Towards an Appropriate Fatigue Loading Sequence for Roof Claddings in Cyclone Prone Areas

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Abstract

Currently two different fatigue tests are being used to investigate the fatigue susceptibility of roof claddings in the cyclone prone areas of Australia. In order to resolve this issue a detailed investigation was conducted to study the nature of cyclonic wind forces using wind tunnel testing and computer modelling and the fatigue behaviour of metal roof claddings using structural testing. This led to the development of an accurate, but complicated loading matrix for a design cyclone. Based on this matrix, a simplified low-high-low loading sequence has been developed for the testing of roofing systems in cyclone prone areas. This paper first reviews the currently used fatigue loading sequences, then presents details of the cyclonic wind loading matrix and finally the development of the new simplified loading sequence. This simplified sequence should become the only suitable test for most of the cyclone prone areas of Australia covered by Region C which suffers from Category 4 cyclones. For Region D which suffers from Category 5 cyclones, the same loading sequence with 20% increased cycles has been recommended. An experimental programme to validate the new simplified loading sequence has been proposed.

Keywords

Cyclonic wind loading, Roof claddings, Fatigue loading sequence, Fatigue testing of roofing systems

1. Introduction

Light gauge crest-fixed metal roof claddings suffer from low cycle fatigue cracking in the vicinity of fasteners under sustained and strongly fluctuating cyclonic wind forces (Figure 1 (a)). This then leads to the loss of roof sheeting (Figure 1 (b)) by pulling over the screw fastener heads (pull-over or pull-through failure). The presence of large stress concentrations (closer to yielding) around the connections in the metal roof claddings under sustained fluctuating loading provided all the ingredients required for such a low cycle fatigue failure[1-5]. The resulting loss of roofing causes severe damage to low-rise buildings such as domestic, industrial, commercial and farm buildings (Figure 1 (c)). This was observed during cyclone Tracy which hit Darwin in 1974. Therefore it is necessary to adopt fatigue testing to verify the adequacy of fatigue strength of roof claddings in tropical cyclone prone areas. Such a fatigue testing should adequately simulate **cyclonic wind forces and/or their fatigue effects** on roof claddings.

At present a number of different cyclic/fatigue loading sequences are being used for the fatigue testing of roof claddings in Australia. It is not known whether anyone of them is representative of the actual cyclonic wind loading and this is not an acceptable situation. Recently a detailed investigation into the nature of cyclonic wind loading on roof claddings and the low cycle fatigue behaviour of roof claddings under such loading has been carried out in Australia in an attempt to develop 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 paper first reviews the current fatigue loading sequences and then presents a summary of the work that has been carried out in Australia including the details of a complicated cyclonic loading sequence. Finally a simplified sequence based on the cyclonic loading sequence is presented.

2. Review of Current Fatigue Loading Sequences Simulating Tropical Cyclones

Following cyclone Tracy, a standard fatigue test, the DABM test[6] was introduced for roof claddings in the cyclone prone areas of Australia (see Table 1) to study the performance of the roof claddings under simulated cyclonic wind forces in the laboratory. This was considered to take into account the reduction in strength due to low cycle fatigue under cyclonic wind loading. Prior to cyclone Tracy, roof claddings were designed based on static testing alone (static load to 1.8 times the design wind load), and the DABM test was the first of its kind. The DABM test was very much needed for the proof testing of roofing systems in the rebuilding of Darwin soon after cyclone Tracy, and therefore it was developed as an interim test. As seen in Table 1, the DABM test sequence is only a single level cyclic test consisting of 10,000 cycles to design wind load P_d, followed by an overload. Obviously such a constant amplitude cyclic testing will not represent a cyclonic loading. However, the Northern Territory building regulations[7] still require the same test, mainly because it is considered that no adequate alternative has been developed yet.

At a workshop in Sydney to review the DABM test method, Melbourne[8] presented an alternative loading sequence to the DABM test sequence. Melbourne[8] developed loading sequences for elements whose loading is dominated by windward wall pressures or large tributary areas, and for those in the separation areas and having small tributary areas such as connections of roof claddings. For each case a cyclic loading sequence which was considered equivalent to the estimated random load fluctuations over an hour at the maximum design wind velocity was recommended. These sequences were derived from an upcrossing analysis. They were defined based on the hourly mean pressure, and the rms of the pressure fluctuations, which were in turn defined in terms of the peak pressure. Melbourne's loading sequence for the *roof claddings* is given in Table 2. The peak pressure is the maximum peak load on the roof cladding during the cyclone, and corresponds to the design wind speed with a 50 year return period (not ultimate). Therefore it corresponds to the design value from the then wind loading code which includes a cyclone multiplier of 1.15 for the wind speed. It is the same as in Table 1 and is given the same symbol P_d.

Beck and Stevens[3] used a method called the discriminate range-counting method which is a modified form of upcrossing analysis. Based on a one hour critical roof pressure record obtained from a wind tunnel study, they developed a sequence shown in Table 2. Unlike Melbourne's sequence, this sequence included only the wind suction loading (no negative load values) since it was considered that only wind suction loading caused fatigue in claddings.

Melbourne recommended repeating his sequence which has a total of 5,000 cycles per hour three times in order to produce a cyclonic loading. Similarly Beck and Stevens recommended repeating their sequence with a total of 2,770 cycles per hour four times. These sequences do not take into account the effects due to changing wind speed and direction during a cyclone. Despite this, their sequences are rather complicated for routine performance tests.

