 1.6 \cdot 0.9 \cdot q\,(f_3 \cdot \mu_e + f_4 \cdot \mu_i)$$

Central area: P_d $1.6 \cdot 0.9 \cdot 1\,340\,(1.0 \cdot 1.0 + 1.0 \cdot 0.7) = 3\,280$ N/m²
Edge area: P_d $1.6 \cdot 0.9 \cdot 1\,340\,(1.0 \cdot 2.0 + 1.0 \cdot 0.7) = 5\,210$ N/m²
Corner area: P_d $1.6 \cdot 0.9 \cdot 1\,340\,(1.0 \cdot 2.5 + 1.0 \cdot 0.7) = 6\,170$ N/m²

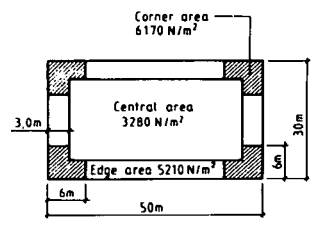

Fig. 4 b
Design wind load for individual areas of roof

5 References

51 This pamphlet has been written by Einar M. Paulsen and edited by Johan Gåsbak. The work was completed in December 1987.

52 Literature

521 TPF-informerer Nr. 2. Mekaniske festemidler for taktekking
522 PAULSEN, E.M. NBI-intern arb.rapport nr. 125. Mekaniske festemidler for taktekking. Prøving og dimensjonering
523 PAULSEN, E.M. NBI Project Report no. 21. Roofing Fasteners

ROOF ATTACHMENT REQUIREMENTS BASED ON FIELD EXPERIENCE

R. P. Baxter
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ABSTRACT

Field experience during recent heavy storms indicates that current recommendations for securing insulation for adhered roofing membranes are sufficient to minimize damage to the roof assembly. Present recommendations for securing mechanically attached roofing membranes appear to be inadequate to minimize damage. More attention is required for recommendations to promote better attachment of perimeter wood and accessory metal, especially some proprietary metal coping assemblies. There is a definite need for relatively simple, understandable guidelines for roofing contractors, specifiers, and owners. Current recommendations are difficult to interpret and, especially in terms of fastening requirements, are confusing and indefinite.

Background Papers

ROOF UPLIFT MECHANISMS

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and
Cermak Peterka Petersen, Inc., Fort Collins, CO

ABSTRACT

Wind damage to single-ply membrane roofing systems is the result of fluctuating wind pressures on roofing elements and may be augmented by wind forces that dislodge ballast. The wind flows that induce roof loading are sufficiently complicated such that wind-tunnel tests are usually used to determine magnitudes of roof loading. Several wind-flow patterns, loading mechanisms, and failure modes are discussed. Possible research methodologies are presented to provide alternatives to a single testing facility for roofing certification.

1. INTRODUCTION

Winds within the earth's atmospheric boundary layer where buildings lie are highly turbulent (gusty) and increase in mean velocity with height above ground. Winds interact with buildings in a complicated way (Fig. 1 shows the mean flow; a fluctuating flow also exists that has large excursions from this mean) that defies accurate definition by analytical means. Determination of wind loads and resulting roofing response must thus rely on wind-tunnel or full-scale tests.

The purpose of this paper is to present a brief description of wind uplift forces and their generation. Research methodologies are also presented.

2. WIND LOAD MECHANISMS

Three wind-flow mechanisms are primarily responsible for wind loading of roofing components. The first is flow separation, shown in Fig. 2. Wind approaches the building, impinges on the front wall, and flows upward past the roof line. The wind is unable to turn the abrupt corner and so continues past the corner, separating from the surface. High upward-acting wind pressures are often found on the roof under the separated flow, especially near the separation point.

The second wind flow mechanism is the roof-corner vortex (sometimes called a delta-wing vortex) shown in Fig. 3. Wind approaches at a quartering angle to the building, flows up over the roof, and rolls up into two vortices of opposite rotational direction originating at the building corner. These vortices are like miniature tornadoes that can induce high uplift pressures at the roof edge near the corner and can cause high velocities to occur over the roof surface under the vortices. The distribution of peak fluctuating pressures under roof vortices for one building is shown in Fig. 4. In addition to the high values of peak pressure, the time variation of pressure fluctuation is rapid. The high velocities under the vortices may cause

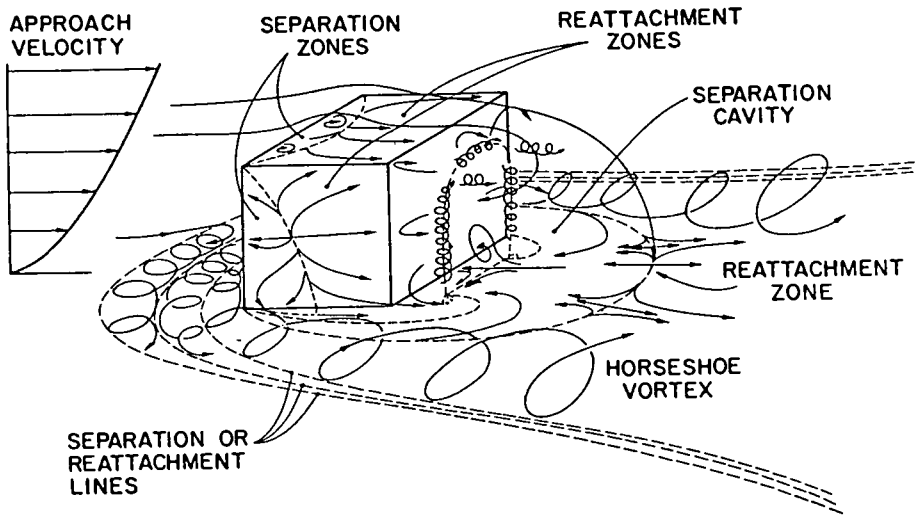

Figure 1. Mean wind flow patterns about a building, from ref. 1.

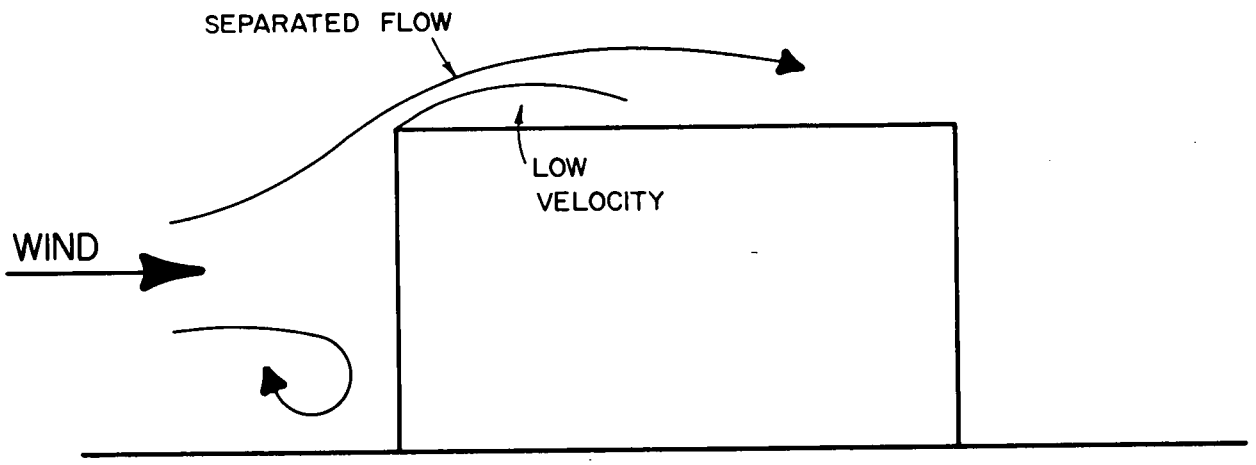

Figure 2. Flow separation.

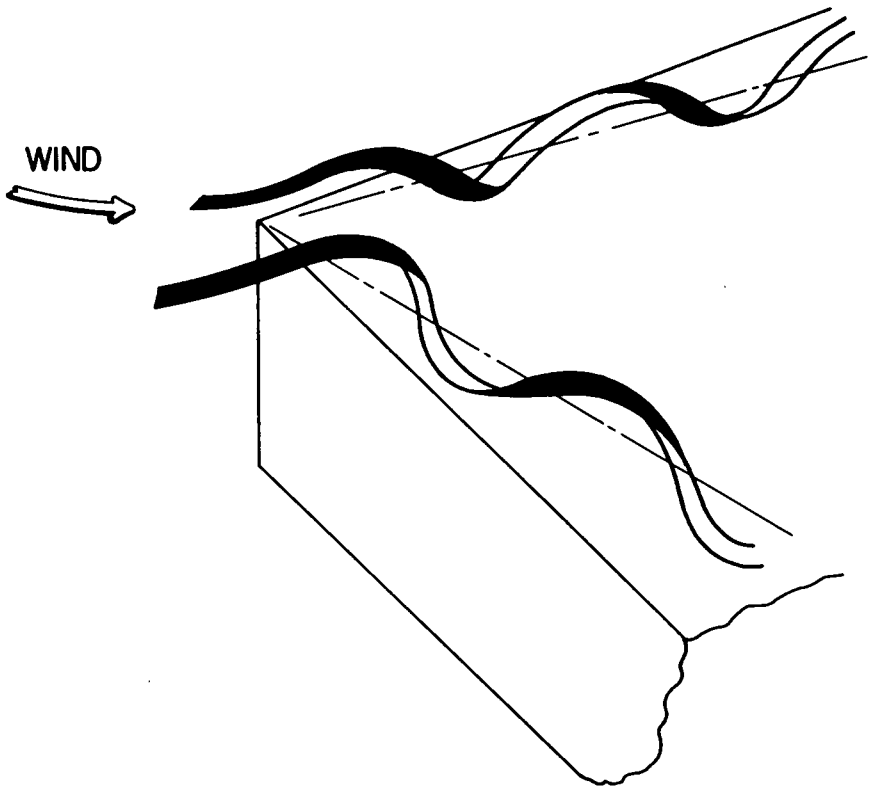

Figure 3. Roof corner vortex.

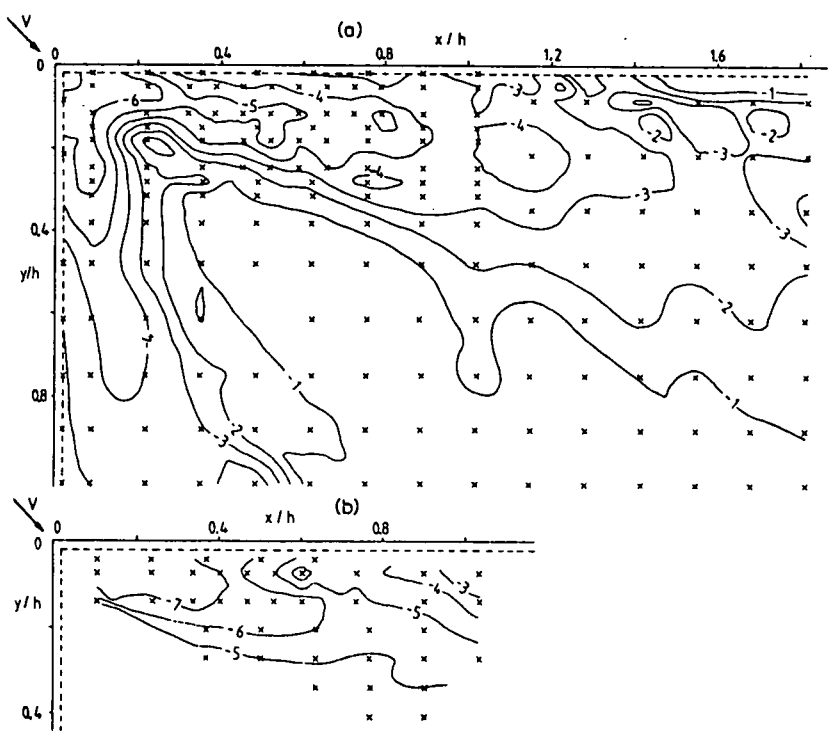

Figure 4. Peak local pressure distribution under roof corner vortices, from ref. 2.

scour of loose ballast material on high-wind days, leading to possible uncovering and ballooning of the underlying membrane.

The third wind-flow mechanism is the generation of a positive pressure under a membrane tending to push up from below. The source of this pressure may be a positive internal pressure generated, as in Fig. 5, by an opening in the windward wall combined with porosity in the roof structure permitting the building internal pressure to reach the underside of the membrane. Other leak paths that can permit positive pressures to reach the bottom side of the membrane without a porous roof are also possible.

Failure mechanisms vary with roofing systems, but may be categorized. Failure may originate from gravel scour, from ballooning of the membrane due to air leakage under the membrane, from lifting of pavers due to horizontal pressure gradients caused by wind action, from paver uplift due to vertical misalignment, or from fatigue of membrane or fasteners.

3. EFFECTS OF TERRAIN AND NEARBY STRUCTURES

The building location and its size in relation to its nearby environment can have a significant effect on roof loads. A building that stands by itself is more exposed to winds than one set into a neighborhood of buildings of the same size. Standing alone will usually result in larger wind uplift pressures on the roof. Wind speeds on the top of a hill are usually higher than those on a flat area and so roof uplifts may be higher for a building located there. Buildings at the edge of open, smooth approaches such as water are more susceptible to high winds and loads than those located away from open areas.

Buildings that are significantly taller than those around them are exposed to higher winds and loads than buildings similar in height to nearby buildings. Small buildings located at the base of much taller buildings may be exposed to high wind speeds due to winds concentrated and deflected by the larger structures. In many locations in the U.S., the strongest winds are expected to blow from westerly directions, so buildings more exposed to westerly winds may be susceptible to higher roof uplifts.

4. EFFECTS OF PARAPETS OR OTHER ROOFTOP FEATURES

There is evidence that parapets higher than about 3 feet tend to reduce roof uplift pressures and scouring velocities by elevating roof corner vortices and separations above the roof surface. While not all evidence is supportive, there is significant evidence that some parapets below 3 feet in height may actually increase roof uplift pressures by enhancing the roof corner vortex strength.

Where building roof edge lines are complicated with horizontal setbacks or other features, the roof corner vortices may not form effectively, and roof forces may be reduced. Stathopoulos [3], has shown that variations in parapet shape alone can reduce roof uplifts.

Steps in roofs, penthouses, or other variations in roof geometry can increase or decrease local wind pressures on the roof. There are no published guidelines that accurately identify areas or magnitudes of pressure increases or decreases due to variations in roof geometry.

5. RESEARCH METHODOLOGIES

A primary objective of this workshop is to define test methods for certifying single-ply membrane roofing products. One possibility is a simulated full-scale test in which a portion of a full-scale building and roof are placed in a large wind tunnel so that the full aerodynamic loading on the roofing system can be applied. This is a possible

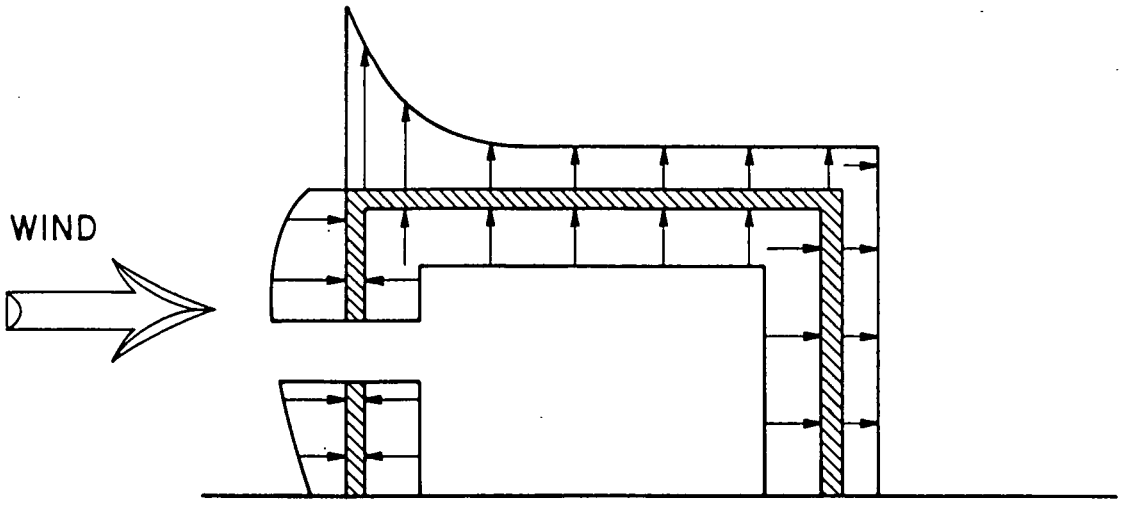

Figure 5. Positive internal pressure with roof porosity as a source of roof membrane uplift.

solution that should be explored further. An alternative to this approach is to conduct research to better understand the failure modes of single-ply membrane roofs.

Four alternate methods exist that can be used to determine wind loads and roofing response to winds. First is full-scale testing. Its advantage is that real roofing systems can be tested in real situations. Its disadvantages are high cost and relative rarity of winds that cause failure. A significant increase in wind loading knowledge is expected to come from the Colorado State/Texas Tech joint research project, which will test a full-scale building for wind loads including roof loads.

The second method is small-scale (1:10 or smaller) wind-tunnel testing in boundary layer wind tunnels capable of simulating atmospheric boundary layer winds and their loads. The advantages are low cost and a controlled experimental environment. Much information has been obtained from tests of this kind and further knowledge can be gained from additional testing. While the loading can be relatively accurately reproduced, not all of the response characteristics of roofing systems can be modeled with sufficient accuracy in the wind tunnel to provide direct certification testing.

A third research method is laboratory testing not involving wind-tunnel tests. These tests might include chambers with static or fluctuating pressures applied to roof systems or might include various bench tests. These tests can determine fatigue strength of materials, fastener strength, elongation under stress, etc.

The fourth method involves analysis. Analysis is limited in application for roof uplift without support from the other three methods, but may be a powerful tool for merging results of the other methods.

A combination of all of these techniques may be necessary to provide the certifications sought at a minimum price. Basic research into roof wind loading and responses of roofing systems to those loads may show that certification testing for some roofing systems may ultimately be performed without expensive testing systems.

A cooperative research program between Colorado State University and Texas Tech University that has been funded by the National Science Foundation will provide several hundred thousand dollars to research roofing loads and failure mechanisms, using both field tests at Texas Tech and wind-tunnel modeling at Colorado State. These funds, however, will not by themselves solve the roofing industry problem addressed at this workshop. Significant additional dollars must be made available to complete the task started by this program.

6. CONCLUSIONS

On the basis of the preceding discussion, and on the basis of the writer's previous experience with definition of wind loads on roofing systems, it is evident that the following conclusions can be drawn:

1. Roof loading mechanisms need further study before loading on any given roof can be accurately predicted.

2. Static and fatigue responses of roofing systems need further study before the performance and failure of a roof design can be predicted with confidence.

3. Research dollars must be spent to accomplish the first two objectives. The roofing industry will have to supply many of those dollars.

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WIND TUNNEL TESTING OF ROOFS

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ABSTRACT

This paper reviews what wind-tunnel testing has told us about the behavior of ballasted roofs. The review includes explanation of the mechanisms by which wind can damage ballasted systems. Current approval test methods do not simulate these mechanisms and are inadequate for ballasted systems. Possible new approaches to testing are briefly considered.

1. INTRODUCTION

Wind tunnel testing has given considerable insight into the behavior of ballasted roof systems in high winds. On the basis of these insights it is clear that current approval-test methods are not appropriate for ballasted systems; these insights also provide a basis for considering new approaches to approval testing. Before considering new approaches to testing, we must understand the mechanisms by which high winds can cause failure of ballasted systems. These mechanisms will therefore be reviewed.

2. INFORMATION GAINED FROM WIND TUNNEL TESTS

2.1 General

Even when large wind tunnels are available, testing of complete roofing systems must be done at reduced scale. Scaling requirements or modeling laws are, however, well established. Atmospheric winds and turbulence can be simulated. Provided that geometry, density, and mechanical properties of systems are properly scaled, reliable quantitative data can be obtained. A very great advantage of wind tunnel testing is that wind speeds and other test conditions are controlled and readily repeatable. The ability to accurately reproduce detailed geometry restricts the amount of scaling down that is acceptable. Excessive scaling down may also result in unacceptably low values of Reynolds number for certain portions of the air flow. More information on modeling requirements is available in reference [1].

