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Vulnerability modelling for residential housing

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Abstract

Modelling the performance of buildings during extreme natural hazards is an important part of modern insurance markets, government policy decision making, and consequently building science research. Vulnerability models are integral to this process. The most robust development of empirical vulnerability models utilizes the relatively large amount of data for hurricane losses in the US. Engineering-based models have also been developed extensively in the US public sector (e.g., HAZUS, FPHLM) and calibrated against empirical data. Development of models for other countries has been more difficult due to relatively smaller amounts of data on losses from severe weather events.

Empirical and engineering-based models for Australian housing do exist in the public domain but they are either very broad (e.g., pre vs post 1980s, or Townsville vs Cairns) or apply only to a select housing type and have not been through a robust validation process, largely due to a lack of data on losses. More recently, a series of heuristic curves for several typical Australian low-rise residential construction types has been developed based on input from recognized vulnerability experts of the Australian wind engineering community. While this is a step towards a more comprehensive set of curves, calibration against previous models, post-storm observations and loss data is needed. This paper briefly reviews the previous models and discusses a preliminary analysis of loss data from one north Queensland insurer during Cyclone Yasi (2011). The work follows from a series of recent studies conducted by the authors and the insurer, which analysed insurance claims from Cyclone Yasi to determine typical drivers of loss (i.e. roofing failures, etc.) for residential housing.

Introduction

Performance modelling of buildings during extreme natural hazards has become an essential part of modern catastrophe insurance analysis, and is largely related to the development of performance-based design in structural engineering. Modern insurance catastrophe models are typically comprised of a series of sub-models that produce probabilistic estimations for: (1) the occurrence of an event, (2) the associated hazards, (3) the properties of interest in terms of characteristics deemed to affect their vulnerability to damage, and (4) the vulnerability of particular sets of building characteristics in terms of predicted insured loss (i.e. vulnerability model) as a function of the associated hazards of the event. Walker (2011) provides a comprehensive review of vulnerability model development over the last 40 years.

Vulnerability models used by the insurance industry are primarily empirical models based on fitting curves to damage data at individual building level as a function of wind speed estimates for the given location. The advantage of empirical models is that they inherently incorporate many of the uncertainties in the relationship between damage loss ratio and wind speed, especially if based on data from several different events for a similar type of building construction.

A typical issue with empirical models is the accuracy at higher wind speeds as data is generally sparse at higher ends of the scale because high-wind events are relatively uncommon. Consequently empirical models are generally more accurate at lower wind speeds. This has implications to estimating losses for extreme winds. Varying construction costs also add uncertainty.

Engineering-based vulnerability relationships rely on estimations of damage level for different hazards based on scientific engineering knowledge of the structural and material behaviours of building components and then estimations for cost of repairing that damage. This methodology relies on a high level of understanding of the mechanics of wind flow around a structure and the resultant forces on different building components including time dependent effects (e.g., fatigue loading) and redistribution of forces after local building element failures. Vickery et al (2006a, 2006b) review the basic elements that should be included for the development of fully engineering-based vulnerability relationships.

There is also considerable uncertainty associated with the estimation of actual wind loads on a structure based on a given wind speed and angle of incidence. These loads vary based on housing construction, surrounding terrain, cladding elements, building height, etc. Partial damages (i.e. failure of door/window) and wind borne debris can also have dramatic effects on load magnitude and damages, and can only be modelled in a probabilistic sense. Because of these uncertainties, the development of fully engineered vulnerability models is a very difficult task that requires large amounts of research on wind load interactions with buildings and the associated structural responses.

Engineering models are far more complex to develop than empirical ones, but they do have the advantage of being able to investigate various scenarios as demonstrated in Figure 1. The figure shows the capability of engineering-based models to perform analysis for specific changes to the structural system (e.g., retrofit upgrade of cladding fasteners) as opposed to empirical models based solely on damage investigation or insurance claim data from past events.

