Cyclone Tracy: Silver Linings and Unfinished Business

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ABSTRACT

Significant silver linings in respect of wind engineering that arose from Cyclone Tracy are the recognition that houses need to be structurally engineered to resist wind loads; recognition of the importance of internal pressure design and fatigue failure of steel cladding fastening systems in cyclonic events; the change from working stress design to limit state design of structures; the use of computer simulation of cyclones as the basis of the determination of return period wind speeds from cyclone events, Australia's standing in international wind engineering circles; and the establishment of the Cyclone Testing Station.

While the death toll in Cyclone Tracy was significant, the loss of functionality of the Darwin community and consequent socio-economic impact on its inhabitants and the nation had a far greater overall impact. Because the damage was so extensive, it was assumed that if the individual buildings had been built to meet the human safety requirements of structural design, then it would not have been a major disaster, so this was the main issue addressed in the recommendations of the report on the damage and their subsequent implementation. However, while effective in reducing major structural damage, just focussing on this limit state has not been sufficient to reduce the community impact of the severest of such events to prevent significant loss of community functionality, the recovery of which has tested the resilience of the impacted communities. This is the unfinished business.

Discussion of the reasons for this situation is presented, along with the implications for design criteria as embedded in building regulations. To achieve community disaster resilience to the severest events all buildings need to be included within the scope of building regulations, not just planned new ones; and the design criteria of individual buildings need to reflect the possible cumulative effects of damaging wind events on the total community within which the individual buildings are located.

This will mean extending building regulations to require all buildings to meet performance standards which will ensure that the contribution they make to the overall loss of functionality of the community in which they are located, and its timely recovery, in a maximum credible event will be within acceptable limits, considering both structural and non-structural factors.

"Was I deceived or did a sable cloud
Turn forth her silver lining on the night?"
John Milton, *Comus*, 1634.

'...those who look only to the past or present are certain to miss the future.'
John F Kennedy 1964.

INTRODUCTION

December 24th 1974 will be etched in the memories of all those impacted by Cyclone Tracy whose centre passed across Darwin on the evening of that day. In addition to being one of Australia's worst disasters it was a landmark event in Australian wind engineering. It was also a landmark experience for me. Many lessons were learned from the event across many aspects of the Australian community, and none more so than the consequences of them for wind engineering from both a research and professional point of view. I was privileged to lead the investigation of the damage and its consequences dominated the rest of my working life.

John Milton suggested every cloud has a silver lining and so it was for Cyclone Tracy. Tragic as it was for many at the time, the longer-term consequences for the whole Australian community, and the wind engineering community in particular, had several silver linings. This discourse - I hesitate to call it a formal paper – presents some personal reflections on these silver linings in the wind engineering field. But cognisant of the advice of John F Kennedy it also presents some reflections on what in retrospect have been missed opportunities to increase these silver linings and how these might be realised in the future..

THE SILVER LININGS

Significant silver linings regarding wind engineering that came out of the disaster are:

- Houses structurally engineered to resist wind loads.
- Recognition of the importance of internal pressures and fatigue failure of steel cladding fastening systems in cyclonic events.
- Acceleration of the move to Limit State Design.
- Computer based probabilistic simulation of cyclones to estimate return period wind speeds.
- Consolidation of Australia's standing in international wind engineering.
- The establishment of the Cyclone Testing Station.

Prior to Cyclone Tracy the construction of houses was largely in accordance with prescriptive rules based on established practice, occasionally updated to correct some observed deficiency. There was no national building code, and in some States – eg Queensland - building control was a local government responsibility and normally did not encompass small buildings like houses, with most control being exercised by lending authorities, especially the Commonwealth Bank with its so called 'Blue Book'. Of about 8000 houses in Darwin at the time, around 55% were destroyed by Cyclone Tracy and a further 45% suffered significant damage with only about 10% remaining continuously habitable. In contrast only about 3% of engineered buildings were destroyed, and only about 20% suffered significant damage rendering them unusable until repaired. This led to the most radical recommendation in the report of the investigation of the damage that all buildings in cyclone prone areas, including houses, should be structurally engineered for wind loads. Initially adopted for the reconstruction of Darwin, it was eventually adopted nationwide and incorporated in the Building Code of Australia (now the National Construction Code.)

