JAMES COOK CYCLONE STRUCTURAL TESTING STATION

CYCLONE TESTING STATION

SIMULATION OF CYCLONIC WIND FORCES ON ROOF CLADDINGS BY RANDOM BLOCK LOAD TESTING

Technical Report No. 38

January 1993

Cyclone Structural Testing Station
James Cook University of North Queensland

Simulation of Cyclonic Wind Forces on Roof Claddings by Random Block Load Testing

by

M. Mahendran
Senior Lecturer
School of Civil Engineering, QUT
(Former Research Engineer
Cyclone Structural Testing Station)

Technical Report No. 38

Mahendran, Mahadeva, 1956-
Simulation of cyclonic wind forces on roof claddings
by random block load testing.

ISBN 0 86443 396 4.
ISSN 0158 - 8338.

1. Roofing. 2. Building, Stormproof. 3. Wind-pressure.
I. James Cook University of North Queensland. Cyclone
Testing Station. II. Title. (Series : Technical Report
(James Cook University of North Queesnland. Cyclone
Testing Station) ; no 38).

690.15

ABSTRACT

Extensive damage to light gauge metal roof claddings during cyclone Tracy led to the introduction of fatigue testing of roof claddings. Currently two different fatigue tests, the DABM test (1976) and the TR440 test (1978), are being used in the cyclone prone areas because the Northern Territory has continued to require the DABM test even after the introduction of TR440 test. This is an unacceptable situation, and thus an extensive research programme was carried out at James Cook University to review the adequacy of these standard fatigue tests. This research programme involved wind tunnel investigations to develop a fatigue wind loading spectrum representing a design cyclone, and structural testing of roof claddings under simulated cyclonic wind forces and standard fatigue test loadings.

The design cyclonic wind loading developed in the form of a matrix of number of wind loading cycles for various load levels was applied to roof claddings by a random block load testing method. This experimental simulation of cyclonic wind forces was carried out using a servo-controlled hydraulic testing machine in the structures laboratory. A computer fed with the random block loading data controlled the tests.

The required results on the design cyclonic wind forces derived from the wind tunnel investigation are presented first in this report, which then describes how the design cyclonic wind forces were simulated on roof claddings using the random block load testing method. The report also describes the suitability of this method for experimental simulation of cyclonic wind forces on roof claddings.

Table of Contents

1. Introduction

Morgan and Beck (1977) and Beck and Morgan (1975) identified fatigue cracking of roofing in the vicinity of fasteners as the major cause of roof cladding failures during cyclone Tracy which hit Darwin in 1974. It is well known how roof cladding failures caused by this low cycle fatigue cracking led to the devastation of most of the housing in Darwin at that time. Walker (1975) documents the damage that cyclone Tracy caused to the city of Darwin.

Following cyclone Tracy, a number of drastic steps was undertaken by the building industry to prevent such cyclone disasters. One of them is the introduction of fatigue testing of roof claddings. A standard test consisting of 10,000 cycles of zero to design load followed by a single cycle of zero to 1.8 times design load (the DABM test - see Table 1) was adopted by the Darwin Reconstruction Commission (DRC, 1976), and this test was accepted by all the cyclone prone areas of Australia. The purpose of the introduction of this fatigue tests was to simulate cyclonic wind forces on roof claddings in the laboratory to study the behaviour of roof claddings under representative loading. It is to be noted that prior to cyclone Tracy, roof claddings were designed based on static testing alone.

Table 1. Current Standard Fatigue Tests

DABM Test		TR440 Test	
Cycles	Load Range	Cycles	Load Range
10,000	0 to Design Load*	8000	0 to 0.625 x Design Load*
1	1.8 x Design Load	2000	0 to 0.75 x Design Load
		200	0 to Design Load
		1	γ x Design Load,
Note: * - Working design load		γ = 1.6 to 2.0 depending on the number of tests	

In 1977 when researchers in wind engineering, roofing manufacturers and designers met at a workshop, they decided that the single level DABM test does not represent a randomly varying cyclonic wind loading, and that it is too severe. Based on the limited wind pressure data on roof claddings from wind tunnel testing (Melbourne, 1977 and Beck and Stevens, 1979), they recommended a three-level low-high loading sequence shown in Table 1. A new technical record TR440 was published the following year (EBS, 1978), with the above loading sequence becoming the new standard fatigue test, subsequently known as the TR440 test. The TR440 test was considered to be more appropriate in simulating cyclonic wind loading than the DABM test, and was accepted in all the cyclone prone areas except in the Northern Territory. The Northern Territory building authorities rejected the less severe TR440 test, despite the fact that it is more representative of varying cyclonic wind loading. The TR440 test is now incorporated in the new wind loading code (SAA, 1989), however, the Northern Territory requires the DABM test, and this leads to numerous problems for manufacturers and designers of roof claddings. The manufacturers are being compelled to test the same roofing product to two different fatigue criteria, and prepare separate design load tables for the Northern Territory and the rest of the cyclone prone areas. It has also led to a serious debate on the adequacy of both of these standard fatigue tests. This situation is not acceptable, and further research work is required to resolve this issue.

For this purpose, researchers at James Cook University (JCU) initiated a major research programme with an ultimate objective of reviewing the current standard fatigue tests (the DABM test and the TR440 test). Firstly, a wind tunnel investigation of model houses was carried out to determine the actual cyclonic wind loading patterns on the roof claddings. This research with the use of some actual data from cyclone Winifred that hit Innisfail in 1986 led to the development of an analytical model of cyclonic wind forces on roof claddings. Results of this investigation have been already reported in Jancauskas et al. (1989, 1990), however, the research methodology, data used, and selected results will be briefly described in this report for the sake of continuity and completeness.

Secondly, the Cyclone Structural Testing Station (CSTS) at JCU carried out an investigation on light gauge metal roof claddings to determine the basic fatigue characteristics of roof claddings under cyclic wind loading. Results of this investigation can be found in CSTS's Technical Reports (Mahendran, 1988,1989) and also in research papers (Mahendran, 1990 a,b).

Thirdly it was proposed to study the fatigue behaviour of roof claddings under simulated cyclonic wind forces using both analytical and experimental methods. Analytical model of a design cyclone developed by Jancauskas et al. (1989, 1990) was used in both cases. Jancauskas et al. (1989, 1990) presents the details of the analytical simulation of cyclonic wind forces on roof claddings using the cyclonic wind characteristics and the fatigue characteristics of roof claddings developed already. Experimental simulation of cyclonic wind forces on roof claddings was carried out by a random block load testing method using a servo-controlled hydraulic testing machine in JCU's structural laboratory. This report presents the details of the experimental simulation.

Finally the roof claddings were also subjected to current standard fatigue tests in an attempt to compare the fatigue performance of roof claddings under simulated cyclonic wind forces (both analytically and experimentally) and standard fatigue loading. This last stage of investigation was anticipated to provide an answer on the adequacy of the standard fatigue tests. Experimental results of roof claddings subjected to simulated cyclonic wind forces and standard fatigue loading sequences will be reported in Mahendran (1992).

Table 2 summarises the different stages of the overall research programme. As stated earlier, this report presents the details of the experimental simulation of cyclonic wind forces on roof claddings using the results from wind tunnel investigation (Stage 4).