From 1973 onward, extensive testing of ballasted roof systems has been carried out in the National Research Council of Canada (NRCC) 30 ft by 30 ft wind tunnel. This is an unusually large tunnel. Systems comprised of loose stone ballast, concrete pavers, and loose-laid rigid insulation boards have been tested, all at one-tenth scale. The persons listed in reference [2] can be consulted for detailed information on the various tests that were carried out. This paper will review some of what has been learned from these tests and the implications for approval testing.

As sketched in Fig. 1, when the wind

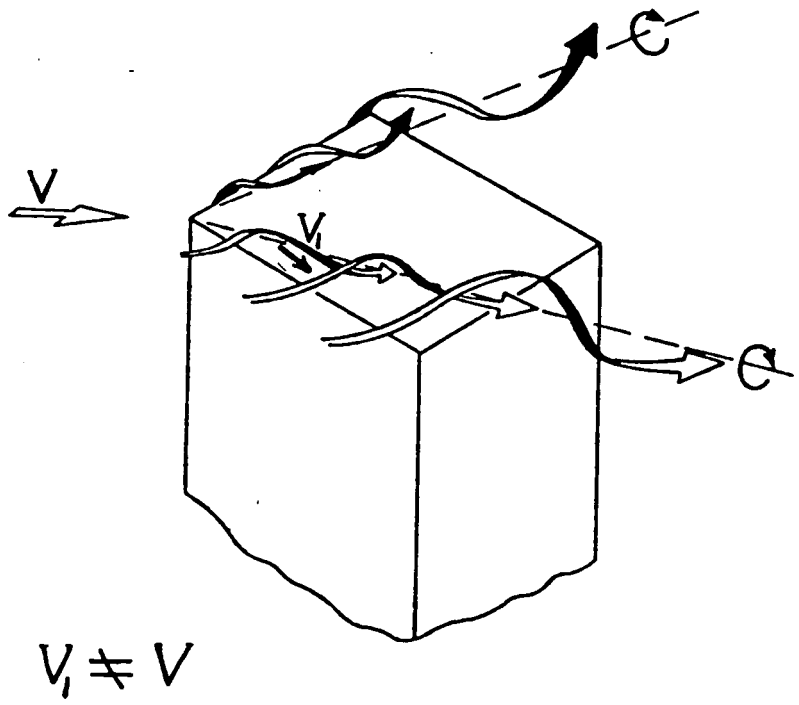


Figure 1. Roof vortex formation for wind at approximately 45° to building walls.

direction is at about 45° to the walls of a building, strong vortices form near the upwind corner of low-slope rooftops. The wind speeds and suction pressures under these vortices are much higher than ambient values at roof level and this has an important influence on roofing system behavior. The test results show that this is the critical wind direction for gravel scour and also for paver or board uplift for the other tested systems. Figure 2 shows pressure patterns near the upwind corner of a rooftop for a 45° wind direction; (a) and (b) are for low and high parapets, respectively. The pressure patterns clearly reflect the presence of the aforementioned vortices. Note the strongly negative (i.e., high suction) pressure-coefficient values and rapid spatial variation of pressure in Fig. 2a. The high suctions correspond to high local air speeds, in accordance with Bernoulli's principle. Although strong suctions and high air speeds prevail over only a small fraction of the roof area, they play a crucial role with respect to wind damage. Increased parapet height, h_p, is beneficial since it results in reduced suctions and air speeds, as seen in Fig. 2b.

2.2 Failure Mechanisms

Three failure mechanisms can be identified: membrane ballooning, stone scour, and paver/board uplift.

2.2.1 Membrane Ballooning

Membrane ballooning of course cannot occur if the membrane is securely adhered or otherwise fastened to the roof deck. Even if the membrane is loose-laid, ballooning can only occur if air can penetrate between the membrane and the deck, either because the deck is not air-tight or the membrane is not well sealed to the deck around the roof perimeter. If the air can penetrate, ballooning will occur if the pressure difference driving the air exceeds the weight per unit area of system elements lying on top of the membrane. In cases where the deck is not air-tight, membrane ballooning would be driven by the difference between building interior and roof exterior pressures.

2.2.2 Stone Scour

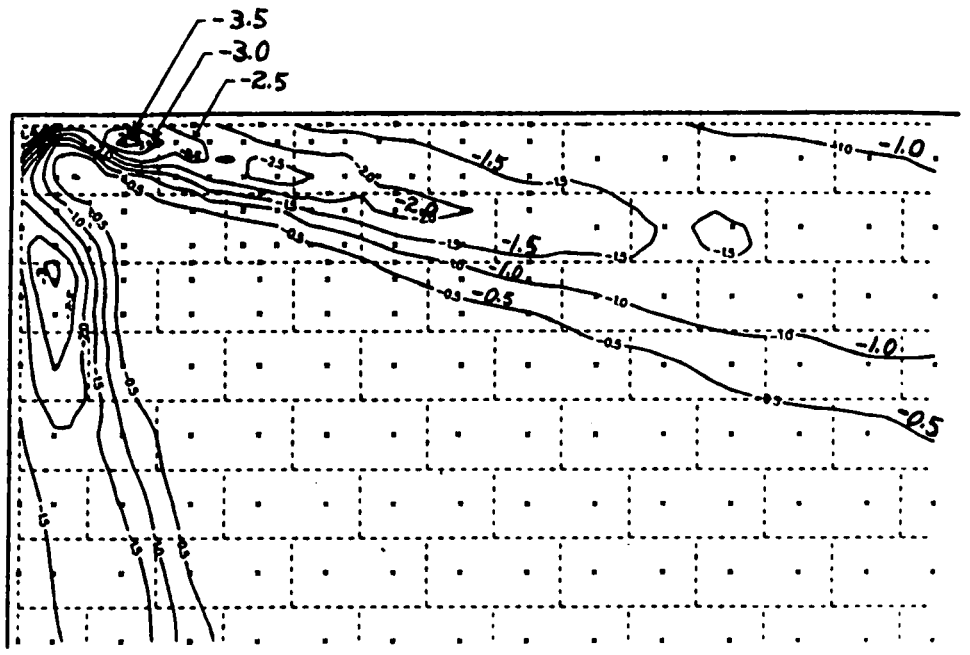
Wind blowing over a bed of stones exerts an aerodynamic force, mainly drag, on individual stones as sketched in Fig. 3. This force is proportional to the square of the local air velocity and it will displace the stones if it overcomes the weight forces that tend to keep stones in place. Areas of the rooftop where high local velocities prevail can be scoured clear of gravel.

By considering the balance between aerodynamic and gravitational forces or moments on an individual stone (Fig. 3), we find

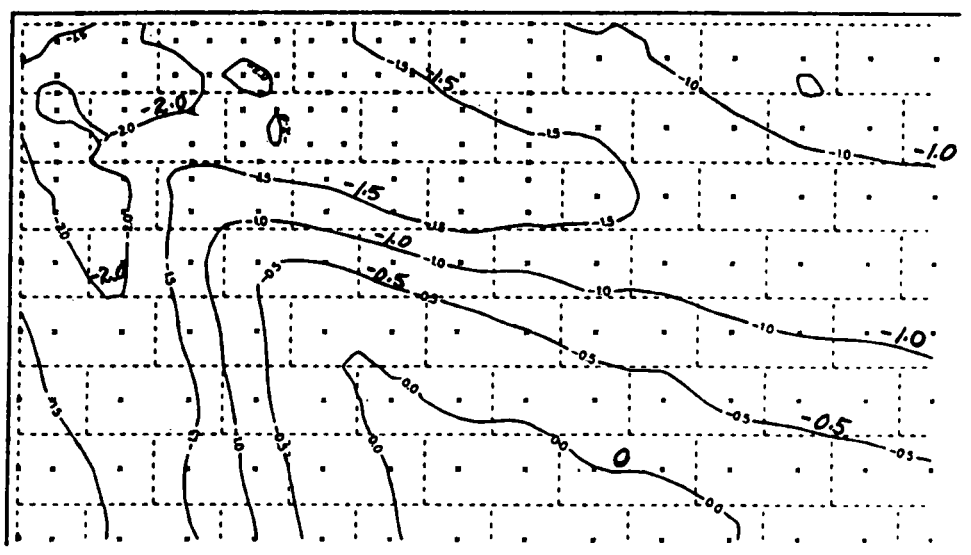
$$V_1 = \sqrt{\rho_s g d / \rho} \qquad (1)$$

where V_1 is the local velocity required to cause stone movement, ρ_s and d are the mass density and nominal diameter of the stones, g is gravitational acceleration, and ρ is the density of the air. Unfortunately, the local velocity at the stone bed, V_1, is not simply related to the ambient wind speed, V, at rooftop level. The ratio V_1/V depends on the details of the flow pattern, and thus on wind direction, building shape, and parapet height as well as position on the rooftop.

Equation (1) indicates that wind speeds required to initiate stone scour are proportional to the square root of nominal stone diameter. However, for design purposes a more complete relationship between V and stone properties is required, one that takes into account the aforementioned factors. The necessary information has been obtained, at least for simple building shapes, by wind tunnel



(a) $h_p/h = 0.027$



(b) $h_p/h = 0.2$

Figure 2. Mean Pressure Coefficient Distribution On Roof Exterior of a Low Rise Building For Two Different Parapet Heights
(h = building height; h_p = parapet height; pressure coefficient $C_p = (p - p_\infty)/1/2\rho V^2$ where p and p_∞ are the local and ambient pressure, respectively, V is the mean speed of the ambient wind at roof level and ρ is the density of the air).

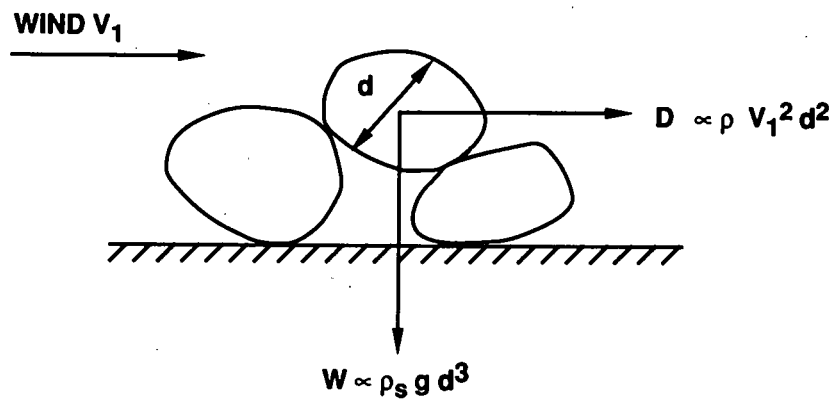


Figure 3. Forces on stone in stone bed on roof.

experiments. Fig. 4 shows an example of a design graph based on the wind tunnel data. The complete design method is available in reference [3]. Experience indicates that this method is consistent with actual behavior in the field. This supports the reliability of wind tunnel testing.

2.2.3 Paver or Board Uplift

In this discussion of paver or board uplift it is assumed that air cannot penetrate under the membrane and ballooning cannot occur. The mechanism by which boards or pavers are dislodged is altogether different from that involved in stone scour. A layer of boards or pavers forms a reasonably flat surface and the airflow is basically parallel to the surface, so that little or no aerodynamic force is developed on a given paver or board. In the case of a bed of stones, on the other hand, there is airflow around a given stone and the aerodynamic forces can cause the stone to move. As outlined in the following paragraphs, pavers or boards are dislodged when the static pressures on their exterior and underneath surfaces develop a difference as a result of wind action.

Figure 5 shows the static pressure distribution measured underneath a layer of model insulation boards in the wind tunnel experiments. Figure 2a shows the corresponding pressure distribution on the exterior or upper surface of the boards. Note that the pressure distribution underneath the boards (Fig. 5) bears a substantial resemblance to the exterior distribution (Fig. 2a). A vee-shaped pattern is evident in both. It should be pointed out that the model insulation boards used in these experiments fit together snugly at all joints between adjacent boards and that their under-surface was smooth and flat and rested on a smooth, flat plexiglass plate that formed the roof of the model building. It is clear that the pressure distribution prevailing over the exterior causes small flows of air through the joints between the boards and underneath the

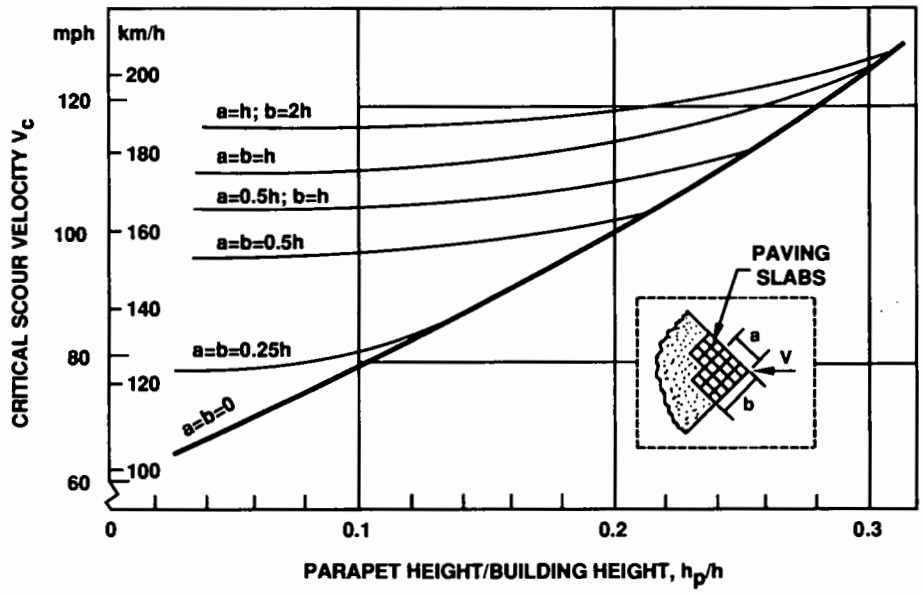


Figure 4. Effect of parapet height and paver arrays on critical wind speeds for stone scour on a low-rise building with 3/4 in. (19 mm) stone.

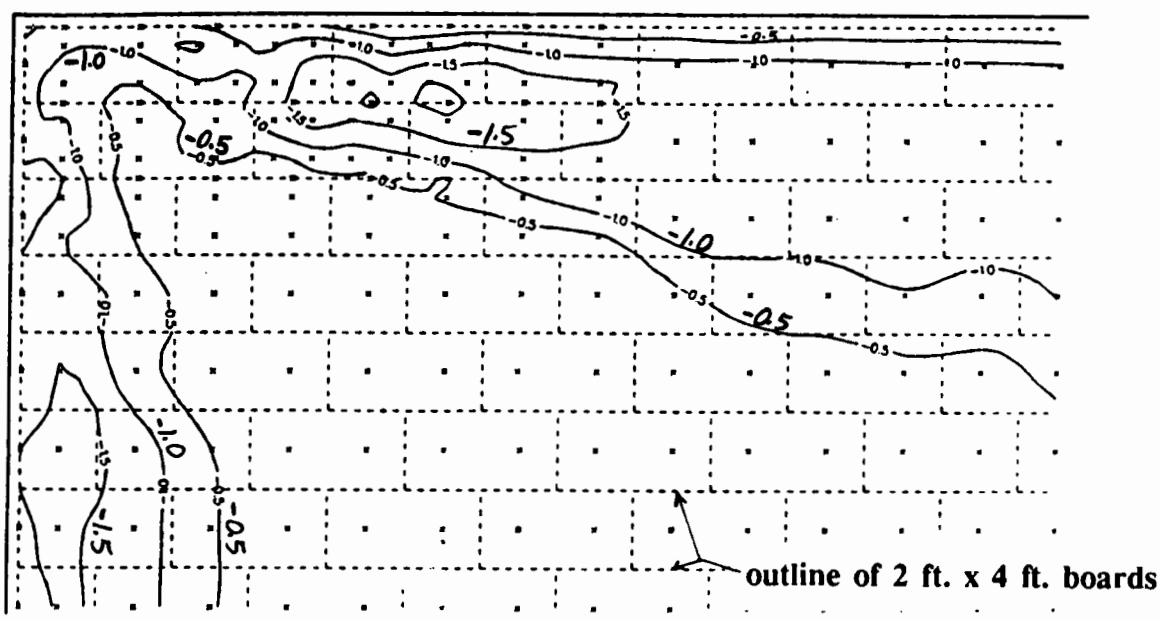


Figure 5. Mean Pressure Coefficient Distribution Underneath Loose-Laid Interlocking Board System, Low-Rise Building, h_p/h = 0.027

boards. As a result, a pressure distribution is established underneath the layer of boards and this distribution is broadly similar to the exterior distribution. The same behavior was observed with layers of model pavers.

By virtue of the process outlined above, pressures under system elements such as boards or pavers tend to become equal to exterior pressures. It has been found that the equalization process occurs very rapidly and can easily keep pace with exterior pressure fluctuations caused by the gustiness of the wind [5].

Although the pressure distributions underneath the system elements are broadly similar to the exterior distributions, they are not identical. That is, equalization is imperfect and there is generally some pressure difference across any given board or paver. In the case of some elements the pressure difference is in the uplifting direction and can become sufficiently large at high wind speeds to dislodge the element. It should, however, be noted that, because of the equalization process, the pressure differences across elements placed above the membrane are generally much less than the pressure difference between the building interior and exterior; most of the latter difference is carried by the roof deck itself. Consequently, relatively light loose-laid boards or pavers can withstand quite high wind speeds without failure.

The flow through the joints and underneath the pavers or boards will normally be dominated by viscous or frictional effects. Consequently the pressure variation under the pavers or boards should be governed by Laplace's equation, for the same reasons that this equation governs groundwater flow. Laplace's equation is a linear partial differential equation. The differences between exterior and under-element pressures will be greatest where the exterior pressure distribution is most non-linear over an element. This is illustrated by Fig. 6. In practice, pressure variation under the elements is not as simple as that suggested in the figure, since complexities result from three-dimensionality and non-uniformity of resistance to flow. Nevertheless, the concept remains valid, and the elements most susceptible to failure are those over which the exterior pressure distribution is most non-linear. Figure 7 shows experimental data that support Fig. 6.

Winds encountered in practice are quite capable of dislodging loose-laid boards or pavers. Even 2 ft. x 2 ft. x 2-in.–thick concrete pavers, weighing about 100 lb., can be dislodged by winds of about 125 mph gust speed.

A design method for board/paver uplift has been proposed [6]. It, too, is based on wind tunnel data from reduced-scale tests. There has been no opportunity for extensive comparisons with field experience and the method must be regarded as preliminary at this time. It can be said, however, that field experience to date indicates that the wind tunnel results are quite valid.

3. POSSIBLE NEW APPROACHES TO APPROVAL TESTING

Approval authorities are understandably reluctant to base approval entirely on reduced-scale wind-tunnel test results. Nevertheless, current approval tests simply apply a uniform static differential pressure across a sample of the roofing system and do not simulate the phenomena outlined above that are responsible for stone scour and paver/board uplift. They are thus inappropriate for testing of ballasted systems. A new test method is highly desirable but will be difficult to find.

The ideal approval-test apparatus would generate a high velocity stream of air and would produce a flow pattern similar to that which actually occurs on a roof (see Fig. 1).

