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Parallels in Tropical Cyclone Design Strategies and Building Performance for Australia and U.S.

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ABSTRACT

Over the last decade, the authors have investigated many severe wind events in Australia and the U.S., most of which invariably result in property damage, community disruption and sometimes tragically, loss of life. Although each event is unique and there are differences in building codes, population and policy, there is commonality in the successes and failures of the two countries in mitigating damaging impacts. This paper summarizes damage investigation findings from four recent tropical cyclones (two in each country) and discusses parallels in damage trends and knowledge gaps for design in high-wind regions of each country. The observations suggest modern building codes are effective at reducing structural failures and improving life safety within communities. However, retrofitting of pre-code structures, water ingress and long-term maintenance remain key challenges for both countries and warrant collaborative effort to develop innovative solutions.

1. Introduction

From 2015 to 2017 there were 21 severe storm (includes hail) events and four tropical cyclone events across the U.S. that exceeded $1 billion in cost for a total in excess of $300 billion in overall losses (NOAA, 2018). Over the same time period Australia suffered from 27 catastrophic storm events and six tropical cyclones totaling over $6.2 billion in insured losses alone (ICA, 2018). Considering the relative scales of gross domestic product ($1.2 vs $18.5 trillion USD) and population (24 vs 323 million), the losses from these synoptic events have been similarly damaging to both countries. It is important that the wind engineering community continue to develop solutions to mitigate these impacts. The authors have been involved in the investigations and analysis for several of the fore noted events. The aim of this paper is to review some of the key findings, highlight common obstacles and promote discussion between researchers and engineers in both countries to develop novel and collaborative solutions to recurring problems. A brief review of historical building code development for high-wind regions is presented and followed by a summary of findings from four recent tropical cyclones in both countries. The paper concludes with a discussion of common damage trends and several research areas that present opportunities for collaboration.

2. Code Development in Southeast U.S. and Northeast Australia

The development of building codes for high-wind region construction in the U.S. and Australia follows a relatively similar sequence of events. There is a stark contrast in performance for homes constructed before and after modern building standards implemented in the mid-1980s in Queensland and the early 2000s in Florida. In Queensland, this contrast is centered on Cyclone Tracy, which caused widespread severe damage to 70-90% of housing in December 1974, especially in the Northern suburbs of Darwin (Walker, 1975) with peak gusts near 245 km/h and 71 fatalities. Hurricane Andrew hit South Florida nearly 20 years later with peak gusts over 280 km/h, and similarly devastating impacts (65 fatalities, ~63,000 homes destroyed [Rappaport, 1993]). Changes to design and building standards of houses were developed during the reconstruction. The Queensland Home Building Code (HBC) and the Florida Building Code (FBC) were introduced as legislation in 1982 and 2002 respectively.

Figure 1. Damage photographs from Cyclone Tracy in Darwin in 1974 (left) and Hurricane Andrew near Miami in 1992 (right)

Although code development followed a similar pattern in these two regions, the engineering methodologies and construction practices differ significantly. In Australia, building design is governed by the National Construction Code (ABCB, 2012) and wind load provisions are set out by AS/NZS 1170.2 (Standards Australia, 2011). Residential buildings are designed to a 500 year mean recurrence interval and in high wind Regions C and D generally assumed to have a dominant opening and therefore are designed to an internal pressure coefficient of +0.7. To achieve the required structural system uplift capacity, cyclone-rods (Standards Australia, 2010) are used in Australian timber-frame construction.

In the U.S., a different approach is used. Building design for wind loading in Florida is governed by the FBC and the structural design loading standard ASCE 7-10 (ASCE, 2010). The general design approach is to create a protected building envelope (ICC, 2011) to avoid increased loading effects due to internal pressure when the building envelope is breached on a windward face. Glazed openings are required to be impact resistant (or protected by a shutter system) in wind-borne debris regions, which in Florida is defined as regions with a 700 year mean reoccurrence interval design wind speed of 225 km/h or greater. The design assumes the exterior of the building is protected and therefore enclosed buildings are designed using an internal pressure coefficient of +0.18. Table 1 summarizes some of the key differences between U.S. (Florida) and Australian residential construction in tropical cyclone-prone regions:

Table 1. Key differences in high-wind design for single-family homes in Australia and U.S.