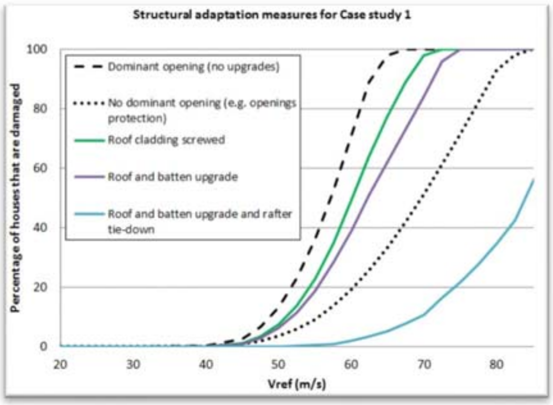

Figure 1. Estimated damage from wind loads to houses with different structural adaptation measures (King et al, 2013)

Pinelli et al (2004) developed a vulnerability model in Florida for the Florida Public Hurricane Loss Model (FPHLM) based on the work of Unanwa et al (2000). A follow-up paper (Pinelli et al, 2008) describes how the model was calibrated against recorded loss data from Hurricane Andrew and then the three damaging hurricanes that crossed Florida in 2004. This paper also provides insight into the model including allowances for contents losses and different building standards.

Vickery et al (2006a, 2006b) describe the methods used in development of the HAZUS hurricane model for the US Federal Emergency Management Agency (FEMA). These papers provide a comprehensive overview of likely the most well developed engineering-based vulnerability model to date. Included is the modelling of debris damage, internal pressurization due to building envelop failure, contents loss as a result primarily of water damage, and modelling of associated rainfall.

Model Development in Australia

Model development in Australia has been mainly focused on residential structures. One of the first models was developed by Leicester and Reardon (1976) in the aftermath of Cyclone Tracy in Darwin (Figure 2). These relationships were developed based on three key analysis components including: a) detailed estimation of the wind field, b) qualitative assessment of damages for a large number of houses of different construction type and c) a set of factors that define the relationship between observed damage states (e.g., 50% roof loss) and the ratio of repair cost to initial value of the building (i.e. Damage Repair Index). The conversion factors allowed qualitative observations to be expressed in terms of monetary loss.

The analysis work from Cyclone Tracy led to the development of a more general methodology for estimating the vulnerability of a given structure and its contents monetarily based on a linear approximation using velocity thresholds for minor and major damage levels (Leicester and Beresford, 1978). The approach included modifications for local topography and exposure, emphasizing the importance of considering these local effects in addition to structural details of the building when estimating damages from cyclone.

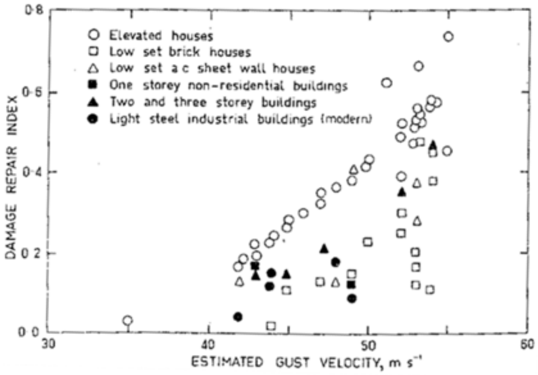

Figure 2. Estimated relationship (Leicester and Reardon, 1976) between damage and wind velocity for various types of buildings from post-event damage assessments following Cyclone Tracy

In the absence of additional loss data, later model development in Australia relied heavily on data from the US. Walker (1995) (as referenced by Walker, 2011) developed vulnerability models for older housing (pre-1980s) in northern Australia by modifying the model developed by Sparks and Bhindarwala (1993) to produce estimates of loss from Cyclones Tracy and Althea similar to recorded values from these events (Walker, 2011). Further modification was made for more contemporary housing (post-1980s) based on engineering judgement and observed relative performance of the two age groups during Cyclone Winifred in 1986 (Walker, 2011).