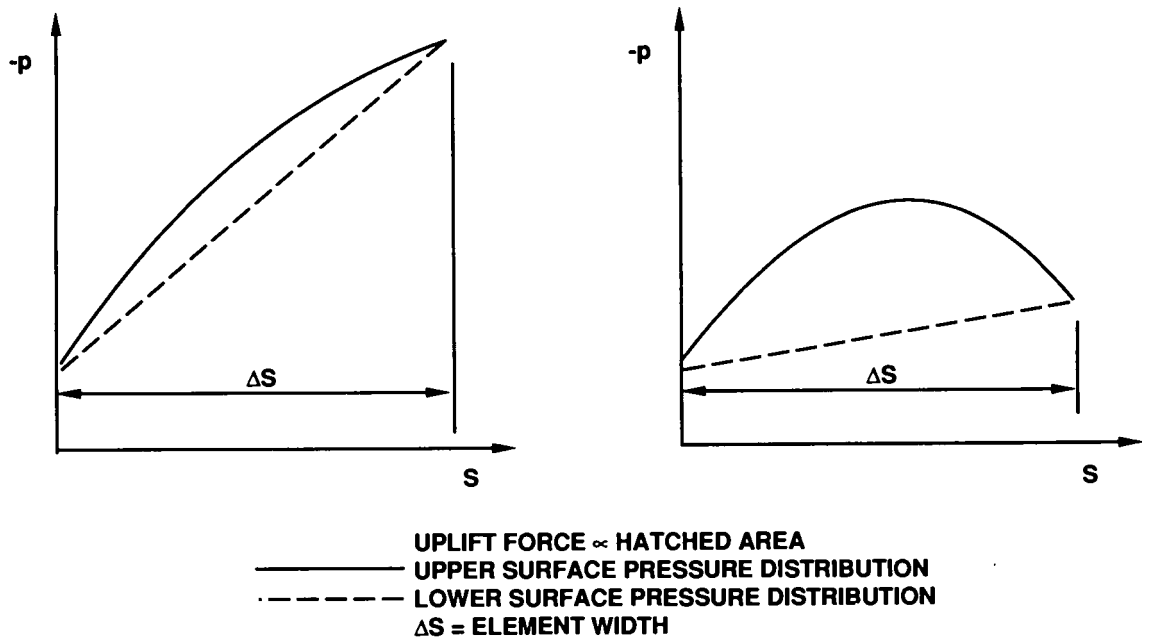


Figure 6. Effect of exterior pressure distribution on the uplift force on a roof element.

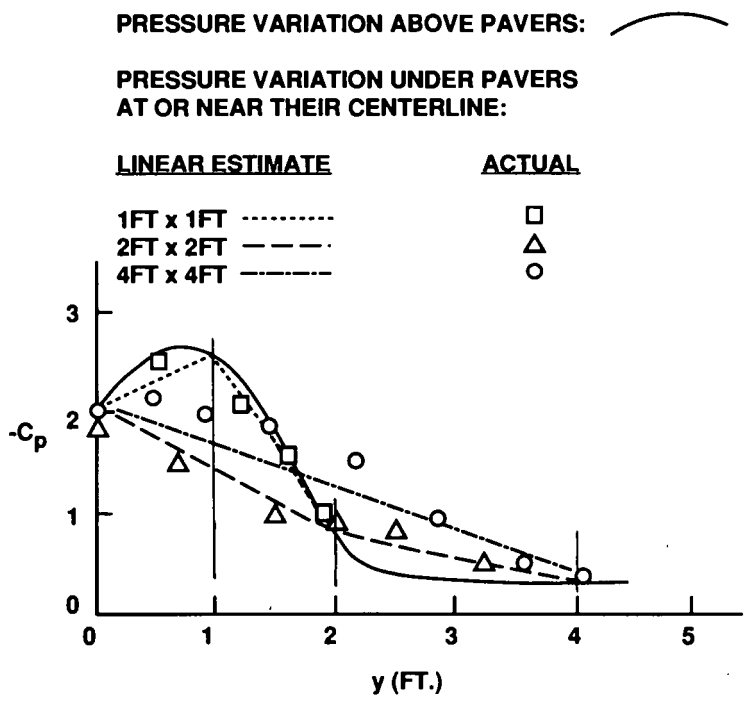


Figure 7. Pressure variation above and under pavers of variouss sizes (low-rise building, $h_p/h = 0.027$).

If the flow pattern is similar, pressure patterns and other aerodynamic effects would also be similar to those which actually occur on roofs. The air stream should be big enough that a reasonably large sample of a full size roofing system could be tested in it. For example, if a system comprised of 2 ft. by 4 ft. interlocking boards were to be tested, Fig. 5 suggests that a sample size of at least 30 ft. by 30 ft. would be required. This would be necessary to ensure that both aerodynamic and mechanical effects in the crucial upwind-corner region of a rooftop are reasonably well represented.

All this is possible in principle. However, the required wind tunnel or test rig would be very large and costly. If a 30 ft. by 30 ft. sample is to be tested, the air stream would have to have roughly similar cross-section dimensions. If maximum wind speed is to be, say, 150 mph, the power requirement would be approximately 20,000 horsepower.

A number of potential approaches to approval testing come to mind:

i) full-scale rig or very large wind tunnel,
ii) reduced scale plus full scale wind tunnel tests,
iii) reduced-scale wind tunnel testing plus "dynamic" testing, and
iv) field testing.

Approach (i) would involve building a large, powerful, and costly test rig. An alternative would be to build an insert that would produce a flow pattern similar to that in Fig. 1 in an existing, very large wind tunnel. The NRCC 30 ft. by 30 ft. tunnel might be suitable. If this approach is adopted, great care will have to be exercised to ensure that behavior of the partial system that is tested is representative of actual overall system behavior.

Approach (ii) would make use of reduced-scale tests to investigate overall system behavior together with testing rather small portions of the full-scale system to investigate for local or detailed effects. Probably some analysis would be required to relate the two sets of tests.

Approach (iii) would also use reduced-scale tests to investigate overall system behavior. Special rigs would then be used to further investigate local or detailed effects, using full-scale specimens. This approach is gaining favor in Europe.

Approach (iv) involves monitoring performance of complete full-scale systems installed on buildings in the field. This approach is straightforward in concept, but, even if favorable test locations are chosen, one has little or no control over test conditions. Results are therefore notoriously slow in coming.

It should be noted that only the "dynamic" testing of approach (iii) is suitable for testing for fatigue, fastener backout, and the like.

4. CONCLUSIONS

Wind tunnel testing has revealed much about the behavior of ballasted roof systems in high winds.

Three failure mechanisms can result in wind damage to ballasted systems: membrane ballooning, stone scour, and paver/board uplift.

Approval test methods should simulate the phenomena involved in these failure mechanisms.

Identification of an approval test method suitable for ballasted systems will require considerable engineering effort.

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Dynamic Testing

WHY IS DYNAMIC TESTING NEEDED?

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Sarnafil, Inc.

Single-ply membranes were first extensively introduced to the United States roofing market in the early seventies and have steadily grown in popularity. Most industry reports show that single-ply membranes have more than 50% of the low-sloped roofing market. Single-ply roof systems are installed in a number of different ways, one of which is mechanically attached. It seems that each manufacturer has a different technique or method of attachment. Roofing systems have been primarily tested and evaluated in the United States with static positive pressure testing. Static testing exposes the roof system to incremental uniform presures. For example, the test procedure may start at 50 psf of pressure for one minute and increase in increments of 15 psf until failure.

Static testing may have evaluated the performance of fully adhered built-up roof systems adequately, but it does not expose the system to cyclic loading that is developed when the wind moves across a mechanically attached roof system.

Dynamic testing refers to tests whereby the roof assembly is exposed to vertical differential pressures that vary with time and intensity. This kind of testing causes the membrane to lift and bellow under cyclic loading (unless an air retarder is used). Dynamic testing has been widely used in Europe for many years to evaluate roof systems. It should incorporate simulation of wind load fluctuations such as wind gusts. Dynamic testing is presently under consideration as the standard wind uplift test procedure of the UEAtc (European Union of Agrémont).

Now why is dynamic testing needed? Dynamic testing is needed:

- to establish realistic fastener loads to prevent backout or pullout due to excessive fastener loading;
- to establish realistic fastener loads for various deck types;
- to account for fatigue behavior of fasteners, deck, and attachment systems;
- to evaluate substrate behavior (critical with lap attached systems);
- to evaluate the membrane seams; and
- to account for decreasing membrane strength with increasing temperatures (important for temperature susceptible materials).

Wind load cycle. The wind load cycle should be based on meteorological data. The wind velocity pressure related to the design wind velocity pressure should be plotted versus the number of occurrences for the desired return period.

The initial high-frequency lower load fluctuations should evaluate the fastener for potential to back out. The maximum load cycle should evaluate the system for resistance to fatigue and deformation.

Can dynamic testing be used to test all roof systems? Dynamic testing appears to be the best method of evaluating the long-term performance of mechanically attached systems. Dynamic testing also seems

appropriate for testing some adhered and partially adhered systems.

SUMMARY OF DYNAMIC TESTING RECOMMENDATIONS FROM TASK GROUPS

1. Incorporate dynamic testing for evaluating mechanically attached systems.

    - Look closely at European procedures.
    - Size of apparatus should be sufficient to test all roof systems.
    - The test edge attachment should not effect test results.
    - A procedure should be available to test roof perimeter edge details.

2. Fastener manufacturers should provide realistic allowable static and dynamic fastener loads per deck type.

3. Uplift forces should be adjusted when building pressure is positive.

4. Adjust safety factors for fastener loading due to variable workmanship and deck deficiencies.

HOW WE USE TEST RESULTS

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Carlisle SynTec Systems

With the advent of a new test method that will supply performance data on a roof system, how are we to apply these test results to roof designs? In studying this question we should start with the procedures that are used today.

The various code bodies supply guidance to determine the loads that are applied to routine roof designs. By locating the building on the wind map and choosing the mean recurrence interval to which you wish to design (50 or 100 years), the loads on the roof structure can be calculated for a known roof height. The code manuals supply details for determining the loads for the field, perimeter, and corner areas of the roof.

For unique structures, the wind tunnel can be used to supply this information.

The next step is the roof system performance. The present "adopted standard" the industry uses is Factory Mutual's (FM's) test method 4470. The roof assembly is placed into the test chamber and stressed by air pressure supplied from underneath the assembly in 15 psf increments. The minimum threshold of 60 psf must be achieved with a second threshold of 90 psf noted for systems that surpass this load level.

Now that the system has been tested, how do we apply these results to the design loads calculated above? FM has supplied documents 1-28 and 1-29 that give recommendations on how to accomplish this task. Document 1-28 supplies charts that relate the design load to the system test results, and both 1-28 and 1-29 show how to apply the results to the perimeter and corner areas of the roof.

The key to the chart is that for the field of the roof requiring design loads of up to 30 psf, the system used must surpass a test load of 60 psf. For values up to 45 psf, systems must have passed 90 psf. For applications over 45 psf, the system must have surpassed 90 psf and be used in conjunction with a concrete deck. By following these charts, a safety factor of two is applied to the field area of the roof design. The justification for this is that the testing is done in a lab, under controlled conditions, keeping errors to a minimum, while in the field the chance of an installation error is much greater.

For I-60 systems, the perimeter uses the field system putting the test value equal to the code design requirements, and the corner requires the design factor of 1.5 over the field, again matching the code design load one for one.

The I-90 system is basically the same except for the perimeter area using the corner design giving a 1.5 safety factor over code design load for the area.

The question to be asked is whether the field performance seen today is the result of this over-design. Have the inaccuracies of the test been compensated for by the application of these factors? This system has not always proven adequate, for in 1982 FM ruled that the

first layer of insulation is to be mechanically fastened instead of asphalt attached to steel decking. This was in response to field data and not results seen in the test method. But, even so, this test method and design guide have given the industry a tool by which to judge field performance.

Now we are contemplating a new test method to evaluate roof systems. The conference is directing the industry towards dynamic cycling testing with a table size adjustment to keep edge effect to a minimum. First, let's talk a little about the test methodology. In reviewing methods from around the world, there are two methodologies. One methodology is to test until failure, and the other is testing to a design load.

In the methodology of testing until failure, a roof system is normally stressed in incremental increases in load (either by positive, negative, or combination of pressures), either by a single load or a type of dynamic loading, until the system fails. With this type of testing the system's ultimate strength is known.

With the methodology of testing to a design load, a roof design load is determined by one of the code methods, which is then used to test the system. The dynamic loading for that wind condition is simulated for a 50- or 100-year mean recurrence interval. The roof system must not fail during the test to be considered an acceptable system. The disadvantage of this methodology is that the roof system maximum capability is not determined, and if a failure does occur at the test load, retesting is required. For these reasons the first methodology is preferred.

It is difficult to address how to actually use the test data, since the test method has not been finalized and one only has ten minutes to discuss the subject. So I will end my part by discussing several questions that will need to be addressed as this test method is finalized. These questions are:

1. Do we test for each design load, say, in ten pound increments, or do we test for ranges of loads up to failure? The wind map shows seven wind zones (six for 50-year occurrence). When this is taken across the multitude of roof heights, a substantial number of loads are calculated. As shown in the 1-28 chart, should the various roof systems be rated for each 10-pound load increment from 20 to 90 pounds of load, or do you group the data and have increments such as 30 and 45, etc.? In the case where systems are rated in, say, 10-pound increments, you can generate a ratings war. One group would say that their system went to 130 psf while their competition's only went to 120 psf. Our laboratory testing is not sophisticated enough to say that 10 pounds will make much difference in the field. By grouping the results in ranges some of this problem is taken away.

2. Is the test conducted to the design loads or is a safety factor applied to the requirements of the test method? History would say that it has been an advantage to have the safety factor built into the test.

3. The next question is correlation of the new test method. We are looking at changing the table size as well as going to dynamic cycle testing. How do the new test results relate to the old test results and field data?

   In my own experience, table size will have a bigger impact on the test results than the dynamic cycle testing. Maybe the larger table size makes the test more accurate; therefore, the

safety factor is not needed or a smaller one could be applied. This would still account for variables in material strength and for minor construction variations.

4. And lastly, who will pull this all together? FM did it in the past. Will FM, ASTM, or an industrial consortium do this? It should be remembered that some of the "adoption" process is driven by the ability to make "do business" type of decisions. A champion is needed to keep the momentum going on this project after the conference so that this work will lead to a test method that the industry will adopt.

HOW SAMPLE SIZE AFFECTS FACTORY MUTUAL RESULTS

George A. Smith
Factory Mutual Research Corporation

INTRODUCTION

Both of the tests to be discussed are static test procedures and will not necessarily reflect performance as evaluated by a dynamic test analysis. However, sample size is of major importance whether static or dynamic test procedures are used.

Over the past two to three years, Factory Mutual Research Corporation (FMRC) has been asked to test and approve roof assemblies that could not be adequately evaluated by a test method utilizing a sample size of 5 ft. by 9 ft. Therefore, a new, larger test frame was built. It measures 12 ft. by 24 ft., and although it is a "static" test identical to the original test (5 ft. by 24 ft.) it allows FMRC to conduct analyses of assemblies which could never be evaluated by a sample size of 5 ft. by 9 ft. The equipment needed for this procedure was purchased and standardized by a joint effort partly funded by FMRC and partly funded by one of our approved manufacturers.

The new 12 ft. by 24 ft. test procedure is used to evaluate:

1. mechanically attached single plies with fastener spacing exceeding the limits of the 5 ft. by 9 ft. test, i.e., batten-attached assemblies with battens positioned greater than 7 ft. on center, grid-affixed assemblies with fasteners spaced greater than 3 ft. by 2 ft.-6 in.;
2. 4 ft. by 8 ft., 4 ft. by 8 ft.-6 in., and 3 ft. by 8 ft.-6 in. insulation board sizes;
3. air/vapor retarder effectiveness from an air infiltration standpoint, and how much enhancement might be obtained from any given air retarder; and
4. metal standing seam roof assemblies.

STATIC VS DYNAMIC

From the beginning in the United States, most approval and testing agencies have used test procedures originally designed to evaluate built up roof (BUR) construction. These procedures have worked well for some constructions but not so well for others.

Air flow over a roof and vertical pressure on the roof are shown schematically in Fig. 1. The forces working on an assembly are made up of two components. One (60%) is on the exterior due to increased air velocity over the surface of the assembly. The uplift force will vary depending on the portion of the roof being analyzed. It will be highest at the corners and perimeter and lower in the field of the roof. The second (40%), from the interior of the building, is due to an infiltration through cracks, windows, and doors. It will be the same on all parts of the roof, corners, edges, and field. In addition, pressurization can occur from HVAC systems.

The currently used static uplift test procedures are adequate for:

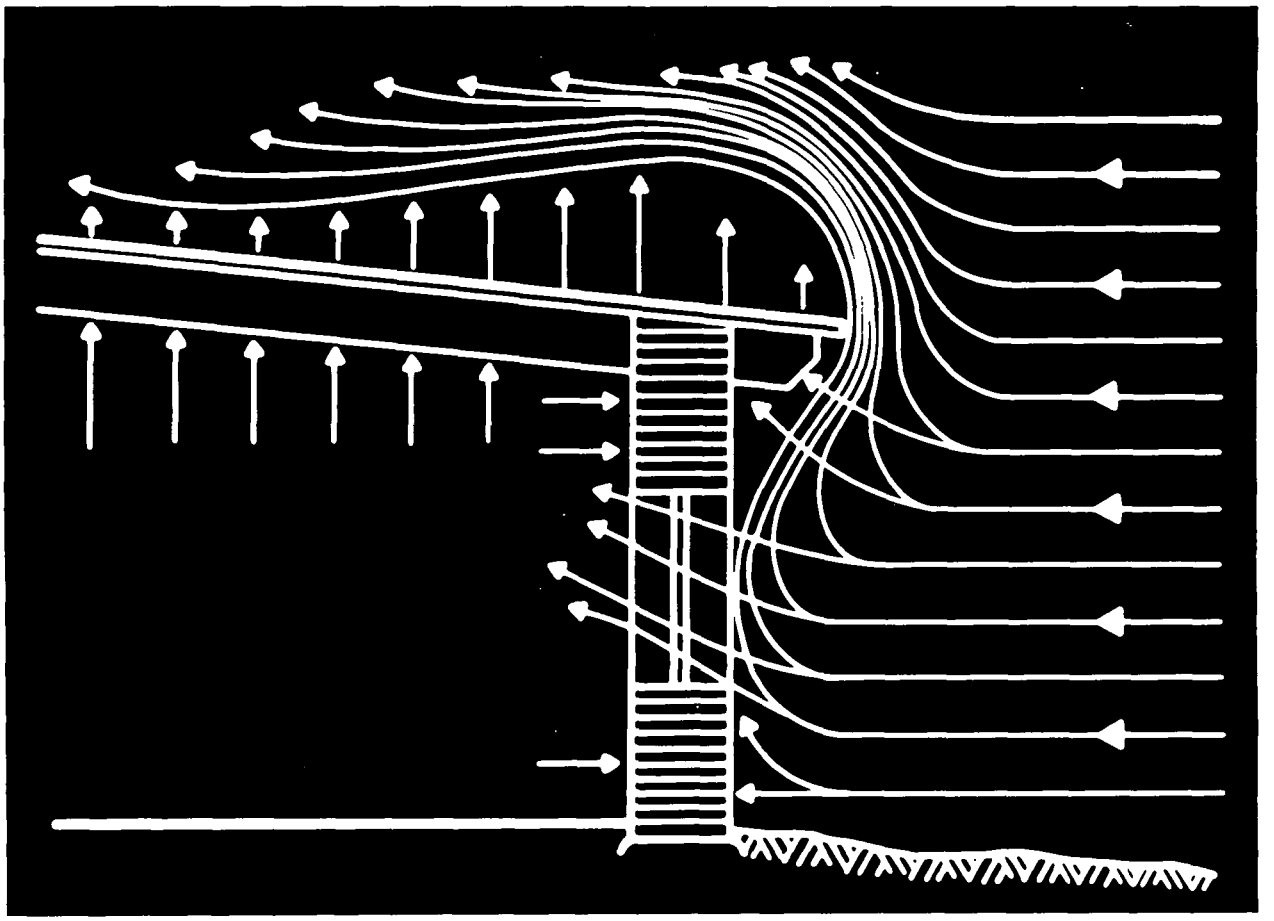


Figure 1. Air flow over roof and vertical pressure on roof.

1. BUR construction,
2. most fully adhered single plies,
3. some partially adhered single plies, and
4. some mechanically attached single plies.

They utilize a system of introducing air to the underside, evacuating air from the topside, or some combination of both.