Design Consideration	Australia (Queensland)	U.S. (Florida)
Internal Pressure	Partially enclosed, $\lvert C_p \rvert = 0.7$	Enclosed, $\lvert C_p \rvert = 0.18$
Openings- Pressure	$C_p = +0.7, -[0.65 \text{ to } 1.3]$	$C_p = +1.0, -[1.1 \text{ to } 1.4]$
Openings- Debris Protection	Not required	Required if design >225 km/h
Openings- Waterproofing	Static test at 5-20% design pressure	Static test at 15% design pressure
Roof Substrate (above rafters)	Cladding over draped flexible waterproofing membrane over horizontal battens	Cladding over waterproof membrane adhered to plywood/OSB sheathing
Gust Averaging	0.2-second	3-second
Exceedance Probability	1:500	1:700
Modern Code Era	>~1985	>~2002

Sources: ASCE, 2010; FBC, 2017; Lopez et al, 2011; Standards Australia, 2012; Standards Australia, 2014

Severe wind design considerations in the U.S. are often centered on findings from hurricanes in the Southeast, however, the state of Texas leads the nation with 58 (Florida had 28) of the total (129) billion-dollar severe wind (tropical cyclone and severe storm) weather and climate disasters from 1980-2017 (NOAA, 2018). In contrast to Florida, there is no statewide building code in Texas. In 2001 Texas did adopt the International Residential Code for One- and Two-Family Dwellings (IRC), but cities and counties were authorized to amend the codes as needed for local needs (Chapman-Henderson et. al., 2017) and this coupled with enforcement and compliance issues has resulted in a wide range of protection levels across the state.

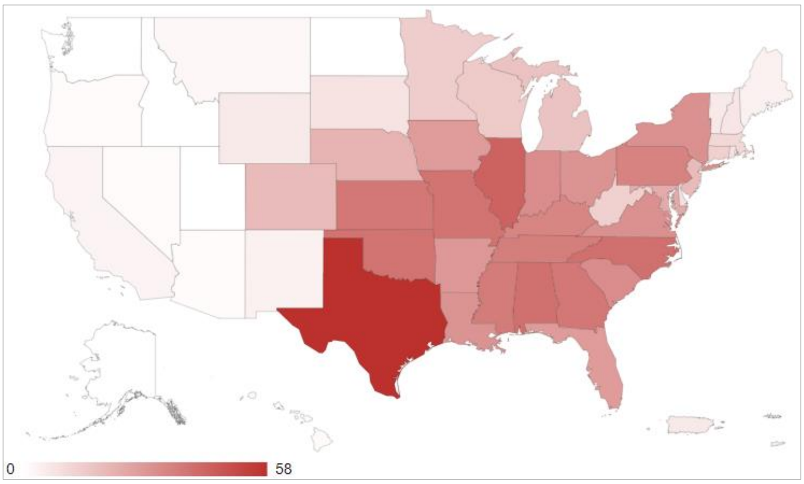

Figure 2. 1980-2017 Billion-Dollar Severe Storm and Tropical Cyclone Disasters in the U.S. by State (CPI-Adjusted) (NOAA, 2018)

3. Tropical Cyclone Damage Investigations

Hurricane Harvey struck the Texas coastline on August 25, 2017, as a Category 4 (Saffir-Simpson, >273 km/, V3) hurricane - the first major hurricane to reach the US in twelve years. Extreme rain was the most dominant cause of damage with over 1.5 m falling in some locations generating floods with exceedance probabilities (MRI) of 1:1000. Rainfall-induced flooding damaged over 300,000 homes (336,000 lost power), many of those in Houston, making Harvey the most significant tropical cyclone rainfall event in U.S. history (Blake and Zelinsky, 2018) and the second most costly at $125B (NOAA, 2018). Wind and surge damage were also significant. Storm tide generated inundation levels of 1.8-3 m in several areas and wind gusts (3-second peak = V3) up to 233 km/h (8 m AGL, Wurman and Kosiba, 2018) destroyed over 15,000 homes and damaged another 25,000 in coastal communities (e.g., Rockport, Aransas Pass). Estimated design wind speed for the region surveyed is 235 km/h (ASCE, 2010), however due to the issues related to building code uniformity in Texas (see Section 2), it is unclear whether the majority of structures were designed to this level.

