TROPICAL CYCLONE YASI – LOAD TESTING OF TIMBER HOUSES ON A LARGE SCALE

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ABSTRACT: Tropical Cyclone Yasi severely affected an area of Queensland between Mission Beach and Cardwell, with peak gust wind speeds estimated at 240 km/hour. This is just less than the wind speed that the majority of buildings in the area were designed to withstand (250 km/hour). The Cyclone Testing Station undertook an investigation into the performance of buildings under these winds and examined over 1900 houses and other low-rise buildings in the most severely affected areas. This paper has a focus on how timber elements performed under the cyclone environment. It raises the importance of selecting the correct materials and connection details not only for the day-to-day environment, but also for extreme conditions during rare loading events.

KEYWORDS: Tropical cyclones, storm tide, wind damage, timber structures, timber housing, connection details

1 INTRODUCTION

Tropical Cyclones are similar large-scale meteorological events to hurricanes and typhoons, and have the capacity to subject a large number of buildings to similar wind loads. The investigation of a population of buildings that have been impacted by similar winds allows quantifiable assessment of good and bad performance. These studies allow the industry to learn from these severe events and to enable effective mitigation strategies.

This paper presents the findings of a comprehensive investigation into the performance of buildings during Tropical Cyclone Yasi [1] with particular emphasis on the behaviour of timber buildings. Both wind loading and storm tide effects are discussed.

2 TROPICAL CYCLONE YASI

Tropical Cyclone Yasi (TC Yasi) was a large diameter severe tropical cyclone that crossed the Queensland coast near Mission Beach in the early hours of 3rd February 2011. On its approach to the coast, TC Yasi was categorised as a marginal Category 5 event (the highest Australian category) [2] and the population in the affected area took appropriate precautions that included evacuation of low lying areas.

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There were no deaths caused by wind or storm tide damage to structures. The Insurance Council of Australia [3] reported that by December 2011, over 72,000 claims had been lodged for this event with a total claim value of AUD$1.33 Billion (USD$1.44 Billion, December 2011).

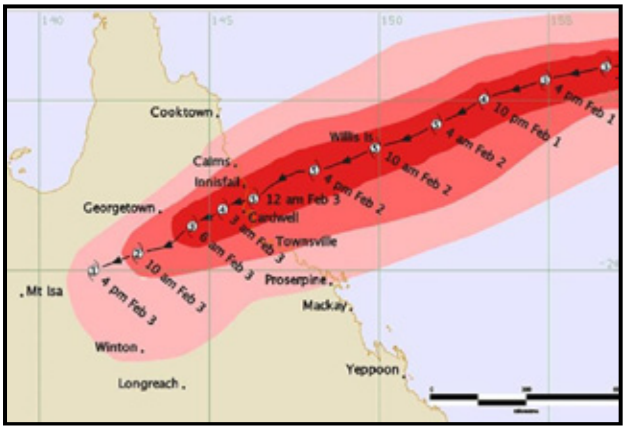

***Figure 1:** TC Yasi track (BoM)*

2.1 TC YASI CHARACTERISTICS

The track of TC Yasi on the Bureau of Meteorology's web site [2] showed that it had reached Category 5 just before landfall, but was Category 4 immediately after landfall. Their estimate of a peak gust on Willis Island was 285 km/h.

The lowest recorded central pressure was 929 hPa near Tully during the passage of the eye and within 20 km of the cyclone's landfall. This central pressure was used in

the Holland model to develop the wind field in the study area.
The cyclone had a very large eye with an estimated radius to maximum winds of over 30 km. A storm tide at Cardwell of 4.5 m was recorded. This placed the peak storm tide level at more than 2.2 m above Highest Astronomical Tide.

2.2 WIND SPEEDS

In assessing the performance of buildings it is necessary to have an estimate of the wind loads on them. This requires a detailed map of wind speeds over the study area. Unfortunately, there were no recording anemometers in the area that sustained the maximum winds and the closest anemometer (60 km from the maximum wind zone) suffered damage in the event and may have recorded unreliable data.