The standard 5 ft. by 9 ft. FMRC test apparatus includes a perimeter gasket (Fig. 2), a pressure box onto which the sample is clamped at the perimeter (Fig. 3), an air compressor, a large tube for air supply, and a manometer to measure the incremental pressure increase.

Air is introduced at pre-established standard rates starting at 30 psf, which is maintained for one full minute. The pressure is increased to 45 and 60 psf and held for one minute at each increment. This schedule is increased in increments of 15 psf every minute until failure occurs. Therefore, the pressure is increased to 75 psf, then 90 psf, and held for one minute at each increment. If an assembly maintains the 60 psf pressure level for a minute and meets all other approval

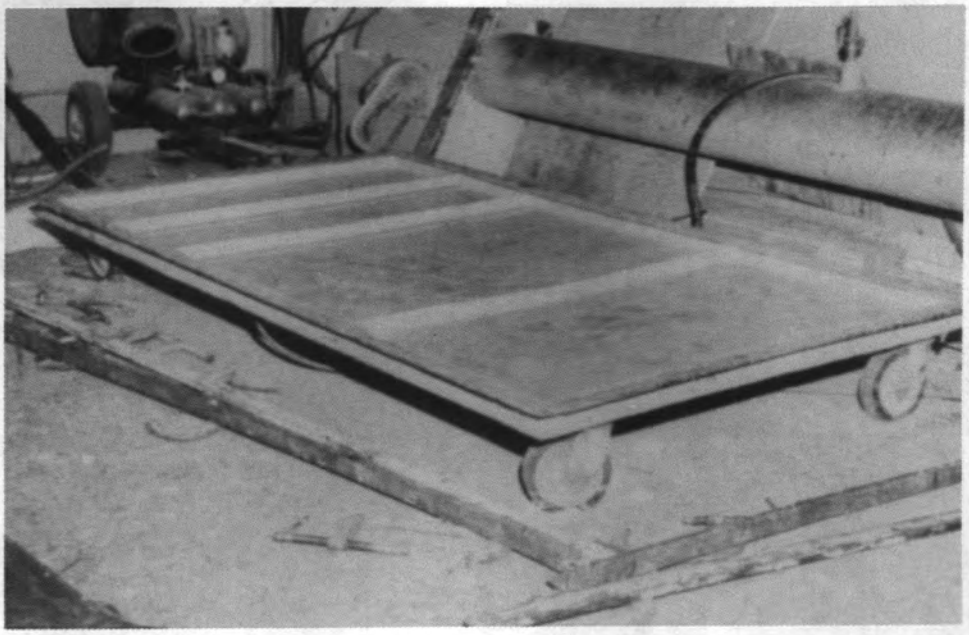


Figure 2. Standard FMRC test apparatus.

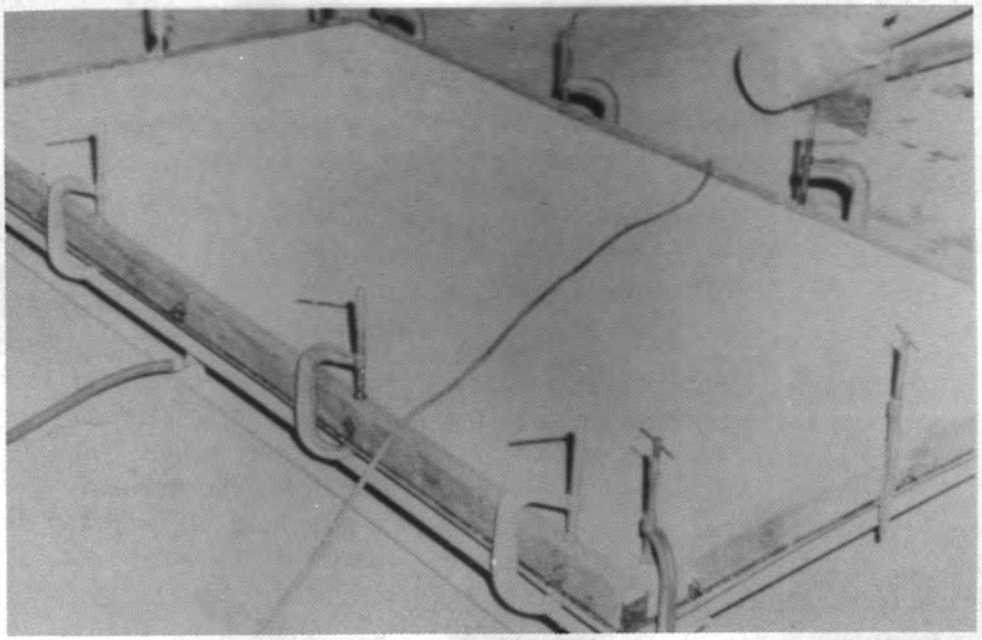


Figure 3. Pressure box onto which the sample is clamped at the perimeter.

requirements, it can obtain a Class I-60 rating. If it maintains the 90 psf pressure level for one minute, it can obtain a Class I-90 approval.

The FMRC 12 by 24 ft. simulated wind uplift test, shown in Fig. 4, utilizes the same procedure. It includes a gasketed perimeter pressure box onto which the sample is placed and clamped, an air compressor, an inlet line, and a manometer connection. Except for size, the equipment and procedure are identical for the 5 x 9 ft. and the 12 by 24 ft. tests.

Test results from a nonreinforced ethylene-propylene terpolymer (EPDM) roof cover, batten-attached 7 ft. on center at 30 psf are shown in Fig. 5. The deflection of the membrane is approximately 24–30 in. off the substrate. When the pressure is increased to 45 psf, the deflection becomes 5 ft., Fig. 6. Finally, failure of the batten at centerline of sample occurs in Fig. 7. "Bubble" height at failure is approximately 10 ft. off the substrate.

Failure of a nonreinforced membrane is shown in Fig. 8. The membrane, with intermittent attachment (grid affixed, 4 ft. by ft. pattern) failed at 15 psf (while testing for leaks). Of interest is that this same construction can be fabricated to withstand 90–105 psf by incorporating an air retarder within the construction.

Fig. 9 shows a reinforced thermoplastic loaded at 90 psf. Bubble height is approximately 9–12 in. Battens are positioned at 10 ft.on center.

With about two-thirds of our research completed in comparing the 5 ft. by 9 ft. test to the 12 ft. by 24 ft. test, some preliminary conclusions have been drawn:

1. The performance of a BUR assembly tested on the 5 by 9 ft. test will be approximately one level above the performance obtained on the 12 ft. by 24 ft. test, i.e., 105 psf vs 90 psf (respectively).
2. The performance of a fully adhered single-ply thermoplastic or thermoset product test on the 5 by 9 ft. test will be approximately three levels above the performance obtained on the 12 ft. by 24 ft. test, i.e., 105 psf vs 60 psf (respectively).
3. The performance of a given batten-attached single-ply thermoset product test on the 5 by 9 ft. test will be approximately three levels above the performance obtained on the 12 ft. by 24 ft. test, i.e., 75 psf vs 30 pst (respectively).
4. The performance of a given 4 by 8 ft. insulation with an air retarder and mechanically attached nonreinforced single ply tested on the 5 by 9 ft. test will be approximately four levels above the performance obtained on the 12 by 24 ft. test, i.e., 135 psf vs 75 psf (respectively).
5. The difference in performance is primarily due to edge effect. The smaller the sample the more the clamping action of the edge will affect test results. With some small test specimens the performance is really a measure of how well the sample can be clamped in place.

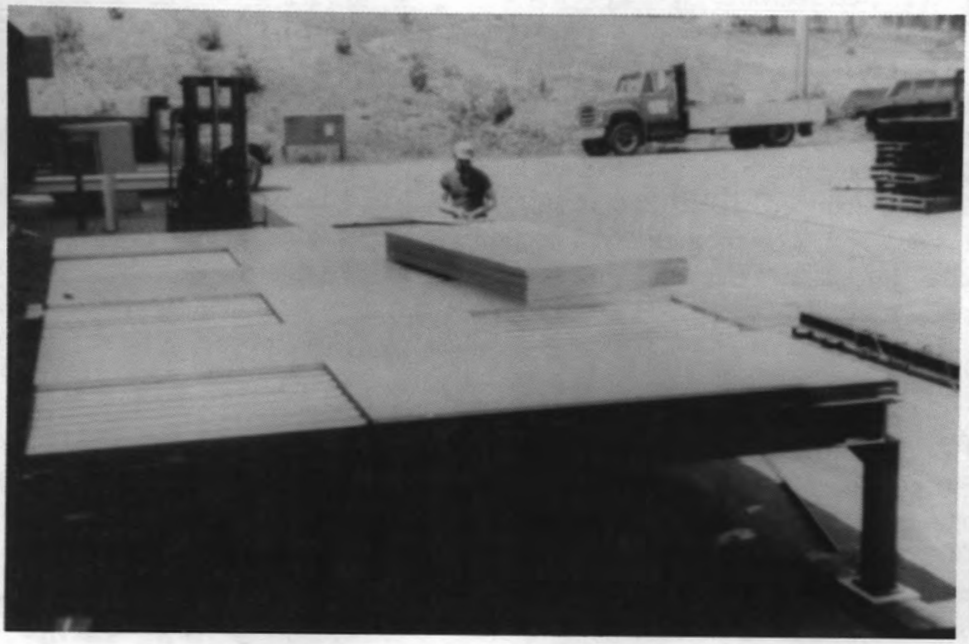


Figure 4. FMRC 12 by 24 ft. simulated wind uplift test.

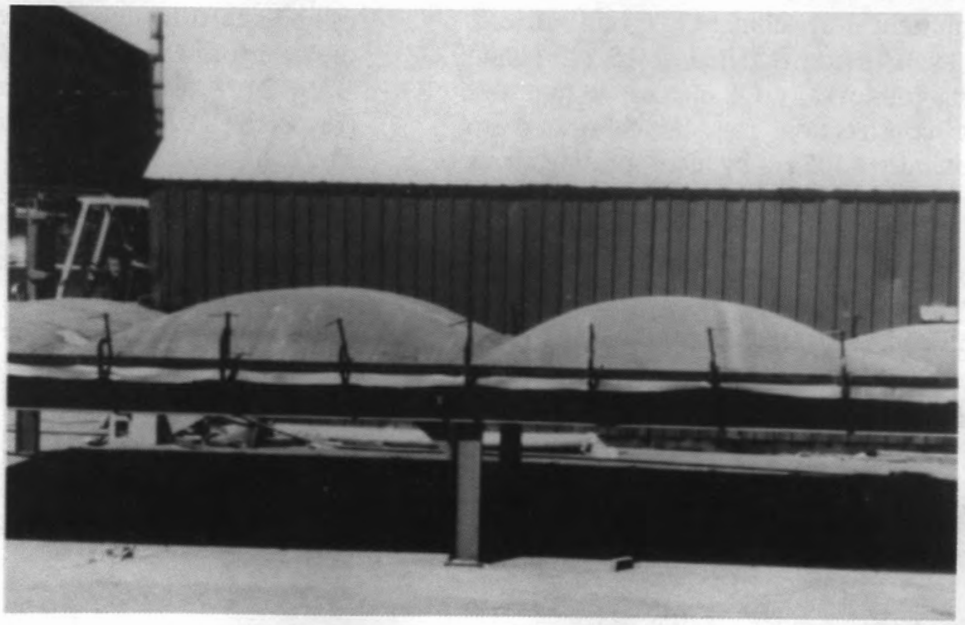


Figure 5. Test results from a nonreinforced ethylene-propylene terpolymer (EPDM) roof cover, batten-attached 7 ft. on center at 30 psf.

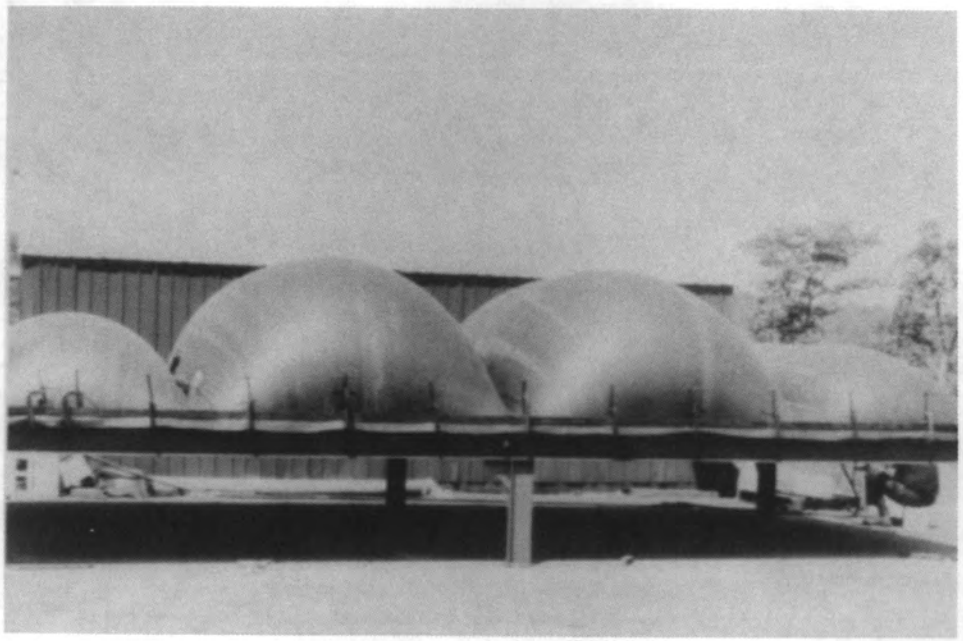


Figure 6. Test results from a nonreinforced ethylene-propylene terpolymer (EPDM) roof cover, batten-attached 7 ft. on center at 45 psf.

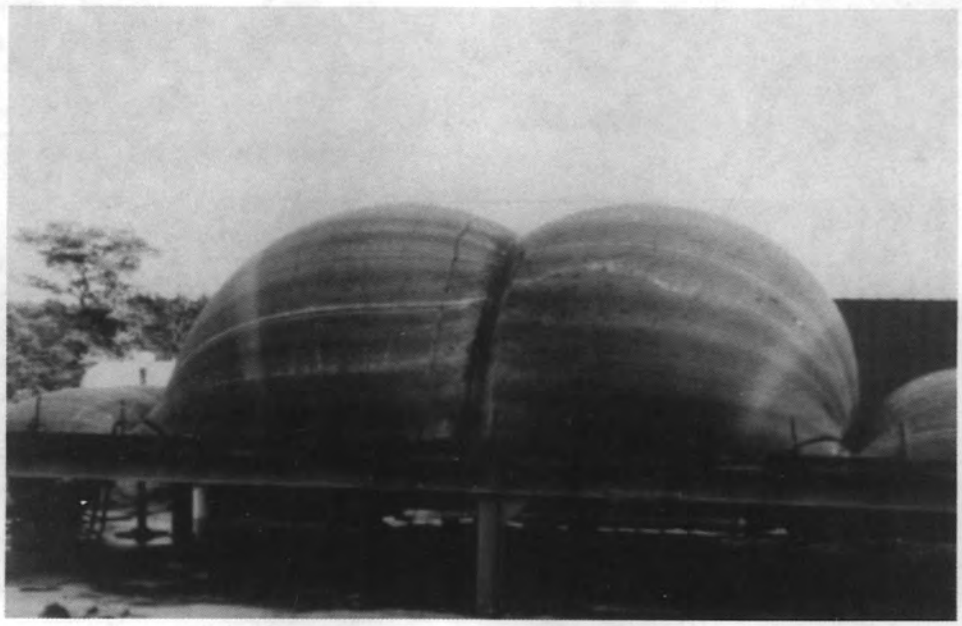


Figure 7. Failure of the batten at centerline of sample.

Figure 8. Failure of a nonreinforced membrane.

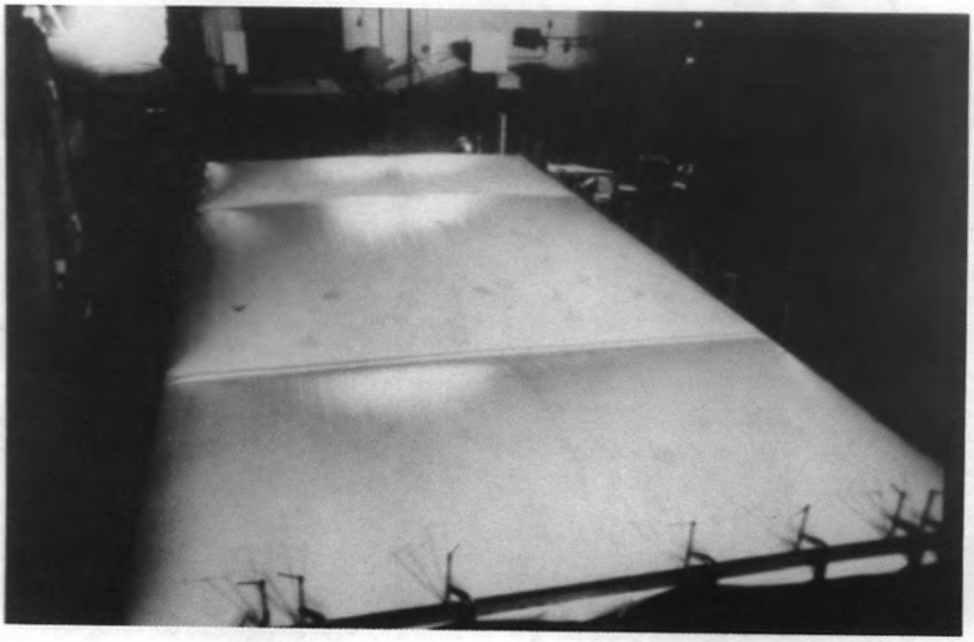


Figure 9. Reinforced thermoplastic loaded at 90 psf, battens at 10 ft. on center, bubble height about 9–12 in.

Ballasted Roofing Systems

DEMYSTIFYING BALLASTED ROOFING SYSTEMS

David L. Roodvoets

Task Group Members: Richard Kind (Carlton University), Kenneth Rhodes (Underwriters Laboratory), Jorge Pardo (Innovative Design Research, Div. NMRC), Lee Ann Lankton (Firestone Building Products), Tom Phalen (Northeastern University), David L. Roodvoets (Dow Chemical Company)

Our team gave four presentations. Summaries of Ken Rhodes' presentation, Lee Ann Lankton's presentation, and Jorge Pardo's presentation follow.

Our conclusions were:

- Extensive wind tunnel data exists on the performance of ballasted systems.
- Field experience has confirmed wind tunnel predictions of ballasted performance.
- Correlations of wind tunnel and field performance have not been done on an extensive basis or on more than a very few modeled buildings. However, that correlation has been quite satisfactory.
- Alternate or new ballast design systems cannot be readily tested.

Our recommendations are:

- Field performance data should be obtained, cataloged, and investigated by an independent organization. This catalog should be similar to the catalog of chemical analysis. It should include a variety of building shapes, building heights, parapet heights, and topographies.
- A full-scale field experiment with ballasted roofing systems should be developed and a system to correlate the data with wind tunnel data should be established.
- A method or program needs to be developed to convince the code authorities that wind tunnel evaluation of roofing systems can be as effective and reliable as wind tunnel testing of aircraft. This would provide the basis to effectively evaluate new and novel ballasting systems.
- Air infiltration studies should be carried further and deck-systems rating for air infiltration potential should be established.
- Stone size factor and wind performance should be further evaluated.

BALLASTED SYSTEMS: DEMYSTIFYING UPLIFT PERFORMANCE

Ken Rhodes
Underwriters Laboratories

MYTHS

1. Pavers lift only as a result of pressure exerted from under a membrane.

2. Ballast systems only resist uplift pressures equivalent to the weight of the ballast.

3. Ballast systems cannot be evaluated by laboratory differential pressure testing.

There has been a good deal of discussion and research regarding the dynamic effects of wind as it flows across, swirls, and impacts the ballast material. Wind tunnels have been used to develop data with respect to the wind velocity and potential for scour or other wind-related movement. Based on the type of ballast and perimeter attachment, it is possible to resist such movement through wind velocities ranging from 80 to 100 mph. There is sufficient evidence and field experience to substantiate that ballasted systems can and do perform under these critical circumstances and beyond. Based on ANSI A58.1, this could translate into uplift pressures up to 40 psf and beyond depending on building height and topography. Yet most ballast systems are 10 psf and sometimes less.

