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FATIGUE BEHAVIOUR OF LIGHT GAUGE STEEL ROOF CLADDINGS UNDER SIMULATED CYCLONIC WIND FORCES

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Fatigue Behaviour of Light Gauge Steel Roof Claddings under Simulated Cyclonic Wind Forces

by

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ABSTRACT

Currently two different fatigue tests, the DABM test and the TR440 test, are being used in the cyclone prone areas to assess the fatigue susceptibilty of roof claddings. This is because the recent TR440 test has not been accepted in the Northern Territory. In order to remedy this unacceptable situation, 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 to 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 using a servo-controlled hydraulic testing machine in the structures laboratory. Two major groups of roofing profiles, namely the corrugated roofing and the trapezoidal roofing, were included in the investigation. Same roof claddings were also subjected to the standard TR440 test.

This report describes the fatigue behaviour of roof claddings when they were subjected to the random block loading tests and the TR440 tests. A few excursions of loading during the random block load test was found to cause significant fatigue damage on corrugated roofing, but caused the reverse effect on trapezoidal roofing. The observation on corrugated roofing was attributed to the dimpling of crests at the fastener holes due to the few excursions of loading. The contrasting behaviour of trapezoidal roofing was due to the membrane action at the crests. Details on the contrasting behaviour, and all the test results are presented in the report.

Comparison of the fatigue performance of roof cladding under random block load tests and TR440 tests was used to decide on the adequacy of the latter tests in simulating the cyclonic wind forces. It appeared that the TR440 test is unconservative for corrugated roofing profiles whereas it is conservative for trapezoidal profiles, mainly due to the contrasting behaviour. Fatigue behaviour of these roof claddings appears to be much more complicated than anticipated. Thus the task of assessing the adequacy of the standard fatigue tests or if necessary, developing a new fatigue test for all the cyclone prone areas, has become complicated. This report discusses the implications of this to the building industry, and suggests interim recommendations to resolve the current conflict over the duplicative fatigue testing.

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1. INTRODUCTION

Low cycle fatigue cracking of crest-fixed light gauge metal roofing in the vicinity of fasteners caused extensive damage to housing during cyclone Tracy (Morgan and Beck, 1977). Following cyclone Tracy, a standard fatigue test, the DABM test (DRC, 1976), was introduced for roof claddings in the cyclone prone areas of Australia (Table 1). The purpose of introduction of this test was to assess the strength of roof cladding under simulated cyclonic wind forces in the laboratory. Subsequently, the single level DABM test was considered to be too severe, and a less severe three-level test, the TR440 test (EBS, 1978), was introduced (Table 1) based on studies described in Beck and Stevens (1979) and Melbourne (1977). This test has now been incorporated in the new Australian wind loading code (SAA, 1989) and the new code on testing of metal claddings (SAA, 1992) in the ultimate limit state format. However, the Northern Territory has continued to require the DABM test. This situation is still continuing and is not acceptable to the roofing manufacturers and designers who have to satisfy two different criteria for the same roofing product. Further, there has been concern among the researchers about the adequacy of these standard fatigue tests in reproducing the randomly fluctuating cyclonic wind forces. There has been some instances when apparently weaker roofing systems passed the TR440 test loading. Therefore an extensive research programme was initiated at James Cook University with an objective of reviewing the current standard fatigue tests and if required, developing an appropriate fatigue test for roof claddings that represents the cyclonic loading adequately and that will be accepted in all the cyclone prone areas of Australia. This involved a study of the nature of cyclonic wind loading on roof claddings and the low cycle fatigue behaviour of steel roof claddings under simulated cyclonic wind loading .

In this process, the cyclonic wind forces on roof claddings were *first* determined using wind tunnel data on model houses and some actual data from cyclone Winifred that hit Innisfail in 1986. Details of this stage of investigation are given in Jancauskas et al. (1990). *Secondly*, the basic fatigue behaviour of roof cladding under simple constant amplitude cyclic wind loading was investigated, and the results are presented in Cyclone Testing Station's Technical Reports (Mahendran, 1988, 1989) and also in journal papers (Mahendran, 1990a,b). *Finally* identical roof claddings were subjected to simulated cyclonic wind loading and to the standard fatigue test loading in order to compare the analytical and experimental fatigue damage values caused by them. This final step of comparing the fatigue damage values was anticipated to resolve the conflict over the adequacy of current fatigue tests. Analytical fatigue damage values were obtained by integrating the cyclonic wind loading data from the first step and the fatigue data on roof cladding from the second step using Miner's law, and are presented in Jancauskas et al. (1990).

This report presents the details and results of the experimental work as regards the final step, in particular, the fatigue behaviour of profiled steel roof claddings when they were subjected to simulated cyclonic loading and standard fatigue test loading. Details of the experimental method for simulating cyclonic wind forces using a random block load testing method are given in another Cyclone Testing Station Technical Report (Mahendran, 1992).

Table 1. Standard Fatigue Tests for Roof Claddings

DABM Test		TR440 Test	
Cycles	Load Range	Cycles	Load Range
10,000	0 to 1.0 x Design Load*	8,000	0 to 0.625** x Design Load*
1	γ x Design Load	2,000	0 to 0.75 x Design Load
	$\gamma = 1.8$	200	0 to 1.0 x Design Load
		1	γ x Design Load,
			$\gamma = 1.6$ to 2.0 depending on the number of tests

Note: * - Working design load

** - In the new wind loading code (SAA, 1989), the coefficients 0.625, 0.75, 1.0 have become 0.4, 0.5 and 0.7, respectively corresponding to the Ultimate design load and $\gamma = 1$ if three samples are tested. If two samples are tested $\gamma = 1.2$ and for one sample $\gamma = 1.3$.