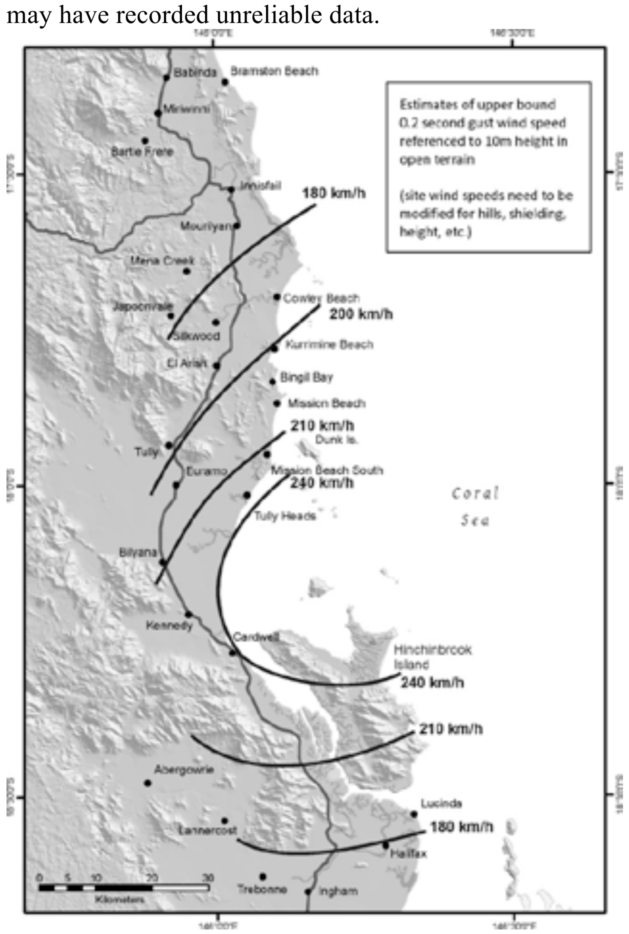

Figure 2: Estimates of peak gust wind field

The wind field was deduced using the combination of field estimates and cyclone wind field modelling:

- Estimates of wind speeds near ground level were derived from the analysis of wind loads on simple structures such as road signs that had survived (upper bound of wind speed) or failed (lower bound of wind speed) [4]. Over 100 such signs were investigated and gave upper and lower bound wind speed estimates over the full study area.
- These speeds were incorporated with a Holland wind field model to estimate the 0.2 second gust wind speeds at the standard reference height [5]. This produced a map of the estimated peak gust wind speed which is shown in Figure 2.

The estimated wind field shows that the peak gust over communities is near 240 km/h or 67 m/s. The ultimate limit states wind speed for Importance Level 2 structures (which include houses) in the same region is 69 m/s. The peak gust estimated was very close to that for the design wind event.

3 BUILDING PERFORMANCE UNDER WIND LOADS

Both general and detailed assessments of buildings were undertaken.

3.1 GENERAL ASSESSMENTS

The Cyclone Testing Station conducted an external survey of nearly 2000 houses in areas that experienced peak gusts of 200 km/h or more as shown in Figure 2. The damage was categorised as a three digit number corresponding to the severity of roof, window and door, and wall damage as shown in Table 1

***Table 1:** Three category damage index*

No	Roof (R)	Openings (O)	Walls (W)
0	None	none	none
1	Gutters downpipes	debris not pierced	debris not pierced
2	Debris damage to roof	debris pierced	debris pierced
3	lifted < 10%	windows/doors leaked	Carport /verandah damage
4	lost roofing < 50%	Windward broken < 30%	One wall panel fallen
5	lost battens < 50%	frames lost < 30%	> 1 wall panels fallen
6	lost battens > 50%	Windward broken 30%-70%	racking damage, cladding attached
7	lost battens > 50% and lifted rafters	Windward broken > 70%	racking damage and lost cladding
8	lost battens > 50% and damaged tie-down	Windward broken > 70% and suction loss	only small rooms intact
9	lost roof structure > 50% including ceiling	100% broken / missing	no walls remaining

In each category of the damage, index 1 to 3 represented fairly minor damage and index 4 and above represented major damage. In each category it was possible to underestimate damage in index 1 to 3, but not in index 4 and above. The damage most relevant to this paper is roof damage, and it is illustrated for all houses surveyed in Figure 3. The inset shows a magnification of the data for index 4 and above.
Figure 3 shows damage segregated into houses built prior to the 1980s and houses built after the 1980s. This classification corresponds with the introduction of requirements for engineered tie-down details into housing in Appendix 4 of the Queensland Home Building Code in 1981 [6].
There is a significant difference between the two types of houses in the zero damage index, with around 70% of the recent houses having undamaged roofs and only around 50% of the older houses.