To understand these phenomena we need to first realize that the research and the evaluation of wind-related movement of the ballast only tells part of the story. It is also necessary to consider the effects of wind as it impacts on a building structure. For any structure in an air flow there is a resultant positive pressure developed on the vertical windward side of the structure as well as a negative (low pressure) uplift on the roof and leeward side of the structure. Positive internal pressures are also introduced through the impact of the wind moving through openings in the structure. Through use of ANSI A58.1 these pressure differentials (uplift force) can be quantified based on a given wind velocity. It is the ability of the roof system to withstand these forces that can be quantified or compared based on laboratory-scale differential pressure testing such as Factory Mutual's 4470, Underwriters Laboratories, Inc. (ULI) UL 580, ULI's Subject 1897, and ASTM E330, as well as European test procedures developed by H. J. Gerhardt, N. Cook (BRERWOLF), and E. M. Paulsen. To evaluate roof systems these tests utilize either positive pressure underneath, negative pressure above, or a combination of the two. Each creates a differential pressure across the roofing system and each will provide similar or identical results so long as the test presentations are engineered so that the uplift pressure is focused on the proper portion of the roof system and in the proper proportion. The effects of edge restraint also need to be factored into the evaluation.

These tests are not necessarily related to the ballast resistance to movement due

to wind and certainly do not provide such information.

The terms commonly used to describe the uplift forces, such as negative or suction, are misleading because these leave one with a false sense of reality as to just what is happening. Perhaps a better way is to relate the uplift force to pressure differential or low versus high pressure. One analogy to provide a more directed thought process is the very familiar event of a balloon rising until it expands and bursts. The basic pressure from within and the reduction in surrounding air pressure causes the failure. If we could raise a building several thousand feet in the air, we could create the same differential uplift pressure effect on the roof, which is analogous to the effect created with high velocity wind.

This thought process permits a more directed vantage point from which to review examples of how design of a roof assembly affects the performance potential of ballasted roofing systems.

Using design concepts such as air retarders, sealed joints in the deck, and perimeter seals of the roof membrane can transfer all or a portion of the uplift load to various components of the roof system, the roof deck, and ultimately the building structure. For some systems it is necessary to have a test apparatus that can develop both high pressure on the underside and low pressure on the topside in order to distribute the uplift loading in proper proportions to the various components of the roofing system as would be experienced in the real constructions.

Tests conducted at ULI on roof systems consisting of an uninsulated single-ply, loose-laid, ballasted (10 psf) membrane over plywood deck have demonstrated that uplift pressures can be raised to nearly the limit of the plywood decking. Insulated assemblies as described above, due to increased air infiltrations, will withstand considerably less uplift pressures unless the plywood deck joints are sealed. With sealed deck joints, the roof system again will withstand uplift pressures essentially as would be permitted by the plywood deck attachment.

Experimentation at ULI with insulated, loose-laid, ballasted membrane roof systems over metal deck have also demonstrated that these systems can withstand 60 psf short-term loadings without excessive movement of the ballast.

In summary, ballasted roof systems, as well as mechanically attached and fully adhered roof systems, can be designed to withstand and to be tested for their resistance to uplift pressures. If there is one thought that should be retained from the discussions in this entire workshop, it is that the testing and evaluation of a given roof assembly also needs to be engineered and designed.

CONSIDERATIONS FOR DESIGN OF GRAVEL BALLASTED SYSTEMS

Lee Ann Lankton
Firestone Building Products Company

When designing the wind resistance of loose-laid ballasted systems there are two primary issues to consider:

1. differential pressure created by the air film beneath the membrane in relation to the negative pressure created by the wind as it flows over the surface of the roof, and
2. scouring of the gravel ballast. In localized areas of high wind force, the stone can be displaced as a result of the force that is exerted on it.

As the wind hits the side of the building it is broken into two components: one that travels down the face of the structure and one that travels up the face of the structure. The downward force is transferred to the ground or to a lower roof. The component that travels up the face of the wall combines with the wind force that is traveling across the surface of the roof to create the negative pressures at the corners and edges of the roof.

The most critical roof loading occurs when the wind direction is at a 45° angle to the building corner; these forces create the critical corner vortexes, which are like small tornadoes on the surface of the roof. The left-hand vortex has a clockwise flow, whereas the right hand vortex has a counterclockwise flow. The net result is that the stones experience wind flows or forces nearly perpendicular to the main wind flow over the roof. It is these forces that create the phenomenon of gravel scour.

In 1976, Dr. R. J. Kind and Dr. R. L. Wardlaw conducted a series of wind tunnel tests to determine a method for estimating the rooftop wind speeds that are required to cause scour or blowoff of gravel ballast. The results of this research are presented in the 1976 publication, "Design of Rooftops Against Gravel Blow-off," by Dr. R. J. Kind and Dr. R. L. Wardlaw. This publication outlines the parameters that affect the performance of rooftop gravel ballast and provides a method for calculation of ballast stability at rooftop wind speeds.

The Kind-Wardlaw research determined that the following parameters affect the performance of rooftop gravel ballast:

Building Height: The speed of the wind increases with increasing height above the surface of the ground. If a building is built on an isolated hill, the height of the hill should be considered when establishing the overall height for ballast performance calculations.

Surrounding Terrain: The rate of the increase in wind speed for the increasing height is dependent on the nature of the surrounding terrain. The rate is lower over rough surfaces than over smooth surfaces because rough surfaces tend to break up the wind flow.

Building Shape: Rooftop gravel performance is dependent on the classification of building type—low rise, medium rise, or high rise. This classification is based on the relationship of the building height to width and length. Buildings are classified as low rise when the height is less than the length and width. Buildings are classified as medium rise when the height is approximately equal to the length and width. Buildings are classified as high rise when the height is greater than the length and width. The Kind-Wardlaw study focused on low rise and high rise with some direction given for interpolation when medium rise situations are encountered.

Parapet Height: Parapets serve to deflect the wind away from the roof surface; the higher the parapet the greater the deflection, which results in lower rooftop pressures.

Gravel Size: The nominal size of the gravel is a significant factor for determining its performance as rooftop ballast. The nominal size is critical because the smallest stones shift to the bottom, leaving the nominal or larger-size stones to interact with the wind. Stone scour is not reduced by adding stone weight, but can be reduced by using a stone gradation incorporating a larger nominal size.

Using the parameters outlined above, the Kind-Wardlaw study developed the following equations to predict three critical gust wind speeds at the roof level:

V_{c1} - The gust speed at which one or more stones are first moved an appreciable distance.

V_{c2} - The gust speed above which scouring of stones would continue more or less indefinitely if the wind speed was maintained.

V_{c3} - The gust speed above which an appreciable number of stones leave the roof by going over the upstream parapet.

$$V_{c1} = V_{c1\,Ref} * F_s * F_{p1,2} \ ,$$

$$V_{c2} = V_{c2\,Ref} * F_s * F_{p1,2} \ , \text{ and}$$

$$V_{c3} = V_{c3\,Ref} * F_s * F_{p3} \ ,$$

where

$V_{c\,Ref}$—critical wind speeds that have been developed from wind tunnel testing and tabulated based on a reference gravel size, parapet height, and building configuration;

F_s—gravel size factor;

$F_{p1,2}$ & F_{p3}—factors to account for parapet height and building configuration.

Meteorological stations in the United States typically report wind speeds as "fastest mile speed" at 10 meters (33 ft) above the ground. Therefore, most building code requirements in the U.S. are based on these reporting parameters.

In order to evaluate the appropriateness of a design with regard to the building code requirements, the building code requirement must be factored to obtain an equivalent hourly mean speed at rooftop.

Once the building code requirement is expressed as an hourly mean speed at rooftop, it should be compared to the value of V_{c2}. In general, if V_{c2} is greater than the required design wind speed, the ballast design is considered acceptable. However, there may be situations where the designer may determine that a more conservative basis is appropriate. For instance, if routine redistribution of the ballast would be difficult for the building under analysis, the value of V_{c3} may need to be the design criteria.

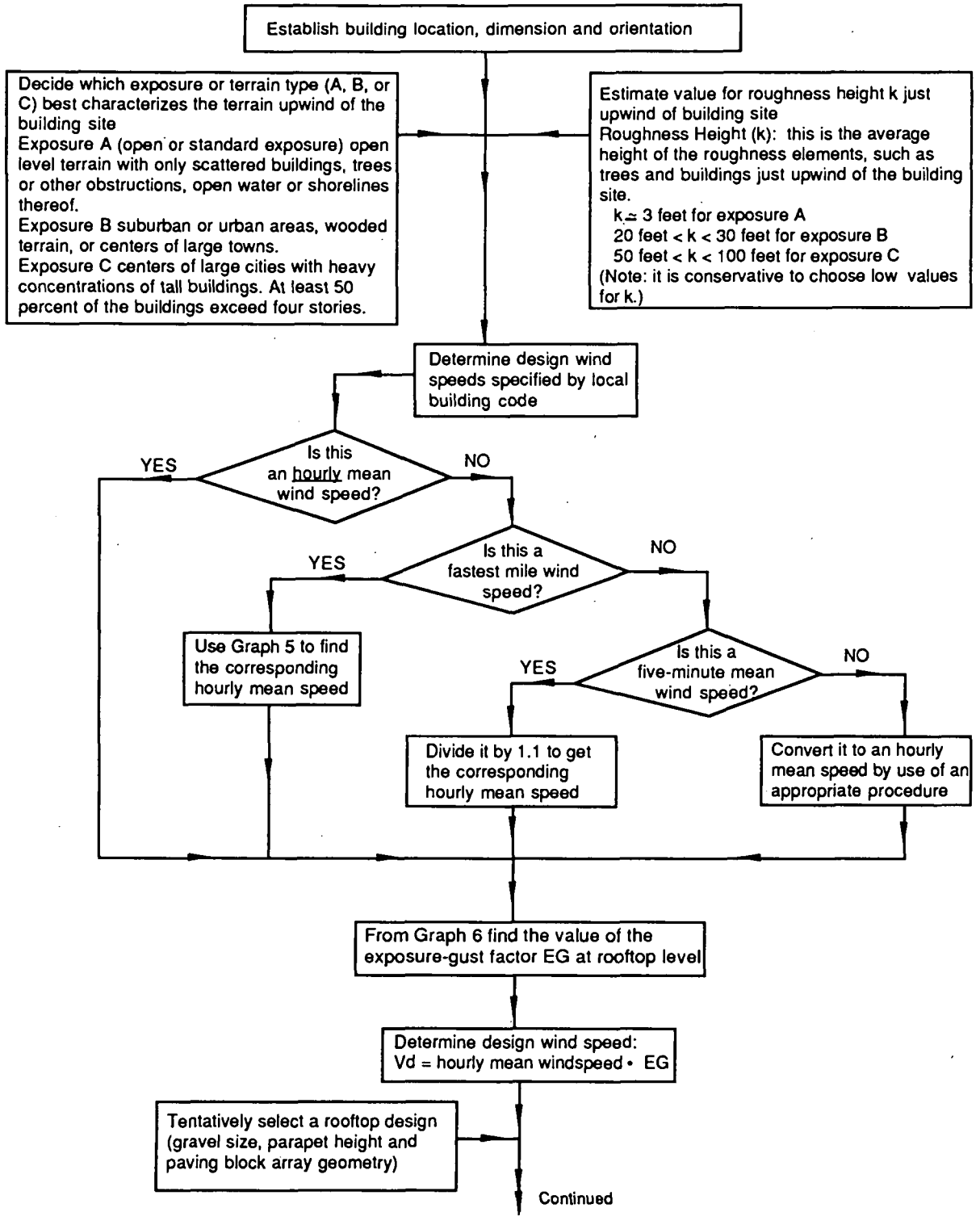
The attached appendix consists of a flow chart of the analysis procedure, followed by the required charts and graphs that have been pulled from the Kind-Wardlaw report.

REFERENCE

Kind, R. J. and R. L. Wardlaw, *Design of Rooftops Against Gravel Blow-off,* National Aeronautical Establishment, National Research Council of Canada, September 1976.

APPENDIX

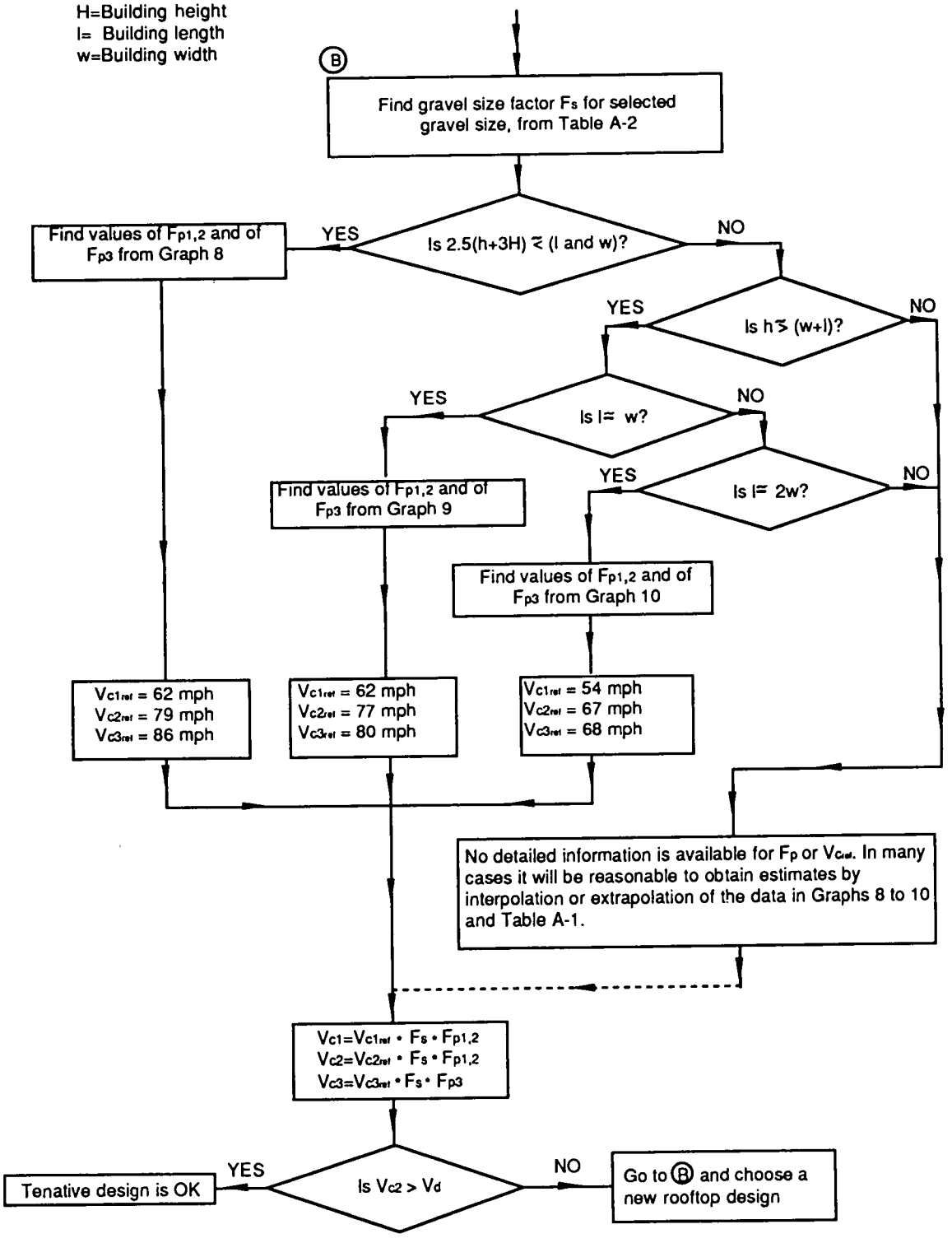
EVALUATION OF GRAVEL BALLAST SYSTEMS



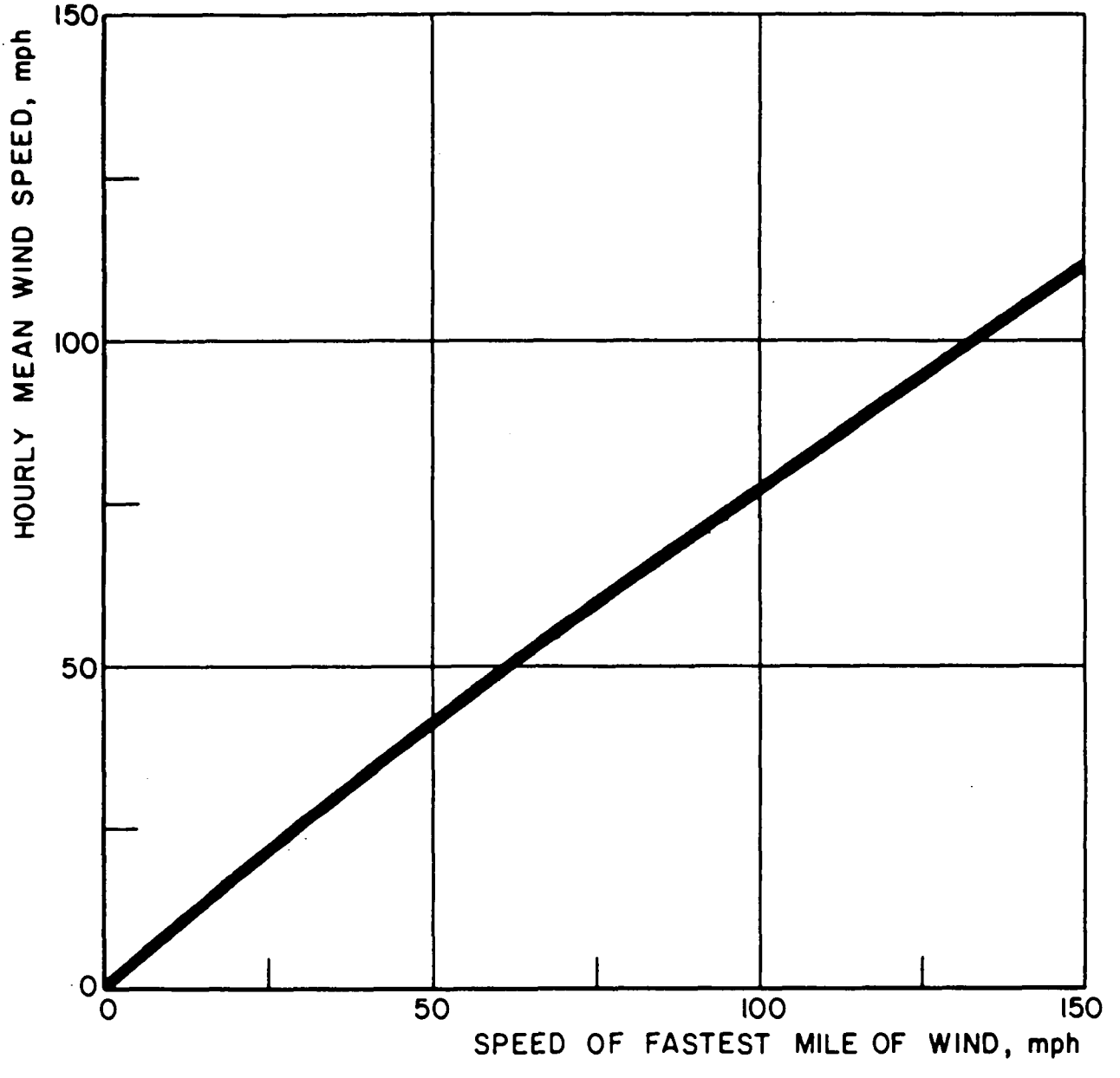
EVALUATION OF GRAVEL BALLAST SYSTEMS, CONTINUED

LEGEND

h= Parapet height
H=Building height
l= Building length
w=Building width

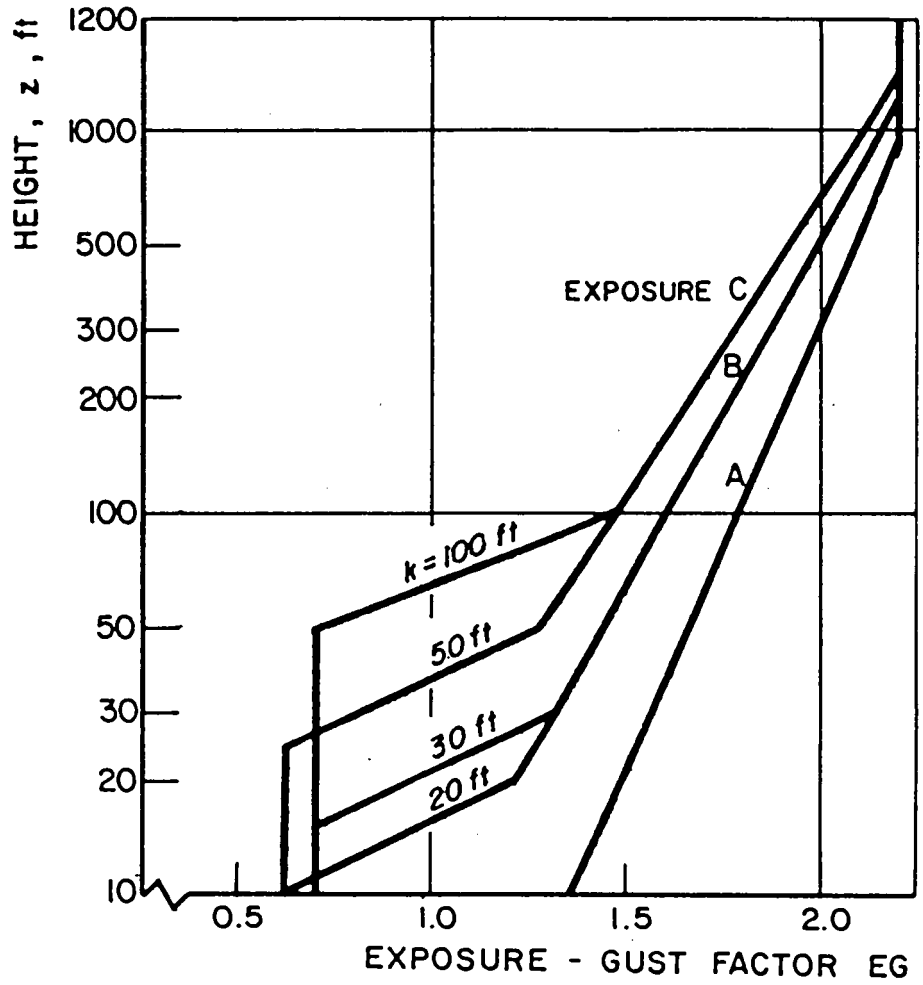


Used with permission of Dr. R. J. Kind.