2. RANDOM BLOCK LOAD TESTS OF ROOF CLADDINGS

A design cyclone of 5 hours duration with an ultimate wind speed of *70 m/s for Region C* in the wind loading code (SAA, 1989) was mathematically modelled by Jancauskas et al. (1990) using the wind tunnel data on roof pressures for various wind directions. They used the data obtained from cyclone Winifred with cyclone parameters of central pressure of *930 mb, 25 kms radius to maximum winds* and a forward speed of *15 km/h*. Both effects of wind speed and direction with time were included in the model. They showed that the design cyclonic loading can be represented by a matrix consisting of the number of loading cycles for various combinations of range and mean level of loading expressed as a ratio of ultimate design wind load. This fatigue wind loading matrix is shown in Table 2. This matrix for the *gable end location* on the roof and *rural terrain* conditions was chosen as it was the most severe loading matrix.

Mahendran (1992) then describes how this matrix of loading representing a design cyclone could be simulated on steel roof claddings using a random block load (RBL) testing method. In this method, the 64 blocks of loading in Table 2 were further sub-divided into blocks with a maximum of 200 cycles, were then randomly chosen by a computer and applied to the roof cladding one after the other. This increased the number of block loadings further. However, in order to reduce test time the loading blocks which had a maximum cyclic load level below 80% of the conventional fatigue limit or endurance limit were not included. It is noted that the maximum and minimum cyclic loads for each block of loading was obtained using the current working 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.

The analytical program (Jancauskas et al., 1990) used to derive the fatigue wind loading matrix for the cyclone of five hours duration can be used to derive the loading matrices at any time interval. In order to simulate the cyclonic loading more accurately, a time interval of one hour was chosen which produced five matrices for the design cyclone (sum of these matrices gives the matrix in Table 2). It was noted that the severity of the loading matrix increased and reached a maximum for the third hour, and then decreased again, thus simulating a realistic cyclone. RBL sequence from each matrix was applied to the roof cladding one after the other until failure. Further details of the simulation of cyclonic wind forces using RBL testing method can be found in Mahendran (1992).

Table 2. Fatigue Wind Loading Matrix for the Design Cyclone

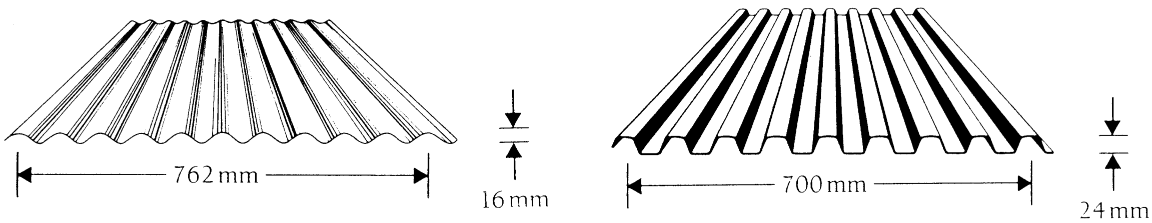
Range/P_u **Mean/P_u**	(1) 0.05	(2) 0.15	(3) 0.25	(4) 0.35	(5) 0.45	(6) 0.55	(7) 0.65	(8) 0.75	(9) 0.85	(10) 0.95	(11) 1.05	(12) 1.15	(13) 1.25
(1) 0.05	82,915	3,682	549	89	7	0	0	0	0	0	0	0	0
(2) 0.15	70,019	9,279	2,413	778	213	51	9	1	0	0	0	0	0
(3) 0.25	29,613	6,923	2,073	894	474	207	72	19	5	1	0	0	0
(4) 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.

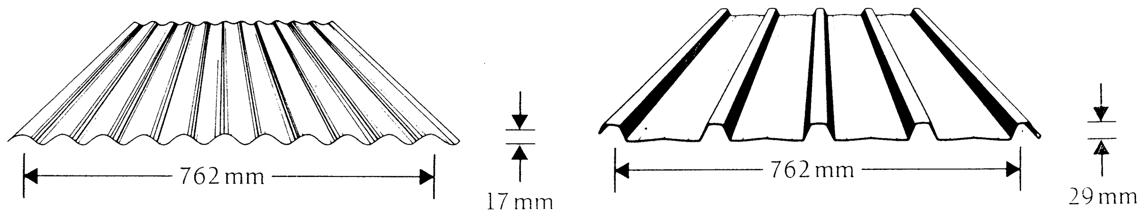
In Australia there are essentially two types of profiled steel roof claddings. This grouping was based on their fatigue behaviour under cyclic wind loading (Mahendran, 1990b). The arc and tangent type corrugated roofing represents the first group whereas the trapezoidal roofing which has trapezoidal ribs represents the second group. Therefore it was considered adequate to test these limited number of roofing profiles shown in Figure 1.

(i)



p=76, d=16, bmt=0.42, DF=550, bmt=0.48, DF=680   p=87.5, d=24, bmt=0.42, DF=395

(ii)



p=76, d=17, bmt=0.60, DF=590   p=190, d=29, bmt=0.42, DF=630

(a) Corrugated Roofing Profiles   **(b) Trapezoidal Roofing Profiles**

Note : bmt = Base Metal Thickness (mm), p = Pitch (mm), d = Depth (mm)
DF = Working Design Load per Fastener (Newtons)
Roofing material yield strength (minimum) = 550 MPa, except for (a) (ii)300 MPa

Figure 1. Profiled Steel Roof Claddings in Australia

Table 3. Cyclone Wind Loading matrix for 0.42 mm bmt Corrugated 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

The working design load per fastener DF for each roofing profile is also given in Figure 1. This information is required to determine the block loading from Table 2 in Newtons. An equivalent table of cyclonic wind loading in Newtons for 0.42 mm bmt corrugated roof cladding from Mahendran (1992) is reproduced here as Table 3. In Table 3, each block of loading is given in terms of minimum and maximum cyclic loads, instead of mean and range in Table 2. For other roof claddings, load levels are easily modified using the ratio of their working design loads. It is noted that the number of cycles in each loading block does not change.

When the design cyclonic loading for five hours was simulated more accurately using a time interval of one hour, it is to be noted that there were five wind loading matrices, each corresponding to an hour's loading in that order. Each loading matrix was then converted to Newtons in a similar format to that of Table 3 for each roof cladding. Thus there were five loading matrices when design cyclonic loading was simulated more accurately.

