Design of Potential Dominant Openings to Resist Cyclonic Winds

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INTRODUCTION

Australian structures may be vulnerable to the impact of cyclones due to potential weaknesses in their building envelopes (Engineers Australia, 2015). Shortfalls in design and construction, and deterioration of materials are among the leading causes for failure (Smith et al., 2016). Given the extreme wind conditions that structures in cyclonic regions are exposed to, it is important to establish whether current design codes are sufficient in ensuring the cyclone resilience of building envelopes – both now and in the future.

Cyclones are a threat to coastal communities, with global climate models predicting future impacts to worsen in intensity (Gettelman et al., 2017). Wind speeds are forecast to increase by up to 10% at the end of the century, which surpass the capacity of existing design codes and necessitates code reviewal (Australian Greenhouse Office, 2007; Knutson, 2010). Coupled with migration trends toward coastal areas, Australian communities are facing increased exposure and risks to tropical cyclones (Stewart et al., 2014). Several factors may influence the vulnerability of a region to cyclonic impacts, including the community's age of construction.

The current housing stock in Australia is often categorised in existing literature as either pre- or post-1980 construction; the latter representing modern engineering design standards (Stewart & Li, 2010). As of 2010, 50% of Queensland housing did not comply with current Australian Standards for wind actions, AS/NZS 1170.2 (Stewart et al., 2014). Furthermore, structures that are built-to-standard have exhibited failures at wind speeds well-below those specified in AS/NZS 1170.2. A common, observable weakness for both types of construction include failures in the building envelope due to the poor performance of hardware furniture and fixings (Engineers Australia, 2015). The creation of dominant openings due to such failures increases a structure's internal pressure. Consequently, these buildings become vulnerable to wind-induced failures in primary structural components.

Reports by the Cyclone Testing Station have highlighted the rising concern for dominant openings caused by the failure of door and window systems under cyclonic wind conditions (Boughton et al., 2011; Henderson et al., 2006; Leitch et al., 2009). It is the focus of this thesis to investigate these secondary structural elements as potential weaknesses in building envelopes when acted on by cyclonic winds.

This thesis establishes effective solutions that mitigate the risk of potential dominant openings from weaknesses in building envelopes of structures situated in areas prone to cyclonic impact.

METHODOLOGY

Wind Tunnel Study

A 1/50 scale hip-roof model house made of Perspex with dimensions 396 mm x 200 mm x 54 mm (equivalent to 19.8 m x 10.0 m x 2.70 m full-scale) was constructed for testing in the Cyclone Testing Station's wind tunnel, as shown in Figure 1. This model was designed to represent contemporary forms of housing in Australia.

Pressure taps were spaced on the surface of the model at a distance that enabled encapsulation of the tributary areas for generic doors and windows for all wind loading scenarios of the building. Experimentation was conducted at 10 degree intervals around the compass, such that the wind direction, θ, rotated 360°. Four tests of 180 second duration were conducted to measure pressure readings at a frequency of 500 Hz on the model. The scales for dimensional analysis that were used in this study are as follows: length = 0.02; velocity = 0.232; time = 0.09. Thus, an observation time of 52 seconds in the wind tunnel was equivalent to 10 minutes in full-scale. Based on the 180 second duration in the wind tunnel, three full-scale time blocks of data were recorded for each test and direction.

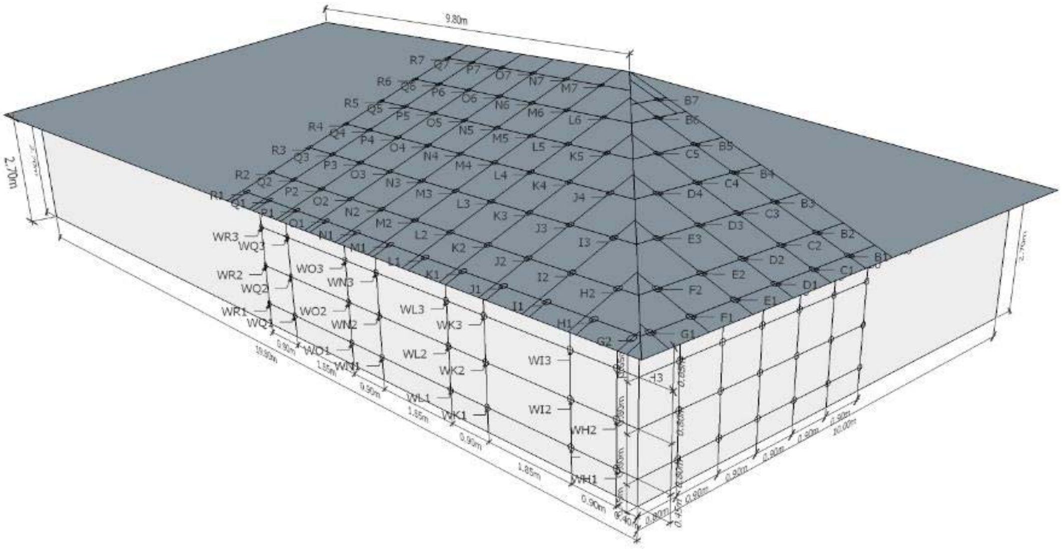


Figure 1. Model used in wind tunnel study.