This graph is used to convert fastest mile wind speeds into equivalent hourly mean wind speeds.

GRAPH 5: RELATION BETWEEN FASTEST MILE AND HOURLY MEAN WIND SPEEDS
(Exposure A; z = 30 ft.)

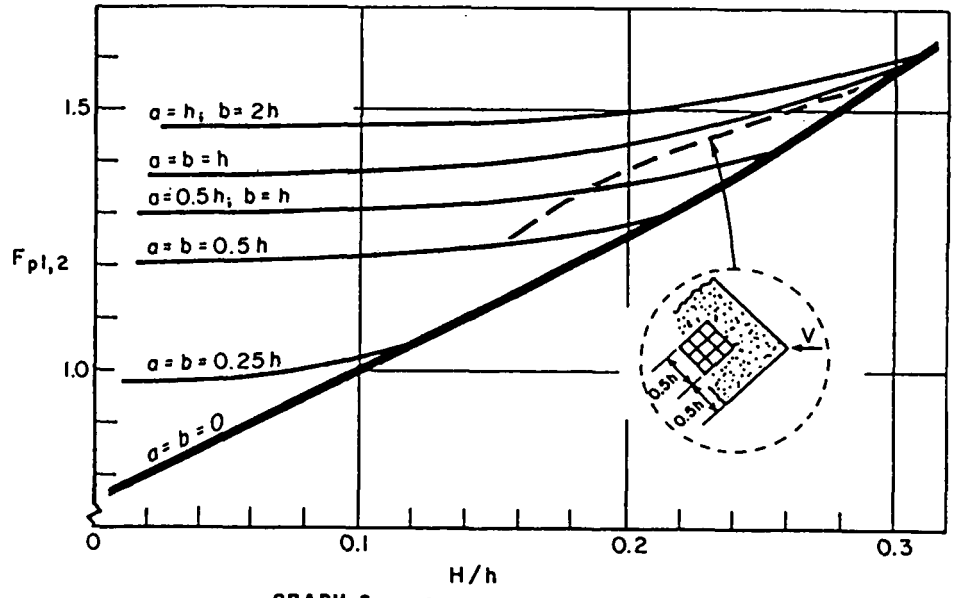


k ≡ height of roughness elements upwind of building site.

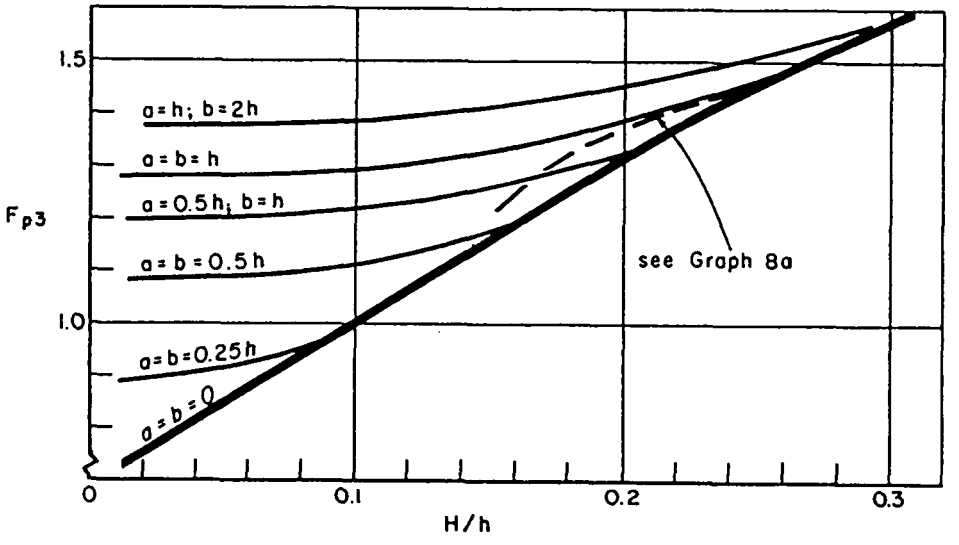
z ≡ height of rooftop above ground level.

This graph should not be used when 'channelling' of the wind is apt to occur at rooftop level or within roughness which is not reasonably homogeneous

GRAPH 6: EXPOSURE-GUST FACTOR VS HEIGHT ABOVE GROUND LEVEL



GRAPH 8a - for V_{c1} and V_{c2} only



GRAPH 8b - for V_{c3} only

H ≡ parapet height (see Graph 1)

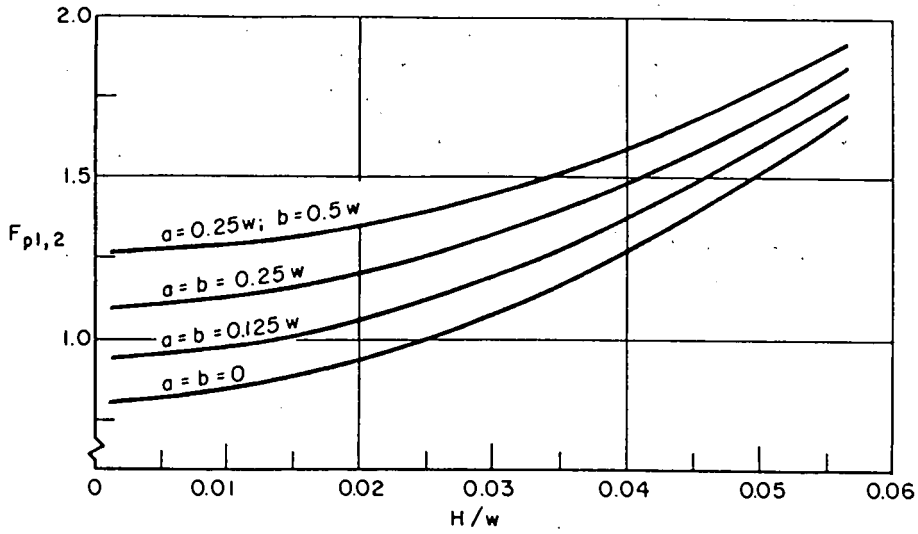
h ≡ building height (see Graph 1)

a, b ≡ dimensions of paving block array (see Graph 1)

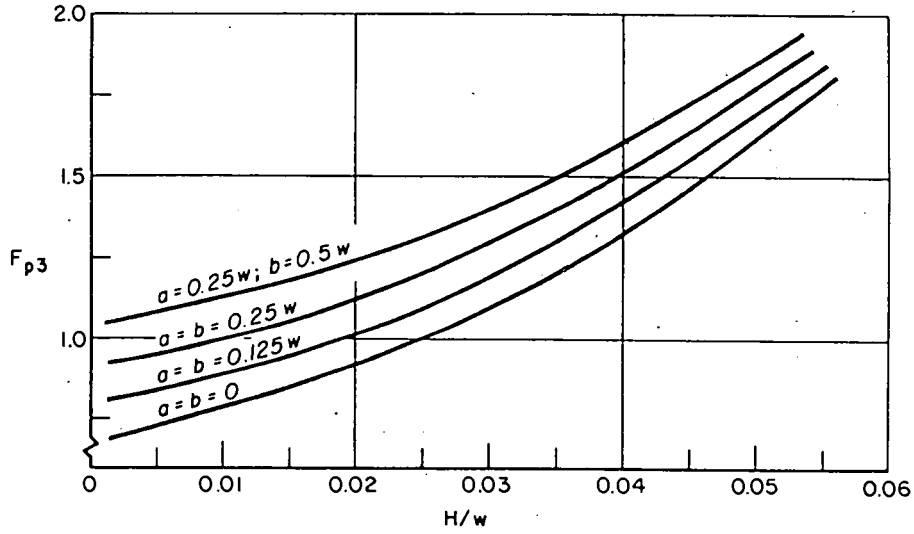
This graph is only valid when 2.5 (h + 3H) ≤ (ℓ and w) where ℓ and w are length and width of the building

The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.

GRAPH 8: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR FOR LOW RISE BUILDING SHAPES



GRAPH 9a - for V_{c1} and V_{c2} only



GRAPH 9b - for V_{c3} only

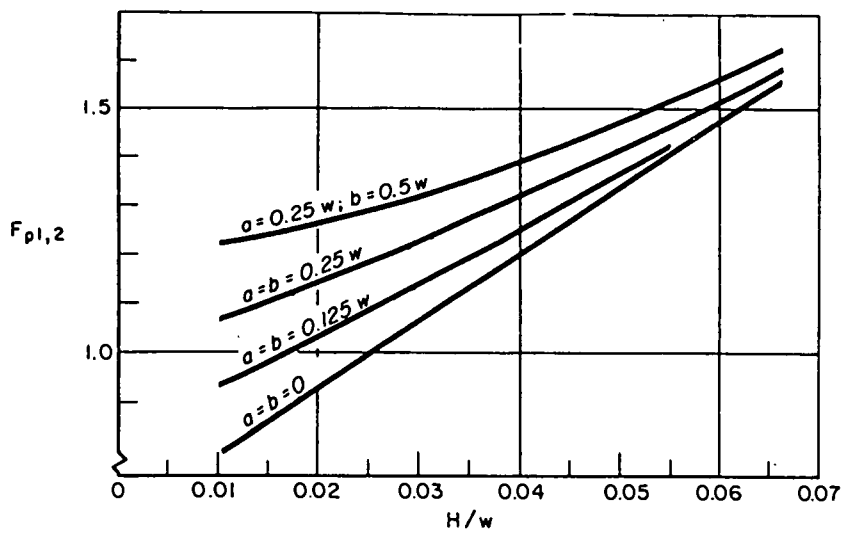
H ≡ parapet height (see Graph 1)

w ≡ building width (see Graph 1)

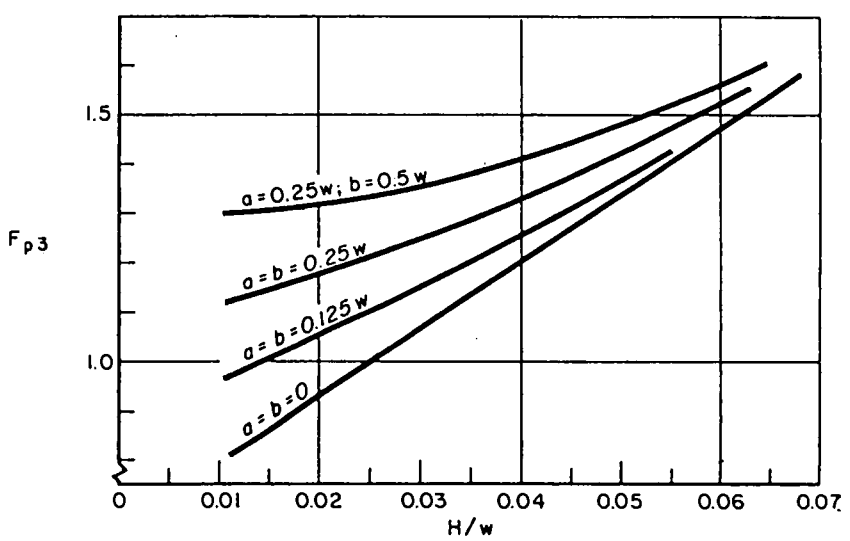
a, b ≡ dimensions of paving block array (see Graph 1)

This graph is only valid when the length:width ratio (ℓ/w) of the building is approximately 1 and when the building is at least twice as high as it is wide (i.e. h ≮ 2w).
The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.

GRAPH 9: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR
FOR HIGH RISE BUILDING SHAPES WITH ℓ = w



GRAPH 10a - for V_{c1} and V_{c2} only



GRAPH 10b - for V_{c3} only

H ≡ parapet height (see Graph 1)

w ≡ building width (the smaller of the two lateral dimensions – see Graph 1)

a, b ≡ dimensions of paving block array (see Graph 1)

This graph is only valid when the length:width ratio (ℓ/w) of the building is approximately 2 and when the building height h satisfies the relation h $\gtrsim$ (w + ℓ).
The factor F_p is used to account for the combined effects of parapets and paving block arrays on the critical wind speeds.

GRAPH 10: PARAPET HEIGHT/PAVING BLOCK ARRAY FACTOR
FOR HIGH RISE BUILDING SHAPES WITH ℓ = 2w

TABLE A-1

REFERENCE CASES AND REFERENCE CRITICAL SPEEDS

Building Shape	Reference Conditions				Reference Critical Speeds (mph)		
	Gravel Size d_{ref} (in.)	Parapet Height Ratio	Paving Block Array	Wind Angle α_{ref}	$V_{c1_{ref}}$	$V_{c2_{ref}}$	$V_{c3_{ref}}$
low rise ($h << \ell,w$)	3/4	H/h = 0.1	None	45°	62.0	79.0	86.0
high rise ($h >> \ell,w$) $\ell/w = 1$	3/4	H/w = 0.025	None	45°	62.0	77.0	80.0
high rise ($h >> \ell,w$) $\ell/w = 2$	3/4	H/w = 0.025	None	45°	54.0	67.0	68.0

TABLE A-2

GRAVEL SIZE FACTORS FOR ASTM GRAVEL GRADATIONS

	ASTM #4	ASTM #2
Fs	1.56	2.05

EXAMPLE

Given: Building 45' High: 150' Wide, 260' Long; (h=45', w=150', l=260')
12" Parapet (H=1')
Located in Indianapolis, IN in a very flat, open terrain with few trees
Building Code Design wind speed 70 MPH (Fastest mile Speed @ 33')

DETERMINE DESIGN ROOFTOP WIND SPEED FROM BUILDING CODE REQUIREMENTS

Terrain defines an Exposure A (open level terrain with scattered trees)

Use Graph 5 to find corresponding hourly mean speed for fastest mile speed of 70 MPH:
hourly mean speed = 55 MPH

Use Graph 6 to determine Exposure-Gust factor at rooftop; Exposure A, at 45':
EG = 1.65

Design Speed Vd = Hourly Mean Speed * Exposure-Gust Factor = (55 MPH) * (1.65)
Design Speed = 91 MPH

TRY A DESIGN WITH ASTM #4 STONE

Determine F_s from Table A-2 for ASTM #4
$F_s = 1.56$

Determine $F_{p1,2}$ and F_{p3} - Based on the relationship of 2.5(h+3H) to l and w and H/h
2.5(h+3H) = 2.5(45+3(1)) = 120 which is less than l = 260 and w = 150
Therefore, use Graph 8
H/h = 1'/45' = 0.02
$F_{p1,2} = 0.8$ $F_{p3} = .075$

Building would be classified as a low rise because h << l or w, 45'<< 260' or 150'
Therefore, from Table A-1
$V_{c1\ Ref} = 62$ MPH
$V_{c2\ Ref} = 79$ MPH
$V_{c3\ Ref} = 86$ MPH

$V_{c1} = V_{c1\ Ref} * F_s * F_{p1,2}$ = (62 MPH) * (1.56) * (0.8) = 77 MPH

$V_{c2} = V_{c2\ Ref} * F_s * F_{p1,2}$ = (79 MPH) * (1.56) * (0.8) = 98 MPH > Design Speed Vd =91MPH

$V_{c3} = V_{c3\ Ref} * F_s * F_{p3}$ = (86MPH) * (1.56) * (0.75) = 100 MPH

Design is acceptable since the wind speed to establish scour is greater than the design wind speed

SUMMARY OF PRESENTATION ON PAVER PERFORMANCE FACTORS

J. Pardo
Innovative Design Research, Div. NMRC

Paver and Board systems utilized as ballast for single-ply roofing provide a number of benefits not easily matched by other systems and not always obvious to designers and specifiers, one of which is the reduced fatigue effects that gravity securement affords. In addition, designers should keep in mind the ease of installation of paver systems relative to design details that may require a roofer to carry out complex operations under difficult conditions.

The proper design and installation of paver systems has therefore been of considerable importance and has been subjected to conservative wind tunnel "microzone" testing, where parameters such as air-permeable roof decks can be studied in comparison to seamless decks, and the effect of air leakage upon the wind uplift resistance of loose-laid systems can be observed.

Experimental evidence gathered by Bienkiewicz and Meroney shows that the effect of air turbulence, as characterized by a particular exposure and roof height, appears to have an analogous negative impact upon wind paver performance, as windspeed per se. This is due to the increase in nonlinearities in the pressure distribution patterns generated on the roof surface as a result of highly turbulent winds.