At the Sydney workshop a simpler three-level low-high sequence, consisting of 10,200 cycles to design load, followed by an overload[9] (TR440 test in Table 1) was recommended because it was considered that the DABM test is too severe, and that Melbourne's[8] and Beck and Stevens's[3] sequences are too complicated. The TR440 sequence has been adopted in all the cyclone prone areas except the Northern Territory. It has now been incorporated in the new wind loading code[10] and the new metal cladding code[11] in the ultimate limit state format.

In the new Australian wind loading code, the country has been divided into four Regions A, B, C and D, where Regions C and D are considered tropical cyclone prone areas. Regions C and D are defined to be the coastal region connecting the two points on the east and west coasts at 25° South. Although Region B is an intermediate region, its ultimate wind speed is still dominated by weakening and/or less frequent tropical cyclones. Among the Regions A and B, most of them are thunderstorm prone areas. Since thunderstorms in Australia are of short duration, fatigue is not considered a problem and static testing will be adequate. The TR440 test is intended for use in Regions C and D only.

Since the question of whether the TR440 low-high sequence is adequate in representing the cyclonic loading is unanswered, it is argued that the TR440 test found its way in the new codes only because of the absence of a suitable alternative. It has been pointed out that some roof cladding systems which passed the TR440 test were not different from those failed during cyclone Tracy.

Further, the Northern Territory has continued to require the DABM test[7]. This situation is not acceptable to the roofing manufacturers and designers who have to satisfy two different criteria for the same roofing product. In fact the loading sequences in Table 2 are also used occasionally as an alternative to the TR440 test. There has been concern among the researchers about the adequacy of these standard fatigue tests in Table 1 in reproducing the randomly fluctuating cyclonic wind forces and/or at least the fatigue effects due to them. All these led to the extensive research programme at James Cook University to develop a single appropriate fatigue test for roof claddings that represents the cyclonic loading adequately for all the cyclone prone areas of Australia. Brief details of this programme and the important results obtained to date are presented in Section 3.

Currently only the Australian design documents include provisions to eliminate low-cycle fatigue cracking of claddings under cyclonic wind loading. This is despite the fact that other countries also suffer from high wind events, for example, cyclones Hugo and Andrew in the USA. However, low cycle fatigue may not be a problem in these countries due to the differences in the use of metal cladding systems. Further, wind uplift may not be the governing load case in the design of metal claddings in these countries.

Although the European and American codes do not give any fatigue loading sequence, ECCS[12] and Cook[2] present fatigue loading sequences for storms. In Europe the winter storms could last for more than four hours, and thus fatigue could be a problem. Therefore these sequences need to be used for the performance evaluation of claddings under storm loading. The ECCS sequence was obtained using Davenport's[13] procedure and upcrossing analyses of the wind climate and load fluctuations. ECCS[12] presents the loading in terms of the number of cycles exceeding load levels expressed as a percentage of the peak design load P_d (same as in Tables 1 and 2), but does not give the sequence of loading cycles. The sequence developed at the Building Research Establishment (BRE) was obtained by counting down from the extreme value distribution of the wind climate and the load fluctuations[2]. Despite the independent approaches used, the BRE sequence is almost identical to the low cycle range of the ECCS sequence[2], and thus only the former is reproduced here in Table 3. As shown in Table 3, it has to be applied five times in that order and should be followed by one cycle of peak load. The BRE sequence is only suitable for the UK climate which is a frontal depression dominated weather system, and will not be appropriate for use in tropical cyclone prone areas. It may not be severe enough and could lead to unsafe design.

Gerhardt and Kramer[14] used quasi-static and peak factor approaches and frequency distributions of wind speed and pressure to develop an alternative fatigue loading shown in Table 4 for the climate in Germany. Only load levels above 40% of the gust pressure were considered. The total load cycles are for a 50-year return period consisting of ten equal cycles. The peak load in Table 4 is for a design wind speed with a 50 year return period (not ultimate). This low-high-low sequence also will not be appropriate for use in tropical cyclone prone areas.

3. Simulation of Cyclonic Wind Forces

3.1 Determination of Cyclonic Wind Forces on Roof Claddings

In the tropical cyclone prone areas the available records of cyclone characteristics such as the maximum wind speed, central pressure, radius to maximum wind, forward speed, etc. are very limited. Currently the basic wind speeds during a tropical cyclone are categorised based on the Saffir-Simpson scale, an Australian version of which is shown in Table 5[15]. The approach taken by the new wind loading code[10] is to relate design criteria to event intensity as per the Saffir-Simpson scale despite the fact the scale is not exact and different versions of it are in use[15]. In Region A, a non-cyclone region which comprises most of the country, thunderstorms are responsible for the most extreme wind speeds. Other regions B, C and D are considered to be at risk from tropical cyclones of Categories 3, 4 and 5, respectively on the Saffir-Simpson scale. The respective ultimate design wind speeds (1000-year return periods) are taken as 60, 70 and 85 m/s.

Catastrophic cyclones (Category 5) only occur in regions where the climatic conditions are most favourable to the formation and intensification of cyclones[15], and as such affect only a limited area. In Australia *only* the stretch of north western coastline from 20° south to 25° south is considered to have a significant risk of occurrence of Category 5 cyclones, and thus zoned Region D. Because of the limited occurrence of Category 5 cyclones and the smaller and unpopulated areas of Region D, a design cyclone may not have to include the Category 5 cyclone.