3. STANDARD FATIGUE TESTS OF ROOF CLADDINGS

It is believed that the loading represented by the fatigue wind loading matrix in Table 2 and simulated as a random block loading sequence on the roof cladding is the most appropriate design cyclone loading that is available at present. Therefore it is only necessary to determine whether the fatigue damage caused by the RBL sequence and the standard fatigue tests on roof claddings are the same. If not, a new, more appropriate, fatigue test needs to be developed.

Between the two standard fatigue tests, it is obvious that a single level cyclic loading test like the DABM test cannot represent a largely variable amplitude type cyclonic loading. The DABM test has always been considered too conservative and that is why the TR440 test was instigated in 1978. Therefore in the process of reviewing the standard fatigue tests, it is only necessary to consider the more appropriate test, the TR440 test, to determine whether it produces the same fatigue damage as that of the RBL sequence on roof claddings.

At present the TR440 test is used only as a low-high sequence followed by a static overload (see Table 1). The low-high sequence was adopted because it was considered to cause the worst fatigue damage to roof claddings (Beck and Stevens, 1979). However, in this research programme, the roof claddings shown in Figure 1 were tested to failure using a number of modified TR440 sequences such as

(i) Repeated low-high sequence with no static overload
- currently used sequence

(ii) Repeated high-low sequence with no static overload

(iii) Single static overload followed by repeated low-high sequence and

(iv) Single static overload followed by repeated high-low sequence
- a fully reversed TR440 sequence

For each roof cladding, the minimum and maximum cyclic loads for the TR440 loading sequences were determined using the working design load given in Figure 1.

4. EXPERIMENTAL METHOD

The same test set-up and testing procedure were used for both the RBL and TR440 tests, and the details of which are given in this section.

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 (Mahendran, 1990a,b). A test span of 650 mm was selected to represent the most common prototype end span of 900 mm. This ensured that the two critical loading parameters, the load per fastener and the bending moment at the critical central support, were modelled correctly.

Roofing specimens were fastened to timber battens at every crest for the trapezoidal roofing with pans, and at alternate crests for others (see Figure 1) by no.14 x 50/65 mm Type 17 self-drilling screws with EPDM seals (LBI, 1987). Fasteners were located centrally and vertically on the crests and were not overtightened. A servo-controlled hydraulic testing machine was used to simulate the cyclic wind uplift loading on roofing via specially made line loading pads at both midspans of the two-span roofing assembly. Figure 2 shows the experimental set-up.

For the RBL tests, a microcomputer fed with all the necessary loading data on the RBL sequence from Table 3 or similar tables (Section 2) controlled the tests. Roofing assembly was loaded from a specified minimum to a specified maximum loading for a specified number of cycles at a constant loading frequency. This was continued for all blocks of loading. Similar procedure was followed for the TR440 tests. However, it is to be noted that in the case of RBL tests there were numerous blocks of loading whereas for TR440 tests there were only three blocks of loading. A haversine waveform was adopted for all tests. Load cycling was controlled by the average load per fastener at the central support.

Average maximum and minimum cyclic loads per fastener at the central support for each block of loading in the RBL sequence or TR440 sequence were maintained by the computer during tests until the fatigue failure when one or more fasteners pulled through the roofing. If the failure did not occur during the first sequence, roofing was subjected to the same sequence again until failure occurred. At failure, the computer terminated the cyclic loading and recorded all the input and output data on loading during the test on a disc.

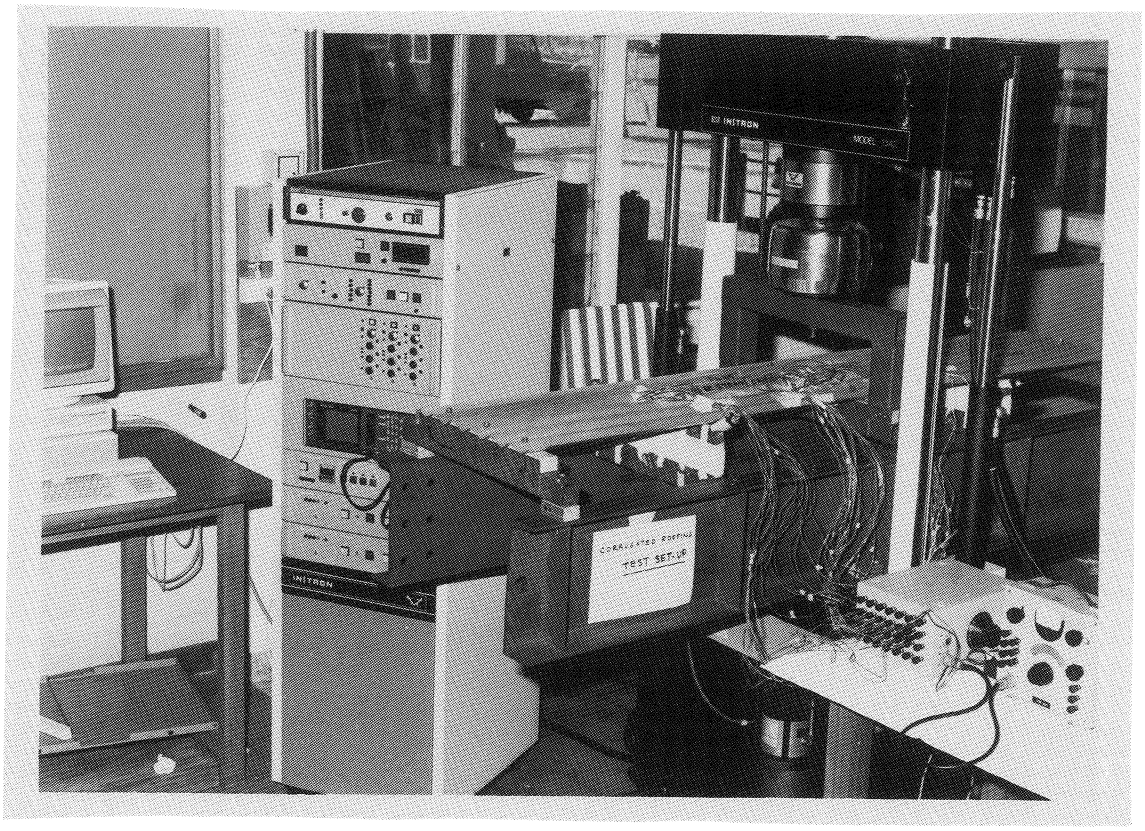


Figure 2. Experimental Set-up

5. RESULTS AND DISCUSSIONS

5.1 Corrugated Roofing Profiles

Table 4 presents the results from the RBL and TR440 tests for 0.42 mm bmt corrugated roofing. In Table 4 average number of applied sequences until failure was obtained by the ratio of the number of applied loading cycles to the total number of cycles per sequence, and was based on **at least two experiments** in each case. Average experimental fatigue damage per sequence was taken as the inverse of the number of applied sequences until failure, assuming that fatigue damage accumulates linearly.