Data Analysis

The data obtained in the wind tunnel was converted into quantitative full-scale pressure and loads occurring across the model. The process for converting data is given in Figure 2.

Figure 2. Process for scaling raw wind tunnel data to full-scale pressure.

The wind tunnel data was applied to a selection of five doors and windows. Details for these potential dominant openings are listed in Table 1. Each door and window was representative of those standard in residential housing.

Table 1. Summary of potential dominant openings used in analysis.

Structure	Dimensions (mm)	Vertical position on wall (mm)	Pressure tap distribution		
			Level 1	Level 2	Level 3
Door 1	820W x 2040H	0.000	0.850	0.800	0.390
Door 2	2026W x 2036H	0.000	0.850	0.800	0.386
Window 1	1200W x 1500H	0.680	0.170	0.800	0.530
Window 2	1800W x 1500H	0.610	0.240	0.800	0.460
Window 3	1800W x 1800H	0.300	0.550	0.800	0.450

Pressures acting on each potential opening was standardised according to their area using Equation 1.

$$Standardisation = \sum_{i=0}^{3} Pressure_i \times Distribution_i \Big/ Height\ of\ opening \qquad 1$$

Full-scale Air-box Testing

Two full-scale tests of an external timber door were undertaken in the air-box at the Cyclone Testing Station, Townsville.

In the air-box, a positive external pressure was applied to each door system via slow, ramped loading. The pressure was increased in increments of 0.1 kPa and held for ten seconds. A positive pressure loading on the door system was assumed to be the critical wind loading scenario.

The first test gauged the capacity of the door system to withstand a positive external pressure. The second test replicated the first test, with the addition of a 100 mm drop bolt installed flush with the top right edge of the door. The purpose of the drop bolt was to increase the door's capacity.

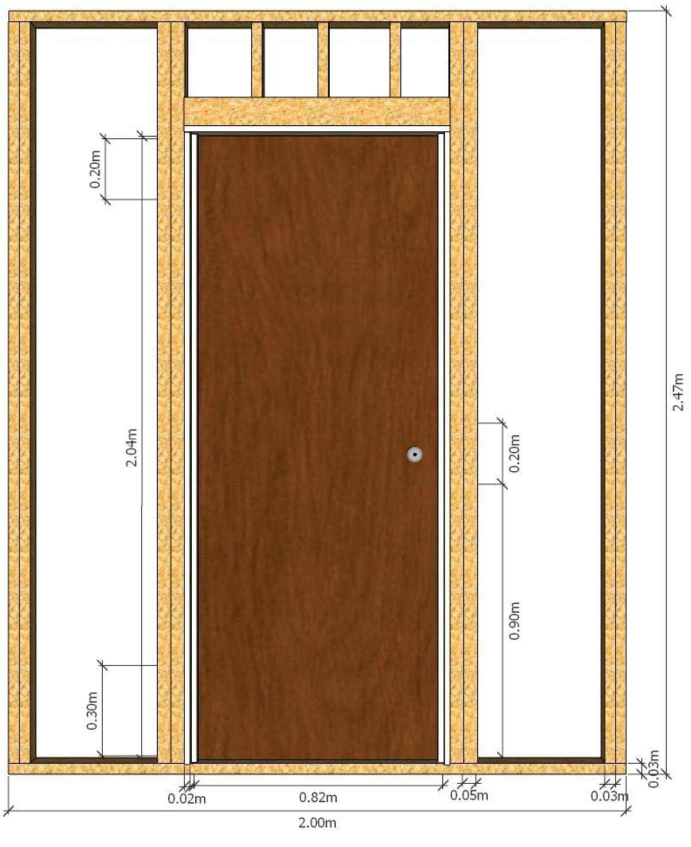
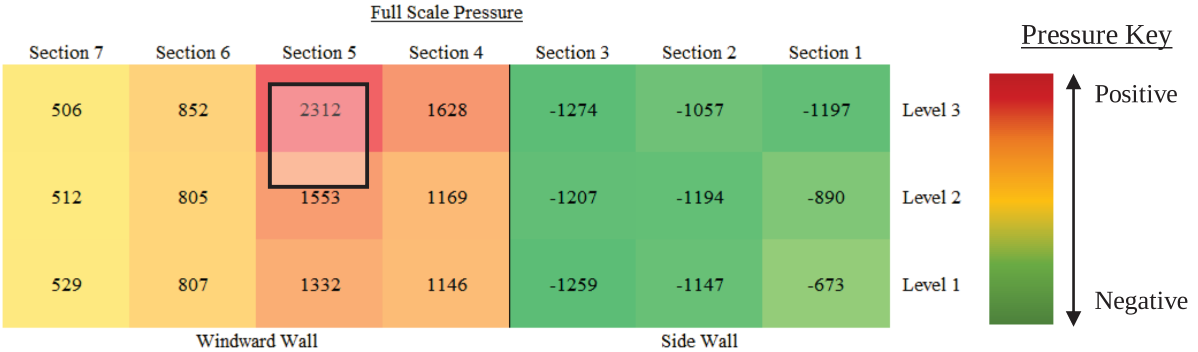


Figure 3. Door system used in full-scale air-box tests.

