Australian Meteorological and Oceanographic Journal 60 (2010) 207-212

Impact statistics of *Tracy* and an opportunity missed

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(Manuscript received May 2008, revised January 2010)

When cyclone *Tracy* struck Darwin in 1974 it caused extensive damage to housing. A survey conducted by the authors included measurement of a damage index for about 1500 timber framed elevated houses of similar size and construction. This large sample provided a unique opportunity for quantifying the spatial variation of the wind-field impact of a typical tropical cyclone.

In addition it was observed that unacceptable levels of damage occurred to all types of housing. An examination of this damage gave rise to the suspicion that the concept of using conventional structural engineering principles to develop 'engineered cottage construction' would not lead to an acceptable level of risk in the event of the occurrence of rare structural hazards. Subsequent data obtained from field studies and laboratory tests have served to reinforce this observation. As a result, it is proposed that the design of houses to resist rare structural loads should include the use of a reliable 'anchor structure'.

The destruction by *Tracy* was so extensive, that it could have been used at that time as a trigger to introduce the radical concept of an anchor structure into building regulations. This was not done, and it was a unique opportunity missed.

Introduction

In December 1969 a wind storm in Melbourne with maximum gusts estimated to be about 30 ms^{-1} caused a fair amount of damage to houses and other buildings. This motivated the authors to initiate a program of using engineering principles to analyse the destructive effects of wind on houses and other low rise buildings (Leicester and Reardon 1970). In the following years they investigated several other wind storms (Leicester and Reardon 1976a) and organised a travelling seminar titled 'Keep Your Roof On' to tour the major cities of Australia. The intention of these seminars was to spread the message that winds could damage Australia's low rise buildings and that the extent of the damage could be mitigated by the application of conventional structural engineering principles. The seminars were presented by a handful of CSIRO scientists assisted by local experts. It would be fair to say that the concept of engineering house construction to resist wind damage met with a degree of scepticism at that time; it was often considered to be only an academic exercise. However all this changed when *Tracy* struck Darwin in December 1974.

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The damage caused by *Tracy* was so extensive, and the houses constructed by the Federal government in Darwin were so limited in design types, that for the first (and hopefully last) time it was possible to use the statistics of damage to assess structural parameters related to wind damage. In addition, the variety and range of damage observed threw doubts on the efficacy of the approach used in Australia to design and construct houses to resist extreme events such as cyclones.

The damage survey

Soon after *Tracy* occurred, damage survey runs were made along 38 selected routes uniformly distributed through the built up areas of Darwin. Most of the survey runs were made in uniformly built up areas in flat terrain. This terrain was similar to that defined as Terrain Category 3 in the loading Code As1170 (Standards Association of Aust 1975) and so the buildings covered by these runs were defined as having an exposure category C. Specifically, Category C was taken to refer to houses located in the middle of a uniformly built up area that was almost flat and with a wind fetch being less than 100 m. The damage survey undertaken comprised approximately 2800 buildings, including a sample of 1486 timber framed high-set houses, 532 brick houses and 127

A.C. sheet houses. Details of the survey and the method used for processing the data have been given in a previous paper. (Leicester and Reardon 1976b).

Each house surveyed was allocated a damage index that was defined by

$$\text{damage index} = \frac{\text{cost for repair of damage}}{\text{initial cost of building}} \quad (1)$$

In practice this ideal concept was simplified further by assuming that a house would collapse in a specified sequence of events as the wind gust experienced increased. Accordingly the damage index allocated to each particular house was defined by the 'worst' damage feature observed. The possible range of damage indices is 0.00 to 1.00. As an example, the damage indices used for high-set houses is shown in Table 1.

Table 1. Assumed damage indices for high-set houses.