Over a twelve day period the authors assessed the performance of more than 1,000 residential buildings via smartphone application (Fulcrum) to facilitate rapid collection and collation of geotagged photographs, building attributes and structural damage. The observations show strong gradients in damage between inland and coastal regions. Typical damages for housing included roof and wall cladding failures and wind-driven rainwater ingress. Damage levels to adjacent homes were often drastically different. Collapsed homes were found next to homes with very little to no evidence of structural damage (often attributed to one being an older home).

Hurricane Irma made its first landfall in Florida on September 10, 2017. Prior to this, Category 5 (Saffir-Simpson, >325 km/h, V3) Irma caused severe damage in the Caribbean (St. Maarten, Barbuda, St. Barthelemy and Cuba), destroying 90% of homes on Barbuda with estimated gusts over land in excess of 290 km/h (Amadeo, 2018). The damage prompted an evacuation order for 6.5 million people in

Florida. Irma made its first of two U.S. landfalls in the Florida Keys, having weakened somewhat with estimated gusts of 170 km/h (V3), destroying 25% and significantly damaging 65% of buildings in the Keys (NOAA, 2018). The Florida Coastal Monitoring Program (FCMP) portable weather stations (Balderrama et. al, 2011) deployed near Naples, FL recorded (unadjusted) gusts near 180 km/h as the eyewall came onshore. Since the ASCE 7-10 (ASCE, 2010) design wind speeds for the State of Florida range from 290 to 322 km/h (V3) for critical facilities in the Keys, to 201 km/h for residential low-rise structures in Northeast FL, there was an expectation of reasonably good building performance.

The authors (with partners from University of Florida and several other institutions) conducted damage surveys (using Fulcrum) focusing on the performance of residential structures throughout Florida. In the areas surveyed, observed wind vs design wind ratios were in the order of 20-40% with the exception of some areas in Northeast Florida where tornados generated near design level winds and caused extreme damage. Given the large size of the storm and direction of the eye, many areas received several hours of sustained high winds. Generally older structures, built before the 2002 building code changes suffered the most damage. Newer structures sustained minor non-structural damage. Several areas in the Florida Keys, Jacksonville and in Chokoloskee, FL experienced inland flooding and storm surge (Figure 3) as high as 1.2 m (4 ft) above grade.


Figure 3. Roofing failure due to failed roof/wall connection in Hurricane Harvey (left) and severe storm surge damage along Northeast coast of Florida from Hurricane Irma (right)

Cyclone Debbie crossed the Queensland coast Northeast of Airlie Beach on March 28, 2017 as a Category 4 (BoM, >225 km/h, V3) cyclone. Before the event, the Cyclone Testing Station (CTS) deployed six mobile anemometers via SWIRLnet (Mason and Henderson, 2015) in the area between Ayr and Proserpine. After the event, the authors and other CTS partners investigated the performance of houses; larger residential structures such as apartments, strata properties and resort accommodation; commercial and public buildings; and sheds (Boughton, 2017). A wind field was developed using CTS and BoM anemometer data and showed that buildings within the high-wind study area (Bowen, Proserpine) in general experienced wind speeds 70-80% of design (80-90% in parts of Airlie Beach).