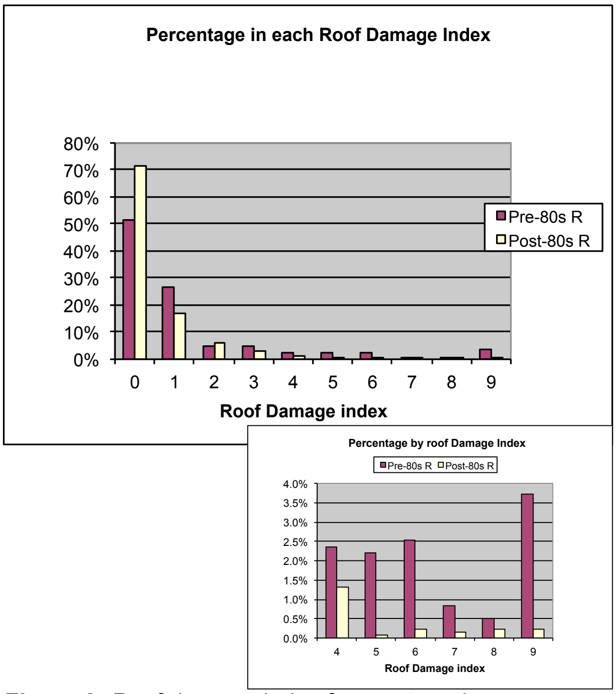

Figure 3: *Roof damage index from external survey*

When viewing the more significant damage in the inset to Figure 3, it can be seen that the Pre-80s housing had higher percentages of more serious damage than the Post-80s housing.

- A total of less than 3% of the Post-80s houses had roof damage rated at level 4 or above.
- More than 12% of the Pre-80s houses had roof damage rated at level 4 above.

Figure 4: *Roof damage to Pre-80s house*

Figure 4 illustrates some of the roof damage to Pre-80s housing. Many of the Pre-80s houses had hardwood timber wall and roof frames. In some cases, the roofs were trussed, but in many the rafters were supported by ridge boards and underpurlins as shown in Figure 4.
Figure 5 shows roof damage to a Post-80s house. Many of the Post-80s houses had reinforced concrete blockwork walls with timber trussed roofs. Many of the houses built in the 1980s and early 1990s had hardwood roof frames, but from the mid 1990s onwards, softwood roof trusses predominate. No difference in performance of hardwood and softwood roof frames was noted.

Figure 5: *Roof damage to Post-80s roof*

Both Figures 4 and 5 show connection failures. The most common failure in the Pre-80s housing was the batten-to-rafter connection as shown in Figure 4. Current requirements are not satisfied by the nailed connections that were commonly used prior to the release of Appendix 4 [6].
In most of the damaged Pre-80s houses, the roofing had been replaced at least once since the release of Appendix 4, but no attempt had been made to improve the connections within the roof structure. In contrast, the majority of the relatively smaller number of failures observed in the Post-80s houses were deeper in the structure such as the truss to wall connection failure shown in Figure 5.

3.2 DETAILED ASSESSMENTS PRE-80S HOUSES

In a number of cases apparently undamaged houses or damaged structures were subjected to a detailed assessment.
Figure 6 shows a batten-to-rafter connection in an apparently undamaged Pre-80s house. (This damage would not have been captured during the street survey) It is clear that under the actions of the wind forces, the nailed connection had started to work free, but had not completely withdrawn [7]. This type of connection would be compromised in its ability to resist future events.

Figure 6: *Partial withdrawal of nailed connection*

By contrast, Figure 7 shows a roof structure from a house that was a similar age, but had its roof sheeting replaced 4 years prior to TC Yasi. All of its roof connections were also upgraded while the roof was off. There was no observed incipient connection damage.

***Figure 7:** Better performance of refurbished roof*

It is recognised that the structural requirements in Pre-80s houses were lower than the current requirements, and it was observed that upgrading the details to meet current requirements proved an effective way of improving the performance of Pre-80s houses (e.g. via publications such as AS 1684 [8] and HB 132.2 [9].

The study made a recommendation that a public education program be mounted to inform home owners of the steps that could be taken to improve the performance of their Pre-80s houses for future wind events.

A number of older beach-side structures showed significant signs of corrosion of connections. The truss anchorage brackets shown in Figure 8 had almost completely disappeared. Wood rot at the same location had compromised the holding power of the timber as well.

***Figure 8:** Corrosion of fasteners*

Regular building maintenance should find and address corrosion or rot in structural elements. A number of owners we spoke to were unaware of the extent of the deterioration of structural elements in their homes.

3.3 DETAILED ASSESSMENTS POST-80S HOUSES

Again in this house type, a number of cases of apparently undamaged houses or damaged structures were subjected to a detailed assessment.

