5. Conclusions

Tropical Cyclone Yasi (TC Yasi) made landfall in the early hours of Thursday 3rd February 2011 with the eye passing over the Mission Beach region. There was no official anemometer in the path of the core of the cyclone to measure wind speeds. The estimated wind field for the study area was mapped using the Holland (1981) model for winds in tropical cyclones. The model was calibrated on meteorological information sourced from the Bureau of Meteorology and other sources including pressure and available anemometer data. Anemometer data was augmented with estimates of wind speeds at other locations based on the wind load required to form a plastic hinge in the post holding up a road sign. The study highlighted the dearth of recording anemometers along the tropical coast. A robust anemometer chain is proposed.

Estimated maximum wind gusts
Based on the wind field model and available data, the wind field's estimated maximum gusts experienced by structures in the highest wind areas of the study area were around 225 km/h (standardized to 10 m height over Terrain Category 2, as defined in AS/NZS 1170.2). The estimation error was +/-10%. The significance of this speed is that it is around 90% of the regional wind speed for Importance Level 2 (BCA) buildings in the region. That is, a very severe event, but below the wind speeds that would be expected to cause structural damage to current construction.

House structure performance
It was found that less than 3% of houses built post-1980s (i.e. housing built to current standards) and located in the area of highest estimated wind speeds, suffered significant roof damage. However, more than 12% of Pre-80s housing in the same area suffered significant roof damage. This level of damage indicates that this group has a lower structural reliability than the Post-80s housing. Where possible, roof space inspections should be performed on all houses that experienced winds near the design wind speed to look for structural damage that cannot be seen from outside the building.

The report found that the main reasons for the poorer performance of Pre-80s housing were deterioration of the structure with time, and the fact that the specified tie-down methods used at the time of construction do not meet the current requirements. Both of these problems can be addressed by inspection of the structural elements in the roof space and maintenance and/or upgrading of any elements that do not satisfy current requirements.

Roller door failures
Roller door failures were over-represented in the damage with a frequency of occurrence in Post-80s housing of about ten times the frequency of serious roof damage in the same housing. Sectional doors had a damage frequency in Post-80s housing of about twice that of serious roof damage in the same housing. Both types of doors were vulnerable to debris damage with small impacts causing major damage to the door. However, the roller doors had a significant number of failures under wind pressures. Improvements in door performance are urgently required, but also solutions for retrofitting existing doors to give them additional support to resist ultimate wind events also need to be developed.

Tiled roof damage
Tiled roofs also had a higher frequency of damage compared with sheet roofs. Failures of tile anchorage systems were most noticeable in ridge capping but also extended into the main body of the roof particularly from the ridges that ran along hips. Many of the ridges that had
failed used flexible pointing as the only fastening method, and more resilient systems for anchoring ridges need to be developed. Failures in Post-80s tiled roofs were particularly frequent in exposed locations with more than half of the tiled roofs in C3 locations and all of the tiled roofs in C4 locations suffering some damage.

**Structural damage to sheds**
Wind damaged sheds were observed in rural, suburban and commercial settings. In very few of these settings could a shed have been classed as an Importance Level 1 building either due to the proximity of other habitable structures or because the shed was being used as a dwelling. Some failures had been initiated by prior roller door failures and in other cases, the sheds were open on one or more sides. Design and construction to resist pressures derived from dominant openings would have reduced the level of damage considerably.

**Non compliance with codes, standards and industry information**
Failures of most structures could be tracked to detailing that was not in compliance with current Codes, Standards and industry information. Some of the areas in which improvement is needed were found to be:

- Determining the wind classification of sites.
- Selection of the right connections for use with the given wind classification.
- Selection of sufficiently durable materials for use in near coastal environment.
- Installation of sheeting and tiles fasteners in accordance with the manufacturer’s recommendations.
- Connection of window frames to the supporting members to transmit wind forces to the rest of the structure.
- Detailing windows to resist the wind pressures.
- Selecting appropriate door and window furniture to transmit wind loads without allowing the door or window to open.
- Care in installation of connections to ensure that the correct size of fastener and the correct number of fasteners is used for the Wind Classification. In a number of connections, care is also needed to ensure that the fastener is driven into the innermost member (particularly with roofing fasteners where the installer cannot see the batten or purlin into which they are fixed).