Table 2. Various Stages in the Overall Research Programme

Stage 1	: Wind tunnel investigation of typical low-rise building models in order to develop cyclonic wind loading characteristics
Stage 2	: Fatigue testing of roof claddings to develop the fatigue characteristics of roof cladding under cyclic wind loading
Stage 3	: Analytical simulation of cyclonic wind forces on roof claddings using data from Stages 1 and 2
Stage 4	: Experimental simulation of cyclonic wind forces on roof claddings using data from Stage 1
Stage 5	: Fatigue testing of the same roof claddings to standard fatigue loading sequences (TR440, DABM tests)
Stage 6	: Comparison of results of fatigue damage caused by cyclonic wind forces, and standard fatigue loading sequences to decide on the adequacy of the latter
Stage 7	: Development of an appropriate fatigue test, if required

2. Development of Cyclonic Wind Loading Characteristics on Roof Claddings

2.1 General

This was an important step in the overall research programme (see Stage 1 in Table 2) as it provided the base for other stages of the programme. Jancauskas et al. (1989, 1990) presents the research methodology used to develop the cyclonic wind loading characteristics, and the results. Additional details are also available in Capitanio (1987) and Prien (1989). Brief details of the research methodology used and some relevant results are reported in this section for the sake of completeness.

2.2 Research Methodology

Roof pressure fluctuates randomly during a cyclone. This is caused by varying wind speed and wind direction during the cyclone. Therefore in order to quantify the roof pressure during a cyclone, a wind tunnel model (1/50 scale) of a typical single storey house (14 m x 7 m) with gable end and low-pitched roof (10°) was tested under both rural and terrain conditions. Roof pressure records were obtained for two critical locations of gable and eaves on the roof and for a range of different wind directions at 15° apart (i.e., 13 wind directions $\theta = 0$ to 180°). The roof pressures were pneumatically averaged over an area equivalent to 0.9 m x 0.15 m in full scale, which represents the typical tributary area of a single cladding fastener. A typical roof pressure record is shown in Figure 1. Details of wind tunnel testing can be found in Capitanio (1987) and Prien (1989).

Roof pressure records were then reduced to a pressure coefficient form and analysed using a rainflow method of analysis. Each fluctuation in the pressure record was sorted according to its mean level and range and recorded into a cell of a matrix having dimensions equivalent to ten percent of maximum measured peak pressure coefficient at each location for all the thirteen wind directions. It is to be noted that for each wind direction and location, there were ten wind tunnel runs of 40 seconds each, resulting in 320,000 pressure records which were then sorted and counted. This analysis resulted in 52 wind tunnel fatigue matrices, one of which is shown in Table 3. Other wind tunnel matrices are presented in Prien (1989). A few cycles of positive pressure cycles were found, but were not included in the analysis since they were assumed to cause negligible fatigue damage on roofing.

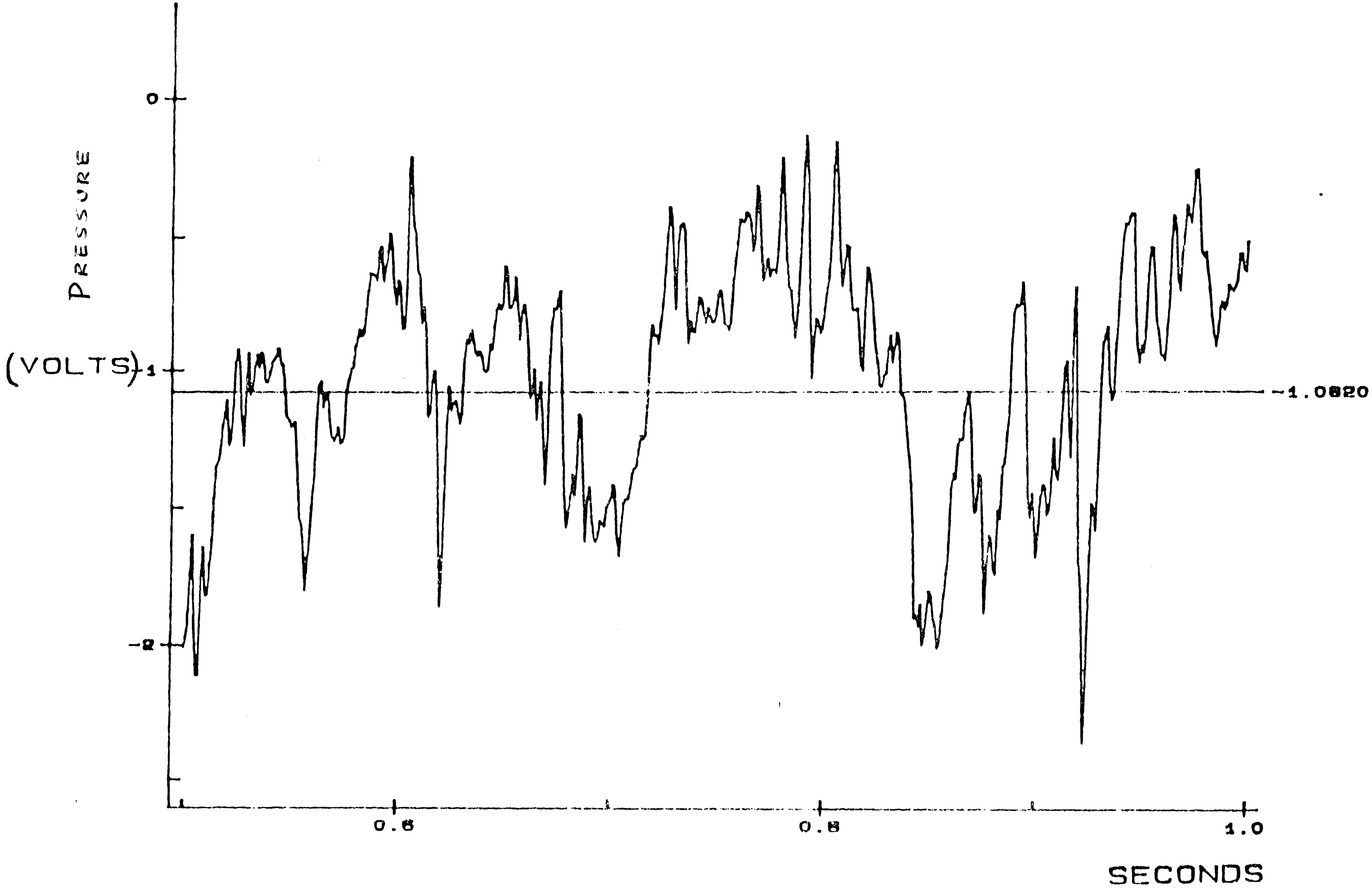


Figure 1. Random Wind Pressure Trace on Roof Claddings

Table 3. Wind Tunnel Fatigue Matrix for $\theta = 75°$, Gable End Roof and Rural Terrain

Range/P_{uc}	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Mean/P_{uc}	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15	1.25
(1) 0.05	5,821	132	5	1	0	0	0	0	0	0	0	0	0
(2) 0.15	23,296	2,604	479	151	15	1	0	0	0	0	0	0	0
(3) 0.25	18,344	4,828	1,529	667	302	135	26	0	0	0	0	0	0
(4) 0.35	6,852	2,888	1,029	375	234	154	122	66	31	5	0	0	0
(5) 0.45	1,942	970	377	139	61	27	9	15	15	6	9	1	0
(6) 0.55	556	254	110	36	15	8	6	1	1	1	0	1	0
(7) 0.65	149	59	32	8	3	0	0	0	0	0	0	0	0
(8) 0.75	55	22	2	2	0	0	0	0	0	0	0	0	0
(9) 0.85	9	5	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	2	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_{uc}}$ = Maximum Peak Pressure Coefficient at the given location for all wind directions

All pressure cycles are negative, i.e., suction on roof.