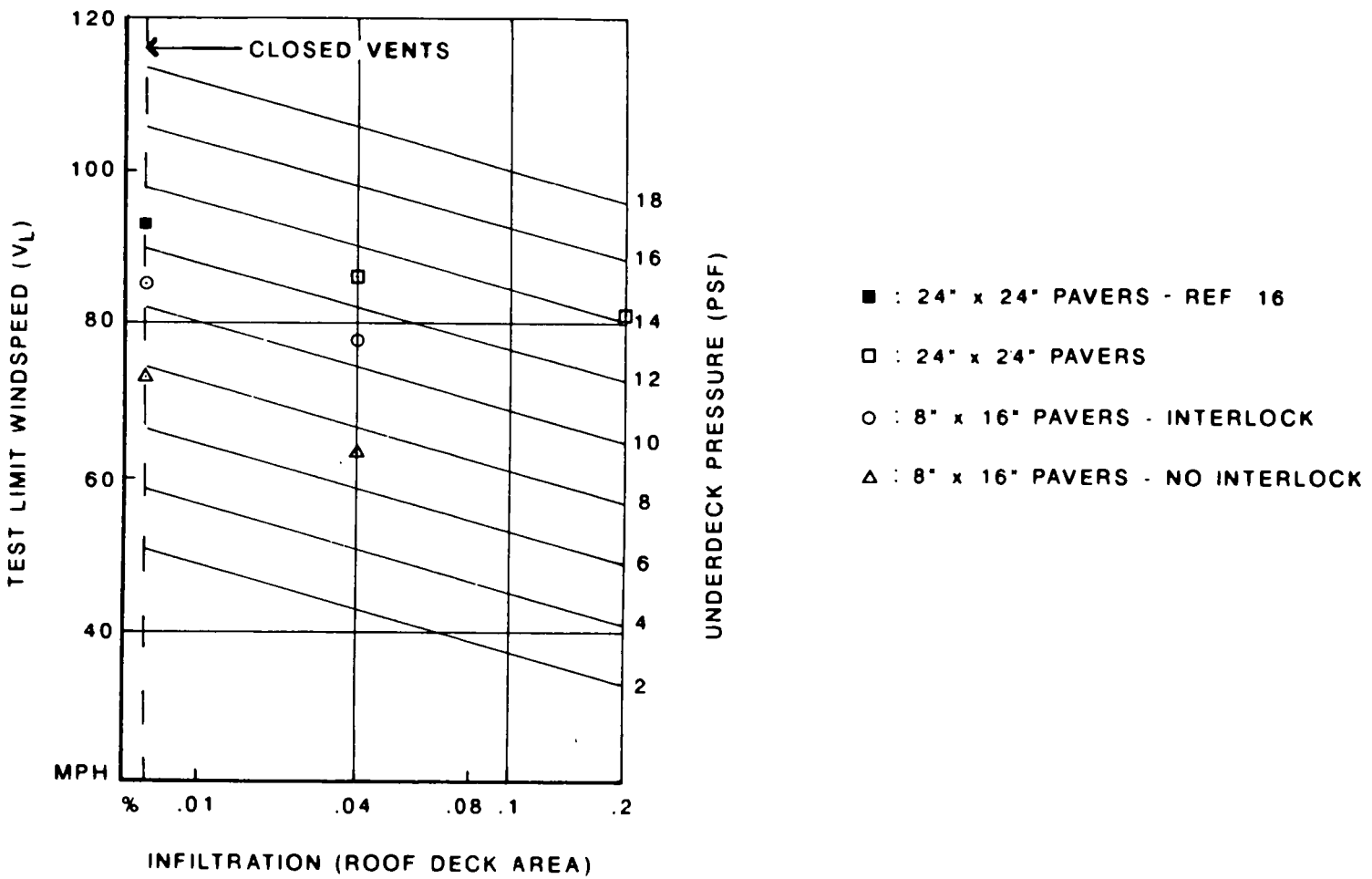
Another important parameter in the wind performance of roof pavers and boards is weight per unit area. As the literature shows, investigations by Kind and others indicate a straightforward relationship between weight and wind uplift resistance.

Weight of prefabricated ballasts is, however, not a direct measure of paver performance, i.e., an identical paver weight is not required to overcome a certain negative roof pressure.

The reason for this is the "pressure equalization" effect that occurs across paver and board arrays, transmitting quite rapidly the pressures above the pavers through the joints to the bottom surface of the array.

Pressure equalization thus results in much lower net forces acting on paver systems than on homogeneous assemblies, as illustrated in the following pressure graphs.

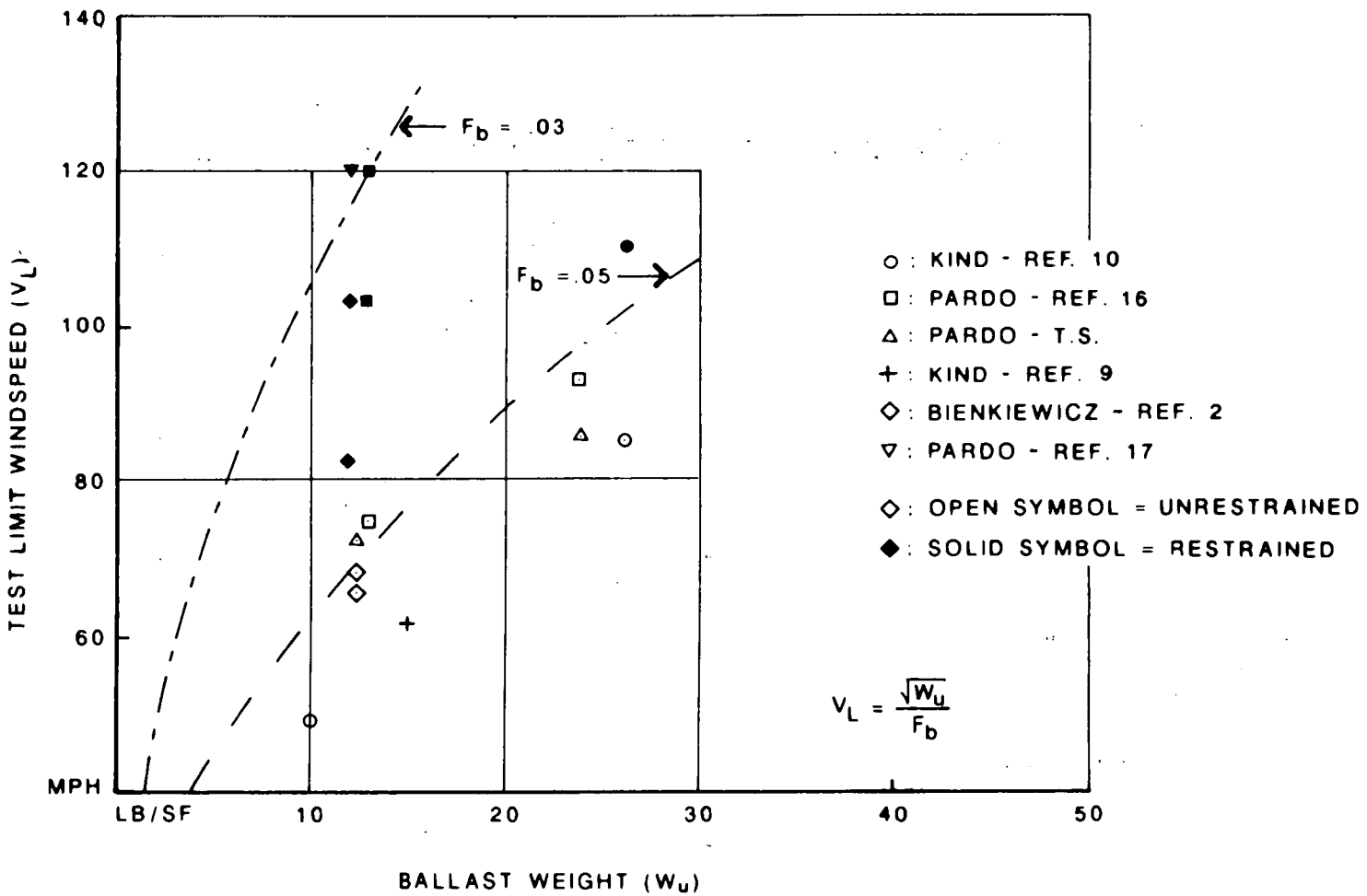
The addition of interlocking features has greatly enhanced the uplift capabilities of roof paving systems, as interlocking allows localized negative pressures to be distributed over much larger tributary areas, thereby relieving peak pressures. Here is a series of experiments illustrating the effects of interlocking paver joints.



EFFECT OF ENVELOPE INFILTRATION

BALLAST PAVERS - WIND UPLIFT

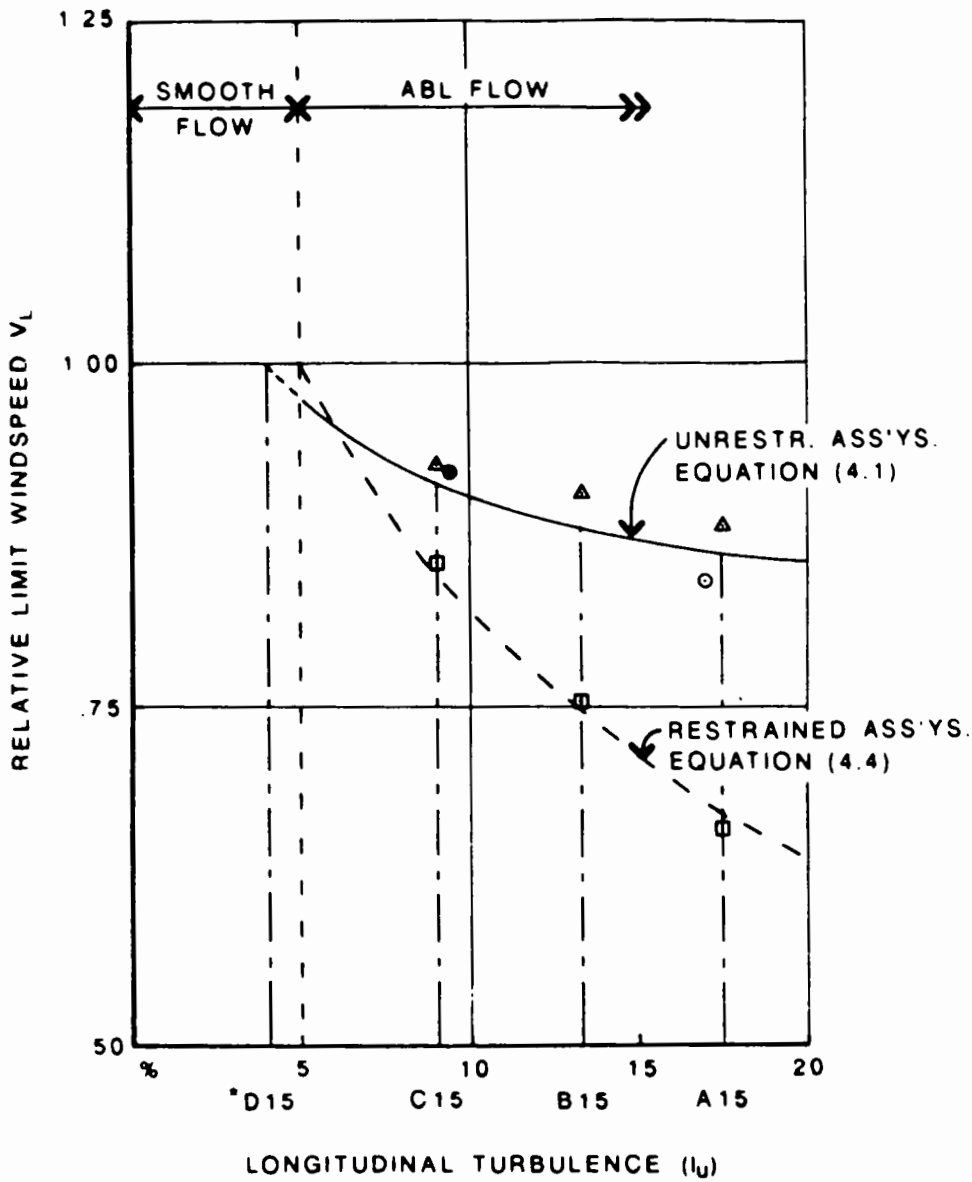
Pressure graph 1.



RESTRAINED vs. UNRESTRAINED ARRAYS

BALLAST PAVER WIND TEST RESULTS - 6" PARAPET HEIGHT

Pressure graph 2.



EFFECT OF TURBULENCE ON V_L

FOR LOOSE-LAID ROOF ELEMENTS

*Approx turbulence at 15 ft. ht. for Exposure Type given

○ = REFERENCE 9 (Not Interconnected)
● = REFERENCE 10 (Not Interconnected)
△ = REFERENCE 2 (Not Interconnected)
□ = REFERENCE 2 (Interconnected)

Pressure graph 3.

The uplifting force necessary to pick up a single paver from a non-interlocked array is equivalent to its weight.

The addition of interlocking, however, makes higher force application necessary in order to uplift a paver, because, as visible in the figure, a number of surrounding units are resisting the uplift being applied on one unit.

The extent of the tributary area through which uplift forces are distributed appears to be a function of the strength of the interlock, which, if exceeded, will result in joint shear as shown here in some board experiments.

The unique features of infinite resistance to fatigue provided by gravity, pressure equalization, and interlock have been successfully exploited by a number of lightweight paver systems, which, unlike stone ballast, were developed as a result of extensive research programs.

A generic overview of systems in the marketplace follows:

System A utilizes a bevel joint to transmit uplift forces from one paver to another. As with most lightweight interlocking systems, this paver contains integral drainage grooves on its bottom surface.

System B is made up of extruded units with a "ship-lap" type of joint, which also accepts metal clips for more severe wind exposures.

System C utilizes plastic interlocks, in addition to providing a "wind spoiler" top surface.

System D is an insulation board system for protective membrane roofs which contains integral ballasting in the form of a cementitious topping. The interlock feature here is a tongue and groove joint.

Pavers and boards are sometimes used together, with paver arrays reinforcing the more vulnerable areas of the roof around corners and perimeter.

It is advisable to provide a form of engagement of the paver system to the eave of the roof in order to contain the interlocking effect.

Field Data

TASK GROUP REPORT
FIELD INFORMATION

R. Johnson, Consultant (Leader); R. Dupuis, Structural Engineering, Inc.; R. J. Gillenwater, Carlisle SynTec Systems; D. B. Hales, Moisture Systems, Inc.; J. R. McDonald, Texas Tech University; J. P. Sheahan, J. P. Sheahan Associates, Inc.; and T. L. Smith, National Roofing Contractors Association

This Task Group conducted a search to determine the availability of: (1) loss data from previous wind storms, (2) buildings that are or have been field instrumented, and (3) data from field instrumented buildings. The search was conducted in Europe, Canada, Australia, and the United States.

The results of this search indicate that little information is available on roof-covering loss data from previous wind storms or from instrumented buildings. Few buildings are or have been instrumented because of the cost involved in installing instruments and the cost of collecting the data. The need for instrumentation, known instrumented buildings and the extent and availability of data from these buildings, and the need for post-storm damage investigation is as follows.

THE NEED FOR FULL-SCALE MEASUREMENTS

Wind pressure measurements are needed on instrumented full-scale buildings to determine the pressure or force distribution on roofing systems and their components. These measurements are used to validate wind pressure distributions measured in wind tunnels, to establish benchmark data for wind uplift tests, and to better understand roof failure mechanisms observed in wind storm damage.

Wind pressure distributions on the surface of a large building are found in the wind tunnel by constructing a scale model of the building and surrounding terrain. The dynamic characteristics of the boundary-layer wind are also modeled. Scales ranging from 1:100 to 1:500 are not uncommon. At these scales, roof components are difficult to model. Only the broad pressure distributions can be obtained from these tests. An alternative approach is to place a full-scale mock-up of the roofing system in a wind tunnel and measure pressures or forces on the roofing system components. While this approach has appeal because of its simplicity, the wind characteristics are not properly modeled and may not produce valid results. A third alternative approach is to place full-scale mock-ups of roofing systems in a very large wind tunnel, where the wind can be more properly modeled. Such large tunnels exist, but the energy required to achieve high wind speeds is very expensive. In all cases, measurements from full-scale buildings are needed for comparison with the wind tunnel tests.

Measurements on full-scale buildings are also needed to establish benchmark data for wind uplift tests. Future acceptance test criteria are likely to require dynamic loading of the roofing system components. The

criteria should be established from measurements on full-scale buildings.

Measurements of wind pressures on full-scale buildings will give clues to possible roofing failure mechanisms and will help explain the damage mechanisms observed in post-storm damage investigations. With improved knowledge of the failure mechanisms, materials and systems can be modified to give better performance.

Full-scale measurements of interest to the roofing community include the effects of parapet wall heights. The deck structure and air tightness of the roof assembly may also interact with a given type of roof system. These factors suggest numerous variables that must be accounted for in any instrumented roof. The flexibility to account for many variables usually is not possible when an existing building is instrumented for pressure measurements. For this reason research buildings have been constructed for the sole purpose of wind pressure measurements. The Aylesbury House in England and the Texas Tech rotatable building are two examples of special-purpose research buildings.

BUILDINGS THAT HAVE BEEN INSTRUMENTED

A fairly extensive survey of research organizations throughout the world revealed that few buildings exist that have been instrumented for the purpose of determining wind pressures on roofs. Four buildings were most prominently mentioned. A few others were mentioned in the survey, but either they were designed for other specific purposes, or the studies have not progressed to the point of publishing results. The four buildings are briefly described in the paragraphs that follow.

COMMERCE COURT TOWER

This 57-story office tower is located in Toronto, Canada. Studies were conducted to compare full-scale and wind tunnel pressure measurements. The wind tunnel study, sponsored by the structural engineers for the project, was conducted in 1969. With full cooperation of the project owner, design consultants, contractors, and building management staff, the National Research Council of Canada (NRCC) instrumented and monitored the building continuously from first tenancy in 1973 until October 1980. The building was fitted with 32 pressure ports in its exterior walls at four different levels. The results compared favorably, but no measurements were taken on the roof. Alan Dalgliesh of NRCC and P. A. Irwin with Morrison Hershfield were involved in the studies.

AYLESBURY HOUSE

The Building Research Establishment (BRE) of the United Kingdom took full-scale wind pressure measurements on the Aylesbury House between 1972 and 1974. The experimental building had plan dimensions of 7 m by 13.3 m and a height to eave of 5 m. An adjustable roof permitted a roof pitch from 5° to 45°. The building was located at a site with fairly complicated terrain features. Wind tunnel tests of models of the Aylesbury House have been conducted by wind tunnel facilities all over the world. Wind tunnel tests have shown general agreement with the full-scale data and with each other. The wind parameters that affect good comparisons have been identified. Some inherent variables in the full-scale data limits the agreement that can be achieved. N. J. Cook was the BRE researcher on the project.

SILSOE BUILDING

The AFRC Institute of Engineering Research is conducting full-scale and wind tunnel measurements on a portal-framed agricultural building in Silsoe, England. Similar to pre-engineered metal buildings in the USA, the structure has a 10° slope on its gable roof construction. Preliminary results show good comparison of mean pressures between model and full-scale buildings and less favorable agreement of peak pressures. Roger Hoxey is principal investigator on the project.

TEXAS TECH FIELD SITE BUILDING

A small low-rise metal building that is rotatable on a circular track has been constructed for research purposes on the Texas Tech University campus in Lubbock, Texas. The building is 45 ft by 30 ft in plan and has a 13 ft eave height. The current configuration has a low-slope roof pitch. The ability to rotate the building gives the researchers tremendous flexibility in selecting the angle of attack of the wind relative to the building orientation. The building is located in flat open terrain with very few obstructions to affect the upstream wind. Comparison of full-scale data with wind tunnel measurements is currently underway. One task of a cooperative research program between Texas Tech University (TTU) and Colorado State University (CSU) calls for a ballasted single-ply membrane roofing system to be installed in the spring of 1990. Measurements of pressure on the membrane and forces on the pavers will be taken during high wind conditions. Analogous wind tunnel measurements will be made on a model in the CSU wind tunnel. The research is sponsored by the National Science Foundation (NSF). Kishor C. Mehta from TTU and Bob Meroney from CSU head the multi-disciplinary NSF project team.

THE NEED FOR POST-STORM DAMAGE INVESTIGATION

Our task group's search turned up little publicly available information on roof performance in previous wind storms. Although there has been a considerable amount of roof system investigation over the years, it has been done mostly by manufacturers who have kept the information proprietary and by consultants who have been unable to release their findings due to their client's request. Some information was made available on ballasted systems in a 1984 symposium which was used as the basis for the ANSI Standard "Wind Design Guide for Ballasted Single-Ply Roofing Systems," generated through the efforts of RMA (Rubber Manufacturers Association) and SPRI.

National storm-damage investigation teams' past investigations of major wind storms have typically focused on performances of buildings' structures. Roof systems have typically been given only a cursory look, thus leaving the detailed causes of failure lost in the debris. This lost information would have been valuable in understanding and improving roof system wind performance.

By having a specific group that is part of the post-storm damage investigation team concentrate on roofing, specific field performance information on roofing can be gathered and disseminated.

