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Wind Loads on Contemporary Australian Housing

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Abstract

Contemporary 1 and 2-storey houses being built in and around Brisbane and Melbourne have been surveyed and representative houses defined. Wind tunnel studies on 1/50 scale wind tunnel models are used to determine the spatial and temporal variation in wind pressures across the roof surface and data used to determine truss hold down loads. This study showed that 1-storey houses experience smaller roof truss hold-down forces that those determined from the Standards AS/NZS 1170.2 and AS4055 whereas 2 storey houses experienced hold-downs equal to or greater than those specified in AS/NZS 1170.2.

Introduction

Windstorms cause significant structural damage to houses in many parts of world. The roof, often consisting of timber trusses, metal battens and corrugated metal sheeting experiences large loads and is particularly vulnerable to damage during these events (Leitch, Ginger et al. 2010).

Design pressures on roofs given in standards such as AS/NZS1170.2 and AS4055 are based on gable or hip-end shaped roofs of rectangular plan buildings (Standards Australia 2011; Standards Australia 2012) The earlier studies that these standards were based on were also limited by technology and hence unable to satisfactorily account for the spatial and temporal variation in pressures across roof surfaces. Contemporary housing in Australia often have complex, asymmetrical hip and gable type roofs and a range of plan footprints. Thus, an accurate description of the pressure distribution on a contemporary representative house is required to assess its structural performance and vulnerability in a windstorm.

The structural vulnerability of houses is dependent on the wind load distribution and the structural system's response to these loads. A detailed description of the spatial and temporal variation of the wind loads and the resulting structural load effects is required in order to assess the vulnerability of critical structural components. This paper defines the typical configuration of contemporary 1-storey and 2-storey brick veneer houses with metal roof cladding being built in the cities of Melbourne and Brisbane in Australia. From wind tunnel model tests, external pressures acting on the roof surfaces are obtained and subsequently the wind loads on truss to top-plate connections are determined. The results are also compared with design data provided in codes and standards.

Representative House

The Cyclone Testing Station, as part of the CSIRO CAEX Flagship project, carried out a survey of contemporary housing in suburbs of Brisbane and Melbourne. The data from this detailed survey was used to define a representative 1-storey and 2-storey house with specified dimensions, roof shape and pitch, plan footprint, construction method and materials, and structural system.

Figures 1 and 2 show the representative 1-storey and 2-storey houses respectively. The structural system consists of timber framed brick-veneer construction with timber trusses spaced 600mm apart on a complex hip-end roof. Roof pitches are 21.5° for the 1-storey house and 22.5° for the 2-storey house.

Trusses are arranged with general trusses in the middle part of the roof and jack trusses fixed to girder trusses at the hip-ends. Roof cladding is corrugated metal sheeting attached to metal top-hat battens at 900 mm spacings. Wall framing consists of 90 × 35 mm timber studs spaced 450mm apart that span from the top-plate to the bottom-plate of the wall.

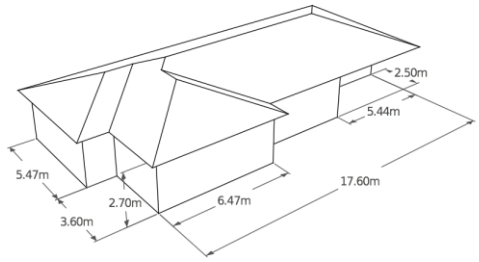

Figure 1. The representative 1-storey house

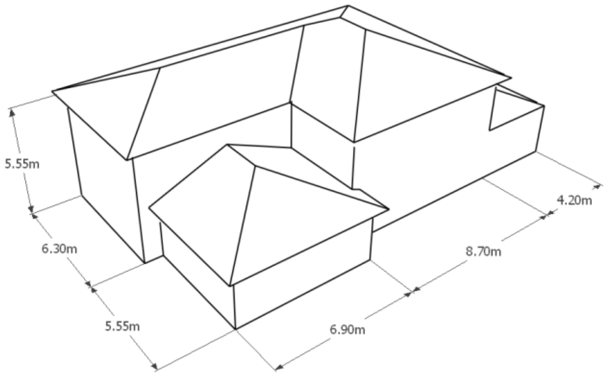

Figure 2. The representative 2-storey house

Experimental Set-Up

Tests were carried out on wind tunnel models of the representative houses at a length scale (Lr) of 1/50 using the 2.0m high × 2.5m wide × 22m long boundary layer wind tunnel at the Cyclone Testing Station, James Cook University.

The approach atmospheric boundary layer was modelled using an array of 50mm blocks on the floor of the upstream fetch of the wind tunnel. A Turbulent Flow Instruments (TFI) *'Cobra Probe'* was used to measure the approach wind velocity and turbulence intensity at heights (z) above the floor of the tunnel to validate that the flow simulated in the wind tunnel matches Terrain Category 3 (a suburban environment) for heights below 10m in full-scale.

Wind tunnel Model

The 1/50 scale wind tunnel model of the 1-storey representative house was constructed with 320 pressure taps on the external roof surface and 108 on the eaves to measure the spatial and temporal variation in external pressure. Additionally, an alfresco area typical of the surveyed houses was modelled at the rear of the 1-storey house with pressure taps on the soffit/ceiling. The 2-storey house, with a larger roof area, had 559 pressure taps on the roof and 114 taps on the eaves.

Pressure taps are arranged on the model in a 12×18mm grid-pattern (representative of the 600×900 mm truss-batten spacings in full-scale) to enable cladding loads, batten-truss loads and the resulting wind load effects on the trusses to be determined. As described by Jayasinghe (2012): pressures on groups of taps within the tributary area of a batten-truss connection were combined to obtain the fluctuating wind load acting on that particular connection. These simultaneously acting loads from several batten-truss connections within a specified area were applied to derive the load effects on trusses.