A study of the effectiveness of repairs after TC Larry showed that many repaired structures were able to safely resist the loads from similar wind speeds in the Kurrimine Beach area. However, from the limited survey sample, the results indicated that the performance of repaired buildings had a lower success rate than newly constructed buildings.

**Damage and topographic exposure**
There was a positive correlation between damage to buildings and the topographic exposure. For Post-80s houses, higher topographic class sites generally had more damage. Unconservative modeling of topography for ridges and escarpments in AS 4055 was one reason for this trend, and recommendations to address this have been made.
Wind-borne debris hazard
The study observed a range of different sizes of materials that had become wind-borne debris:

- Detached roof tiles had become wind-borne debris that had impacted other part of the roof from which they had been removed and nearby buildings. Tiles were observed to have broken windows and penetrated steel roofing and wall cladding.
- Some pieces of timber close to the size of the standard test piece were observed. Some of these had penetrated the outer cladding of buildings but few had made it into the inside other than through windows. One piece was observed to have come through a roof.
- Very large pieces of buildings had become wind-borne debris. These items included large assemblies of roofing and battens, significant portions of the roof structure, whole sheds and a complete shipping container.

The larger sized items of debris caused significant damage to buildings that they struck. Where these buildings had been able to resist the effects of dominant opening internal pressure, the damage was contained to the impact site. Where the building was not able to resist the higher internal pressures that came from damage to the building envelope, then the damage of the struck building escalated.

As a result of this conclusion, the Street Survey data was used to show that between 20% and 40% of the large pieces of debris released from Post-80s houses caused further damage to down-wind buildings. This will help in assessment of the costs and benefits of mandating the requirement that all low-rise buildings in Regions C and D should be designed to resist internal pressures arising from dominant openings.

Strengthened compartment in houses
The presence of large wind-borne debris and/or the risk of wind speeds exceeding design in an extreme event raised the issue of life safety of occupants of buildings and led to the consideration of “strong compartments” within residential buildings. A “strong compartment” within the building would give protection to the occupants even if large sized wind-borne debris was to penetrate the building envelope.

Guttering and solar hot water systems
Conclusions were also drawn on a range of other specific issues:

- Guttering and flashing had higher frequency of damage than most roof structures. While these items are generally thought of as non-structural, their repair has the potential to prolong the recovery process. Flashing damage also contributed to water entry.
- Solar hot water systems and solar photovoltaic panels were observed with no damage, with debris damage, and cases were observed where panels had become detached from the roof. Due to the mixed performance of these items and the variations in manufacturer further work on the wind loading and tie down of these elements is required.

Water penetration
Water penetration of the building envelope was observed in a large number of both Pre-80s buildings and Post-80s buildings. In the Post-80s buildings the common use of plasterboard linings and carpet floor coverings meant that many buildings that sustained no structural damage still had significant damage to linings and contents from water ingress. Some options
for minimizing the impact of this water ingress on the community and its recovery from the event were proposed.

Inspections of large apartment and resort buildings showed that all had issues with water ingress, wind driven debris damage, and flashing and soffit damage, but there was no observed damage to major structural elements.

**Storm tide damage**

Studies of the structural damage in storm tide showed that the buildings that performed best had their ground floor level above the storm tide crest and were sufficiently open underneath to allow the water to move past the building unimpeded. The study found that while most structural components of houses could resist 200 mm above the floor level with minimal impact on the structure, at depths above floor level of approximately one metre, structural damage resulted. Requirements for the construction of buildings within the storm tide zone need to be developed for Australia.
6. Recommendations

In general, buildings constructed since the 1980s performed well in TC Yasi, but this investigation has highlighted some potential problems in buildings of all ages and the following recommendations aim to improve future performance of buildings in tropical cyclones.

6.1 Buildings in storm surge zone

Addressing the risk to the building stock through either avoiding or resisting the loads induced by storm surge will require both planning and building design considerations. Requirements have been written for other jurisdictions and these need to be examined to see if they can be modified to suit the Australian built environment.