At the more detailed level, in addition to the large number of houses that failed by racking under the horizontal wind loads, which was covered by the recommendation for houses to be structurally engineered, it was observed that much of the roof damage due to uplift could be attributed to increased internal pressures due to window and door failure under the extreme winds and especially the large amount of wind borne debris that accompanied them. This led to a recommendation that in cyclone prone areas buildings should be designed for full internal pressures assuming a dominant windward opening unless the windows and doors had protection from the wind and debris, the implementation of which is now well established in the designated cyclone regions.

More puzzling was the extensive failure of roof cladding when previous testing following Cyclone Althea in 1971 had indicated the fastening systems being used should have been adequate despite the high wind loads. It turned out that not long after Cyclone Althea the steel roofing manufacturers had changed the material used from ductile mild steel to thinner more brittle high strength steel. Some great work by John Morgan and Vaughan Beck at the then Experimental Building Station in Sydney showed that the rapidly fluctuating wind pressures on the roof cladding over the relatively long period of time experienced in Cyclone Tracy could produce fatigue failure around the fasteners, the characteristic features of which were observed to have occurred in failed roof cladding. This led to the establishment of fatigue testing of metal roof cladding intended for use in designated cyclone regions, which after some iterations based on extensive research remains in force.

This combination of requiring houses to be structurally engineered for wind, which meant designing for both vertical and horizontal wind loads, in association with designing for full internal pressures and fatigue failure of metal cladding systems, has led to a big reduction in wind damage to newer construction, particularly in designated cyclone regions.

Professor Len Stevens from the University of Melbourne was already advocating that Australian structural engineers should be replacing the then normal Working Stress Design (WSD) approach to structural design by a Limit State Design (LSD) approach. The roofs of so many structures failed because their dead weight was approximately the same as the WSD wind uplift loads, meaning they hardly needed to be designed for uplift, that such a change became a no brainer – with Australia becoming an international leader in such a change.

At that time Barry Vickery at Sydney University was supervising a PhD student, Lew Gomes, who was investigating the probabilistic characteristics of tropical cyclone wind speeds around the Australian coast using a technique based on computer-based simulation of tropical cyclones using historical information of tracks, intensities, eye diameter, etc which had been proposed by a researcher in the US a few years before. Because it appeared to be a much superior method than basing return period wind speeds on Gumbel analysis of annual maximum wind speeds, which were dominated by non-cyclone winds, as used up until then, the results of his study, confirmed by a parallel Government study based on the same approach, were immediately applied to produce a radical revision of design wind speeds in the cyclone prone areas of Australia. It was the first application of this approach worldwide and it underpins the code design wind speeds to this day. (Its most significant application however has been its use by the insurance industry for estimating the risk to insurance companies of catastrophe loss from tropical cyclones.)

Barry Vickery and Bill Melbourne at Monash University were already establishing Australia as a significant player in the then fledgling international wind engineering research and development community. Following Cyclone Tracy, greatly increased funding for such R&D became available in Australia, leading to a much greater Australian presence at international wind engineering gatherings and interaction with international wind engineering research centres by Australian researchers.

One consequence of the increased funding was the establishment at James Cook University of the Cyclone Testing Station as a cooperative venture between industry and the University to particularly focus on R&D relevant to implementing the recommendation that houses and other low-rise buildings be engineered to resist the design loads specified for cyclone prone regions, an activity that has continued to the present day. Its work has underpinned the successful implementation of this recommendation, and in the process, it has developed its own international recognition and areas of international cooperation.

UNFINISHED BUSINESS

Despite the huge amount of damage to houses in which most of the population of about 40,000 was sheltering during Cyclone Tracy, the death toll was relatively small with an estimated 65 persons killed in total, of whom 45 died on land and the remainder at sea. It was not the death toll that made it one of Australia's worst disasters – by comparison over 3500 were killed by road accidents in the same year and nearly 20,000 died from the Covid pandemic. It was the loss of functionality of the Darwin community and the consequent socio-economic impact on its inhabitants and the nation.