It was then required to specify a design cyclone by the variation of wind speed and direction for the duration of **five hours**. The wind speed at a particular location and time during a tropical cyclone depends on the central pressure, the radius to maximum winds, the forward speed of the eye, the surface terrain and other meteorological factors. An empirical formula based on the observed data during cyclone Winifred (Reardon et al. 1986) was used for this purpose. The design cyclone in this analysis was assumed to have similar characteristics as cyclone Winifred (Reardon et al. 1986), but at the same time as severe as cyclone Tracy. Accordingly, a central pressure of 930 mb, a forward speed of the eye of 15 km/hour, a radius to maximum winds of 25 kms and a few empirical factors and constants were assumed in the analysis. The selection of the cyclone parameters as above produced a cyclone with a peak wind speed that matched the corresponding ultimate wind speed of 70 m/s specified by the wind loading code for cyclone Region C and rural terrain conditions (SAA, 1989).

In the analysis described in Jancauskas et al. (1990) simple trigonometry and vector addition rules were used. Peak wind speed during the cyclone was made to coincide with the direction producing the maximum peak pressure at the particular location under study. A Fortran program "MATRIX" was written by Jancauskas et al. (1990) to do the analysis, which could use any time interval. Figure 2 shows the variation of wind speed and direction at 4 m height and gable end location during the design cyclone for rural terrain conditions. Similar figures (total of four) were obtained for other locations and terrain conditions. It is to be noted that a time interval of 1 minute was used to obtain Figure 2. However, it was found that a time interval of 15 minutes would have been adequate to give sufficient accuracy.

For each location and terrain conditions, there were 13 wind tunnel matrices for a range of wind directions similar to that shown in Table 3, and time history information on wind speed and direction for a design cyclone as in Figure 2. Program MATRIX was then used to determine the full scale fatigue wind loading matrix. A suitable analysis time interval was first chosen. For each time interval a wind tunnel matrix was determined based on the wind direction given by Figure 2, by interpolating between the appropriate wind tunnel matrices. It was then converted to full scale conditions as shown in Jancauskas et al. (1990). The sum of all these full scale matrices gave the fatigue wind loading matrix for the design cyclone for the selected location and terrain conditions.

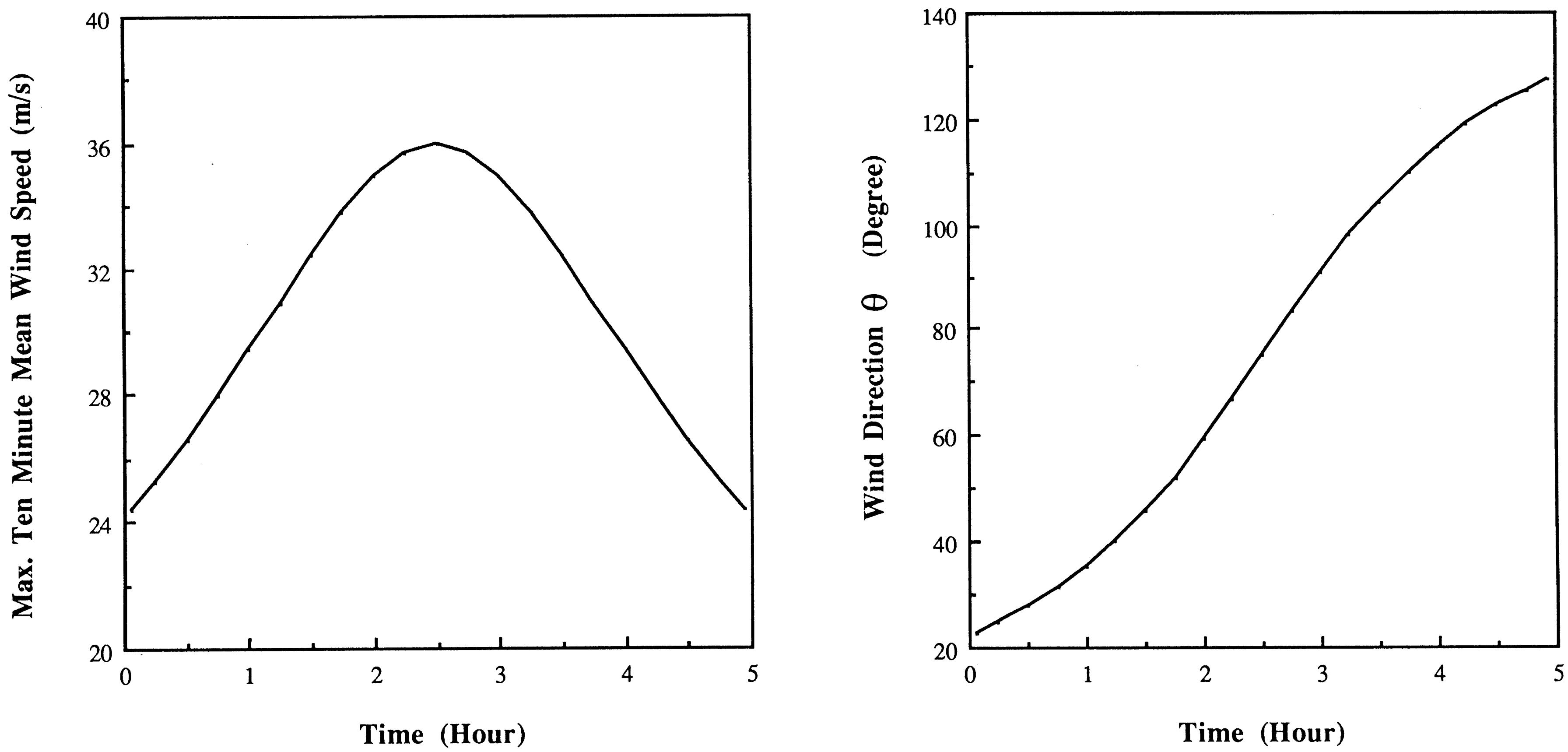


Figure 2. Variation of Wind Speed and Direction during the Design Cyclone

For an analysis time interval of 15 minutes, 21 full scale fatigue wind loading matrices were derived to represent the 5-hour design cyclone in a matrix format similar to that in Table 3. Addition of all the 21 matrices produced the fatigue wind loading matrix for the design cyclone. Table 4 presents the fatigue wind loading matrix for the gable end location and rural terrain conditions, which was found to be the worst case (highest loading). Table 4 matrix is also shown as a three-dimensional plot in Figure 3. Since Program MATRIX allows any time interval, a much smaller time interval of 1 minute also can be used to improve the accuracy of results. It was found that the results converged after the time interval has been reduced to 15 minutes, and thus for most cases a time interval of 15 minutes was chosen.