RESULTS AND DISCUSSION

Wind Tunnel Study

Several key findings were made from the wind tunnel study. Firstly, windows typically experienced greater pressures than doors when on the windward wall. This can be attributed to the raised position of windows on the wall, given in Figure 4, which suggests that larger pressures may occur at increased heights on a wall's surface. Although a trend was evident for the critical pressures observed at this point in the wind tunnel study, there was insufficient evidence to conclude a definitive trend exists across all data sets. A summary of the critical pressures obtained from each potential dominant opening is provided in Table 2.



Full Scale Pressure

Section 7	Section 6	Section 5	Section 4	Section 3	Section 2	Section 1	
506	852	2312	1628	-1274	-1057	-1197	Level 3
512	805	1553	1169	-1207	-1194	-890	Level 2
529	807	1332	1146	-1259	-1147	-673	Level 1

Windward Wall

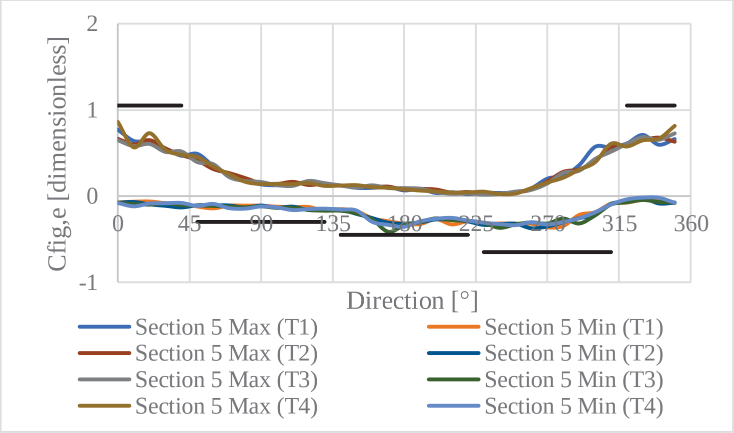
Side Wall

Figure 4. Pressure map at critical pressure. Example of window positioned on map.

Table 2. Summary of critical pressures obtained for each potential dominant opening.

Structure	Dimension	Critical Pressure [kPa]	
		Maximum	Minimum
Door 1	820W x 2040H	1.71	-1.50
Door 2	2026W x 2036H	1.71	-1.50
Window 1	1200W x 1500H	1.80	-1.48
Window 2	1800W x 1500H	1.75	-1.48
Window 3	1800W x 1800H	1.71	-1.49

Significant over- and under-estimations of critical pressure were discovered in AS 4055 when compared to the wind tunnel study. Areas within 1200 mm of a house's edge, denoted Region SC in AS 4055, were overconservative in design pressure by up to 50%. Conversely, areas 1200 mm or greater from an edge, denoted Region G and General in AS 4055, were insufficient in providing the necessary ultimate pressures to ensure structural rigidity by up to 10%. In regards to $C_{fig,e}$, AS/NZS 1170.2 was generally conservative.



Graph 1. Comparison of Cfig,e from wind tunnel to AS/NZS 1170.2.

Full-scale Air-box Testing

The ultimate strength and failure mode for each door system is summarised in Table 3. The addition of a drop bolt was found to increase the capacity of Door 2 by 16%. The design pressures derived from the air-box were insufficient in providing the strength requirements determined from the numerical simulation of wind tunnel data. The percentage difference of the two methods, the air-box and the wind tunnel study, is given in Table 4.

Table 3. Results from air-box tests.

Test	Ultimate pressure [kPa]	Failure Mode	Cause
1	+ 1.9 ± 0.5	Brittle	Door handle loosened and sheared door.
2	+ 2.20 ± 0.5	Brittle	Striker plate loosened and timber jamb split.

Table 4. Comparison of air-box tests to wind tunnel study.

Design Pressure [kPa]		% Difference
Test 1	Door 1	+61.3
1.06	1.71	
Test 2	Door 1	+39.0
1.23	1.71	

CONCLUSIONS

This thesis reinforces the importance of preventing potential dominant openings to maximise the resilience of structures in cyclonic regions. Several key findings were derived from this research, including guidelines for design critical wind loadings on potential openings and the capacity of existing design standards in safely facilitating these loading scenarios. This study's recommendations include:

I. AS 4055 should be reviewed so ultimate external pressures better reflect those prescribed in AS/NZS 1170.2.
II. Houses of all wind classifications per AS 4055 should be designed for the presence of dominant openings.
III. Design of door systems should be regulated by comprehensive guidelines that are incorporated into design standards.
IV. This study recommends general entrance doors withstand an external design pressure of +1.75 kPa for housing in wind classification C2.
V. Existing doors should be fitted with additional support to increase door capacity and encourage a safer failure mode under severe wind actions.

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