When RBL tests based on the full design cyclone matrix in Tables 2 and 3 were conducted roofing failed prematurely. A total of three such tests was carried out and the average number of sequences applied until failure was 0.36. However, when the design cyclonic loading was simulated more correctly by using the five matrices obtained using an analysis time interval of one hour, the RBL tests (a total of two) gave an average value of 0.5 sequence until failure. In fact, in both tests, roofing failed during the RBL application of the third matrix, i.e., 2.5 hours from the beginning of the 5-hour cyclone. During the RBL tests, it was clear that roofing appeared to suffer noticeable cracking once the roof cladding had been loaded by the few higher load cycles in the RBL sequence, which dimpled the crests of roofing. Following the higher load cycles, cracking appeared to get worse even under lower load cycles.

In contrast to the above results, on average 2.25 TR440 sequences were required to cause the same fatigue failure of roofing. This implies that the TR440 test as it is used in its current low-high sequence form is **unconservative** for 0.42 mm bmt corrugated roofing. During the TR440 low-high sequence loading, roofing did not undergo the same dimpling of crests observed during RBL tests. Cracking appeared to have been mainly caused by the third/higher level of loading.

When only the cycles at lower loading levels were removed from the original RBL sequence, the fatigue damage caused by the RBL test decreased significantly (compare row numbers 1 and 2). This implies that even the cycles at lower load levels in the RBL sequence could be very damaging if they follow higher load cycles. This is in agreement with Ekvall and Young (1979) who observed that stress cycles to as low as 70 or 80% of the endurance limit can produce significant fatigue damage to aircraft components when included in the variable amplitude loading spectrum. It is noted that Jancauskas et al.'s

(1990) analysis using Miner's law did not predict such a reduction as it does not include the interaction effects between higher and lower load cycles.

TABLE 4. RBL and TR440 Test Results for Corrugated Roofing (0.42 mm bmt)

	Type of Test	Ave. No. of Applied Sequences until Failure	Ave.Fatigue Damage per Sequence
	RBL Tests		
1	RBL Test based on matrix in Table 2, Total Cycles=12,500	0.36	2.78
2	Subset of RBL Test in (1) above without lower loading blocks Total Cycles = 315 only	1.9	0.53
3	Subset of RBL Test in (1) above without lower loading blocks as in (2) and also higher load cycles causing dimpling of crests Total Cycles = 273 only	4.5	0.22
4	RBL Test simulating the cyclone more correctly by using 5 matrices each representing 1 hour cyclonic loading	0.5	2.0
	TR440 Tests		
5	TR440 Test-Low-High sequence without static overload	2.25	0.44
6	TR440 Test-High-Low sequence without static overload	1.5	0.67
7	Reverse TR440 Test - Overload then High-Low Sequence	0.5	2.0
8	Reverse TR440 Test - Overload then Low-High Sequence	1.0	1.0