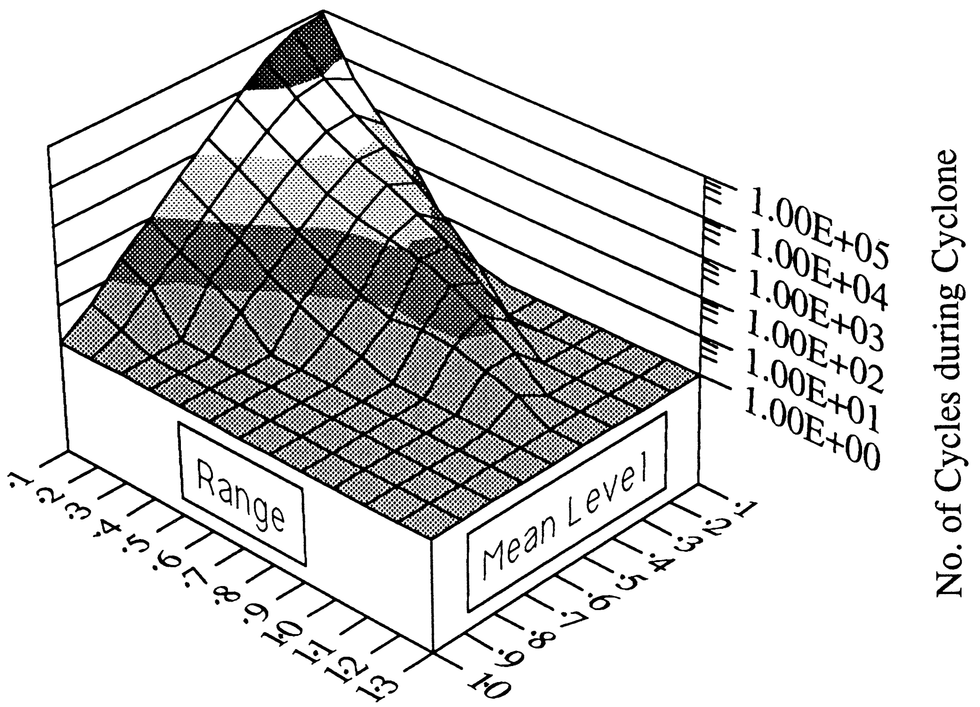


Figure 3. Fatigue Wind Loading matrix for the Design Cyclone

Table 4. Fatigue Wind Loading Matrix for the Design Cyclone

Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	82,915	3,682	549	89	7	0	0	0	0	0	0	0	0
(2) 0.15	70,019	9,279	2,413	778	213	51	9	1	0	0	0	0	0
(3) 0.25	29,613	6,923	2,073	894	474	207	72	19	5	1	0	0	0
(4) 0.35	7,415	2,478	838	317	175	120	87	48	19	5	1	0	0
(5) 0.45	1,716	675	242	86	31	13	7	9	8	5	3	0	0
(6) 0.55	403	154	60	19	7	3	2	1	0	0	0	0	0
(7) 0.65	92	34	14	5	1	0	0	0	0	0	0	0	0
(8) 0.75	25	10	1	1	0	0	0	0	0	0	0	0	0
(9) 0.85	4	2	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

3. Simulation of Cyclonic Wind Forces by Random Block Load Testing

3.1 General

This section describes how the cyclonic wind forces were simulated experimentally based on the fatigue wind loading matrix presented in Section 2. The loading on aircraft during service or on roof claddings during cyclonic winds is of a variable amplitude type (random). Therefore as done in the aircraft industry the loading on roofing can be simulated by a number of ways such as random loading using a random wind pressure trace similar to that in Figure 1 or programmed random block loading using the cyclonic wind loading matrix shown in Table 4. Figure 4 illustrates how the loading matrix in Table 4 can be applied in random block load testing.

In this research project it was decided to test all the common steel roofing profiles under simulated cyclonic wind loading. The common steel roofing profiles manufactured by Lysaght Building Industries (LBI) are shown in Figure 5. Figure 5 shows the geometry and the current design load of each profile. This section presents how cyclonic wind forces were simulated on these roofing profiles.

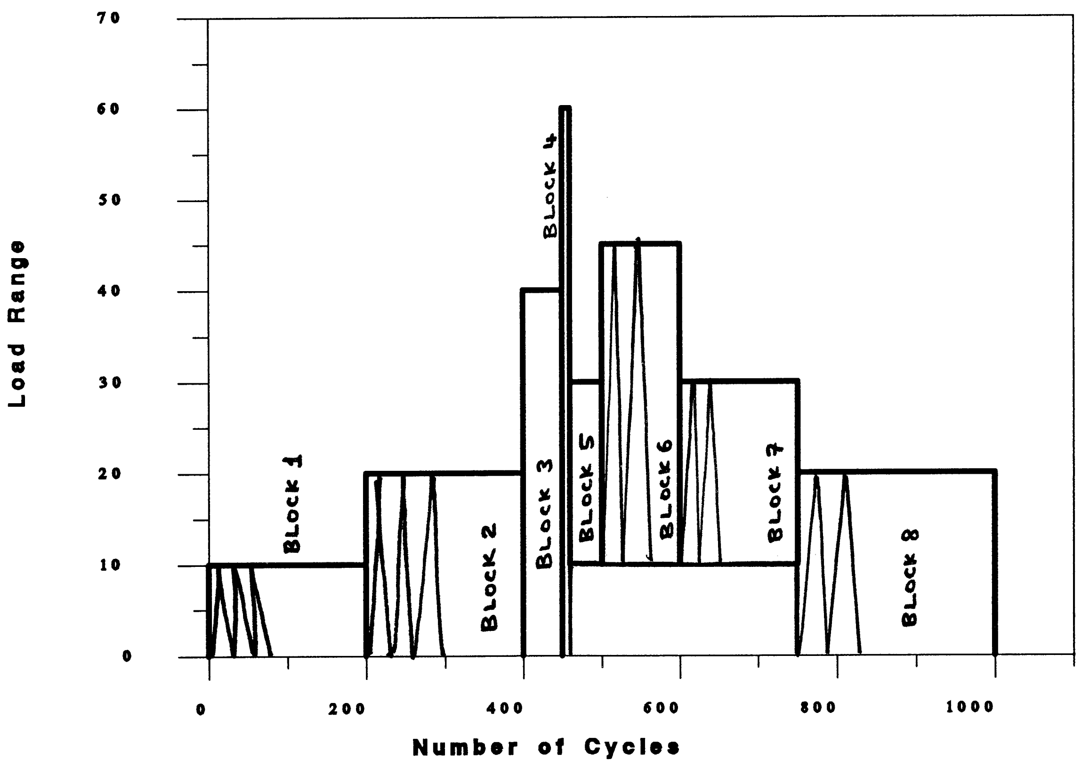
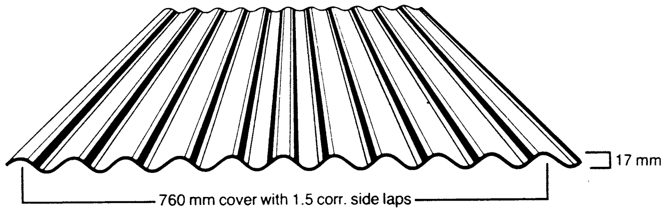