The estimated economic impact of Cyclone Tracy has been estimated at over $7.5 billion in present day terms and the human impact on the inhabitants of Darwin who experienced it was immense. This was the driving force behind the recommendation that houses be engineered to resist wind loads in cyclone areas, not human safety per se, it being assumed that if the individual buildings had been built to meet the human safety requirements of structural design, then it would not have been such a major disaster. Consequently, this became the focus of subsequent building regulations. The huge socio-economic impact also influenced the revision of design wind speeds based on the new methodology of computer simulation of cyclones, a conservative approach to the interpretation of the results being taken based on community impact rather than individual building impact. Today we would say that the driving force was improving community disaster resilience, but unfortunately over time this objective has been lost.

In retrospect I believe the primary cause of the loss of this primary objective was the establishment of the performance based national Building Code of Australia in the 1990's, of which I was a strong supporter. In a performance-based code, the objectives in terms of performance must be clearly specified, and in respect of structural design these were specified as safety and amenity of individual buildings, safety being covered by designing for ultimate strength at a probability of loading considered acceptable in terms of the human safety of the occupants, and amenity being covered by serviceability requirements at more frequently occurring loads. This appeared consistent with the recommendations that had followed the Cyclone Tracy investigation of damage. However, this then became interpreted in mathematical form in terms of the probability of occurrence of wind speeds impacting individual buildings. This began to govern design wind speeds with little respect for the overall community impact of building failure in a single event, it being assumed that this would automatically satisfy the requirements for what has subsequently come to be known as community disaster resilience. However, while effective in significantly reducing the level of major structural damage to individual buildings, this approach has not been sufficient to reduce the community impact of the severest such events to a manageable level resulting in calls for greater community resilience to such events.

Community Disaster Resilience

Resilience is a word used widely in a technical sense in a range of fields including human psychology, the natural environment, disaster risk management and product specification. However, it is currently also used widely in the political and public domain more as a concept, rather than a technical property. The word is derived from the Latin word 'resilio' which means rebound and in most cases its use retains this concept either literally as a mechanical property of materials like rubber, or figuratively in terms of the quickness of recovery of functionality of systems whose functionality has been disrupted by the impact of a sudden event. It has also been adapted in the climate change field to describe the ability of systems prone to impact from climate change to retain their functionality by adapting to gradual changes in the environment arising from this.

While it is easy to talk about resilience in a general sense it is more difficult to use it in a technical sense since that requires a more precise definition in terms of the system to which the word is being applied, the characteristics of the impact to which the resilience of the system is being described, and the loss of functionality of the system impacted and its recovery following the impact. Note that if there is no loss of functionality the system is fully resilient as the recovery time is zero, but most discussion about resilience concerns situations where there is an impact on functionality, and the issues of concern are at what level of impact will there be a loss of functionality, and at what level of impact greater than this will the time taken to recover functionality be unacceptable,.

In respect of community disaster resilience to natural hazards, the prime interest is the loss of **community** functionality from the natural hazard **event**, and the **rapidity** of recovery of full community functionality. It is not about the resilience of individual buildings or individual citizens per se, but very much about how the aggregate impact of an event on all the buildings and its citizens affects the functionality of the community and recovery of any loss of this community functionality. This is the primary concern of Local, State and/or National authorities, and the reason they believe resilience is important, and therefore the driving force behind much of their policy making on emergency risk management over and above ensuring human safety concerns are satisfied.