CTS teams assessed the causes of damage to buildings from wind, wind-driven rainwater and storm surge. Inadequate tie-down details between battens and rafters (Figure 4) or trusses, and between the roof structure and walls caused many of the structural failures in buildings constructed before the 1980s. Tie-down connections between roof structure and walls that had been inappropriately detailed also failed on some contemporary buildings. Debbie generated over 1 m of rainfall (including as a low over central and SE Qld) that was often driven by wind through windows and doors or under flashings despite the absence of structural damage to the building envelope. In addition, storm tide in lower-lying buildings in Wilson Beach were inundated to a height of up to 1.1 m causing damage to structures, interiors and contents.

Figure 4. Roofing failure due to failed roof/wall connection in Cyclone Marcia (left) and failure at batten/rafter connection from Cyclone Debbie (right)

On February 20, 2015 Cyclone Marcia crossed the Queensland coast ~100 km Northwest of Yeppoon as a Category 5 cyclone (Australian BoM Scale, >279 km/h, V3). Marcia crossed the coast in a relatively unpopulated region with gust winds (V3) of 208 km/h recorded at Middle Percy Island, a significant distance west of the eyewall. The nearest maximum Automatic Weather Station (AWS) gusts measured at population areas during the event were 156 km/h (V3) in Yeppoon and 113 km/h (V3) in Rockhampton. The design wind speed for these areas (Region C cyclonic) is 250 km/h (0.2-second peak = V0.2) for a 500 year return period (single family housing). Despite less than design level wind speeds (50-70%), significant structural damage was still observed. The majority of severe damage occurred in older housing, with some cases of roof failure for retrofitted installation of new roof cladding on old roof structure (without proper connection upgrades). Despite wind damages, widespread flooding (caused by the heavy rains [300 mm], coastal erosion) and wind-driven rain (water ingress) were the main contributors to building/infrastructure losses. Fortunately, storm surge in populated regions coincided with low tide and there was little to no surge-induced inundation.

5. Summary and Discussion

Each event discussed above is distinctly unique in terms of location (i.e. exposure), hazard intensity (rain, wind, surge, etc.) and vulnerability (or design wind speed as a proxy). Table 2 summarizes key observations and losses for the four events. The two U.S. events were orders of magnitude more costly in both lives and dollars. The disparity is not readily explained by differences in hazard intensity and likely due to the level of exposure considering populations in Queensland, Florida and Texas are 4.6, 20.6 and 27.9 million respectively.

Table 2. Summary of observations and loss from four recent tropical cyclones

Event Name	Min. Pressure (mbar)	Max Recorded Gust (V3) (km/h)	Est. Wind to Design Ratio for Housing	Surge Induced Inundation (m)	Rainfall (m)	Direct Fatalities	Est. Loss (USD)
Marcia	932	208	50-70%	n/a	0.3	n/a	$0.59B
Debbie	943	206	70-90%	1.1	1.0	14	$1.85B
Harvey	937	233	80-100%	2.4-3.0	1.5	89	$125B
Irma	914	*180	*20-40%	0.9-1.5	0.4	97	$50B

**Mainland U.S. (Florida) only, excludes Caribbean (290 km/h estimates) and Florida tornados (~209 km/h, EF2)*
Sources: Blake and Zelinsky, 2018; NOAA, 2018; Boughton et al, 2016; BoM, 2017; Wurman and Kosiba 2018

Despite the unique conditions and costs associated with each event, trends in damage emerge, particularly with respect to wind and water-ingress driven failures. The most significant may be the performance of contemporary (modern building code) vs legacy structures. The majority of homes for all four events experienced wind speeds below design level. In each case, structural failures were still observed and more often in legacy homes. In cyclone-prone regions of Australia, approximately 40% and 60% of homes in Western Australia and Queensland respectively were constructed before modern building code changes of the 1980s. In Florida, at least 60% of homes are pre-code with proportions as high as 80-90% in some areas. Estimates for Texas were more difficult to obtain but in Rockport an estimated 74% of homes were built before 2002 (IRC was adopted in TX in 2001). The implications for Australia and the U.S. are both positive and negative.