Henderson and Harper (2003) developed broad estimates of potential damage from a simulated cyclone event for several north Queensland communities (e.g., Cairns, Townsville, Mackay).The analysis used a simulated deterministic wind field model and a probabilistic vulnerability model including five failure modes for various residential construction types in north Queensland. Results included postcode-level estimates of frequency and intensity of damage for a simulated event and populations of houses.

Henderson and Ginger (2007) developed an engineering-based vulnerability model for a typical legacy northern Australian house. They modelled both the probability of damage occurring to a house from different modes of failure as the wind speed increased, and the probabilities of various levels of damage occurring at different wind speeds as a result of progressive failure, including the effect of debris damage and consequent internal pressurisation.

Geoscience Australia facilitated a workshop at the Cyclone Testing Station to develop a series of heuristic vulnerability curves to broadly cover a range of building types in Australia (Figure 3). The study was largely based on expert opinion from the Australian wind engineering community (Wehner et al, 2010). These curves were developed to provide preliminary validation of outputs from an engineering-based software model (VAWS) the two institutions are currently developing with project support from the Bushfire and Natural Hazards Cooperative Research Centre. The project will expand the current VAWS output (single construction type) over the next four years. A primary aim of the project is to use the models outputs for cost-benefit analysis of wind damage mitigation strategies.

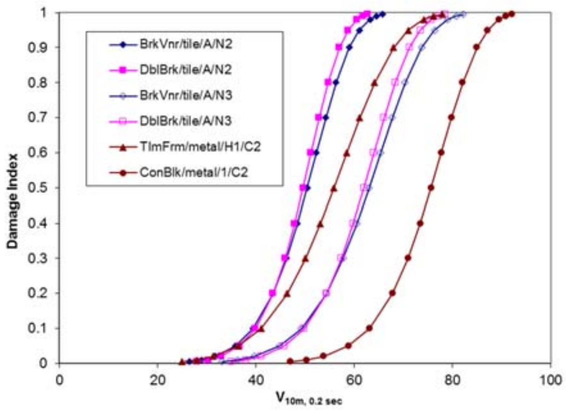

Figure 3. Heuristic vulnerability curves for six representative Australian building classifications (Timber ED, 2006)

Claims Analysis

Public domain vulnerability models for damage to Australian housing from wind storms have, to date, not had robust validation from insurance data. To begin addressing this, policy data from one insurer in north Queensland during Cyclone Yasi were analysed to identify correlations between claim value, typical damage modes, and construction age. This was achieved by extracting qualitative and quantitative insights from aggregated insurance policy data. The data included information on policies both with and without a claim for Cyclone Yasi. A detailed analysis that addresses topographic effects, etc. and accuracy of the assumed wind field at policy level has not yet been completed. Therefore, the current analysis is limited to relative claim rates and sizes for different geographic areas and between various ages of housing. References to wind speed are based on 3-second peak gust as per Boughton et al (2012).

Loss Ratio

The claims data were subdivided by loss ratio (i.e. claim value / insured value) into four bins (Table 1). Bins were specified based on the most severe damage modes observed for a corresponding loss ratio bin. These relationships were determined by a review of 180 assessor's reports for claims of varying loss ratio.

Loss Ratio	Most Severe Damage Modes
0	No claim filed (i.e. no damage)
0 – 0.1	Minor roofing issues and water ingress, minor debris impact damage, fencing, fabric shade coverings, roofing vents
0.1 – 0.5	Moderate roofing failures (<50% roof) and water ingress, ceiling damage, broken fenestration, exterior cladding
0.5 – 1	Severe roofing failures (>50% roof), extensive water ingress damages, interior components damage, broken fenestration

Table 1. Loss ratios with typical damage modes extracted from assessor's reports (note: typical damages for higher loss ratio bins also include all damages from lower ratio bins).