Community resilience to the impact of tropical cyclones is therefore primarily about loss of community functionality if the magnitude of the impact is sufficient to cause this, and the rapidity with which this loss of functionality can be restored for credible magnitudes of impact above this level. The performance of residential, commercial, and industrial buildings, which are the primary concern of this address, can play a major role in this. If overall damage, including both structural and non-structural damage, is negligible, then the impact on the overall community will be negligible, and the community disaster resilience will not be an issue. However, if the overall damage is large then it can make a significant contribution to the overall loss of community functionality and the rapidity of its recovery. The larger it is, the greater the impact on community functionality due to the loss of functionality of the damaged individual buildings. If the primary function of the building is providing services to the community, then its damage will have a direct impact on community functionality. If the primary function is providing a home for the occupants then its damage may contribute to increased numbers of occupants seeking financial and social aid, and alternative shelter, causing a greater demand on funding mechanisms like insurance, government agencies, charitable organisations, and the real estate industry, in meeting this need. The ability to restore the resultant loss of community functionality in a timely manner, which is the measure of community disaster resilience, will be a function of the rapidity with which repairs or reconstruction, temporary or permanent, can be undertaken, which will usually also depend on how quickly the funding for them can be put in place and the capacity of the building industry to meet the demand for this work.

By designing buildings in accordance with the current building regulations, the level of potential damage to them during cyclones can be significantly reduced, thus significantly reducing the impact on the overall community, but it doesn't eliminate overall building damage risk. Consequently, in major cyclonic wind events with high intensity winds impacting a large urban region, community resilience may still be seriously tested.

Major reasons for this are:

1) The building regulations are only focussed on new construction.
2) They neglect consideration of the consequences of wind speeds exceeding prescribed design wind speeds based purely on individual building occupant life safety (initially accounted for by applying a conservative approach to the wind speed modelling results).
3) They neglect the consequences of structural design criteria being based on structural reliability theory which implies that if subjected to the specified ultimate limit state (ULS) loads, structures can have up to a 5% probability of their strength being exceeded.
4) They assume that only primary structural damage is important and that damage to internal non-structural items and contents from water entry during extreme events is acceptable.
5) They are focussed on limiting building damage – ie they are impact focussed – without consideration of the community consequences in relation to repair and reconstruction if damage does occur.

Major consequences of these failures to fully address community disaster resilience are:

1. In designated cyclone regions the vulnerability of many older buildings whose construction predates the implementation of cyclone resistant building regulations is not much better than that of the houses in Darwin at the time of Cyclone Tracy. As a result, because these buildings still form a large proportion of all building construction in most communities (Darwin excepted), in a major event the damage to these buildings usually makes a major contribution to any loss of community functionality arising from the event (in addition to the associated risk of human casualties due to the damage).
2. In determining design wind speeds the code writers focus only on the return wind speeds at the prescribed risk of exceedance – for most buildings 5% in 50 years or about 500 years at a point location – without regard to the nature of these winds, treating thunderstorm winds the same as

cyclone winds. If thunderstorm winds prove larger at this level of risk of exceedance at a point location, such locations are designated as non-cyclone and hence not requiring the extra design criteria specified for cyclone regions. Consequently, the largest urban area in Australia at significant risk from tropical cyclones, Southeast Queensland from Noosa to south of the NSW border, is deemed non-cyclone, creating a situation where a credible event like a Category 3 cyclone crossing the coast anywhere along this coastline could result in a major disaster with a socio-economic impact larger than that due to Cyclone Tracy in real terms.

3. The underlying basis of the Limit State Design approach adopted in the Australian Construction Code is structural reliability theory which accepts that both the design loading and the design strength can only be specified in probabilistic terms, and that consequently design is about limiting the risk of structural failure to acceptable levels, not preventing failure. In other words, the design philosophy assumes there will be a risk of some damage, the risk increasing with the intensity and extent of the winds. Normal design of the main structure assumes that the specified ultimate strength of a component will have a 95% probability of being exceeded – ie there will be a 5% probability of the component having a strength less than its prescribed ultimate strength, which must be not less than the prescribed ultimate load. Assumptions regarding internal pressures complicate this relationship. In defined cyclone regions if design is based on assuming full internal pressures, then not all buildings will be exposed to these. The proportion broken will depend on the probability of windows being broken by either wind pressures, for which window design assumes a maximum risk of failure or about 10% at the ultimate design wind pressures, or debris impact. The probability increases with increasing wind speed. In general, this means that the probability of the specified ultimate strength of components being exceeded will be less than 5%. In defined non-cyclone regions, however, the reverse will apply, since design assumes windows are not broken and as loads approach and exceed design loads there will be an increasing proportion broken. Consequently, at ultimate design loads it is highly likely that the probability of the ultimate strength being exceeded is significantly greater than 5%. In an event like a thunderstorm affecting only a relatively small number of buildings this may not have a big impact on the resilience of the community. However, in an event like a cyclone, with the potential to have a much larger footprint, the same percentage of buildings affected could mean a much larger number of buildings affected, which added to the expected damage to older buildings predating modern building regulations, could test the community resilience.