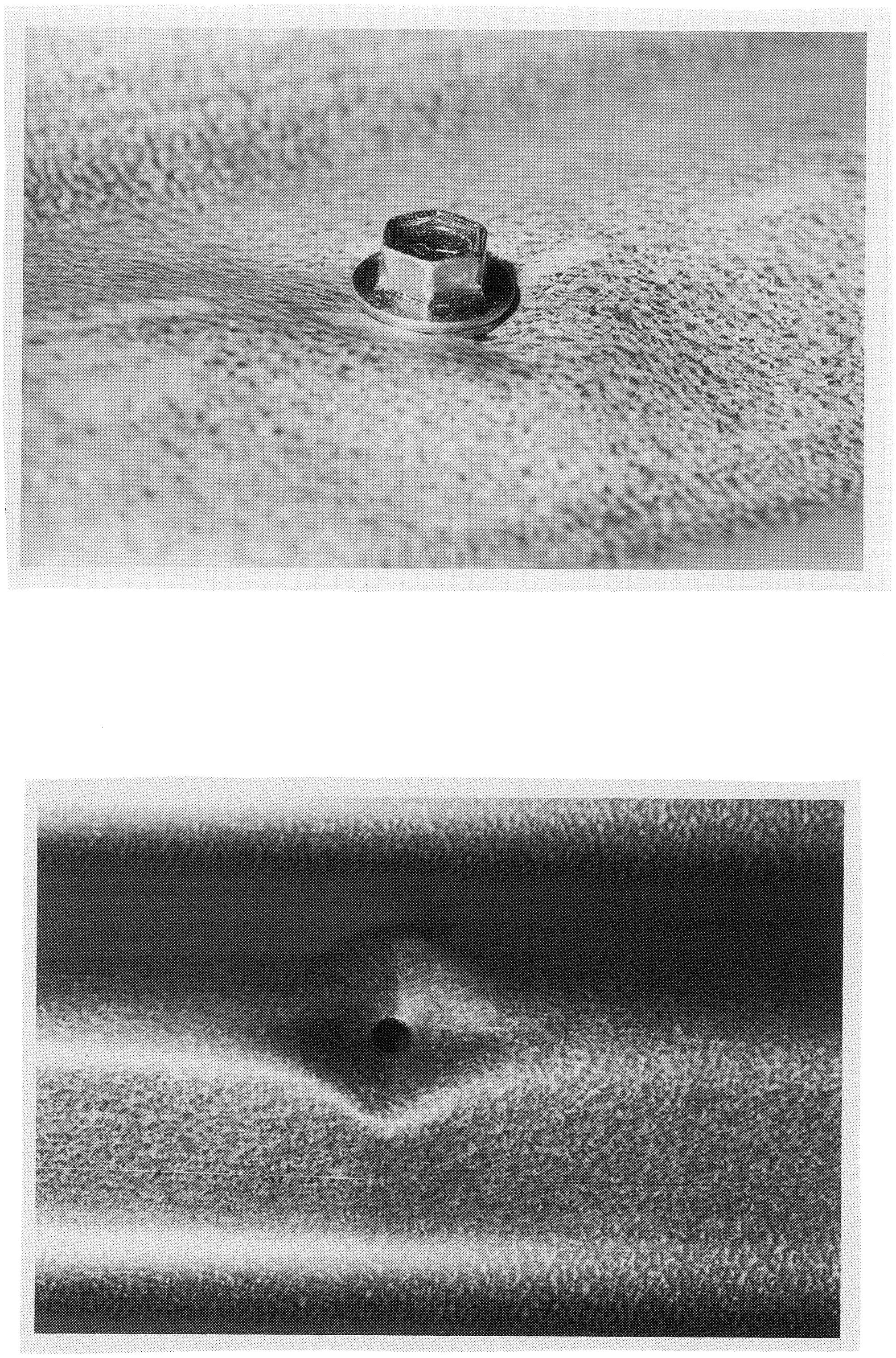


Figure 3. Local Plastic Deformations (Dimpling) at the Crests of Corrugated Roofing after a Higher Load Cycle

Static testing of corrugated roofing under wind uplift revealed that corrugated roofing suffers from dimpling of crests (see Figure 3) involving localised plastic deformations and well-defined yield lines around the fastener holes (Mahendran, 1990a). Unlike the TR440 low-high sequence, the RBL sequence had a few higher loading cycles in the middle of it that caused localised dimpling of crests. When they were removed from the RBL sequence, the fatigue damage caused by it was reduced further (compare row numbers 2 and 3). This shows the significant fatigue damage caused by these higher load cycles due to the development of plastic zones and yield lines around the holes.

From the above results, it can be seen that when higher loading cycles causing dimpling of crests were present, the roofing appeared to be less stiffer and there was a mechanism-like behaviour during the following cycles of loading. This accelerated the fatigue crack initiation along these yield lines, and thus forced a premature fatigue failure. Lower load cycles also caused significant fatigue damage. This explains the observation of reduced fatigue life of corrugated roofing when it was overloaded first.

Following this observation, a number of corrugated roof claddings were tested under constant amplitude cyclic loading, corresponding to the loading in Table 2, but they were first subjected to a few cycles of overloading that caused dimpling of crests. This led to the development of a second fatigue characteristics matrix (Mahendran, 1990b), but with significantly **smaller** number of cycles to failure. It is to be noted that the first fatigue characteristics matrix was obtained by testing the roof cladding under constant amplitude cyclic loading corresponding to the loading in Table 2, but without any prior overloading. Both these fatigue characteristics matrices are given in Mahendran (1990b). These matrices were used by Jancauskas et al. (1990) to determine the analytical fatigue damage caused by the RBL and TR440 sequences using Miner's law. Jancauskas et al. (1990) compares the analytical and experimental fatigue damage values, which did not agree in most cases. This indicated that the use of Miner's law in its simple form is not adequate to predict the fatigue damage of an RBL type sequence.

The TR440 test series also confirmed the greater damage caused by the higher/overload cycles. The reverse TR440 test caused a significant reduction in fatigue life because the preceding static overload caused dimpling of crests, and thus all the following lower load cycling whether low-high or high-low sequences, caused much greater fatigue damage. An increase in the magnitude of the static overload did not affect the results. This indicates that the onset of dimpling of crests is the significant factor in reducing the fatigue life. It is interesting to note that an exact reverse TR440 test (static overload-High-Low sequence) caused approximately the same fatigue damage as the design cyclone. This indicates the need to include a few cycles of excursions to the ultimate design load level in the TR440 sequence in order to simulate those in a cyclone.

As seen in Table 4, in both cases of TR440 and Reverse TR440 tests, the high-low sequence caused a greater fatigue damage than the low-high sequence. It appears then irrespective of the presence of the higher loading cycles causing dimpling of crests, the high-low sequence caused greater fatigue damage than the low-high sequence for corrugated roofing.

Figures 4 and 5 show the typical cracks observed during the RBL tests and the TR440 tests, respectively. The fatigue cracks observed during the usual TR440 low-high sequence test and the RBL test have no similarity between them. This again highlights the fact that the TR440 test does not represent the design cyclonic loading in the case of corrugated roofing. However, the crack observed during the reverse TR440 test is quite similar to that observed during the RBL test. This observation also confirms the need for the inclusion of a few cycles of excursions in the TR440 sequence. There were some differences in the cracks of those of low-high and high-low sequence tests. This emphasises why it is necessary to specify the type of sequence in a fatigue test, i.e. whether low-high or high-low.