Observations on the performance of buildings in the storm surge zone in TC Yasi indicated that only those buildings with a floor level above the surge height and with open areas that allowed the unimpeded flow of water and debris around, under or through the building fared well in the storm surge experienced. However requirements should recognize that in events where the design storm surge level is exceeded, the damage can be catastrophic for the affected communities.

6.2 Recommended changes to Standards

6.2.1 AS/NZS 1170.2 Structural design actions – wind actions

At present, Clause 5.3.2 allows the ultimate limit states design internal pressures to be calculated assuming that all openings that can be protected against wind-borne debris, are closed and unbroken, provided it can be demonstrated by a test that the protection is adequate. This study has shown that the size of many items of observed wind-borne debris is significantly larger than the test pieces of debris and the larger items would have significantly more energy and momentum than the current and revised debris tests in AS/NZS 1170.2.

A detailed study should be undertaken to examine the costs and benefits of revising AS/NZS 1170.2 so that low-rise buildings in wind regions C and D should only be designed for wind pressures obtained using potential dominant openings. Such a requirement is compatible with the robustness provisions of AS/NZS 1170.0 which require that the repair of a structure be a function of the extent of damage to it. In other words, if a window is broken by any means, the owner should only have to repair the window rather than replace the whole roof.

6.2.2 AS 4055 Wind loads on housing

At present AS 4055 underestimates the topographic class of sites on ridges and escarpments. It is recommended that the Standard be amended so that the maximum slope is considered rather than the average of the maximum and minimum slope.
AS 4055 does not give net pressure coefficients for soffits (eaves lining). These items can have significant differential pressure and the investigation showed that they experienced high levels of damage in TC Yasi leading to other failures in the structure (often ceiling panels). Design pressures for soffits and supporting structures should be included in AS 4055 to permit them to be designed to resist these differential pressures.

6.2.3 Strong compartment within residential buildings

As indicated in Section 6.2.1, large debris has the potential to breach the building envelope at winds near the ultimate limits state design wind speed. To protect occupants from the harm that this debris may cause, residential buildings should have a strong compartment. Such a compartment can be a purpose built room, or strengthened small rooms that are a normal part of the building.

Some requirements for the construction of small rooms with strength to resist debris impact have been developed in the past.

The implementation of this recommendation does not lessen the need to design the whole envelope of buildings to resist expected wind pressures. It offers a means of protecting the life and safety of occupants in the event of large debris impact.

6.2.4 AS/NZS 4505 Domestic garage doors

At present, AS/NZS 4505 presents wind pressures that do not align with those calculated for garage doors using AS/NZS 1170.2. AS/NZS 4505 should be amended to make design wind pressures compatible with those presented in AS/NZS 1170.2.

The scope of AS/NZS 4505 should also be expanded to include commercial and industrial doors or, a separate part developed for commercial and industrial doors, as there is currently no Standard for these larger doors. (The current Standard is limited to domestic garage doors.)

6.2.5 AS 2050 Installation of roof tiles

The failures of tile anchorage systems particularly at ridge tiles, indicates that the means of fastening ridge tiles and part tiles near ridges and hips should be reviewed.

The current practice of downgrading wind classifications for tiled roofs where the roof is sarked may need to be reevaluated in the light of the particularly high levels of tile damage in high wind classification areas.

6.3 Reconstruction

As part of the reconstruction effort after TC Yasi and other major wind events that cause significant damage, there is an urgent need for all builders and owner repairers to have access to relevant information and training to ensure that they are aware of the requirements for construction in cyclonic areas.

Trades that have minimal or no experience in building in cyclonic regions should also be made aware of the requirements of the relevant Standards and industry information to ensure that their work is appropriate for the wind loads of the cyclone region.
Roof space inspections should be undertaken to look for partial or hidden failures of structural connections within the roof. If these are not repaired at this stage, the strength of the structure will have been compromised with the potential for reduced performance in the next cyclonic event.

Where part of the roof has been damaged, the whole roof should be upgraded to the required standard or in accordance with Standards Australia Handbook HB 132.2. The investigation showed that where the undamaged portion was left unimproved, it could initiate failure of the whole roof in the next event.