4. By inherently accepting that windows and doors may fail in severe events with wind speeds approaching the ultimate design wind speeds and requiring buildings in cyclone regions to be designed for them, the building regulations accept this type of damage in extreme events. In most cyclonic events the strong winds are accompanied by heavy rain, the combination of which will drive rain through any opening created in the building envelope. Furthermore, the design of window and door systems does not required them to be able to resist water entry under the combination of extreme wind and rain that may be experienced in a cyclone, being regarded as a serviceability limit state. At the time of Cyclone Tracy this was regarded as acceptable as rainwater entry was not regarded as life threatening, and the likely internal damage from rainwater damage was not considered high because the contents, furnishings and wall linings in tropical Australia were not highly vulnerable to water damage. The situation nowadays is quite different, with most of these very vulnerable to water damage, particularly due to the increasing dependence on electronic devices with the development of smart house technology, and the much higher level of expensive internal furnishings and wall and roof linings susceptible to water damage. At minor levels, water damage does not threaten building functionality, but if severe it can seriously affect living conditions, creating social and financial issues which put additional pressures on the response to disasters by insurers, government agencies and charities when they may be already inundated by other more serious pressures on them.

5. Community disaster resilience is about recovery from loss of functionality of an impacted community following a disaster. Current building regulations may reduce the damage caused by a cyclone, but they do not address the issue of rapidity of repair and reconstruction if damage does occur. Much of this is outside the scope of the designer and builder as it is concerned with

the availability of temporary housing, the funding of the repair and reconstruction, and the capacity of the building industry to do it. However, there may be design features that could be incorporated in the initial construction which would facilitate a quick recovery of a building's functionality, if not full restoration to original condition. This is an issue that is being addressed by earthquake engineers following the Christchurch earthquake in 2011 in which many modern buildings in the CBD designed to the code performed well in terms of life safety, but still had to be demolished and rebuilt, creating a big loss of community functionality in the CBD, and from which it took a long time to recover. As a result incorporating features to ensure a much quicker restoration of the functionality of buildings is now a major topic of earthquake research and development.

Designing for Community Resilience

Designing buildings with community resilience in mind in addition to the life safety of the occupants of individual buildings will require a big change in the paradigm underlying the development of building regulations. To address community disaster resilience to extreme events, it will require recognition of the following:

1. The risk that extreme events pose to the whole community in which the individual buildings are located needs to be considered.
2. The potential size of the community that could be impacted by an extreme event during a single event during the life of the building needs to be considered which means that design will be community based not regionally based.
3. The potential performance of all buildings in the community, new and old, in an extreme event needs to be addressed.
4. All the consequences of possible damage to individual buildings during extreme events which may impact on the community resilience need to be considered.
5. Measures to facilitate the quick recovery from potential damage from extreme events should be considered in the design of individual buildings.

Achieving this will be a challenging task for the current and up and coming generation of structural engineers and building professionals. First and foremost, it will mean defining a framework within which community disaster resilience can be defined in technical terms. This would need to encompass at least the following factors:

1. Identification of the characteristics of the major communities at risk from cyclones, including their present extent and their potential future growth.
2. Identification of the magnitude and intensity of the potential extreme cyclones which could impact these communities.
3. Identification of the potential loss of community functionality arising from damage to buildings and their contents, including services, due to the impact of these extreme events.
4. Identification of the potential contribution of individual buildings to this.
5. Specification of the required level of recovery of any identified potential contribution to loss of community functionality in terms of the time taken to achieve this.