In the research programme at James Cook University, the randomly fluctuating cyclonic wind forces on roof claddings were determined using a wind tunnel investigation and computer modelling. **A design cyclone of 5 hours duration** was specified by a variation of wind speed and direction with time using data obtained from cyclone Winifred[16]. An ultimate wind speed of **70 m/s for Region C** in the wind loading code[10] was assumed with cyclone parameters of **a central pressure (p_c) of 930 mb, 25 kms radius to maximum winds (R) and a forward speed (U) of 15 km/h.**

Wind pressure traces were then obtained from wind tunnel tests on a typical house model for many wind directions, and were analysed using a rain flow method of analysis to reduce them to matrices of the format as in Table 6. The wind tunnel matrices were then modified appropriately for full scale conditions and used in the process to derive the fatigue wind loading matrix for the assumed design cyclone. It is noted that this process includes the **effect of both wind speed and direction** during the cyclone.

The fatigue wind loading matrix for the *gable end location* on the roof and *rural terrain* conditions was found to be the most severe loading matrix, and was thus used in all the subsequent analysis and experiments. This matrix for a roof height of 4 m is shown in Table 6. As seen in Table 6, a random variation of wind pressure during a cyclone lasting five hours is 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**. Only a few cells had positive pressure cycles, indicating that the wind pressure on the roof cladding is essentially suction. They were not included in the matrix as they were assumed to cause negligible fatigue damage to roofing. Full details of the procedure used in deriving the Table 6 matrix are given in Jancauskas et al.[17].

In this analysis the design cyclone was assumed to be for Region C[10] and thus had an ultimate wind speed of 70 m/s with a p_c of 930 mb, R of 25 kms and U of *15 km/h.* Despite the fact that tropical cyclones which cross Region C are variable, these parameters were assumed to give the best results for a reasonable design cyclone for Region C. Past records indicate that U can vary from *7 to 50 km/h* and that R from *10 to 60 kms.*

A computer program developed by Jancauskas et al.[17] was used to calculate the fatigue damage to corrugated steel roof claddings caused by cyclones with the same ultimate wind speed, but with different U and R. It was found that fatigue damage increased significantly when U was decreased or when R was increased. Therefore a Category 4 cyclone as per the Saffir-Simpson scale or a Region C design cyclone specified by only the ultimate wind speed and central pressure will not cause the same fatigue damage to roof claddings if other parameters are different. The cyclone with an ultimate wind speed of 70 m/s, a smaller U and a larger R will cause very severe fatigue damage. However, it is unlikely that all the cyclone parameters will take the worst values. In fact, cyclone Tracy was a Category 4 cyclone in Region C with a gust speed of 70 m/s and smaller values of U and R (7 km/h and 11 kms), and thus based on Jancauskas et al.'s[17] fatigue program it causes almost the same fatigue damage as the design cyclone assumed here. Some Category 4 cyclones in the USA such as Cyclone Andrew in 1992 (gust speed = 70 m/s, p_c = 930 hPa, R= 24 kms) and cyclone Celia in 1970 (gust speed = 70-75 m/s, p_c = 940-950 mb, R = 25-30 kms, U = 20-25 Km/h) had characteristics which are either similar to or less damaging than the assumed design cyclone. The design cyclone assumed here is considered to be the most probable worst cyclone in Region C. Therefore it is believed that the Table 6 loading matrix will represent a design cyclone adequately.

3.2 Experimental Simulation of Cyclonic Wind Forces

As seen in Table 6, there are 64 blocks of loading (cells with nonzero cycles) representing the design cyclonic loading, which need to be applied to the roof claddings. The design cyclone has a range of loading blocks with some having a few cycles reaching the ultimate design load level (cell 5x11 in Table 6). A random block load (RBL) testing method based on the loading matrix in Table 6 can be used to simulate the cyclonic loading on roof claddings. Such a testing will include the effects of change of wind speed and direction during the cyclone. In this method loading blocks are further subdivided into smaller basic loading blocks with each having no more than 200 cycles which are then chosen randomly for application on roof claddings. Loading blocks with a maximum load below 80% of the fatigue or endurance limit can be eliminated as they cause little or no fatigue damage.

The RBL testing method using the Table 6 matrix does not reproduce the low-high-low nature of a cyclonic loading. The analytical program[17] used to derive the Table 6 matrix can be used to obtain the loading matrices at any time interval. In order to simulate the cyclonic loading as a low-high-low sequence, a time interval of one hour was chosen which produces five matrices for the design cyclone[18] in the same format as in Table 6. Each of these matrices gives the number of cycles at the end of each hour of the five hour design cyclone. Sum of these matrices gives the Table 6 matrix. The severity of the loading matrix increases and reaches a maximum for the third hour, and then decreases again, thus simulating a realistic cyclone. RBL sequence from each matrix can be applied to the roof cladding one after the other until failure to simulate the low-high-low nature of cyclonic loading. Further details of the simulation of cyclonic wind forces using a random block load testing method including the five hourly loading matrices can be found in Mahendran[18-20].

3.3 Fatigue Behaviour of Steel Roof Claddings under Simulated Cyclonic Wind Forces

It is believed that the loading represented by the fatigue wind loading matrix in Table 6 or the five matrices simulating each hour of cyclonic loading and simulated as a random block loading (RBL) sequence on the roof cladding is the most appropriate design cyclone loading that is available at present. It is obvious that simplified sequences as per the TR440 and DABM tests (Table 1) do not match the complicated cyclonic loading sequence. Therefore they should **at least produce the same fatigue damage** on roof claddings as the design cyclone. In fact, even at the time of instigation of the simple tests, they were considered to be producing the fatigue effects of cyclonic loading rather than the actual cyclonic loading. A single level cyclic loading test like the DABM test cannot represent a largely variable amplitude type cyclonic loading and the DABM test has always been considered too conservative. Therefore in the process of reviewing the standard fatigue tests, only the more appropriate test, the TR440 test, was considered to determine whether it produces the same fatigue damage as that of the design cyclone.