In Figure 9, the roof on an outdoor entertainment area had appeared to perform well under the wind actions, but a split had opened up under the action of tension perpendicular to the grain. In this case, the purlins are securely bolted to the rafters, but the brackets fix only to the upper edge of the timber rafter. With the post anchorage only engaging the lower edge of the rafter, wind forces must be transmitted across the centreline of the rafter by tension perpendicular to grain. This type of failure could have been avoided by ensuring that the rafter to post connection extended to the top surface of the rafter. Connecting the purlins to the full depth of the rafter may also have helped.

***Figure 9:** Tension perpendicular to grain in rafters*

The roof damage shown in Figure 10 was caused by failure of bolted connections between the roof structure and verandah beams and top plates. Careful study of bolts that had been removed, and some that were still in place but partly undone (circled in inset in Figure 10), showed that the nuts had come off the bolts during the event. It was postulated that the repeated loading had enabled them to rattle themselves free.

***Figure 10:** Roof loss as a result of bolts rattling undone*

Both of these connection failures were associated with details that complied with current standards, however, in both the difference between compliance and fitness for purpose was quite subtle. The small improvement in detail for the rafter to post connection in Figure 9 has already been discussed. In the case of the bolted connection, the galvanised nut turned freely on the stainless steel bolt. It is recommended that the replacement nuts be self-locking nuts.

3.4 ROLE OF INTERNAL PRESSURES

Figure 11 shows a house in which "cyclone screens" had been installed to protect windows, but in which a door had failed and still caused the high internal pressures that initiated the roof loss.

Figure 11: *Roof loss as a result of door failure*

In a significant number of buildings a dominant opening created internal pressures that may have contributed to substantial roof damage. The reason for these openings varied:

- Failure of door furniture (latches, bolts, hinges);
- Failure of window frames causing the whole window assembly to be blown out of the wall frame;
- Failure of garage doors under wind pressure;
- Failures of windows, doors and cladding under wind-borne debris impact.

Currently, AS/NZS 1170.2 [10] allows design for lower internal pressures in tropical cyclone-prone areas where openings are protected against debris impact. Many of these failures (including the one illustrated in Figure 11) would not have been avoided by debris protection measures. The wind loads on houses taken from AS 4055 [11] use full dominant opening internal pressures by default.

3.5 WATER INGRESS

Tropical cyclones are accompanied by driving rain and the very high wind speeds can drive the wind-borne water up walls and windows under flashings and into buildings. During near-ultimate limit states events such as TC Yasi, there is often a very high differential pressure from the outside of the building to inside which also contributes to water entry.
Many substantial insurance claims were made in houses that had suffered little or no structural damage, but had lost ceilings and wall linings due to water ingress into the roof space. Significant contents damage was also caused by water ingress.

Internal plasterboard linings are particularly vulnerable to damage if they are saturated during the event. While they are not timber products, they are often associated with lightweight construction and form an integral part of the lateral resilience and load transfer system. Improved performance of "non-structural" elements such as soffit linings, windows and flashings together with the development of more resilient linings for use in cyclone-prone areas is required to address this problem.

4 BUILDING PERFORMANCE UNDER STORM TIDE

As indicated in Section 2.1, a 4.5 m storm tide was recorded at the Cardwell tide gauge [12]. It is shown in Figure 12.

4.1 TC YASI STORM TIDE

Storm tide is the height of the sea surface during the passage of the cyclone. It is caused by the combination of three different effects during the approach and passage of the cyclone which are superimposed on the daily tides:

- The low central pressure can lift the water surface around 1 m.
- The friction from the wind passing over the water forces the water towards the land on one side of the cyclone. This water "piles up" against the land on that side of the crossing point.
- Wave action lifts the water surface, and the waves run up over the water edge under their own momentum. This can further transport the sea water up slopes.