Fully incorporating these principles into building design and construction, and the associated regulations, will require integration with all other aspects affecting community resilience. This will only be achievable through the development of computer-based models capable of simulating community resilience for which a starting point will probably be the catastrophe insurance loss models used in the reinsurance industry for designing reinsurance programs. These already incorporate the damage risk from all causes, not just structural failure, and the costs of repair and reconstruction arising from this damage. However, they do not consider the impact of these on community functionality and recovery times for any loss of functionality. Nor do they consider all the other factors which affect these which a community resilience model will need to do if the relative contribution of individual buildings to overall community resilience is to be assessed, since the primary function of such models should be to determine the relative importance of different contributions so that attention can be focussed on those factors making the most significant contribution. In my opinion the task is no more formidable than was the development of the insurance-based catastrophe loss risk models when they were first mooted over 40 years ago. Indeed, there are no doubt researchers already developing such models but probably as research tools rather than for public use as a basis for community planning including building regulation and design.

However, there are some things that could be done without waiting for such modelling to be implemented in everyday planning and design. Some of these are:

1. The scope of building regulations could be extended to cover all existing buildings with regulations formulated for handling the large number of buildings which are not compliant with current building regulations. New Zealand has already gone down this track in respect of the earthquake resistance of buildings.
2. Ultimate design wind speeds should be based on return period wind speeds to overall communities at risk from tropical cyclones, not just the risk at a single point location.
3. All large urban communities with a credible risk of being impacted by a tropical cyclone should be considered as cyclone regions for the purpose of building design.
4. In individual building design more attention should be given to features which may either increase the loss of functionality due to rainwater entry such as smart house components, or improve building functionality following a major event if they remain undamaged like solar roof panel systems with batteries which can provide limited electricity supply offline from the electricity network if the latter is disabled.

What it Means for Wind Engineering Research

This discourse has been largely centred on the short falls of the current codification of wind engineering knowledge in respect of improving community disaster resilience from tropical cyclones, and the ways this could be addressed. Underpinning this wind engineering knowledge is the large amount of wind engineering research conducted over the past 50 years or so. To date this has been largely focussed on building performance under wind actions with human safety and comfort the primary focus. Increasing the focus to include community disaster resilience will increase the scope of this research. Some perceived areas of this widened scope follow.

1. The focus to date of damage investigations following extreme wind events has been on the structural damage and the reason for it, primarily in relation to buildings. To be useful in relation to community disaster resilience the scope of these investigations needs to be expanded to include the impact of the damage on the functionality of both the buildings themselves and the overall community. This needs to be done within a framework of community disaster resilience linking the attributes of the communities with the attributes of the events with the potential to cause the disasters, the object being to quantify these linkages.
2. The issue of wind driven rain is a wind engineering issue demanding more rather than less attention if its effect on community resilience is to be reduced. There are two aspects of this.
   a. Water entry assuming no failure of the envelope, particularly windows, which in most events will be the case for most buildings. A significant driving force for this water entry is the difference between internal and external pressures. There is a need for a better understanding of this phenomenon, which has the potential to result in possible measures which could be incorporated in design to reduce the pressure differences, or even maintain higher internal pressures.
   b. Water entry following envelope penetration due to debris. In the aftermath of Cyclone Tracy there was an increased use of debris resistant window screens satisfying the specified debris impact criteria. Maybe there needs to be a renewed emphasis on this aspect of design.
3. Although much work has been done on internal pressures in recent years, I believe there is still

much to be learned. It does puzzle me that for wind tunnel studies internal pressure coefficients are assumed dependent on wind speeds while in practice they are assumed invariant of wind speeds. With my structural dynamics background, I am also aware that the structural response to sudden impacts is to overshoot the response to steady state fluctuating loads. This makes me wonder whether in dealing with internal pressures following the sudden creation of a dominant opening we should be simulating the transient response to such an event rather than the steady state conditions used in wind tunnel studies.