In the investigation at James Cook University, the RBL and TR440 tests were carried out on identical roof cladding systems to compare the experimental fatigue damage caused by them. The basic fatigue behaviour of roof cladding under simple constant amplitude cyclic wind loading was also investigated which produced the basic fatigue characteristics of roof claddings[5]. Analytical fatigue damage values were obtained by integrating the cyclonic wind loading data and the fatigue data on roof cladding using Miner's law[17].

The final step of comparing the fatigue damage values was anticipated to resolve the conflict over the adequacy of current fatigue tests. However, because of the complexities due to cyclonic loading and the behaviour of crest-fixed light gauge steel roofing under such variable loading, the conflict has not been resolved yet. It was found that the TR440 test is conservative for some roof claddings whereas it is not conservative for others[19]. This is because the cyclonic loading test had a few overload cycles in the middle of it whereas the TR440 test had one only at the end. Some roof claddings suffered a loss of fatigue life when they were overloaded first and the reverse occurred for other claddings. Thus the difference in the location of overload cycles caused a contrasting fatigue behaviour of the claddings, which led to the above conclusion about the adequacy of TR440 test. Obviously the TR440 low-high sequence without the overload cycles in the middle does not represent the low-high-low cyclonic loading sequence, but it does not even produce the same fatigue damage as the cyclonic loading on all the roof claddings. A modified TR440 low-high-low sequence shown in Figure 2 was recommended[19], however, the adequacy of it is unknown. Therefore the cyclonic loading sequence based on Table 6 has to be used although it is quite complicated. As illustrated in the next section it has been simplified without losing accuracy.

4. Development of a Simplified Fatigue Loading Sequence

At present, cyclonic wind loading is best simulated on roof claddings using the random block load testing method and the five-hour design cyclone loading matrix in Table 6 or the five matrices representing every hour of the cyclone. Such a method is an excellent tool for research purposes, however, it may be considered too complicated, time consuming and expensive for routine testing for the purpose of product assessment and evaluation for cyclone prone areas. Therefore it is necessary to determine a simplified version of the cyclone loading sequence that produces the **same fatigue damage** on roof claddings. *For this purpose, it was decided to simplify the Table 6 matrix and rearrange it as a low-high-low sequence rather than simplifying all the five hourly loading matrices.* A new fatigue loading sequence should still be simple enough like the TR440 test to be acceptable to the building industry. A loading sequence with many different loading levels as in the RBL test will not be acceptable.

In Table 6, each block of cyclic loading is expressed with a mean and a range. Fatigue investigation of light gauge steel roof cladding[5] has shown that the maximum load and the range are more important. This is mainly because the crest-fixed roof claddings suffer from localised dimpling and yielding deformations around the fastener holes if the maximum load is high[5,19]. Local dimpling or yielding during the cyclic loading affect the fatigue behaviour of these claddings significantly. Therefore the 64 loading blocks in Table 6 were first expressed in terms of the *range* and *maximum* load and number of cycles. They were then simplified to form a loading sequence which has only five loading blocks with a zero minimum load and a maximum load (equals range) of 0.2, 0.4, 0.6, 0.8 and 1.0 times the ultimate design load P_u (see Figure 3), but which still produces the same fatigue damage.

In developing the simplified sequence, the Table 6 loading blocks were first allocated to one of the above five simplified loading blocks depending on the maximum load. For example, all the blocks of loading in Table 6 with a maximum value between 0.3 and 0.5 were allocated to the simple loading block with a maximum value of 0.4 (see Figure 3), and similarly Table 6 loading blocks with a maximum value between 0.1 and 0.3 were allocated to the simple loading block with a maximum value of 0.2 and so on. When allocating to the new block of loading, the equivalent number of cycles in the simple loading block (N_{1s}, N_{2s}, N_{3s} etc.) corresponding to the Table 6 loading blocks (N_{1c}, N_{2c}, N_{3c} etc.) was calculated based on the Palmgren-Miner linear damage model[21] such that they produce the same fatigue damage (see Figure 3).

The use of the linear damage model assumes that the damage produced by individual cycles in a variable-amplitude load history can be calculated directly from the fatigue-life equation $N_f = AS_f^{-m}$ (see Figure 4) and the well-known Palmgren-Miner's law. To determine the total damage produced by the history, damage produced by the individual cycles making up that history is added linearly. It is assumed that all cycles are damaging and that cycles of different sizes do not interact to retard or accelerate crack growth. However, it is to be noted that in this investigation Miner's law was only used to compare fatigue damage of loading blocks of similar load levels, and thus was expected to produce reasonably accurate answers. This is in contrast to the use of Miner's law in the past[17] where it was used to calculate the fatigue damage caused by the complete cyclonic loading sequence in Table 6 with loading blocks of varying load levels. In this case it was found to be inadequate in predicting the fatigue damage except for comparative purposes. Such a limitation does not exist in the use of Miner's law in this investigation. It was used to calculate the equivalent number of cycles N_s in a loading block of the simplified sequence corresponding to the number of cycles N_c in a loading block with similar load levels from the cyclone loading matrix in Table 6 such that they produce the same fatigue damage. Accordingly, the following equations are derived.