Figure 4. Random Block Load Testing



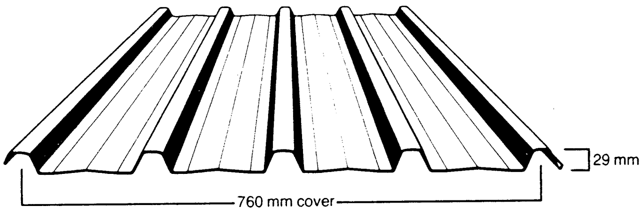
p = 76 mm, d = 17 mm

Custom Orb : BMT = 0.42 mm TCT = 0.47 mm, D = 550 N/f

BMT = 0.48 mm TCT = 0.53 mm, D = 680 N/f

Custom Blue Orb: BMT = 0.61 mm TCT = 0.66 mm, D = 590 N/f

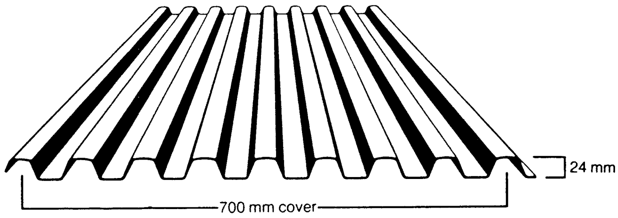
Corrugated Roofing Profiles



p = 190 mm, d= 29 mm

Trimdek : BMT = 0.42 mm TCT = 0.47 mm, D = 630 N/f

BMT = 0.48 mm TCT = 0.53 mm, D = 660 N/f



p = 87.5 mm, d = 24 mm

Spandek : BMT = 0.42 mm TCT = 0.47 mm, D = 395 N/f

BMT = 0.48 mm TCT = 0.53 mm, D = 600 N/f

Trapezoidal Roofing Profiles

Figure 5. Common Steel roofing Profiles (LBI, 1987)

Note: BMT = base metal thickness, TCT = Total Coated Thickness

p = pitch, d = depth, D = Working design Load in Newtons per Fastener (N/f)

Roofing material yield strength (minimum) = 550 MPa,

except for Custom Blue Orb for which it is 300 MPa

3.2 Random Block Load Testing Method

It is true that a random load testing method will simulate quite well a randomly varying cyclonic wind loading shown in Figure 1. However, in this research project it was decided to use a random block load testing method rather than a random load testing method. This was due to the following reasons.

(1) The wind tunnel investigation produced only a fatigue wind loading matrix representing a design cyclone (Table 4), which obviously suited a random block load testing method. It is noted that this wind loading matrix accounts for the change of wind direction during a cyclone and represents full scale conditions. If a random load testing method is to be used, the wind tunnel random wind pressure traces that were obtained for various wind directions and model conditions need to be modified and integrated to derive a single random pressure trace representing a design cyclone. This was considered a difficult task than deriving the fatigue wind loading matrix in Table 4.

(2) The commercially available hydraulic testing machines usually handle random block load testing more easily than random load testing.

As seen in the fatigue wind loading matrix in Table 4, there are **64 blocks of loading**, i.e., cells without nonzero cycles, representing a design cyclone. Each block of loading has a mean level and range expressed as a ratio of ultimate design wind load. Accordingly the maximum and minimum cyclic loads for each cell of loading could be obtained by using the current design load per fastener used by the manufacturers of roofing and a factor of 1.5 to convert the working design load to ultimate design load. For example, consider one of LBI's roofing profiles shown in Figure 5, Custom Orb with 0.42 mm base metal thickness (BMT) and 0.47 mm total coated thickness (TCT). The current working design load per fastener for this roofing is 550 N (LBI, 1987).

For cell 5 x 7,

$$\text{Minimum cyclic load} = \text{Mean level} - 0.5 \times \text{Range}$$
$$= 0.45 - 0.5 \times 0.65 = 0.125$$
$$\text{Maximum cyclic load} = \text{Mean Level} + 0.5 \times \text{Range}$$
$$= 0.45 + 0.5 \times 0.65 = 0.775$$

The above values are given as ratios of ultimate design wind load. Since the ultimate design load of roofing is 550 x 1.5 = 825 Newtons per fastener (N/f), the above ratios can now be converted to N/f. They will be 103 and 639 N/f, respectively.

Table 5. Cyclone Wind Loading Matrix for Custom Orb (BMT=0.42mm) Roof Cladding

Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	21 - 62 82,915	0 - 103 3,682	0 - 144 549	0 - 186 89	0 - 227 7	0 - 268 0	0 - 309 0	0 - 351 0	0 - 392 0	0 - 433 0	0 - 474 0	0 - 516 0	0 - 557 0
(2) 0.15	103-144 70,019	62-186 9,279	21-227 2,413	0 - 268 778	0 - 309 213	0 - 351 51	0 - 392 9	0 - 433 1	0 - 474 0	0 - 516 0	0 - 557 0	0 - 598 0	0 - 639 0
(3) 0.25	186-227 29,613	144-268 6,923	103-309 2,073	62-351 894	21-392 474	0 - 433 207	0 - 474 72	0 - 516 19	0 - 557 5	0 - 598 1	0 - 639 0	0 - 681 0	0 - 722 0
(4) 0.35	286-309 7,415	227-351 2,478	186-392 838	144-433 317	103-474 175	62-516 120	21-557 87	0 - 598 48	0 - 639 19	0 - 681 5	0 - 722 1	0 - 763 0	0 - 804 0
(5) 0.45	351-392 1,716	309-433 675	268-474 242	227-516 86	186-557 31	144-598 13	103-639 7	62-681 9	21-722 8	0 - 763 5	0 - 804 3	0 - 846 0	0 - 887 0
(6) 0.55	433-474 403	392-516 154	351-557 60	309-598 19	268-639 7	227-681 3	186-772 2	144-763 1	103-804 0	62-846 0	21-887 0	0-928 0	0-969 0
(7) 0.65	516-557 92	474-598 34	433-639 14	392-681 5	351-722 1	309-763 0	268-804 0	227-846 0	186-887 0	144-928 0	103-969 0	62-1011 0	21-1051 0
(8) 0.75	598-639 25	557-681 10	516-722 1	474-763 1	433-804 0	392-846 0	351-887 0	309-928 0	268-929 0	227-1011 0	186-1052 0	144-1093 0	103-1134 0
(9) 0.85	681-722 4	639-763 2	598-804 0	557-846 0	516-887 0	474-928 0	433-969 0	392-1011 0	351-1052 0	309-1093 0	268-1134 0	227-1176 0	186-1217 0
(10) 0.95	763-804 0	722-846 2	681-887 0	639-928 0	598-969 0	557-1011 0	516-1052 0	474-1093 0	433-1134 0	392-1176 0	351-1217 0	309-1258 0	268-1299 0

Note : 1. **P_u** = Ultimate Design Wind Load

2. Each cell has first the load range (Minimum to Maximum cyclic load) in Newtons and then the Number of loading cycles

3. All loading cycles are negative, i.e., suction on roof

It is to be noted that the above values represent wind uplift (suction pressure). In some cases, for example cell 1 x 4, when the minimum cyclic load is a negative value, it represents a downward loading on roofing (positive pressure). Since this loading is considered to cause negligible fatigue damage to roofing, the minimum cyclic load was taken as zero, and thus the cell 1 x 4 loading becomes 0 to 186 N/f. Table 5 presents the cyclic load range calculated thus for each block of loading in the fatigue wind loading matrix in Table 4 for 0.42 mm BMT Custom Orb roofing profile. Similar tables can be obtained for other roofing profiles. The only data required is the current design load per fastener of the roofing, which is shown in Figure 5.