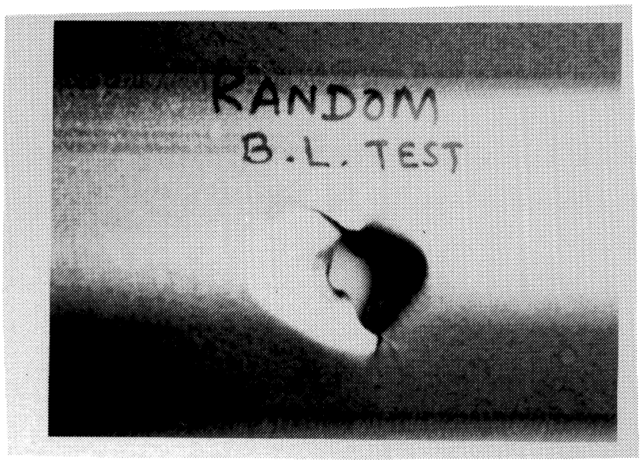
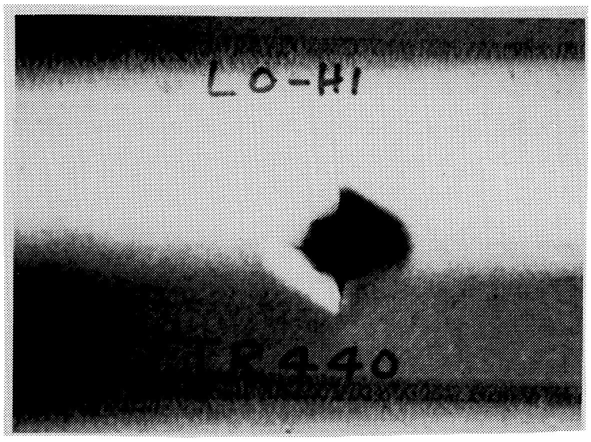
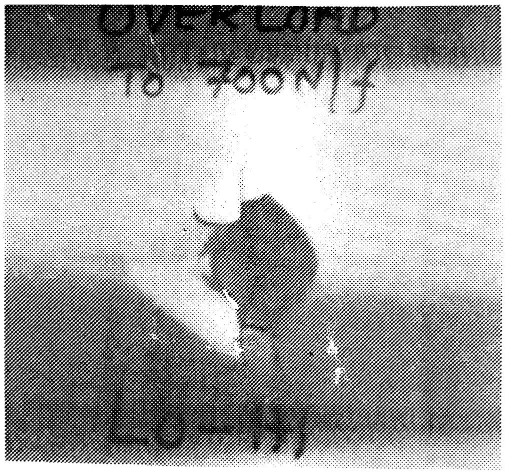


Figure 4. Cracks Observed during RBL Tests on Corrugated Roofing



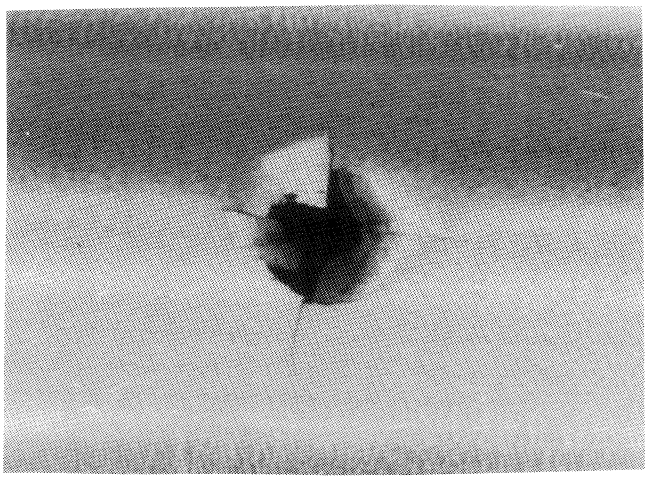
TR440 Low-high



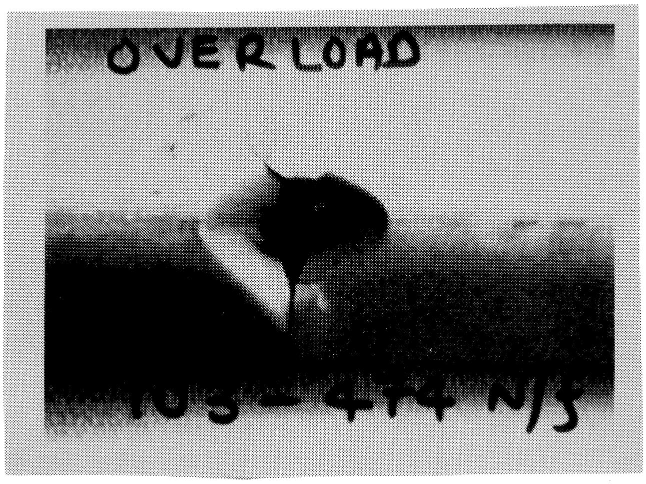
Reverse TR440 Test

Figure 5. Cracks Observed during TR440 Tests on Corrugated Roofing

Typical cracks observed during the constant amplitude cyclic tests with and without prior overload cycles are shown in Figure 6. Cracks observed during the tests with prior overload cycles were similar to that observed during reverse TR440 tests and RBL tests.



(a) No Prior Overload Cycles



(b) With Prior Overload Cycles

Figure 6. Cracks Observed during Overload Tests on Corrugated Roofing

It was considered necessary to verify the above observations made regarding the adequacy of the TR440 test and other related ones for other corrugated profiles of different thicknesses and yield strengths (see Figure 1). The RBL tests and the TR440 tests were carried out on 0.48 mm bmt corrugated roofing (different thickness) and 0.60 mm bmt Custom Blue Orb (different yield strength - 300 MPa), and their results are given in Table 5.

TABLE 5. RBL and TR440 Test Results for Corrugated Roofing (0.48 mm and 0.60 mm bmt)

	Roofing	Type of Test	Ave. No. of Applied Sequences until Failure	Ave.Fatigue Damage per Sequence
1	0.48 mm bmt roofing in Fig.1.(a)(i)	**RBL Test** using 5 matrices each representing 1 hour cyclone loading	0.5	2.0
2		**TR440 Test** Low-High Sequence without Static Overload	1.5	0.67
3		**TR440 Test** High-Low Sequence without Static Overload	1.0	1.0
4		**Reverse TR440 Test** - Overload then High-Low Sequence	0.4	2.5
5	0.60 mm bmt roofing (300 MPa) in Fig.1.(a)(ii)	**RBL Test** using 5 matrices each representing 1 hour cyclone loading	2.5	0.4
6		**TR440 Test** Low-High Sequence without Static Overload	5.0	0.2
7		**Reverse TR440 Test** - Overload then High-low Sequence	2.0	0.5

As seen in Table 5, both types of roofing survived more RBL sequences than TR440 sequences. This confirms that the TR440 test is less severe than the design cyclone and thus unconservative for all the corrugated roofing profiles. Results in Table 5 also indicate that the high-low sequence loading caused greater fatigue damage than the low-high sequence loading, and the fully reversed TR440 loading sequence caused the worst fatigue damage. Cracks observed in this case were also similar to those observed earlier for 0.42 mm bmt corrugated roofing (see Figures 4 and 5).