For the fatigue damage to be the same,

$$\frac{N_s}{A_s S_s^{-m_s}} = \frac{N_c}{A_c S_c^{-m_c}}$$

where S_c = Stress range of each loading block in the cyclone matrix in Table 6

S_s = Stress range of the loading block in the simplified loading sequence

m_c, m_s = Slopes of Fatigue life curve for roof claddings corresponding to S_c, S_s (Figure 4)

A_c, A_s = Constants of Fatigue life curve for roof claddings corresponding to S_c, S_s(Figure 4)

$$N_s = N_c \frac{A_s S_c^{m_c}}{A_c S_s^{m_s}} \qquad (1)$$

Since in most cases the cyclonic loading blocks are converted to simplified loading blocks, but of similar load level, then $m_c = m_s = m$ and $A_c = A_s$,

$$N_s = N_c \; (S_c / S_s)^m \tag{2}$$

Fatigue life equation will not be the same for all the roof claddings. It could be more complicated than that of the common structural details[21], for which m is either 2 or 3. In this case m was assumed to be 1 as it is the worst case (larger N_s). All the loading blocks in Table 6 including those below the fatigue limit were converted to simplified loading blocks using Equation (2), except the smallest loading block in cell 1x1.

As an example, consider a loading block from cell 4x3 in Table 6 which has a maximum load of 0.475, a range of 0.25 and number of cycles of 838. This was therefore allocated to the simpler loading block with a minimum load of zero and a maximum load of 0.4. The number of equivalent cycles for this block was then calculated to be 838 x 0.25/0.4 = 600 using Equation (2). In this manner when the Table 6 loading blocks were converted the number of cycles for the new five block loading sequence was obtained (column 2 in Table 7).

In the fatigue life equation for roof claddings m will not be a constant (see Figure 4). For lower loadings with the maximum value less than 0.3 P_u, it was more appropriate for m to be 3. This is referred to as the root mean cube model[21]. In this case the loading blocks were allocated to the simplified loading block of 0 to 0.2 P_u. Consider the loading block from the cell 2x1 in Table 6 which has 70,019 cycles with a maximum of 0.175 and a range of 0.05. These cycles were converted into the 0 to 0.2 P_u block loading as 70,019 x ratio of range $(0.05/0.2)^3$ = 1,094 cycles. This led to the third column in Table 7.

In order to simplify the sequence from a five-level sequence to a four-level sequence, the 0 to 0.2 P_u cycles were converted to 0 to 0.4 P_u cycles using Equation (1) with $m_s = 1$ and $m_c = 3$ and $A_c = 0.5\ A_s$. The 11,596 cycles of 0 to 0.2 P_u load was thus converted to 464 cycles of 0 to 0.4 P_u load, increasing the number of cycles in the latter to 9162. However, this was then conservatively assumed to be 10,000. Similarly the number of cycles in the other loading blocks was also rounded up, and the final simplified sequence is shown in the fourth column of Table 7.

Melbourne's[8] and Beck and Stevens's[3] sequences and TR440 sequence were also simplified in a similar manner using Equation (2) and m=1 and are compared with the final simplified sequence in Table 7 (compare columns 4, 5, 6 and 7). It appears that all the sequences are somewhat of the same order despite the fact they were obtained from independent approaches. However, since the fatigue loading sequence derived here was based on extensive wind tunnel testing and computer modelling[17], it should replace the current loading sequences.

The simplified loading sequence shown in Table 7 appears to be a low-high sequence, but in order to represent the cyclonic loading accurately, it should be applied as a low-high-low sequence. Figure 5 shows the sequence in which the Table 7 loading sequence should be applied on roof claddings. This appears to be of the same format and order as the modified TR440 low-high-low sequence of Mahendran[19] (see Figure 2). It is considered that if the new fatigue loading sequence proposed in Table 7 and Figure 5 is not adopted, the TR440 sequence should be at least used as a low-high-low sequence proposed by Mahendran[19]. The Figure 5 loading sequence appears to be similar to Gerhardt and Kramer's[14] sequence, but the former sequence is more severe than the latter as it is defined in terms of the ultimate design wind load.

The Table 6 loading blocks were simplified into a 10-level loading sequence with a minimum load of zero and maximum loads of 0.1 to 1.0 P_u at 0.1 P_u intervals using the same procedure and the resulting sequence is given elsewhere[20]. However, since the 10-level loading sequence was considered to be somewhat too complicated for product evaluation testing, it may be of little use.

The loading sequences developed here are essentially for Category 4 cyclones which affect Region C since it was considered that a design cyclone may not have to include Category 5 cyclones which affect Region D. However, for the sake of completeness, the design cyclone was redefined with an increased ultimate wind speed of 85 m/s and a reduced central pressure of 905 mb, but with no changes to other cyclone parameters. The analysis was then carried out in a similar manner to that in Sections 3 and 4, and a simplified loading sequence similar to that in Table 7 was derived for Region D (see Table 8). It was found that it had approximately 20% more cycles than the Table 7 sequence at the same load levels, with P_u being that for Region D. Therefore the same simplified fatigue loading sequence in Figure 5 but with 20% increased number of cycles can be used for Region D.

Although early stages of this research project were involved with the fatigue behaviour of steel roof claddings only, the simplified loading sequence developed here is not restricted to steel roof claddings. In the development of the sequence, fatigue life equation with m values that produced the worst case was used rather than the m value for steel cladding.