DAMAGE CLASS	*TYPE OF DAMAGE*	*DAMAGE INDEX*
1	Negligible	0.00
2	Missile damage to cladding or windows	0.05
3	Loss of half roof sheeting	0.10
4	Loss of all roof sheeting	0.20
5	Loss of roof structure	0.25
6	Loss of half walls	0.50
7	Loss of all walls	0.75
8	Loss of half floor	0.85
9	Loss of all floor	0.95
10	Collapse of floor support piers	1.00

Because the high-set houses surveyed comprised a large sample of roughly similar buildings, these were chosen as the sample to provide an estimate of the wind field of cyclone *Tracy*. In the following, the wind speed is defined as the peak three-second gust occurring during cyclone *Tracy* at the height of single storey eaves. The procedure used was to first obtain a histogram of damage classes such as that shown in Fig.1 for high-set houses. Then assuming that the damage classes would occur sequentially as the wind pressures increased, sequential ranges of wind pressures were allocated to each damage class. It was found that a reasonable fit with the wind pressures estimated by experts in the aftermath of the destruction by *Tracy* could be achieved if the assumption were made that the range of wind pressures corresponded to a lognormal distribution having a mean value corresponding to peak wind gusts of 50 ms^{-1} and a coefficient of variation of 40 percent. With this assumption together with the assumption of sequential failure modes mentioned earlier, the distribution of wind pressures corresponding to each damage class was obtained as illustrated in Fig. 2. These results are tabulated in Table 2.

Fig.1 Distribution of damage classes for high-set houses in Category C exposure.

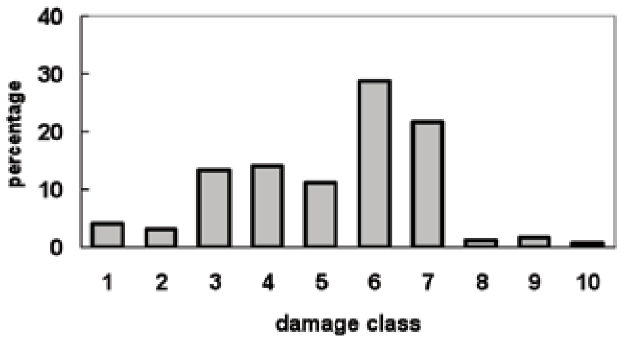
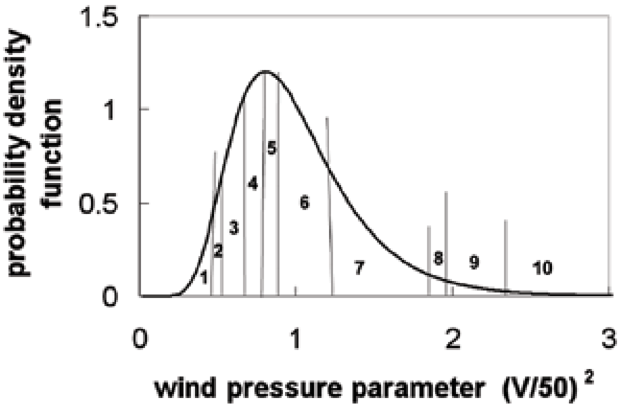


Fig.2 Wind pressures related to damage classes for high-set houses in Category C exposure.



Finally, using the data in Table 2 to allocate an estimated wind gust to damage each house, an average gust estimate was obtained for each survey location. The wind field derived in this way is shown in Fig. 3.

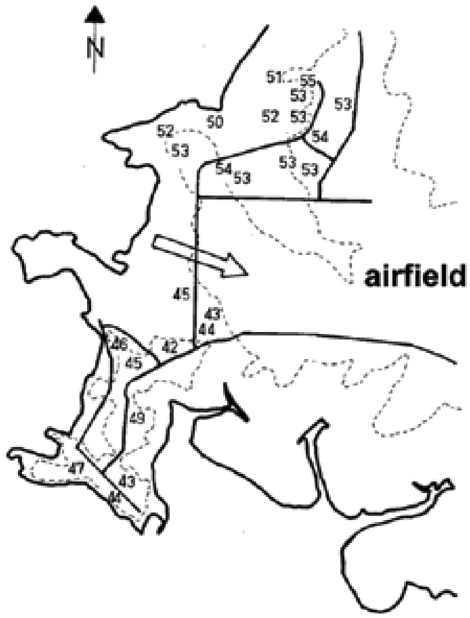
Table 2. Wind speeds related to damage classes for high-set houses in Category C exposure.