RECOMMENDATIONS

Realizing the need for reliable field data related to instrumentation and wind storm performance, **this task group recommends that the following actions be taken:**

1. Encourage and support (via **technical input and monetary contributions**) continued field instrumentation at those facilities that are now in operation. Complement existing instrumented facilities with additional facilities. Monitoring of additional instrumented buildings should be performed by a research or academic group.
2. Establish a clearing house to collect, analyze, distribute, and store information obtained from field instrumentation.
3. Establish a post-storm damage investigation team immediately after damage occurs to specifically investigate roof performance. The team should include experts on roofing, structural engineering, atmospheric science, and insurance, and any others from entities concerned with such losses. A Field Investigation Work Sheet should be developed for use by the investigation team.

Research and Development

RESEARCH NEEDS: WIND RESISTANCE TESTING OF ROOFING SYSTEMS

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INTRODUCTION

At the first session of the Workshop on Wind Uplift Resistance Test Procedures for Roof Systems held in Dallas, Texas, in May 1989, a list of research issues in this area was formulated and a task group was established to consider these and recommend any other pertinent research issues. This task group consisted of the following members:

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Naval Civil Engineering Laboratory

James Goodwillie
H. B. Fishman & Co., Inc.

Riaz Hasan
I.T.W. Buildex

Richard D. Marshall
National Institute of Standards and Technology

Thomas Lee Smith
National Roofing Contractors Association

Jon A. Peterka
Cermak Peterka Petersen, Inc.

Robert L. Wardlaw
National Research Council of Canada

The task group prepared a preliminary report that was presented to the attendees at the second Wind Uplift Resistance Testing Workshop in Oak Ridge, Tennessee, in November 1989. The preliminary report included a listing of research issues that were determined by the task group to be of sufficient importance to merit further consideration. The issues were not discussed in great detail in the report, but an attempt was made to provide enough information to define the issues and suggest direction for the research. This research agenda was discussed at the November workshop and additional research issues were added to the agenda by the attendees. On the last day of the workshop, the attendees balloted on the three research issues from the agenda that they considered to have the greatest need for research. The research agenda, a discussion of the research issues, and the ranking of the research issues within the agenda are given at the end of this paper.

BACKGROUND

The character of low-slope roofing has been revolutionized in recent years. The exclusive use of fully adhered bituminous roofs has been replaced by use of a mixture of single-ply roofing systems (SPRS) that are fully or partially adhered, mechanically attached, loose laid and ballasted, or

pressure equalized. In the total roof system, membrane attachment is complicated by the design of decks, demands for additional insulation, use of vapor retarders, and increased degrees of reroofing over old roofs.

Test methods that have been developed for one type of roofing system perhaps are not adequate for other types. For instance, some of the standard industry test methods for determining how well a roof can resist wind forces involve holding a predetermined pressure differential between the upper and lower surfaces of the test specimen for a given period of time, then rapidly increasing the differential to another predetermined differential. This process is carried on until the system fails or a designated pressure is achieved. This static method, although providing satisfactory results for totally adhered systems, does not adequately determine the ability of partially adhered, mechanically attached, and loose-laid and ballasted SPRS to resist actual wind uplift forces and flutter. Dynamic testing, which has become associated with the application of cyclic, time-varying pressure differentials across a roof surface, characterizes more reliable test methods for some of these types of systems. Such tests simulate roof system fatigue, and, currently, are primarily applicable to mechanically attached systems.

Experience has shown that strong winds blowing across a roof generate dynamic, non-uniform, pulsing forces that cause fatigue in roof system components. These random pulsations combine with negative pressure differentials in SPRS that are not totally adhered to create the environment that leads to blowoff or other varieties of failure. This phenomenon is observed as a "ballooning" and fluttering of the membrane, indicating rapid changes in the direction and magnitude of the stresses impacting the system components.

There are few systematic procedures for gathering field data related to wind damage, cause, and effect. Most existing databases are not readily available because they are the result of litigation and/or product development. Little attention has been paid to field measurement techniques or to obtaining actual uplift forces. Most of this type of data has been generated in wind tunnels.

Most field data on actual blowoffs are based on wind speed rather than uplift forces. The wind speeds are often determined at weather stations some distance from the damaged roof and may not be representative of specific roof-top conditions.

SCOPE

This paper provides a listing (a research agenda) and discusses research issues on roof wind uplift resistance test procedures. In addition, results of balloting conducted at the second Workshop on the most important roof wind uplift resistance research issues are given.

RESEARCH ISSUES

The following paragraphs list the research issues, some thoughts about them, and what appears to be needed. The research issues are listed alphabetically.

1. Aerodynamic Spoilers (Passive Systems)

The use of aerodynamic spoilers and similar devices to reduce net uplift in the critical perimeter areas of roof systems should be explored. This could be carried out in a boundary-layer wind tunnel with a limited number of full-scale measurements to validate the model tests and guarantee that scale effects are acceptably small. Of course any spoiler system would have to be

architecturally acceptable and would have to function under snow and ice conditions to be considered successful.

2. Air Retarders

Air retarders are used to prevent a serious pressure differential from developing between the underneath and top sides of roofing membranes. The purpose of an air retarder is to transfer the wind loading forces to the deck and structural members rather than to the roof membrane. Air retarders are generally applied on top of the roof deck but underneath the roof system. If effective, they would be helpful in increasing the wind resistance of the roofing system. Factory Mutual (FM) Research Corporation (and presumably other insurers or researchers) have found far fewer wind-related losses over monolithic cementitious decks than they have over air permeable decks, especially steel. This is reflected in the requirements for FM Approval—a safety factor of 2 is used for steel and wood whereas 1.5 is considered sufficient for concrete. FM also recognizes a difference between air permeable decks and monolithic decks in their data sheet on ballasted systems. However, there is a lack of information about air retarder material requirements, their design and application, and their effectiveness. Research needs to be conducted to determine if air retarders are effective and to define their requirements and proper application techniques if they are found to be satisfactory.

3. Basic Research Items

There are a number of areas where basic research is required to add to the knowledge already available on wind loading of roofs. Basic research is needed to:

- validate wind pressures on low-rise roofs,
- determine the influence of bluff bodies (buildings located near cliffs and on steep slopes), and
- validate the Basic Wind Speed map and various coefficients that are used in developing loads.

4. Cataloging of Wind/Building Data

Some data are available on wind and its effect on roofs. Much of it has been developed in wind tunnel testing. Very little data has been obtained in measurements of actual wind forces that occur on full-scale roofs. The Field Information Task Group is investigating the availability of this type of information. Information on wind forces, whether determined in wind tunnels or in the field, should be searched out, listed, and cataloged at a central location so that it is readily available.

5. Correlation Between Rooftop Pressure, Wind Speed/Direction, and Building Geometry

All analyses and test methods for roof uplift resistance require knowledge of rooftop pressure distribution. This variable is primarily determined by wind speed and direction of attack and by the geometry and height of the building. Once known, this pressure distribution is used with data on the building interior pressure and the air permeability of the roof system to deduce wind forces on the membranes. Some data on rooftop pressure distribution is available from wind tunnel testing and from field test sites. This database needs to be expanded so that adequate information is available for major wind damage locations and for a range of building types.

6. Design Safety Factors

Research needs to be conducted to quantify appropriate safety factors for roof systems. For example, the safety factor for a mechanical fastener for a mechanically attached single-ply in a cement-wood fiber deck should probably be higher than the safety factor for a mechanical fastener for a fully adhered single-ply in a steel deck. At present there are no accepted criteria for these issues.

7. Development of a Standardized Wind Damage Assessment Procedure

As stated at the outset, there appear to be few, if any, systematic procedures for gathering field data related to wind damage, cause, and effect. Any seriously wind-damaged roof usually attacts the attention and interest of one or more "study teams." The data collected from such "studies," even if made available to the research community after disposition by the "study groups," would not be in a systematized format suitable for installation in a data bank. A typical questionaire and standardized "assessment procedure," if developed and made available to any team embarking on an inspection, would aid immensely in systematizing the data collection and cataloging process. This procedure would ask for key data on wind details, building geometry, geographic details, roof system details, etc. The value of this procedure would lie in the uniformity of the phrasing and reporting and the subsequent systematic collection of data for statistical analysis by the research community. In light of the recent hurricane "Hugo," this needs to be done soon, else much of what data may be available will be lost forever.

8. Edge Metal Detailing

It would seem that much thought has been given to the design of edge metal insofar as expansion and contraction is concerned, while little attention has been paid to the probability of blowoff when edge metal is subjected to high winds. On roofs where there are no parapets this is of much concern. Inevitably, if the edge metal is damaged, the roof (membrane) will also sustain considerable damage. Factory Mutual I-49 is one of the few documents that provides information on edge metal requirements. Research needs to be conducted on the influence of metal thickness, requirements for attachment load and strength, and requirements for a good interlock between the cleat and edge metal. In addition, the information contained in FM I-49 should be validated and updated. Knowledge from this research will result in materials, procedures, and details for properly fastening the edge metal to the building to prevent wind damage to the edge metal. The effect of high pressure differentials that exist during severe wind storms can be minimized by proper edge metal specification and utilization.

9. Evaluation of Available Dynamic Testing Methodologies

Dynamic testing, which is the application of time-varying pressure differences across roofing systems, has been suggested as the most reliable method for testing the wind resistance of mechanically attached systems. This research topic should utilize results from the Dynamic Testing Task Group as a starting point. If that task group finds dynamic test methods that appear to have merit, those methods should be further refined to enhance their ability to duplicate field wind uplift conditions. Little data exists on the applicability of

dynamic test apparatus to U.S.A. roofing. Side-by-side testing of identical roof systems in different apparatus will accelerate the determination of the role of dynamic testing in North America. If satisfactory methods are validated, these should be standardized utilizing existing standards organizations such as ASTM so that the finished method(s) would be acceptable to the industry.

10. Fastener Pullout, Backout, and Fatigue

Fastener failures may contribute directly to wind uplift losses of SPRS and to other problems such as membrane punctures. Since SPRS are subject to the various factors involved in aging, particularly the dynamic wind loads, they may deteriorate. Failure or damage to SPRS has occurred because of fastener backout resulting in tearing of the membrane, insulation compression or loss of insulation thickness, or fatigue failure of the deck or of the fastener itself. There are some methods available for determining pullout resistance of fasteners in the field, but these are not considered satisfactory. They provide data on whether the deck or substrate to which the fastener is attached is sufficiently strong. In some cases this is merely a spring-loaded scale. Because of the different types of equipment used for field testing, large variations may occur in pullout resistance measurements, and correlation between values and quality is neither dependable nor reproducible. Moreover, test equipment and procedures are presently well defined only for the laboratory.

A test apparatus and procedures should be developed that adequately determine fastener backout, pullout, and fatigue failure on the roof. This may include development of a dynamic laboratory test bench for accelerating fastener pullout/backout failure to provide data necessary to aid in the development of the field equipment.

11. Field Uplift Resistance Testing

It would be very desirable to be able to determine the uplift resistance of a roof system after it has been constructed to determine if it has been constructed according to specification and thus meets the specified wind uplift requirements. It may be even more important to determine the uplift resistance of an aged roof to determine if blowoff is likely because of fastener corrosion, fastener fatigue, or other causes. Although some equipment for determining uplift resistance exists, little information is available on its operation and performance. Research should be directed toward investigating existing equipment for its suitability, and if it is found to be acceptable, the parameters necessary for its successful use should be determined. If it is found to be unacceptable, new, on-the-roof, wind uplift resistance test methods and equipment should be developed and validated and parameters established for their use.

12. Load Distribution

Research is needed to further understand how loads are imposed and distributed by the different types of roofing systems. The influences of temperature, aging, and membrane stiffness on load distribution all require study.

13. Modification of Large Wind Tunnels

Wind tunnels can provide valuable aerodynamic information on wind resistance of roofing systems. Results from wind tunnel tests correlate better with field results than most other types of roof wind uplift tests. Using reduced-scale models,

wind tunnels can be used to determine the pressure distribution on building roofs, including the fluctuations of pressure that arise as a result of wind turbulence and building shape. They can also be used to assess the influences of nearby buildings and local topography on the wind speeds and turbulence levels that can be expected at a particular building location. For loose-laid systems, the ballast items such as gravel and pavers can be modeled at reduced scale and the critical velocities for wind blowoff or liftoff can be determined. However, wind tunnels cannot, at model scale, reproduce all of the elastic resistance of single-ply membranes, and therefore do not fully replicate actual field conditions.

On the other hand, full scale testing at full scale wind speeds cannot normally be achieved in wind tunnels because of limitations on the physical size of the wind tunnels. However, for very large wind tunnels, the idea of using partial models of the structure (for example, a model of an upwind corner of a building) could provide a procedure for proof testing specific systems. Such a procedure would not be used for routine testing but for developing additional data. It is proposed that research using this approach be undertaken.

14. Parapet Height Requirements

It has been demonstrated by reliable wind tunnel tests that the geometry of roof parapets can be used to reduce locally intense negative pressures near corners and along roof-wall intersections. Similar wind tunnel research has shown how high winds affect aggregate scouring on BUR and ballasted SPRS. Research needs to be conducted to quantify the geometry and parapet height requirements to prevent blowoff of BUR aggregate and single-ply stone ballast.

15. Pressure Equalization Methodologies

One of the principal preconditions necessary for wind blowoff is a pressure differential between the top of the roof system and the inside or underside of the system. Major problems in this area occur with metal roof decks or other decks that allow air to pass into the roof system from inside the building (i.e. roof decks that are porous), which happens quite rapidly. Thus, with a higher pressure underneath than on top of the membrane, the necessary pressure differential exists to initiate a blowoff when other conditions are right. A properly designed membrane pressure equalization system could, perhaps, eliminate the pressure difference, equalizing the pressure on both sides of the membrane. Although there is at least one such system available, a great deal is not known about the parameters necessary for such a system to be successful. It is known that a rather large installation of an air-sealed and pressure-equalized system successfully survived Hurricane Hugo near San Juan, Puerto Rico, where wind speeds were reported by various sources as 82 mph with gusts up to 118 mph. Research should be conducted to determine the various parameters, such as equalization valve design and seal, required air flow to minimize pressure differentials, required valve spacing, allowable drag forces, and effect of building configuration and height. While some data can probably be generated in wind tunnel experiments, it may be necessary to conduct experimentation in some type of dynamic wind testing machine or to use full scale testing.

16. Inexpensive Maximum-Reading Roof-Top Anemometers

Information on wind velocities during wind storms is generally determined by

instrumentation at the closest weather station. Thus, when a roof blowoff occurs, the only information available is that the failure resulted from a high wind velocity of so many miles per hour at the airport or other weather station. In many cases, the weather station may be quite some distance from where the blowoff occurred. This suggests that very often the actual wind velocity at which the blowoff occurred is not known with any certainty and probably is quite different from that recorded at the weather station. If ultra cheap anemometers were attached to each roof as the roof's system is installed, we would have a much better indication of the severity of the wind where the blowoff occurred.

Research in this area should be directed toward finding or developing an inexpensive roof-top anemometer that will determine and permanently record the maximum wind velocity during high winds on the roof where it is mounted. The anemometer might be designed so that it could be reset to zero following the storm, or, if it is sufficiently low in price (say $5 to $25) it could be discarded and replaced. The local wind velocity near the building roof will be different from the undisturbed or "free stream" wind velocity because of the influence of the building itself on the wind. A study should be undertaken of how to position the anemometer in order to minimize this error. Such an investigation could be undertaken at reduced scale in a wind tunnel.

17. Wind Tunnel Modeling

Much effort has gone into the modeling of gravel and paver ballasts in various wind tunnels, and a large amount of excellent data on these materials has been developed. Most, if not all, of the testing has been done without a modeled roofing system under the ballast, probably because of the difficulty of modeling both the roof membrane and its attachment to both the roof perimeter and various penetrations. Because of these difficulties, the wind tunnel data for ballasted systems may be suspect, and other types of roofing systems cannot even be tested reliably in the wind tunnel. Research should be initiated to determine how to best model entire roofing systems including membranes, decks, air retarders, insulation, fastening systems, etc., for wind tunnel study.

18. Mathematical Modeling

Mathematical modeling of a roofing system's resistance to wind uplift damage could be most useful. Such modeling could be validated by wind tunnel testing or by dynamic testing methods once dynamic testing methods are fully developed.

19. Additional Research Items

A number of additional research items were suggested during the balloting process. These are listed below without comment to make them a matter of record and permit discussion by follow-on committees in the future. There is some overlap among some of these as well as among some of these and the first 18 research items on the agenda.

a. (Investigate) well rounded ballast versus broken particles.
b. Who is ultimately responsible for the wind resistance design? Architects? Engineers? Manufacturers?
c. (Investigate) porosity of roof deck/structural systems and (their) effect on uplift loads. (Determine) when (air) barriers are required.
d. Develop and agree on one industry-wide dynamic test.

e. (Develop) wind uplift design guide that the design community can use.
f. (Investigate) correlation between field data and proposed lab tests.
g. Submit consensus test procedures to model codes.
h. (Investigate) fully adhered systems.
i. Full scale testing—like the White House Test for fire. Use it once, then go to small scale like they did for fire with the tunnel test.
j. (Investigate) attachment of membrane to perimeter/edge.
k. Do statistical analysis of wind speed versus categorical failures.
l. Correlate wind tunnel modeling/full-scale performance.
m. (Investigate) entire edge design—not just metal.
n. Develop standardized design criteria for ballasted (and) mechanically fastened systems.
o. Evaluate substrates (insulation) with respect to uplift resistance on adhered systems.
p. Investigate correlation of design pressure versus actual pressure on buildings.
q. Fastener/disc fixing point—allowable design values that can be utilized for all fastener and disc combinations with various membrane systems.
r. (Investigate) CFD computational fluid dynamics.
s. Develop requirements for perimeter and corner definitions to which all roof system marketers would be required to adhere.
t. (Investigate) extent of corner and perimeter areas based on building geometry.
u. (Investigate) design pressure versus actual pressure (on the roof system).
v. (Develop) standards and calculational uniform procedures.

RANKING OF RESEARCH ISSUES

One hundred nine of the 143 workshop attendees cast ballots on research issues that they considered to be most important. Each attendee was provided with three equal weight votes that could be used to vote for three separate research issues or could all be cast for only one issue. These ballots were tallied following the first day of the Oak Ridge Workshop and results were presented and discussed in detail during the concluding morning session of the second day. Results are listed in Table 1 for those research issues receiving two or more votes. The remainder of those research items listed in paragraph 19 received either one or no votes.

The consensus of the Workshop was that five issues were significantly more important than the others discussed during the proceedings. These were:

(1) evaluation (and standardization) of available dynamic testing methodologies (#9);
(2) edge metal detailing (#8);
(3) air retarders (and roof system air permeability and interior pressure distribution) (#2);
(4) fastener pullout, backout, and fatigue (#10); and
(5) correlation between rooftop windspeed/direction and building geometry (#5).

The most interest in both discussions and balloting appeared to be focused on dynamic testing procedures.

Table 1. Consensus ranking of wind uplift resistance research issues

Ranking	Agenda Number	Research Item	Number of Votes
1.	9	Evaluation of available Dynamic Testing Methodologies	41
2.	8	Edge Metal Detailing	38
3.	2	Air Retarders	33
4.	10	Fastener Pullout and Fatigue	32
5.	5	Correlation Between Rooftop Windspeed/ Direction and Building Geometry	29
6.	7	Development of a Standardized Wind Assessment procedure	19
7.	11	Field Uplift Resistance Testing	18
8.	4	Catagloging of Wind/Building Data	17
8.	14	Parapet Height Requirements	17
10.	15	Pressure Equalization Methodologies	13
10.	16	Inexpensive Maximum Reading Rooftop Anemometers	13
12.	13	Modification of Large Wind Tunnels	10
13.	6	Design Safety Factors	9
14.	3	Basic Research Items	8
14.	17	Wind Tunnel Modeling	8
16.	1	Aerodynamic Spoilers	4
17.	12	Load Distribution	3
17.	18	Mathematical Modeling	3
19.	19d	Develop and Agree on One Industry Wide Dynamic Test Procedure	2

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