Since the development of the simplified loading sequence was based on analysis alone, experimental validation is considered useful. For this purpose a series of experiments on various types of roof claddings under the cyclonic loading sequence based on Table 6 and/or the five hourly loading matrices, and the simplified loading sequence is proposed to verify whether the sequences produce the same fatigue damage on all the roof claddings.

5. Conclusions

Currently used fatigue loading sequences representing a cyclonic loading on roof claddings were reviewed in this paper. This was followed by the presentation of a more accurate but complicated fatigue loading sequence derived from extensive wind tunnel testing (Table 6).

This is suitable for Category 4 cyclones which affect Australian wind Region C. The effects of cyclonic characteristics on this sequence were also briefly studied.

Based on the complicated cyclonic loading sequence, a simplified low-high-low loading sequence has been developed for testing of roofing systems in cyclone prone areas. Despite the fact that this sequence is somewhat of the same order as the current fatigue loading sequences, it is believed that it should replace both the TR440 and DABM test sequences, and become the only suitable cyclone test for most of the cyclone prone areas (Region C) of Australia. For Region D which suffers from Category 5 cyclones, the same loading sequence with 20% increased cycles has been recommended. An experimental programme to validate the new simplified loading sequence has been proposed.

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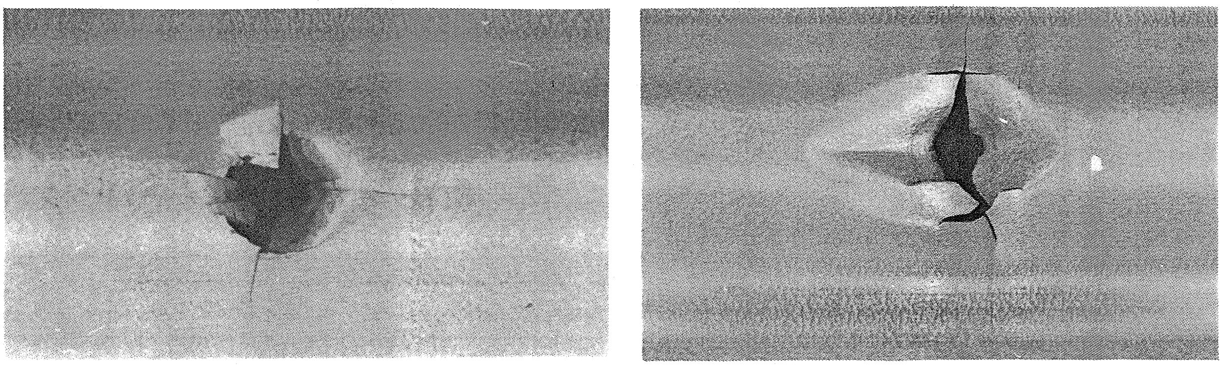
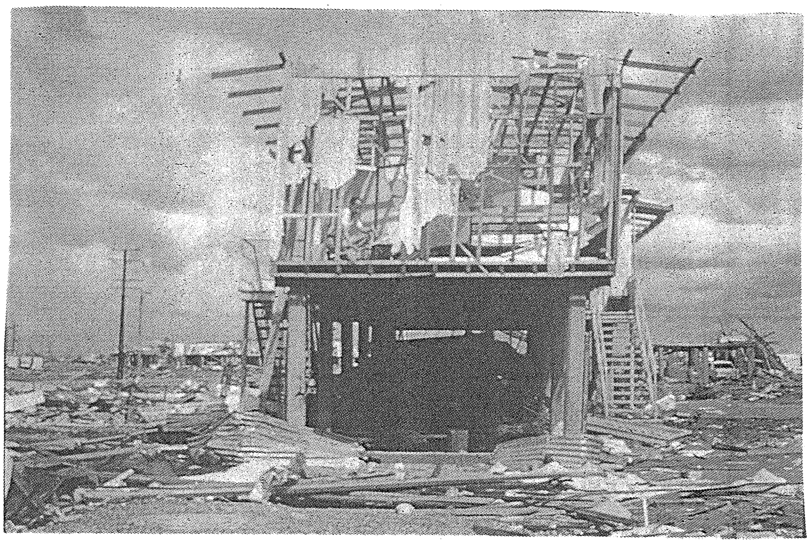


(a) Fatigue Cracking-caused Pull-through Failure in Metal Roof Claddings

(b) Damaged Metal Roof Claddings



(c) Damaged Building

Figure 1. Damage to Roof Claddings and Low-rise Buildings during Cyclonic Winds

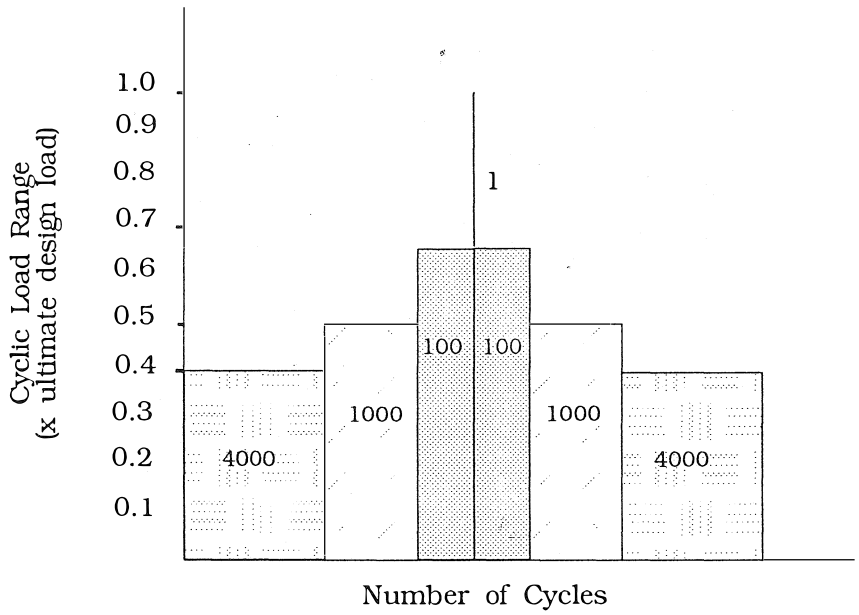


Figure 2. Modified TR440 Low-high-low Loading Sequence (From Mahendran[19])