4. As mentioned previously, the Limit State Design approach on which structural design is based is underpinned by structural reliability theory. Design using the design codes is regarded by the National Construction Code (NCC) as a deemed-to-comply solution. However, the NCC does allow design from first principles using structural reliability theory, specifying target reliability indices, and the statistical distributions to use for the loading. The outcome of such analysis are the partial load factors to be used for strength and loadings under different load combinations. Structural reliability theory is intended to allow for all the uncertainties in respect of the assumed designed loadings and strength to resist them, including in the case of loadings, not only the assumed distribution of extreme wind speeds, but the reliability of the analysis of these, and the uncertainties associated with the conversion of these to loads and pressures based on wind engineering knowledge. The present load combinations in AS1170.1 are largely based on structural reliability analysis undertaken 40 years ago. The wind engineering research undertaken in the last 40 years has greatly improved our knowledge both of wind speed distributions and the conversion of wind speeds into loads and pressures. A consequence of this research should have been a reduction of the overall uncertainty and possibly a change in the mean values, the two critical parameters used. Furthermore, the original studies were focussed on main structural members, and the reliability indices developed for them may not be appropriate to elements like roof fastenings. It seems to me there is a strong case for relooking at this analysis in respect of wind loads. There may be also a case for investigating whether the current target reliability indices are appropriate for a community disaster resilience limit state, when the loading is strongly correlated – the theory assumes it is independent from one building to the next – and is concerned with the impact of an event on a community, not of a single hazard on a single building.
5. In addition to the performance of buildings there needs to be a greater focus on the wind sensitive elements of infrastructure whose failure in a major event could seriously impact community functionality. If current Government policy objectives in relation to the reduction of the use of non-renewable energy sources is to be achieved the two electricity generating systems that are currently seen as playing a much larger role than at present are solar and wind energy. Both involve wind sensitive structural elements and, it is anticipated, will require a significant extension of the transmission line network, which is also a wind sensitive system. Some excellent wind engineering research is already being undertaken in this area, but I suspect much more needs to be done to ensure the reliability of the vastly expanded network of these systems if impacted by a severe wind event.

IN CONCLUSION

This is not an exhaustive description of the issues involved or an exhaustive list of suggested future actions, but hopefully it is enough to excite the minds of some of the current and up and coming generation of wind researchers to address these issues and in so doing ensure future communities at risk from extreme tropical cyclone events are designed to be disaster resilient to them.

ACKNOWLEDGEMENTS

Many engineers, architects, builders and building materials manufacturers were involved in the investigations of Cyclone Tracy. Although I took responsibility for the final report, it took account of the large amount of work these folk did and put on paper in reports which formed 2 volumes of Appendices, along with the role they played in the peer review of the draft report that preceded its finalisation. Their contribution and support of the final recommendations along with that from two

invited overseas experts, Joe Minor and Dick Marshall, played a major role in their subsequent acceptance. Many more were involved in the subsequent project led by Standards Australia to establish a standard for cyclone resistant housing construction of which the main outcomes were a very informed building and construction industry on the cyclone resistant construction which greatly helped the implementation of the report's recommendations, and a document called TR440 produced by the Commonwealth Department of Housing and Construction, which became the defacto design standard for cyclone resistant construction until incorporated into building standards and the Building Code of Australia. There were too many involved to name here, but the principal ones are listed in the main report. Two people, however, do stand out whose contribution in respect of my involvement and the subsequent implementation of the recommendations was critical. If it hadn't been for the vision and strong support that I had from my Head of Department at James Cook University, Professor Hugh Trollope, the University along with myself would not have been involved. Charles Bubb was the Commonwealth Government Chief Structural Engineer and the whole investigation and implementation of its findings in the reconstruction of Darwin was undertaken under his direction. Without his strong backing I suspect the radical changes to housing that followed would not have happened. Wind engineering as we know it today owes much to him. Sadly, engineers like him are no longer to be found in positions like he had in Government.

I thank the organisers of AWES22 for inviting me to give this Keynote Address. I regard it as a great privilege to participate in this Workshop/Conference in this way at my age. I also thank Geoff Boughton, a longtime friend and wind engineering colleague, for his assistance by reviewing my first draft and advising me on improvements which greatly enhanced the final version.