It is to be noted that the RBL and TR440 sequences for each roofing profile were based on the values of design load per fastener used by the manufacturer (LBI, 1987). This means that the results are dependent on the assumed design load, however, it is believed that the comparison between RBL and TR440 sequences will still hold. Since 0.60 mm bmt corrugated roofing survived more than two RBL sequences, it implies that the current design load for this roofing results in a much greater margin of safety than that for the other two profiles. This observed unequal margin of safety among the various roof claddings is not desirable.

5.2 Trapezoidal Roofing Profiles

Table 6 presents the results from the RBL and TR440 tests for both types of trapezoidal roofing.

TABLE 6. RBL and TR440 Test Results for Trapezoidal Roofing

	Roofing	Type of Test	Ave. No. of Applied Sequences until Failure	Ave.Fatigue Damage per Sequence
1	Roofing without wide pans in Fig.1(b)(i)	**RBL Test** using 5 matrices each representing 1 hour cyclone loading	Did not fail within the first sequence	< 1.0
2		**TR440 Test** Low-High Sequence without Static Overload	1.0	1.0
3		**TR440 Test** High-Low Sequence without Static Overload	5.0	0.2
4		**Reverse TR440 Test** - Overload then High-Low Sequence	3.5	0.3
5	Roofing with wide pans in Fig.1(b)(ii)	**RBL Test** using 5 matrices each representing 1 hour cyclone loading	Did not fail within the first sequence	< 1.0
6		**TR440 Test** Low-High Sequence without Static Overload	1.0	1.0
7		**TR440 Test** High-Low Sequence without Static Overload	1.0	1.0

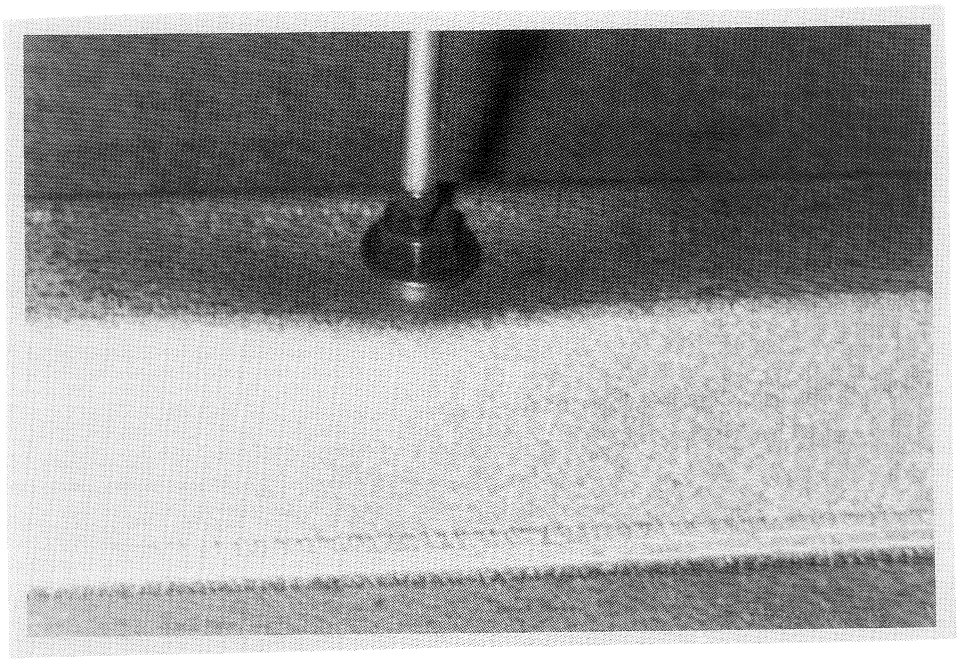
As seen from the results in Table 6, the RBL sequence caused less fatigue damage than the TR440 test on both types of trapezoidal roofing. This implies that the TR440 sequence is conservative in this case, which is **contradictory** to the observation for corrugated roofing profiles. This is because the few higher load cycles in the RBL sequence were beneficial for trapezoidal roofing in contrast to that in the case of corrugated roofing. Simple constant amplitude cyclic tests preceded by one cycle of higher load were conducted on trapezoidal roofing to verify this, and the results are presented in Table 7. For the purpose of comparison, Table 7 also shows the results of similar tests on 0.42 mm bmt corrugated roofing from Mahendran (1990b).

TABLE 7. Effect of Prior Overload Cycles on the Fatigue Life of Roof Claddings

	Roofing	Constant Amplitude Cyclic Loading Range	No Prior Overload Cycles	With Five Prior Overload Cycles
1	Trapezoidal Roofing without wide pans in Fig.1(b)(i)	0 to 700 N/fastener	7,225	24,770
2		0 to 800 N/fastener	2,220	5,020
3	0.42 mm bmt Corrugated Roofing in Fig.1(a)(i)	0 to 310 N/fastener	512,970	34,680
4		0 to 390 N/fastener	53,900	8,090
5		0 to 475 N/fastener	8,920	1,920

As seen in Table 7, there was a significant increase in the fatigue life of trapezoidal roofing when it was overloaded first, whereas the reverse occurred in the case of corrugated roofing. Reverse TR440 test result in Table 6 also confirms this.

The higher load cycles in the case of both types of trapezoidal roofing caused yielding in the region around the crests during the early stages of loading, but soon developed a membrane type action. A permanent deformation formed under the fastener head, but there was no well-defined yield lines as in the case of corrugated roofing. Figure 7 shows this permanent deformation of roofing due to the higher load. This new permanent deformed shape provided a stronger membrane action and thus during the following cycles, the fatigue cracking was delayed. This explains the observation of increased fatigue life of trapezoidal roofing when it was overloaded first.