DAMAGE CLASS	*NUMBER OF HOUSES (%)*	*MEAN WIND SPEED (ms^{-1})*	*THRESH-OLD WIND SPEED (ms^{-1})*
1	4	32	
2	3	36	34
3	13	39	36
4	14	43	41
5	11	46	45
6	29	51	47
7	22	60	55
8	1	69*	68*
9	2	73*	70*
10	1	81*	77*

* Assessment unreliable because of limited sample sizes

The wind field shown in Fig.3 was then used as a basis to relate wind speed to damage class for other types of houses and commercial buildings. It provides a procedure for making a quantitative assessment of the vulnerability of various building types. Details of this procedure and the derived vulnerability profiles are given in the paper cited previously (Leicester and Reardon 1976b).

Fig. 3 Estimate of wind gust speeds (ms^{-1}) for houses in category C exposure.



The damage indices for buildings located in areas subjected to similar wind fields also provided a useful quantitative method for assessing comparative structural performances. In doing this, one criterion applied was to assume that the uncertainty in the mean damage index would be less than 0.05 if the sample size was greater than twenty. Using this and other similar criteria, the following findings were obtained:

- high-set houses with a mean damage index of 0.39 were considerably more damaged than the corresponding low-set houses which sustained a damage index of 0.22 (at a mean wind gust speed estimated to be 49 ms^{-1});
- in the northern suburbs, the high-set housing constructed in 1973-74 sustained a damage index of 0.68, which was significantly larger than the value of 0.52 sustained by the high-set housing constructed before 1971;
- old steel industrial buildings with a mean damage index of 0.63 were considerably more damaged than new steel buildings which sustained a damage index of only 0.14 (at a mean wind gust speed estimated to be 46 ms^{-1});
- there were no noticeable differences in the performances of pre and post war high-set housing on the RAAF and Navy bases;
- the presence of high-set houses did not provide any measurable wind protection to low-set houses; and
- the presence of an open wind fetch greater than 200 m caused a significant increase in wind damage.

Building houses to resist cyclones

The vulnerability of current housing construction

A valuable lesson that should have been learned from examining the damage of cyclone *Tracy* was the significant role of unintended errors, particularly human errors (anon 1975). Every type of housing was damaged by the cyclone, whether high-set, low-set, timber framed, brick, steel or concrete construction. Worse, even houses designed and supervised by professional engineers fared badly, notwithstanding all the excellent engineering lessons learned from the destruction caused by cyclone *Althea* to housing in Townsville a few years earlier; in particular it should be noted that the 1973-74 high-set houses in the northern suburbs that sustained abnormally high destruction rates were the most recently constructed houses and had been constructed by Darwin's Department of Housing, at that time serviced by a very conscientious and capable group of engineers.

The average builder is a person who endeavours to construct the structure of houses by connecting together several hundred elements according to a set of code specifications; this builder has only limited knowledge of sophisticated engineering concepts such as the racking action of a shear wall. It is very difficult to train such a person to construct a strong building through simply following a set of rules. And the problem for the professional structural engineer is that they may be dealing with modes of failure and structural materials with which he has had no previous experience and for which in fact there may be no test data; some examples of this that were exposed by the damage that occurred due to cyclone *Tracy* included attack by wind-borne debris, the fatigue strength of metal straps, the performance of brickwork reinforced by unconventional systems, and the distribution of racking loads to the various shear walls.

Since the occurrence of *Tracy*, there have been several other experiences that have served to reinforce the concern with the importance of human error effects. The following are some examples that illustrate this concern.

In 1978 the Australian Federal Government was considering the introduction of a national natural hazards insurance scheme and to assist in developing this proposal, the Australian Department of Housing and Construction commissioned a team from CSIRO to undertake a tour to examine the housing construction being used in the northern coastal cities of Australia. The purpose was to assess the vulnerability of housing to cyclone damage. During this investigation it became abundantly clear to the investigation team that numerous structural errors were being built into housing and that neither the builders nor the inspectors were aware of this. As a result, the vulnerability model developed during the investigation took into account the effects of the probability of the occurrences of errors (Leicester et al. 1979;

Leicester 1981).

These impressions were further reinforced during the course of another commissioned survey which was undertaken to assess the strength of houses built during the reconstruction of Darwin following the destruction by *Tracy*. Again, errors in construction were noticed and the omissions noted here were of particular concern as the design and supervision of this housing was to a large extent done by professional engineers.