The improved performance of contemporary structures demonstrates that building codes in both countries effectively address the life safety issues highlighted by Hurricane Andrew and Cyclone Tracy (Reardon, 1996). However, there still exists an alarming proportion of homes constructed prior to those changes. Cost effective retrofit solutions for upgrading roof framing connections are needed with the key obstacle being accessibility of those connections without removing an otherwise structurally sound roof. The obstacles slightly differ in the U.S. (roof cladding over plywood roof decking) vs Australia (cladding direct to horizontal battens) but the premise is the same and solutions can and should be developed collaboratively. The commonality of other damage modes also present good opportunities for shared innovation, for example:

- Technology associated with windows designed to higher pressures and with impact resistance in the U.S. could fill a critical gap in performance of Australian openings, especially with respect to water ingress.
- Issues related to power failure also (e.g., business and home disruption, food spoilage, damaged electronics) have a significant cost and could be mitigated with the advancement of solar technologies for use during grid failures in both countries.

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References

ASCE. 2010. Minimum Design Loads for Buildings and Other Structures. ASCE/SEI Standard 7-10.

Australian Bureau of Meteorology (BoM), 2015. Severe Tropical Cyclone Marcia. http://www.bom.gov.au/cyclone/history/marcia.shtml

Australian Bureau of Meteorology (BoM), 2017. Severe Tropical Cyclone Debbie. http://www.bom.gov.au/announcements/sevwx/qld/qldtc20170325.shtml

Amadeo, Kimberly, 2018: Hurricane Irma: Facts, Damage and Costs. TheBalance.com. https://www.thebalance.com/hurricane-irma-facts-timeline-damage-costs-4150395

Balderrama, J.A., Masters, F.J., Gurley, K.R., Prevatt, D.O., Aponte-Bermúdez, L.D., Reinhold, T.A., Pinelli, J.P., Subramanian, C.S., Schiff, S.D., Chowdhury, A.G., 2011. The Florida Coastal Monitoring Program (FCMP): A review. J Wind Eng Ind Aerod 99, 979-995.

Blake, Eric S., Zelinsky, David, A., 2018. Tropical Cyclone Report on Hurricane Harvey (AL092017). National Hurricane Center. https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf

Chapman-Henderson, L., Rierson, A.K., Rimoldi, M., Betts Jr., A., 2017. The Status of Texas Residential Building Codes. Federal Alliance for Safe Homes (FLASH).

Florida Building Code (FBC), 2017. Florida Building Code – Building, 6th Ed. Florida Building Commission.

Insurance Council of Australia (ICA Dataglobe) 2018. At: www.icadataglobe.com/access-catastrophe-data/.

International Code Council. (2011). International residential code for one- and two-family dwellings 2012. Country Club Hills, IL: International Code Council.

Lopez, C., Masters, F.J., Bolton, S., 2011. Water penetration resistance of residential window and wall systems subjected to steady and unsteady wind loading. Building and Environment 46, 1329-1342.

Mason, M.S., Henderson, D.J., 2015. Deployment of the Surface Weather Information Relay and Logging Network (SWIRLnet) during Tropical Cyclone Ita (2014), in: Proceedings of the 17th Australasian Wind Engineering Society Workshop.

NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2018). https://www.ncdc.noaa.gov/billions/

Rappaport, E., 1993. Preliminary Report Hurricane Andrew, 16-28 August 1992. National Hurricane Center.

Reardon, G., 1996. Cyclones, Hurricanes and Houses – An Overview. National Engineering Conference. Darwin, AU.

Standards Australia, 2010. AS 1684 Residential timber-framed construction. Standards Australia Limited, Sydney NSW, AU.

Standards Australia, 2012. AS 4055 Wind loads for housing, Sydney NSW, AU.

Standards Australia, 2014. Windows and external glazed doors in buildings. Sydney, NSW, AU.

Wurman, J., and K. Kosiba, 2018: The role of small-scale vortices in enhancing surface winds and damage in Hurricane Harvey (2017). Mon. Wea. Rev. doi:10.1175/MWR-D-17-0327.1, in press.