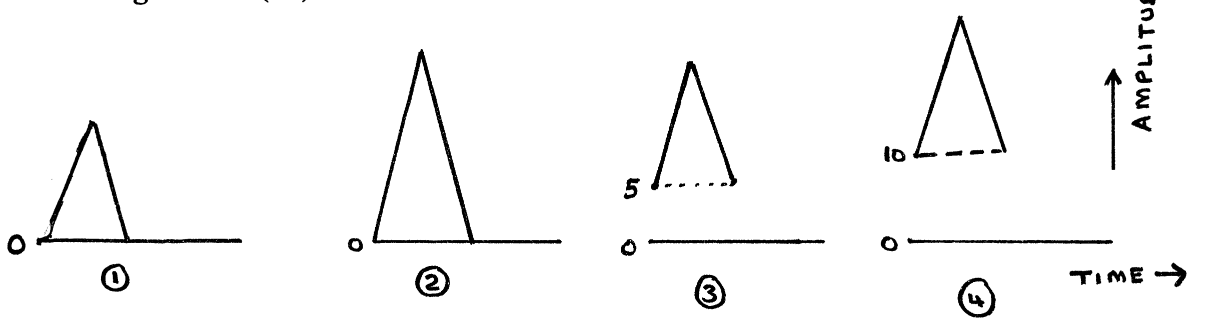
It is noted that in Table 5 loading is expressed in terms of the average load per fastener (N/f) because it is the critical loading parameter governing the fatigue behaviour of roof claddings (Mahendran, 1989). However, if it is required to rewrite Table 5 in terms of uplift wind pressure, the corresponding wind pressures can be easily calculated for each roofing profile and span.

In the process of deriving the fatigue wind loading matrix for the design cyclone, the order in which the loads were applied, the sequence, was lost. In order to re-introduce the lost random nature of loading, the loading blocks were randomly chosen from the matrix.

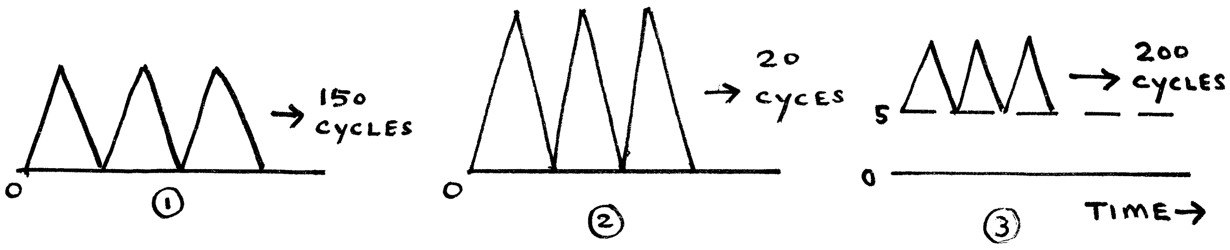
It can be seen from Table 4 or 5 that loading blocks with lower magnitude (those in the right hand top corner of Table 5) had many thousands of cycles. It is known that loading blocks with smaller magnitude, for example, loading block represented by cell 1 x 1, causes negligible fatigue damage to roofing. Based on Ekvall and Young (1976), it was decided not to include the blocks of loading which had a maximum cyclic load level below 80% of the conventional fatigue limit or endurance limit. In the case of 0.47 mm TCT Custom Orb roofing, Mahendran (1989) found the endurance limit to be 285 N/f at 10^6 cycles based on the fatigue curve derived from constant amplitude cyclic tests. This value was used to eliminate the lower loading blocks. This reduced the number of loading blocks to be considered for random selection from **64 to 43** (see Table 5). This meant that so many thousands of lower loading cycles need not be included in testing, and resulted in significant reduction of testing time.

It is known that a more realistic random loading is produced by using a basic loading block with a small number of cycles. Hence it was decided to limit the **number of cycles in a block to 200**, considering all other practical reasons. Therefore the loading block such as that represented by cell 3 x 4 which has 894 cycles, will have to be divided into 5 smaller blocks of same loading (each with 179 cycles). This increased the blocks of loading for random selection from **43 to 89**. However, it is noted that the standard number of loading events was still 43 (some of 89 blocks repeating). That is, the 5 blocks of loading in cell 3 x 4 are of the same standard loading event with a load range from 62 N to 351 N.

Loading Events (43):



Loading Blocks (89):



Loading Sequence (1):

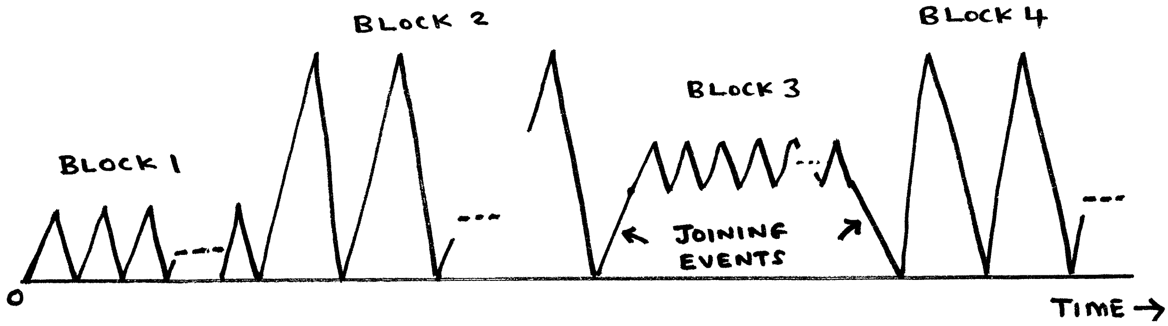


Figure 6. Events, Blocks and Sequences in Random Block Load Testing

All the 89 blocks of loading mentioned above were then assigned the numbers from 1 to 89. A Hewelett Packard-85B computer was then used to select numbers randomly from 1 to 89, and this formed the sequence of loading for the random block loading test. In summary the 43 standard loading events formed 89 loading blocks which formed a single final sequence (Figure 6).

When the loading blocks were selected randomly, there was discontinuity between many blocks because of the differing magnitudes. Therefore joining events (one half cycle only) were added in the form of ramp loading between the end of one block of loading to the beginning of the other as illustrated in Figure 6. The additional loading introduced by the joining events to the random block loading sequence was comparatively very small, however, they were accounted for by subtracting the cycles from the corresponding equivalent blocks of loading. Addition of joining events increased the standard number of events representing the RBL sequence to 120.

The same method was used for other roofing profiles of different thicknesses and geometry such as Custom Orb with BMT = 0.48 and TCT = 0.53, Custom Blue Orb with BMT = 0.60 and TCT = 0.66, Trimdek with BMT = 0.42 and TCT = 0.47 and Spandek with BMT = 0.42 and TCT = 0.47, shown in Figure 5. In each case, Table 5 was first modified for the given design load, and blocks of loading were again chosen randomly.