Finally, an interesting source of examples of structural errors can be found in the reports on full scale house tests undertaken by the Cyclone Testing Station at James Cook University in Townsville, Australia. These tests were huge undertakings, in which full size commercial houses were subjected to simulated cyclonic wind loads, typically with about 10 000 cycles of loading (Fig. 4.) During these tests, four of the first six houses tested failed prematurely and needed to be repaired or modified before the tests could be completed. The detailed reports on the tests of these four houses, shown in Fig. 5, are given in the attached references. Some of the errors noted were as follows:

- High-set house (Boughton and Reardon 1983); premature failure of sub-floor bracing system.
- Logan house (Reardon and Boughton 1984); a prefabricated system which revealed an unintended weakness in the tie-down of a steel channel purlin.
- Tongan Hurricane house (Boughton and Reardon 1984); premature fatigue failure of a tie-down metal strap.
- Brick veneer house (Reardon 1986); premature failure of looped metal straps and also a brick pier.

There was also an additional concern that wind tunnel studies often indicated higher loads would occur in practice than the code specified loads which were usually used as the basis for selecting the applied test loads. Combining all the above information, it would appear inescapable that the concept of 'engineered cottage construction' used in Australia, i.e. the design of traditional housing systems to resist wind loads with a specified reliability, does not appear

Fig. 4 Simulation of cyclonic loads on a full scale house.

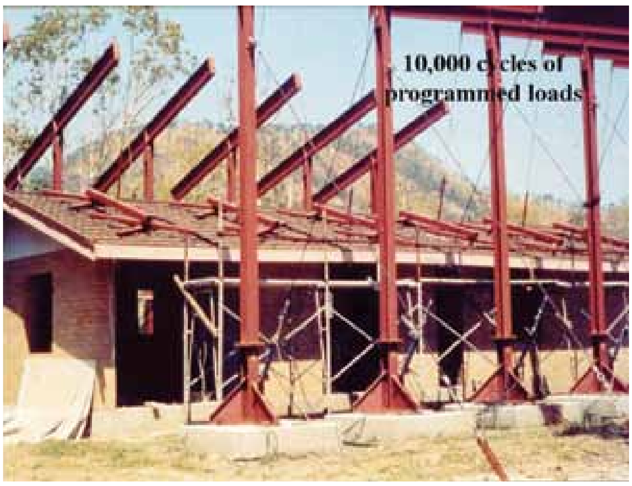
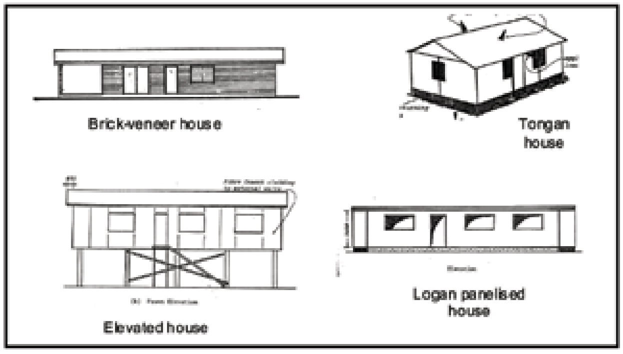


Fig. 5 Full size houses that exhibited premature failure.



to be suitable for use in producing housing that can resist extreme events with acceptable reliability because of the possibility of the occurrence of unintended errors.

The way forward

The damage incurred by cyclone *Tracy* and subsequent experiences cited, indicate that the process of engineered cottage construction used in Australia cannot be relied on to produce houses that can reliably resist rare and extreme wind pressures such as those that occurred during the course of cyclone *Tracy*. The historical record of wind pressures in Darwin, as shown in Fig. 6, illustrates the difficulty of relying solely on past experience in design and construction to deal with rare loads. By contrast, conventionally engineered structures in Darwin, such as for example the steel framed drive-in screen shown in Fig. 7, performed perfectly.

One solution is to include within each house an 'anchor structure' that is a conventionally engineered structure, constructed with conventional engineering materials, and that is easy to construct and inspect.