6.4 Improving performance of Pre-80s houses

The investigation found that Pre-80s houses had significantly more damage than Post-80s houses. The strength of these houses should be assessed, and where necessary, upgraded to comply with the current Standards. For timber structures, the current requirements can be found in AS 1684.3:2010 and supporting industry documentation. General information on upgrading structural performance in existing houses can be found in Standards Australia Handbook HB 132.2.

This recommendation applies to all Pre-80s buildings in Wind regions C and D whether they have been affected by TC Yasi or not. The assessment and upgrading is easiest when the roofing has been removed for other maintenance.

6.5 Issues requiring education

6.5.1 New construction

The correct use of most structural elements in a building is supported by documents – either Codes and Standards or manufacturer’s design and installation guides. The latest versions of this information should be used to assist in the appropriate use of building elements to resist cyclonic wind loads.

The study has highlighted the need for continuing education in the following areas of new building construction:

Connections are the key element in wind resistance of all types of construction. They must be detailed correctly and maintained if they are to continue to provide their intended function for the life of the structure. In particular:

- Trades need to have training that all connections should be installed to provide their correct edge distances and depth of embedment. This includes all timber connectors and masonry anchors.
- Building specifiers need to understand that materials used for connectors should be carefully considered in near coastal environments. High exposure sites also often have high salt loading, so the connectors need to be especially durable.

Because the external cladding, including doors and windows is the building envelope, each element is important for separating internal and external pressures in buildings. Designers and certifiers should receive training on the need for all doors (including large access doors) and windows to be designed in accordance with the current Codes and Standards to resist the
differential pressures at the design wind speed. This includes not only the glazing, but also the frame, connections to the structure and any furniture that secures opening panels.

Care is required that metal sheet roofs are installed in accordance with recommendations. Failures of incorrectly installed sheet roofing systems, indicates that there is a continuing need for education of installers and certifiers. Installers must be sure that all fasteners penetrate the purlin or batten properly so that they can be relied on for their full capacity.

For both tiled roofs and secret fixed steel roofs, particular care is required in following installation guidelines as it is practically impossible to inspect the anchorage systems for compliance once the roof construction is completed.

6.5.2 Maintenance
All building materials deteriorate with time. Investigators observed signs of deterioration in some buildings that had been classified as Post-80s buildings. It is particularly important that builders be trained to inspect structural elements for deterioration, tighten bolts and reapply any protective coatings when the elements are visible. Inspection and maintenance of structural elements within the roof space should be undertaken for all buildings:
- after any event in areas where the applies loads were near the design ultimate wind loads, or
- whenever the roofing is removed (eg for replacement of roof sheeting), or
- at a maximum of ten yearly intervals.

These recommendations will need to be understood and in some cases, implemented by building owners, and they must be informed of the need to undertake this work.

6.5.3 Curriculum changes
It is particularly important for all practicing trades that are involved in constructing the building structure to be aware of the importance of connections in the structural system, and the need to match capacity to wind load requirements. These topics should also be included in trade training programs and syllabuses.

Training in the correct determination of site wind classification should be included in courses for designers, certifiers and builders. Basic training and continuing education for trades should deliver an understanding of the construction needs of different wind classifications.

6.5.4 Community education
A program for educating the public at large with respect to maintenance of buildings should be undertaken.

Section 3.2.10 highlighted the dangers of wind driven debris. Public education programs should continue to stress the importance of minimizing potential debris in the lead up to the cyclone season and then during cyclone warnings.

Home owners need to be informed of the expected damage to contents from water ingress through wind driven rain in severe events.
6.6 Measuring wind speeds
Anemometer records are vital to reassess the design wind speeds used in Australia, and the peak gusts in the zone of maximum winds were not measured by anemometers in TC Yasi. Systems should be implemented to take more anemometer readings in tropical cyclone events. This can be achieved by:

- Establishing additional robust AWS stations in populated parts of the cyclone affected area with the maximum spacing between stations of around 50 km.
- Setting up a number of portable anemometers and providing resources to use them so that they can be deployed just before an event makes land-fall, and the wind speeds recorded at a number of strategic locations for the duration of the event.