3.3 Improvement to the Simulation of Cyclonic Wind Forces

The wind loading matrix shown in Figure 3 and Table 4 contain all the loading cycles during the entire 5-hour design cyclone. Random block load testing method explained in previous section re-introduced the lost randomness as part of a loading matrix for the full 5-hour cyclone. It is common knowledge that cyclone builds up during the first half and it loses its strength in the second half. This is reflected in Figure 2 in which the wind speed increases to its maximum after 2 ½ hours, and then decreases during the following 2 ½ hours. In order to reproduce this in the simulation, the computer program "MATRIX" was used to develop the wind loading matrix for every hour for the 5-hour design cyclone. The analysis time interval used was still 15 minutes, but wind loading matrix was output at the end of every hour. These five matrices are given in Tables 6 (a) to (e). It is to be noted that the sum of these five matrices will give the full loading matrix in Table 4..

For each roofing profile, the cyclic load range corresponding to each cell of each of the matrices in Tables 6 (a) to (e) was calculated using the design load as explained in the previous section. This resulted in five matrices similar to the overall matrix given in Table 5 for Custom Orb (0.42 mm BMT). The same procedure used in the previous section to re-introduce the lost randomness was used for each matrix corresponding to every hour of the cyclone. They were then applied to the roof cladding one after the other in that order, simulating the cyclone of 5 hours duration.

Table 6 (a). Fatigue Wind Loading Matrix for the Design Cyclone at the end of First Hour

Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	34,849	728	82	1	0	0	0	0	0	0	0	0	0
(2) 0.15	1271	146	76	34	5	0	0	0	0	0	0	0	0
(3) 0.25	142	12	5	1	1	0	0	0	0	0	0	0	0
(4) 0.35	17	1	0	0	0	0	0	0	0	0	0	0	0
(5) 0.45	0	0	0	0	0	0	0	0	0	0	0	0	0
(6) 0.55	0	0	0	0	0	0	0	0	0	0	0	0	0
(7) 0.65	0	0	0	0	0	0	0	0	0	0	0	0	0
(8) 0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
(9) 0.85	0	0	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

Table 6 (b). Fatigue Wind Loading Matrix for the Design Cyclone at the end of Second Hour

Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	22,474	2,244	478	102	5	0	0	0	0	0	0	0	0
(2) 0.15	11,493	2,667	1,143	436	138	48	7	0	0	0	0	0	0
(3) 0.25	5,182	1,213	377	190	126	59	26	6	1	0	0	0	0
(4) 0.35	1,195	346	90	24	9	6	5	3	0	0	0	0	0
(5) 0.45	155	42	13	2	1	0	0	0	0	0	0	0	0
(6) 0.55	19	4	3	1	0	0	0	0	0	0	0	0	0
(7) 0.65	2	0	0	0	0	0	0	0	0	0	0	0	0
(8) 0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
(9) 0.85	0	0	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

Table 6 (c). Fatigue Wind Loading Matrix for the Design Cyclone at the end of Third Hour

Range/P_u	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Mean/P_u	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15	1.25
(1) 0.05	4,821	176	19	5	0	0	0	0	0	0	0	0	0
(2) 0.15	16,481	1,968	398	129	28	8	1	0	0	0	0	0	0
(3) 0.25	12,103	3,196	1,005	421	191	82	22	6	2	0	0	0	0
(4) 0.35	4,308	1,771	614	228	137	91	64	34	13	3	1	0	0
(5) 0.45	1,175	561	212	76	32	14	7	9	6	4	3	0	0
(6) 0.55	319	139	59	18	8	4	2	1	1	0	0	0	0
(7) 0.65	85	33	14	4	1	0	0	0	0	0	0	0	0
(8) 0.75	27	10	1	1	0	0	0	0	0	0	0	0	0
(9) 0.85	4	2	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	1	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

Table 6 (d). Fatigue Wind Loading Matrix for the Design Cyclone at the end of Fourth Hour

Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	8,979	500	34	1	0	0	0	0	0	0	0	0	0
(2) 0.15	21,888	2,636	477	110	19	2	0	0	0	0	0	0	0
(3) 0.25	8,970	1,904	559	173	72	26	7	0	0	0	0	0	0
(4) 0.35	1,060	286	94	26	14	7	3	1	0	0	0	0	0
(5) 0.45	65	19	7	2	0	0	0	0	0	0	0	0	0
(6) 0.55	9	3	1	0	0	0	0	0	0	0	0	0	0
(7) 0.65	0	0	0	0	0	0	0	0	0	0	0	0	0
(8) 0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
(9) 0.85	0	0	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

Table 6 (e). Fatigue Wind Loading Matrix for the Design Cyclone at the end of Fiifth Hour

Range/P_u	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Mean/P_u	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15	1.25
(1) 0.05	12,240	216	3	0	0	0	0	0	0	0	0	0	0
(2) 0.15	21,020	1,931	319	65	8	0	0	0	0	0	0	0	0
(3) 0.25	3,646	620	110	33	14	2	0	0	0	0	0	0	0
(4) 0.35	197	43	6	0	0	0	0	0	0	0	0	0	0
(5) 0.45	5	2	0	0	0	0	0	0	0	0	0	0	0
(6) 0.55	0	0	0	0	0	0	0	0	0	0	0	0	0
(7) 0.65	0	0	0	0	0	0	0	0	0	0	0	0	0
(8) 0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
(9) 0.85	0	0	0	0	0	0	0	0	0	0	0	0	0
(10) 0.95	0	0	0	0	0	0	0	0	0	0	0	0	0

Note : $\mathbf{P_u}$ = Ultimate Design Wind Load

All pressure cycles are negative, i.e., suction on roof.

3.4 Experimental Method

A two-span roofing assembly with simply supported ends subjected to midspan line loads was considered adequate to model the critical regions of a multi-span roofing assembly for all the RBL tests. The test set-up was identical to that used by Mahendran (1988, 1989,1990a,b) for the constant amplitude cyclic test series. A test span of 650 mm was selected to represent the most common prototype end span of 900 mm. This ensured that the critical loading parameters, the load per fastener and the bending moment at the central support were modelled correctly. Roofing specimens were fastened to timber battens as per the manufacturer's specifications (LBI, 1987), i.e., Custom Orb and Custom Blue Orb (corrugated roofing), and Spandek at alternate crests, Trimdek at every ribbed crest. The fasteners were No. 14 x 50/65 mm Type 17 self-drilling screws with EPDM seals. A servo-controlled hydraulic testing machine was used to load the specimen cyclically. The reaction at the central support was measured using a load cell. Average load per fastener at the central support (reaction force/number of fasteners) was then used to control the tests. Figure 7 shows the test set-up.