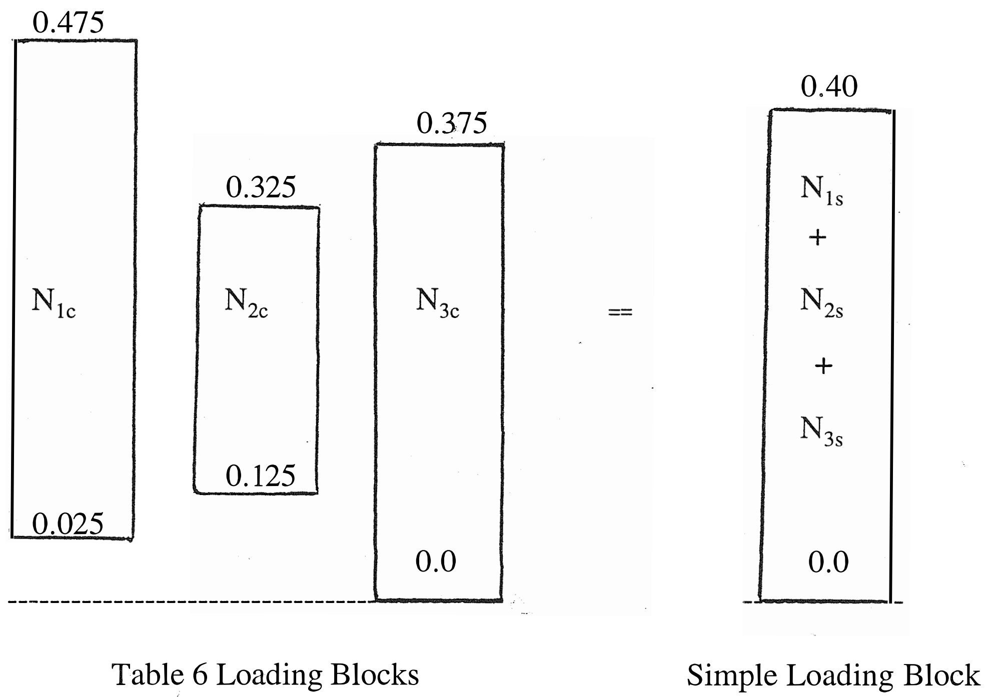


Figure 3. Simplifying the Cyclonic Loading Sequence

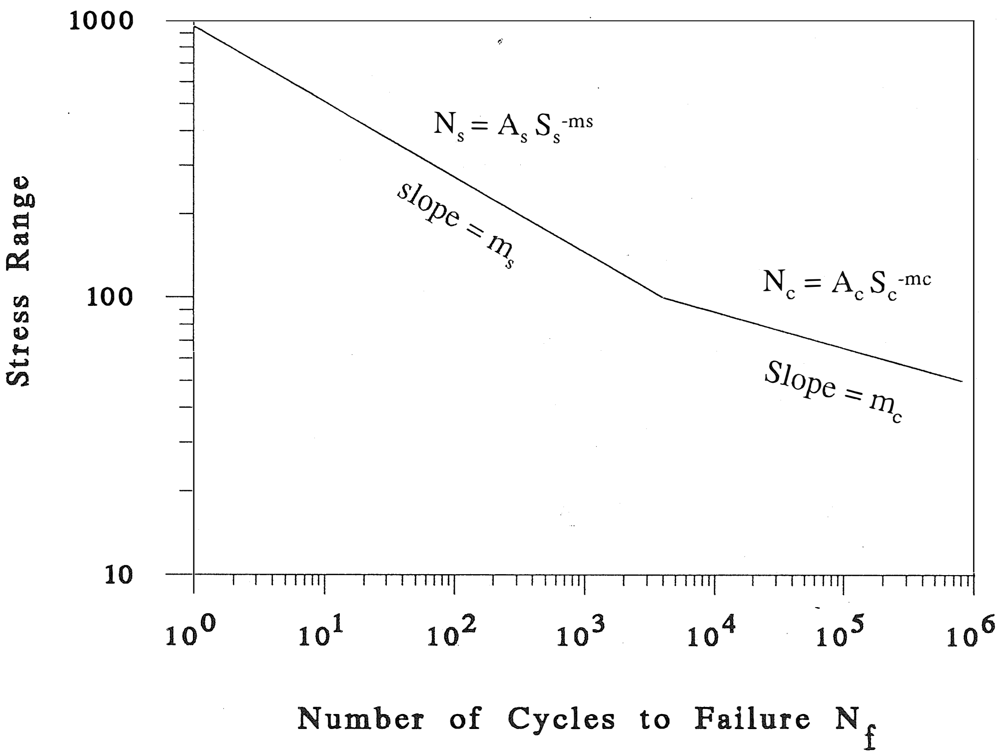


Figure 4. Fatigue Life Curve

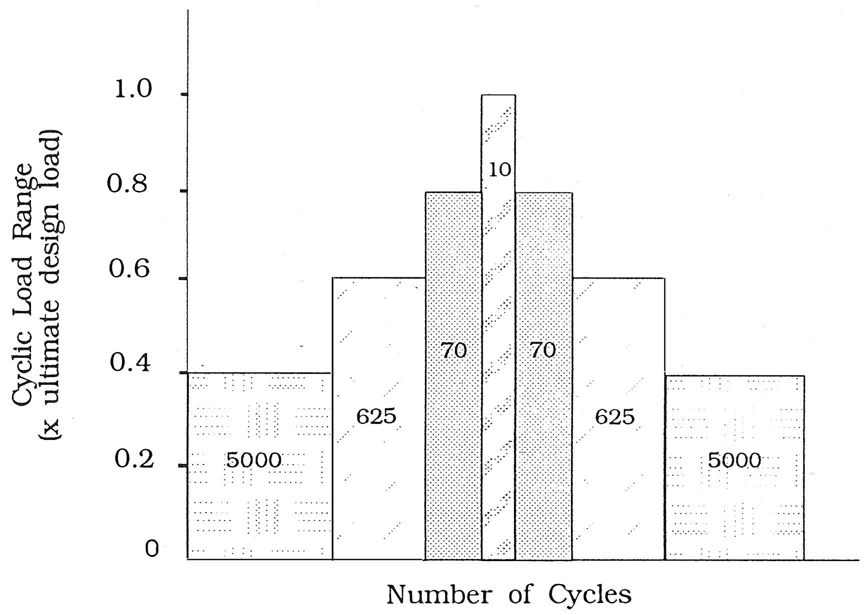


Figure 5. Appropriate Fatigue Loading Sequence

Table 1. Standard Fatigue Test Sequences for Roof Claddings

DABM Test Sequence[6]		TR440 Test Sequence[9]	
Cycles	Load Range	Cycles	Load Range*
10,000	0 to 1.0 P_d	8,000	0 to 0.625 P_d
1	γ x P_d	2,000	0 to 0.75 P_d
γ = 1.8		200	0 to 1.0 P_d
		1	γ x P_d
		γ = 1.6 to 2.0 depending on the number of tests	

Note: 1. P_d - Design wind load

2.* - In the new wind loading code[10] the coefficients 0.625, 0.75, and 1.0 have become 0.4, 0.5 and 0.65, respectively, and γ = 1 to 1.3 corresponding to the ultimate design wind load P_u

Table 2. Fatigue Loading Sequences Recommended by Melbourne[8] and Beck and Stevens[3]

Melbourne's Sequence[8]		Beck and Stevens's Sequence[3]	
Cycles	Load Range	Cycles	Load Range
3,445	0.15625 P_d to 0.34375 P_d	400	0 to 0.2075 P_d
1,000	0.0625 P_d to 0.4375 P_d	1,800	0 to 0.3225 P_d
500	-0.125 P_d to 0.625 P_d	70	0 to 0.52375 P_d
50	-0.3125 P_d to 0.8125 P_d	400	0.2075 P_d to 0.5525P_d
5	-0.50 P_d to 1.00 P_d	70	0 to 0.75375 P_d
		25	0.4375 P_d to 0.7825 P_d
P_d - Design wind load		5	0.23625 P_d to 0.98375 P_d
Sequence to be repeated 3 times		Sequence to be repeated 4 times	

Table 3 Fatigue loading sequence recommended by BRE[2]

Number of cycles	1	960	60	240	5	14
Percentage of peak load P_d	90	40	60	50	80	70