The frequency of large loss ratios (i.e. large claims) was greatest, in geographic locations nearest the point of landfall (i.e. Cardwell, Mission Beach, etc.) where wind speed estimates were 58-66 m/s. However, claim frequency was significant for the entire north Queensland region, even in areas of relatively low wind speed estimates (i.e. 37 m/s in Townsville, 25 m/s in Cairns). A total of 26% (14,282) of policies from Bowen to Port Douglas filed a claim. Approximately 86% (12,296) of those claims had a loss ratio of less than 0.1. These claims represent 29% of the total claims payout cost. Approximately 12% (1,665) of claims had loss ratios between 0.1 and 0.5, contributing 44% to the total payout cost. The majority of claims this size were filed near the point of landfall (Figure 4). Severe damage claims (i.e. loss ratio >0.5) represented 27% of the total payout cost.

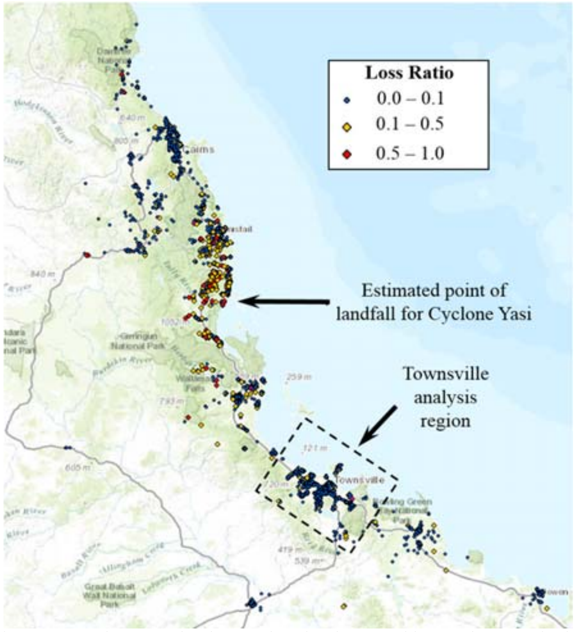

Figure 4. North Queensland coastal region impacted by Cyclone Yasi with distribution of claims subdivided by loss ratio bins (claim value/insured value)

Townsville Analysis Region

To isolate a relatively high population of housing subjected to a similar range of wind field characteristics (i.e. velocity, direction, and duration) and rain fall intensity, preliminary analysis emphasized the Townsville region. Peak 3-second gust wind speed measured at the Townsville airport 3-cup anemometer (10 m height) was ~37 m/s during Cyclone Yasi. A Dines anemometer at the same airport measured a peak 0.2-second gust wind speed of ~45 m/s, reflecting the higher frequency response of the apparatus. In addition, a lower limit of ~41 m/s was estimated from failed signpost calculations near the airport.

A total of 23,878 policies were included in the Townsville region, 30% of which filed a claim associated with Cyclone Yasi. Considering wind speeds were just above 50% design level for the region, there was an unexpectedly high frequency of claims throughout the city and across all housing age groups. Minor claims (i.e. loss ratio <0.1) were dominant and occurred uniformly throughout the region. Their occurrence appeared to be independent of housing age and proximity to the coast. However, larger claims (i.e. loss ratio >0.1) were more prevalent in areas near the coastline where older housing is also more prevalent.

Table 2 shows the relative contributions of claims in each loss ratio bin as a proportion of the total number of claims filed in the Townsville region. The majority of claims (94%) were associated with minor damages. The total insured loss for the Townsville region was $AUD 63.5 million, of which loss due to minor damages comprised 60%. Moderate claims (loss ratio = 0.1-0.5) in the Townsville Region totalled 390 and severe claims (loss ratio >0.5) totalled 27. These claims were generally associated with moderate to severe damage to the roofing structure, water ingress damages to the building interior, etc. and occurred for wind speed estimates that were significantly less than design level.