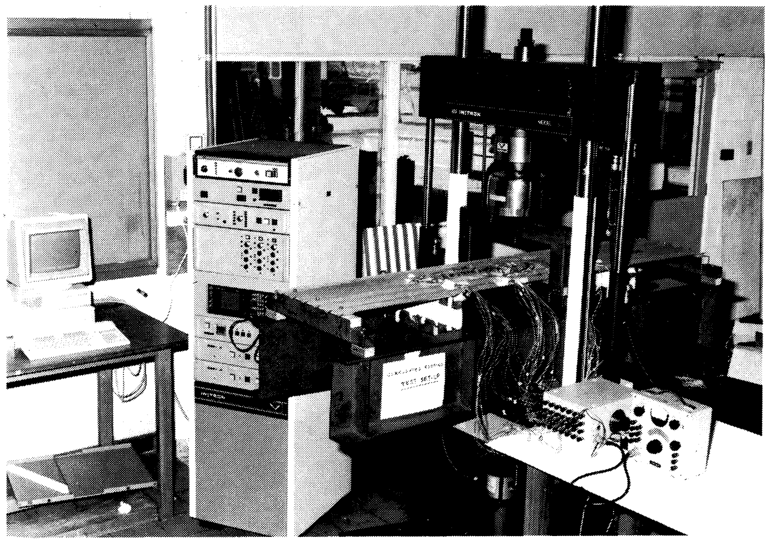


Figure 7. Test Set-up

All the RBL tests were conducted under computer control. A microcomputer connected to the hydraulic testing machine (see Figure 7) controlled the tests. All the loading data on the RBL sequence **in terms of Newtons per fastener** were fed to the computer using a computer program BLOCK. This program requires the user to define all the standard events first in terms of minimum and maximum cyclic loads, type of wave form, number of cycles and the loading frequency. In this case there were 43 major standard events which had a maximum of 200 cycles, and a few joining events with only half cycle. For all the events a haver sine waveform was chosen. Same frequency was used for all the events in a test. Initial tests were attempted at a frequency of 1 Hz, but was lowered to 0.3 Hz for later tests due to various problems in conducting the RBL test.

The program was then instructed regarding the order in which these loading events should be applied for the random block loading sequence. For this purpose, blocks of loading were then defined in terms of the standard events and the sequence in terms of the blocks. After inputting all the above required data, the RUN option was pressed which let the computer take control of the servo-controlled hydraulic machine. The loading blocks were applied to the roofing assembly according to the RBL sequence. Test was continued until the failure of roofing when one or more fasteners pulled through the cracked roofing. When the failure occurred, computer terminated testing. If the roofing survived one full sequence, computer repeated the loading sequence until failure.

During the RBL test, computer printed input loading data for the current block of loading, and the corresponding output loading. This enabled monitoring of the test continuously. All the input and output data on the peak loads of each block of loading was written to a file during the test. Examination of the output file revealed all the information of the RBL test even if it was totally unattended.

3.5 Suitability of Random Block Load Testing Method

Random block testing method using the fatigue wind loading data from wind tunnel testing is complicated and time consuming, particularly when the cyclonic wind forces are simulated on an hourly basis for five hours (see Section 3.3). However, it is currently the best method to simulate cyclonic wind forces accurately by including the effects of wind direction and wind speed which occur during the cyclone. Obviously it is an excellent tool for research in this area, but may not suit the routine product testing. Therefore, it will not replace the current fatigue tests, the TR440 test or DABM test.

Research should be continued in this area using the RBL testing in an attempt to verify the adequacy of current fatigue tests. If the fatigue tests are found to be inadequate, a new fatigue test needs to be developed which is simpler like the current fatigue tests, but at the same time accurate as the RBL test. This can be achieved with further research in this area using RBL testing.

4. Conclusions

A random block load testing method to simulate the cyclonic wind forces on roof claddings was described in this report. Cyclonic wind loading characteristics derived from wind tunnel testing and analysis (Jancauskas et al. 1990) was used to simulate the loading on the most common steel roof claddings. Suitability of this method was discussed, particularly as a research tool to verify the adequacy of current fatigue tests, and if necessary to develop a new test.

5. Acknowledgements

This research project was carried out while the author was a Research Engineer at the Cyclone Testing Station. The author wishes to thank the Building Research and Development Advisory Committee for their financial support, and Lysaght Building Industries and W.A. Deutsher Pty. Ltd. for donating the roofing materials required for testing. Thanks are due to the Station's Technical Director, Mr. G.F. Reardon and Dr. G.R. Walker, the Chief Research Scientist of the Division of Building, Construction and Engineering of CSIRO for their support and guidance in this research project.

6. References

Capitanio, C.R. (1987) Fatigue Characteristics of Wind Loading on Low-rise Buildings, B.E. Thesis, James Cook University, Townsville.

Beck, V.R. and Morgan, J.W. (1975) Appraisal of Metal Roofing under Repeated Wind Loading - Cyclone Tracy Darwin 1974, Australian Department of Housing and Construction, Housing Research Branch, Tech. Rept. No.1, Feb.

Beck, V.R. and Stevens, L.K. (1979) Wind Loading Failures of Corrugated Roof Cladding, Civil Eng. Transactions, Vol. CE21, No.1, pp.45-56.

Darwin Reconstruction Commission (DRC) (1976), DABM - Darwin Area Building Manual, Darwin.

Ekvall, J.C. and Young, L. (1976) Converting Fatigue Loading Spectra for Flight-by-Flight Testing of Aircraft and Helicopter Components, J. of Testing and Evaluation, Vol.4, No.4.

Experimental Building Station (EBS) (1978), TR440 - Guidelines for the Testing and Evaluation of Products for Cyclone Prone Areas, Sydney.

Jancauskas, E.D.J., Walker, G.R. and Mahendran, M. (1989) Fatigue Characteristics of Wind Loads on Roof Cladding, Proc. of the 2nd Asia-Pacific Symposium on Wind Engineering, Beijing, China.

Jancauskas, E.D.J., Mahendran, M., Walker, G.R., Capitanio, C. and Prien, G.D. (1990) Computer Simulation of the Fatigue Behaviour of Roof Cladding During the Passage of a Tropical Cyclone, Proc. of the 12th ACMSM Conf., Queensland University of Technology, Brisbane, pp.327-334.

Lysaghts Building Industries (LBI) (1987) LBI Reference Manual, Sydney.

Mahendran, M. (1988) Static Behaviour of Corrugated Roofing under Simulated Wind Loading, Technical Report No.33, Cyclone Testing Station, James Cook University.

Mahendran, M. (1989) Fatigue Behaviour of Corrugated Roofing under Cyclic Wind Loading, Technical Report No.35, Cyclone Testing Station, James Cook University.

Mahendran, M. (1990a) Static Behaviour of Corrugated Roofing under Simulated Wind Loading, Civil Eng. Transactions, I.E.Aust., Vol. CE32, No.4, pp.212-218.

Mahendran, M. (1990b) Fatigue Behaviour of Corrugated Roofing under Cyclic Wind Loading, Civil Eng. Transactions, I.E.Aust., Vol. CE32, No.4, pp.219-226.

Mahendran, M. (1992) Fatigue Behaviour of Light Gauge Steel Roof Claddings under Simulated Cyclonic Wind Forces, Technical Report, Cyclone Testing Station, James Cook University, In Print.

Melbourne, W.H. (1977) Loading Cycles for Simulation of Wind Loading, Proc. of Workshop on Guidelines for Cyclone Product Testing and Evaluation, Experimental Building Station, Sydney.

Morgan, J.W. and Beck, V.R. (1977) Failure of Sheet-metal Roofing under Repeated Wind Loading, Civil Eng. Transactions, Vol.CE19, No.1, pp.1-5.

Prien, G.D. (1989) Analysis of the Fatigue Behaviour of Corrugated Roof Cladding during Tropical Cyclones, B.E. Thesis, James Cook University, Townsville.

Reardon, G.F., Walker, G.R. and Jancauskas, E.D.J. (1986) Effect of Cyclone Winifred on Buildings, Tech. Report No.27, Technical Report, Cyclone Testing Station, James Cook University, Townsville.

Standards Australia (SAA) (1989) AS1170.2 - SAA Loading Code, Part 2: Wind Loads.