Sequence to be repeated five times, followed by one cycle to 100% peak load P_d

Table 4 Fatigue loading sequence recommended by Gerhardt and Kramer[14]

Number of loadings per loading cycle	4000	400	40	4	1	5	50	500	5000
Percentage of peak load P_d	40	60	80	90	100	90	80	60	40

Table 5. Saffir-Simpson Scale of Tropical Cyclone Intensity/Category[15]

Intensity	Saffir-Simpson Scale / Category	Central Pressure (hPa)	Max. Basic Wind Speed (m/s)
Mild	1	> 990	20 - 30
Medium	2	970 - 985	35 - 45
Severe	3	950 - 965	50 - 60
Very Severe	4	930 - 945	65 - 75
Catastrophic	5	< 925	80 - 90

Table 6. Fatigue Wind Loading Cycles for a 5-hour Cyclone of Category 4[17]

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

Note : Pu = Ultimate Design Wind Load. All pressure cycles are suction on roof.

Table 7 Simplified fatigue loading sequence

Load range	Number of cycles $m=1$	Number of cycles $m=1$ and 3	Number of cycles – simplified	TR440 test[9]	Melbourne sequence[8]	Beck and Stevens sequence[3]
0–0.2 P_u	37 775	11 596	...	...	...	1660
0–0.4 P_u	8698	8698	10 000	8000	7657	5805
0–0.6 P_u	1245	1245	1250	1883	1562	1164
0–0.8 P_u	134	134	140	...	152	307
0–1.0 P_u	9	9	10	1	15	15

P_u = ultimate design wind load

Table 8 Simplified fatigue loading sequences for regions C and D cyclones

Load range	Number of cycles: Region C cyclone	Number of cycles: Region D cyclone
0–0.2 P_u	37 775	45 714
0–0.4 P_u	8698	10 542
0–0.6 P_u	1245	1506
0–0.8 P_u	134	159
0–1.0 P_u	9	10

P_u = ultimate design wind load for each region