Loss Ratio	% Total Cost	# Claims	% Total Claims
0-0.1	60%	6851	94%
0.1-0.5	32%	390	5%
0.5-1	6%	27	<0.5%

Table 2. Frequency and cost statistics for three loss ratio bins from one insurer in the Townsville Region during Cyclone Yasi.

Figure 5 shows the relationship between loss ratio frequency and age of construction for homes in the Townsville Region. Each percentage represents the proportion of claims in that loss ratio bin relative to the total number of claims for the age grouping. The five construction time periods were selected based on the progression of typical housing material and construction characteristics in Queensland (Henderson and Harper, 2003).

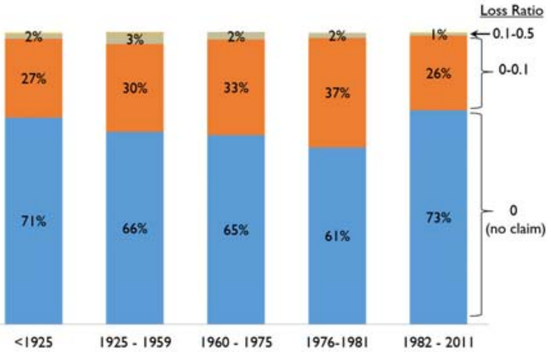

Figure 5. Claims loss ratio proportions for five building age groups to the total number of claims filed in relation to Cyclone Yasi for the Townsville region

The loss ratio trends for construction age in the Townsville region were similar to those for the entire affected coastal region (not shown). This is due in part to the proportion of population in Townsville relative to the broader region. Preliminary findings related to construction age are as follows:

- Post-1980s housing had a smaller claim rate and a smaller proportion of moderate/severe claims than pre-1980s housing. However, the proportion of claims filed for post-1980s housing (~27%) is significant in comparison to older housing (29-39%) considering the design level (67 m/s) of contemporary construction in the region is well above wind speed estimates for the Townsville region (37 m/s). As evidenced by post-event damage observations (Boughton et al, 2012), the majority of contemporary houses remained structurally sound, protecting occupants and therefore meeting the life safety objective of Australia's National Construction Code (NCC). However, contemporary homes did experience significant water ingress (resulting in loss of amenity) and component failures (i.e. doors, soffits, guttering, etc.) with the potential for damage progression to other buildings, thus failing to meet specific objectives and performance requirements of the NCC.
- Housing constructed between 1925 and 1981 in the Townsville region did not perform as well as housing constructed either before or after this time period. Post-event damage observations in the area support this trend. Materials in pre-1925 houses may be less prone to water damages due to construction materials of the time period (e.g., water recedes through timber floors, asbestos/timber ceilings are water-resistant, etc.). Many of these older homes are also more likely to be upgraded structurally or renovated because of increased market value, historic value, etc.

Discussion

While the development of vulnerability models for Australian housing has progressed over the last 40 years, the approaches and assumptions vary widely, as do the outputs. This adds difficulty in directly comparing results of the different models against new loss data. Also, accurate wind field estimations including local effects (i.e. topography, terrain, shielding) are a critical to utility of loss data. Specific modelling information from the current claims analysis is limited by the accuracy of wind field estimates for Cyclone Yasi. However, based on the preliminary analysis, general considerations for model development in the next stage of the research have been made.

The Townsville analysis suggests an upper limit for damage initiation thresholds for all ages of north Queensland housing of 45 m/s (0.2-second gust). The data suggest that housing types from the 1925 to 1981 period are more likely to sustain some form of damage at this wind speed. Further, housing types from this period are also more likely to sustain moderate/severe damages (i.e. loss ratio >0.1) than other housing types. As expected, contemporary housing is less vulnerable than older housing. However, the performance difference between contemporary and older housing may not be as significant as expected at lower wind speeds.

Use of loss data in modelling must also address the inclusion of damages to external items (fences, etc.), water ingress damages to internal linings (not considered contents) and contents.

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