Anemometers should be positioned in flat open terrain far from major obstructions such as large buildings, and be located in regions unlikely to experience debris attack with wind in any direction.

A study should be undertaken to select the options for anemometers that will give best possible information on gust wind speeds in tropical cyclones in Australia.

6.7 Tiled roofs
Post-80s tiled roofs did not perform as well as other Post-80s roofs. Tile anchorage systems utilize elements that may be sensitive to fatigue, so manufacturer’s recommendations should be based on demonstration of performance when tested to a cyclic test regime such as those in AS 4040.3 or the BCA.

The manufacturer’s recommendations require reassessment in order to deliver the same reliability as other components of the building envelope. In particular:

- Methods for securing ridge capping and cut tiles in high winds need to be improved.
- A close examination of tile anchorage in exposed sites (C3 and C4 as defined in AS 4055) is necessary.
- Fastening systems should not allow complete detachment of tiles to prevent them from causing further damage to the same roof or to nearby structures.

6.8 Large access doors
The level of damage to roller doors was significantly greater than any other component of Post-80s housing. These doors should satisfy the BCA requirement that all elements of the building envelope are able to resist the design wind pressure for the building site.

Sectional doors had a lower failure rate than roller doors, but it was still higher than other structural components in contemporary housing, so improvement of their performance is also required.

The following actions are recommended:

- All large access doors should be manufactured to resist the directly applied wind loads. Their anchorages must also be designed and constructed to take those loads to the ground.
- Where the door itself generates secondary loads in resisting the wind forces (e.g. where wind locking devices have been fitted to doors and generate in-plane tensions), the interaction with the remainder of the structure must be able to safely transmit the
secondary loads to the structure and the structure must be designed and constructed to carry these loads to the ground.

- Where doors have demonstrated that they are unable to resist wind loads in TC Yasi, like-for-like replacement should not be specified. In all cases where the damage to the door was not caused by wind-borne debris, stronger doors must be fitted to ensure that the building envelope is capable of resisting the design wind pressures.
- Building designers must include wind design information in the specification of large access doors. All large access doors should have a wind rating fixed to the door so that it can be independently checked against the specific building design requirements.

Consideration should also be given to retrofitting devices to existing doors to ensure that they have an appropriate level of performance in future events. The recommendation for upgrading existing doors is not restricted to those doors that have been affected by TC Yasi, but for all doors in Wind regions C and D.

### 6.9 Sheds

Sheds have to be designed for the same conditions as other buildings with respect to wind loads. This includes the provision of a complete load path to the ground for all elements (including roller doors) that attract wind loads:

- Damaged sheds present a significant debris hazard. Sheds should be designed and constructed using Importance Level 2 or above, unless the shed is to be at least 200 m from any habitable building.
- Shed design should allow for dominant opening internal pressure, while checking that all parts of the building envelope including doors, windows, roller doors, skylights and cladding can resist the stated design wind pressures.
- Evidence should also be provided that the shed itself can resist all loads applied by all structural elements, windows, doors, roller doors and associated connections.
- Where purlins are used as compression bracing members, they should be designed to resist the combined effects of out-of-plane wind loads as well as axial compression loading.

Existing sheds should also be reviewed against the above recommendations.

### 6.10 Wind-driven rain

Using current practices, the water-tightness criteria of most buildings will have been exceeded at wind speeds approaching the ultimate limit states. As a result, significant ingress of water must be expected using current building technologies and this was observed during the investigation. Both structural and non-structural elements appear to have been selected without allowing for the possibility and consequences of water entry.
Water ingress has demonstrated that it can ruin linings and furnishings to the extent that structurally undamaged houses are no longer habitable. It therefore contributes to homelessness after tropical cyclones, and lengthens recovery times for communities. Consideration must be given to options for minimizing the impact of water ingress on the strength and amenity of buildings:

Either

- A standard testing procedure should be drafted to ensure that all elements of the building envelope, including their connections to adjacent elements are weather-tight at the ultimate limit states wind,

Or,

- Structural and other elements should be selected on the understanding that there will be significant water entry to the building when the wind speeds are approaching the ultimate limit states.