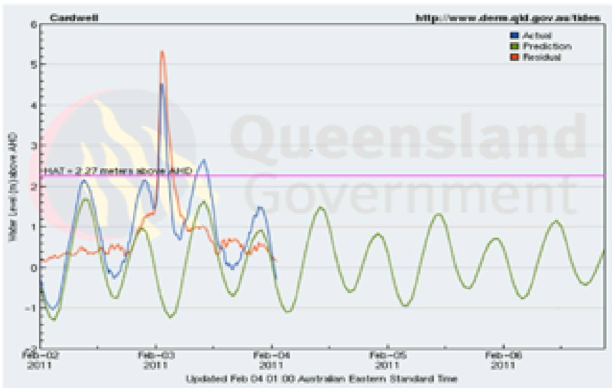

Figure 12: *Cardwell tide gauge showing storm tide [9]*

Figure 12 shows the normal tidal fluctuations in green and the measured tides in blue. The difference is the storm surge and is shown in red. It is the rise in sea surface due to the tropical cyclone. The storm tide is the elevation of the water surface and the peak was 4.5 m above Australian Height Datum (AHD). This means that on a contour map, the water surface would have been at the 4.5 m contour.
TC Yasi caused storm tide damage at Cardwell, Tully Heads and Hull Heads. There is a possibility that the storm tide may have been a little higher in Tully Heads

and Hull Heads than the official tide gauge at Cardwell as those locations were closer to the crossing point. Because of the low-lying nature of those communities, evidence on buildings suggested that the water surface was around 2 m above the ground surface for the beach-front row of houses.

4.2 TC YASI STORM TIDE DAMAGE TO HOUSES

Where the level of water in a house was less than about 0.2 m as illustrated in Figure 13, there was minimal damage to the house itself.

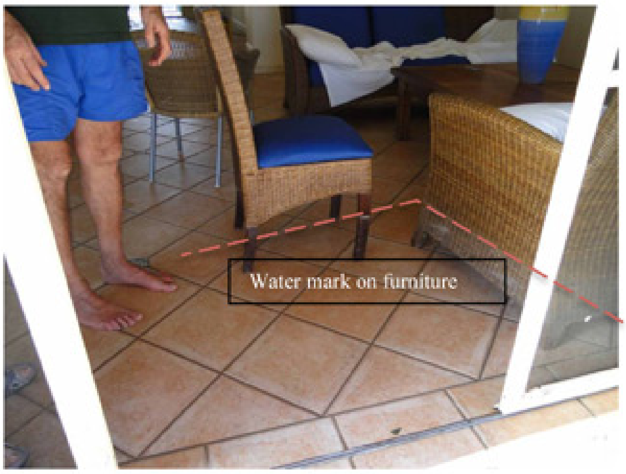

Figure 13: *Water 200 mm above floor*

Water ingress due to storm tide has different effects to rising floodwater, which include:

- Storm tide inundation is of short duration, often less than 2 hours, whereas riverine flooding may last for days.
- Mould growth appears to be stifled by salt water, but can last for months in wall cavities after freshwater flooding.
- Storm tide water in coastal areas is rarely accompanied by sewerage.

Low depths of water above floor level were not able to sustain wave action, so that the effect of water movement on the structure was not important. Therefore, there may not be a need for significant repair work after small inundations with storm tide.
However, where the level of water in the house was around 1 m, there was sufficient water movement to cause largely non-structural damage. For example, the displacement of non-structural walls, movement of contents and damage to linings, as shown in Figure 14.

Figure 14: *Water 1 m above floor*

A 1 m level of water above the floor is sufficient to sustain wave action. Where waves had broken against a door, window, or non-structural wall when the depth of water through the house was around 1 m, the wave was able to break all of those elements as shown in Figure 15.

Figure 15: *Damage to non-structural masonry wall*

A 2 m level of storm tide above floor level in a house was able to break structural walls, as shown in Figure 16.

Figure 16: *Water up to 2 m above ground*

4.3 TIMBER RESPONSE TO STORM TIDE

Figure 16 shows a house in which some structural timber remained although the storm tide was close to the top of the walls. However, in this case, the under-floor structure was compromised and many of the structural walls failed.

Figure 17 shows a timber framed house in which the timber framing and structural plywood cladding remained intact through the event with a similar height of water in the house.

While the structure of this house survived, the internal linings, electrical wiring and particle board floors did not and the building shown has been demolished and a new house built on the site.

Figure 17: *Structural timber intact*

A number of other high-set timber houses were able to remain serviceable after the event as the bulk of the wiring and linings were not submerged. Solid timber linings were able to withstand inundation by the storm tide as shown in Figure 18. However, particle board and interior plywood was not. The plasterboard ceiling was in the splash zone and was destroyed.

Figure 18: *Solid timber linings after submersion*

In general, houses that presented the least obstruction to storm surge water flowing through or under the house sustained the least damage. In some cases, where the lower storey allowed unimpeded passage of the water, the second storey of two storey beach-front houses continued to protect contents throughout the event.