An example of one such anchor structure would be the reinforced concrete ring beam and column system advocated in Florida and the Bahamas (Anon 1975; Ministry of Works 1976; Leicester 1987.). This structure is illustrated in Fig. 8. If a house contains such an anchor structure, and the rest of the house attached to it is engineered cottage construction, then failure of part of the roof or a wall system due to errors

Fig. 6 Annual peak wind pressures measured at Darwin airport.

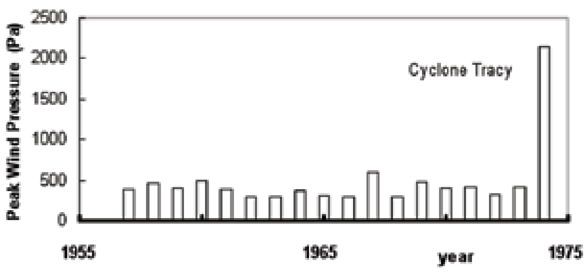


Fig. 7 Drive-in movie screen located in a northern suburb of Darwin.

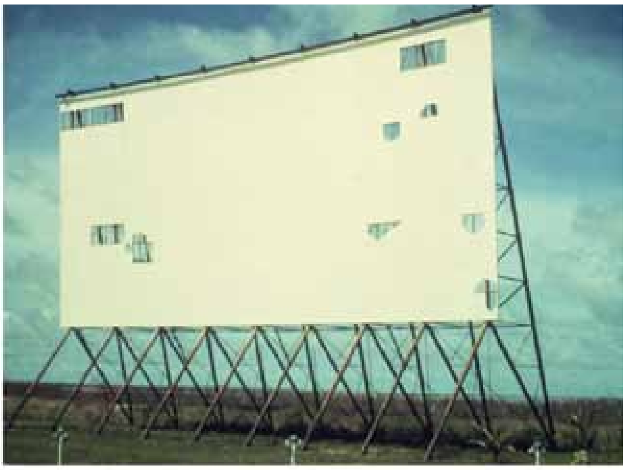
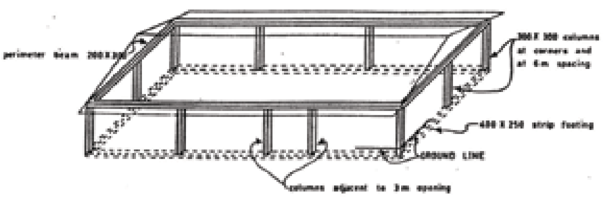


Fig. 8 Anchor structure constructed with reinforced concrete (All main reinforcing to be 16 mm dia.).



in the engineered cottage construction would have only a local effect, and would not lead to the collapse of the total house as frequently occurred to houses struck by cyclone *Tracy*.

These concepts relating to human error were formulated by the authors while examining the damage of *Tracy*, but have never been included in the subsequent drafting of Australian building regulations. Currently these regulations are tied to the concept of engineered cottage construction, coupled with an emphasis on the training of builders and building inspectors; they do not address the possibility or consequences of human error.

The incorporation of a reliable anchor structure within a house can often be done with minimal extra cost. In fact there are some existing building systems that do have reasonably reliable anchor structures. These include heavy section welded steel frames, some reinforced concrete block systems and heavy pre-fabricated houses constructed with room size boxes of reinforced concrete (Fig. 9). However it would be fair to say that these systems contain anchor structures by accident rather than through deliberate design considerations.

Fig. 9 Heavy reinforced concrete boxes act as excellent anchor structures.

Conclusions

The destruction caused by *Tracy* was so extensive that the event provided several unique opportunities. The first was that the damage could be used to provide quantitative information on the cyclone wind field and also on building vulnerability through the application of statistical procedures such as those given herein. The second was that for a while there existed a window of opportunity for implementing a step change in the building process.

The shock resulting from the destruction caused by *Tracy* was so massive, that it would have been possible at that time to introduce significant changes into the technology and processes of the Australian building industry. One such significant change would have been to introduce a requirement for reliable ‘anchor structures’ to be incorporated into houses in cyclone prone regions. There is adequate evidence to demonstrate that the process of engineered cottage construction currently used in Australia, wherein traditional housing systems are designed to meet target strength requirements, frequently does not result in houses that can reliably resist rare and extreme events such as Australian cyclones. The unique opportunity to introduce into building regulations the concept of using anchor structures was unfortunately missed.

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