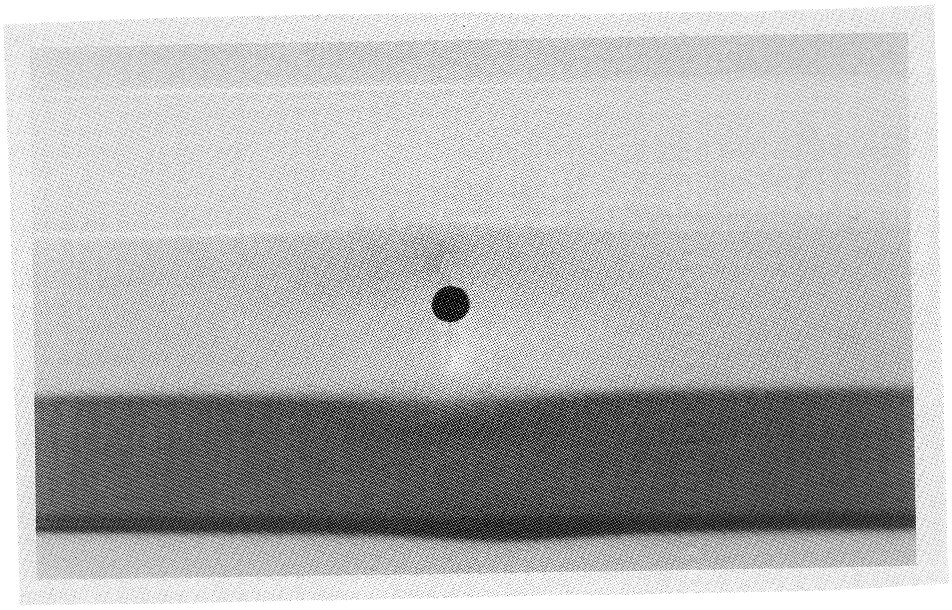


Figure 7. Trapezoidal Roofing after a Higher Load Cycle

Figure 8 shows the typical cracks observed during the TR440 tests of trapezoidal roofing.

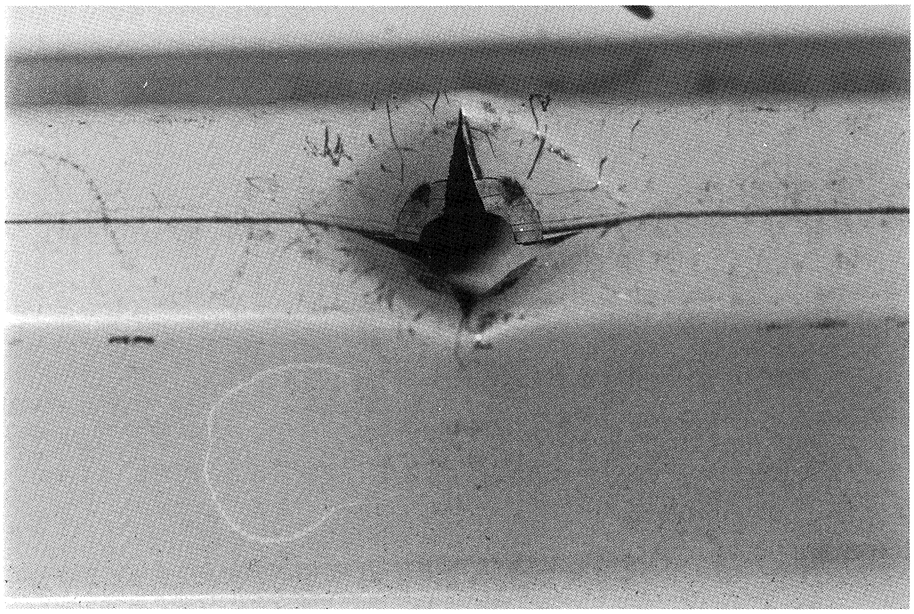


Figure 8. Cracks Observed during TR440 Tests on Trapezoidal Roofing

5.3 Review of Current Standard Fatigue Tests

The contradicting conclusions regarding the adequacy of the TR440 test for the roof claddings have made the review of the standard fatigue tests much more difficult. It appears that the TR440 loading sequence in its current form (low-high) may not be adequate for **all the roof claddings**. This will then mean the unacceptable duplicative fatigue testing being continued. Test results from this investigation indicate that it should be revised once adequate analysis and test data are available. Until then, it may be necessary to test the roof claddings in both low-high and high-low sequences. It may also be necessary to conduct a fully reverse TR440 test including the static overload.

Failure of Miner's law to predict fatigue damage in roof claddings (Jancauskas et al., 1990) means that future work in this area has to be based on experiments alone. RBL tests can be adequately used to investigate the validity of any new fatigue test sequence.

6. CONCLUSIONS

The following conclusions have been drawn from this investigation.

(1) Cyclonic wind forces on roof claddings were simulated by random block load testing based on fatigue wind loading matrices obtained from wind tunnel testing.

(2) A few excursions of loading during the random block load test caused significant fatigue damage on corrugated roofing, but caused the reverse effect on trapezoidal roofing. The observation on corrugated roofing can be attributed to the dimpling of crests at the fastener holes that occurs due to the few excursions of loading. The contrasting behaviour of the trapezoidal roofing is due to the membrane action at the crests.

(3) It appears that the TR440 test is unconservative for corrugated roofing whereas it is conservative for trapezoidal roofing. This is due to the contrasting behaviour of roofing profiles mentioned in (2) above. Thus the task of assessing the adequacy of the current standard fatigue tests has become complicated. This is of concern to the building industry as the current conflict over the duplicative fatigue testing will not be resolved in the near future. As an interim measure, it may be necessary that roof claddings be tested with both low-high and high-low TR440 sequences including the static overload.

(4) The fatigue behaviour of steel roof claddings under cyclonic wind forces appears to be much more complicated than anticipated. The use of Miner's law is not adequate to predict the interactions between various blocks of loading. Therefore extensive fatigue testing in the form of random block load tests or random load tests is required to study the fatigue behaviour of roofing and to develop an appropriate fatigue test.

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