5 IMPROVING STRUCTURAL PERFORMANCE

Even the low level of damage sustained by a number of relatively small communities will take a number of years to repair. Improvement in performance of both existing and new buildings can be improved.

5.1 DETAILING FOR WIND

Current design requirements for timber housing in the affected area involve assessing wind classification using AS 4055 [11] and matching the wind classification with connection details in AS 1684.3 [8]. In some cases, notably the tops of ridges, AS 4055 had not been applied well and led to premature failures, but where the standards had been applied rigorously, buildings performed satisfactorily.

Performance of Pre-80s houses can be improved by upgrading structural details to current standards. All houses require regular structural inspection and maintenance to ensure that structural details continue to remain serviceable.

5.2 DETAILING FOR STORM TIDE

While Australia currently has no mandatory requirements for storm tide resistant construction, reconstruction guidelines have been prepared by the Queensland Reconstruction Authority [13]. These contain some strategies for planning reconstructed and other new buildings in the areas damaged by TC Yasi's storm tide.

- Where possible, the main occupied floor levels should be situated above the anticipated storm tide level defined at an appropriate ULS level.
- Also if possible, the area under the floors should allow flow under the structure with few obstructions.
- Auxiliary structures such as fences, garden sheds and tanks should be kept to a minimum or securely anchored to prevent them being swept away and lodging under otherwise satisfactory houses.
- Where it is not possible to detail houses for storm surge flow under the floor, the house should be detailed to allow flow through. This can be achieved in garages and rumpus rooms by use of knock down walls that are designed to fall over, but remain attached so that water can flow through the building without damaging the facilities above.

Figure 19 shows a timber floor that had performed satisfactorily except near a concrete wall under the floor space. Waves striking this wall were reflected up into the floor and caused significant damage, but only within 3 m of the under-floor obstruction.

Figure 19: *Floor damage near an under-floor obstruction*

The Guidelines [13] also make recommendations about location of wiring and other services, suggesting that, where possible, they are installed above the expected storm tide level.

The Guidelines also had some suggestions about materials and construction standards. There are three zones in the house that require consideration:

- Below the expected storm tide zone, the use of timber should be minimised, but structural timber has demonstrated performance in bracing systems. Extra bracing forces should be provided for in resisting water flow and water-borne debris.
- Just above the storm tide zone, splash resistant materials should be used and any glued timber products should be appropriate for external exposure classes. In this region, design and construction for wind forces gives adequate strength.
- Well above the storm tide zone, materials and detailing should be selected to resist wind forces and prove resistant to wind-driven water ingress as indicated in Section 3.5.

6 CONCLUSIONS

A significant number of timber houses in the coastal strip from Bingil Bay to Cardwell in North Queensland were subjected to winds approaching the current ultimate limit states design wind event. Nearly 2000 houses, the majority of which had timber roof structures, were subjected to various levels of inspection for structural damage.

Less than 3% of houses built since the introduction of structural requirements for houses in the 1980s suffered severe roof damage. This compares favourably with over 12% of houses built prior to that suffering severe roof damage and indicates that current design and construction requirements are generally satisfactory.

For wind resistance, the combination of appropriate wind forces for the site exposure with structural details in AS 1684.3 [8] gave adequate strength. However, it is very important to comply with all of the details including number of fasteners, end and edge distances, and appropriate material selections.

In Pre-80s houses, the structural details installed during construction, especially for tie-down, may not be appropriate for current loadings. However, an opportunity is presented to upgrade the other components in the house whenever the building is subjected to maintenance, for example when roof sheeting is replaced. In cases where batten to rafter connections and rafter to wall connections had been brought up to current standards during refurbishment, the performance under wind load was comparable to that of modern housing. A similar opportunity for structural improvement is presented during repairs following some damage in TC Yasi.

For resistance to storm surge in low lying coastal areas, the main floor should be positioned above the designated storm tide level. Timber can be used for structural and non-structural applications in the splash zone immediately above the expected storm tide level and well above the storm tide level.

For parts of the structure below the expected storm tide zone, buildings should be laid out to allow the storm surge to flow under or through the structure with as little resistance as possible. Solid timber members and linings demonstrated that they could withstand storm surge inundation with minimal deterioration. Extra strength may be required to resist drag caused by water movement in the storm surge and to absorb impacts from water-borne debris.

For the splash zone, any glued timber products should have glues appropriate to external service classes. Structural detailing appropriate to cyclonic wind loads is adequate for this zone, but all materials used within 1 m of the storm tide level should not deteriorate if wet or inundated by sea water.

7 ACKNOWLEDGMENTS

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