External pressures (p_e) on these roof taps were measured for approach wind directions (θ) of 0^o to 350^o at intervals of 10^o. The pressure taps were connected to TFI pressure transducers via a tuned 1.5mm diameter tubing system. The pressure signals were low-pass filtered at a frequency of 625Hz, and sampled at 1250Hz for 30 seconds for a single run. Pressures at each of these taps are analysed to give pressure coefficients that vary with time, t as:

$$C_p(t) = p(t)/(\frac{1}{2}\rho\overline{U_h}^2) \qquad (1)$$

Where, $\frac{1}{2}\rho\overline{U_h}^2$ is the mean dynamic pressure at the mid-roof height (h). Mid-roof-height was taken as h=70mm (3.5m full scale) and h=131mm (6.55m full scale) for the 1 and 2-storey houses respectively. Mean, standard deviation, maximum and minimum pressure coefficients were obtained from three runs for each approach wind direction.

This study, carried out at a length scale: L_r = 1/50 and a velocity scale: U_r = 1/2.5 results in a time scale: T_r = 1/20. Thus an observation time of 30 to 40 seconds in model scale is equivalent to 10 to 15 minutes in full scale.

Truss hold-down load

Spatially and temporally varying external pressures acting on the roof surface are used to determine the fluctuating structural wind load effect $X(t)$ for the truss hold-down force given by Eq. (2):

$$X(t) = \sum_{j=1}^{N} P_j(t)\beta_j \qquad (2)$$

Where $P_j(t)$ is the time varying load at location j, β_j is the influence coefficient for the load effect at location j and N is the number of load application points that influence load effect X being considered. Furthermore, $P_j(t) = p_j(t)A_j$, where $p_j(t)$ is the time varying pressure at j and A_j is tributary area for the pressure at j.

The truss hold-down force on a general truss in the middle of the roof and on a girder truss at the hip-end (locations shown in Figures 3 and 4), are presented in non-dimensional coefficient form, as shown by Equation (3):

$$C_x(t) = X(t)/(\frac{1}{2}\rho\overline{U_h}^2 A_N) \qquad (3)$$

Where $C_X(t)$ is the load effect coefficient, ρ is *the* density of air, $\overline{U_h}$ = mean wind speed at mid roof height and A_N the nominal tributary area of the truss being analysed. For the representative houses, A_N is the nominal tributary area for the selected truss, taken as 5.64m^2 and 12.2 m^2 for the general and girder truss of the 1-storey house and 4.95 m^2 and 13.63m^2 for the general and girder truss of the 2-storey house respectively.

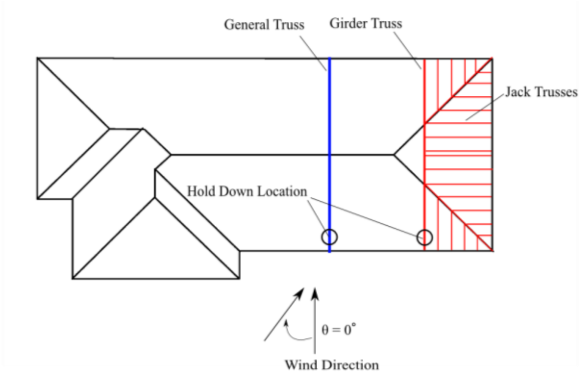

Figure 3. General and girder truss locations on 1-storey house

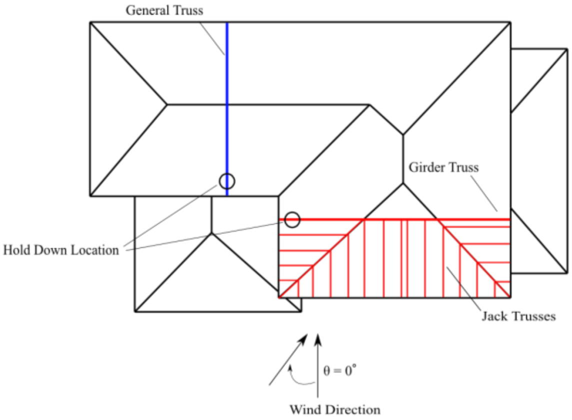

Figure 4. General and girder truss locations on 2-storey house

The structural analysis program SpaceGass 11.1 was used to create structural models of these trusses including the interconnecting jack trusses and hip rafters for the girder truss. Truss to top plate connections were modelled as pin supports and all truss members are pin jointed. Material and section properties were modelled as MGP10 seasoned timber with a 90x75mm cross-section. Unit loads were then applied perpendicular to the roof slope at the location of every batten-truss connection j to determine the influence coefficients (β_j) for the truss hold down force, X for each truss.

Equations (1) and (2) were applied using a customised MATLAB program to obtain the time varying hold-down forces *X(t)* on the general truss and girder truss for each approach wind direction θ, thus accounting for spatial and temporal variability of external pressure across the roof surface. The peak hold-down force coefficients for each θ is calculated for the three runs and presented in Figures 5-6 for general truss and girder truss of the 1 and 2-storey houses. The error bars about the mean, indicated by the solid symbol, show the maximum and minimum values of the 3 runs for each approach wind direction.

Peak hold-down loads are calculated from pressures filtered at 625 Hz (about 30 Hz in full scale) with some likely attenuation of loads as they pass further through the load path or 'hold down chain', as suggested by Stathopoulos (2003).

1-Storey House

Figure 5a shows that large peak hold down force are experienced on the general truss from wind directions θ of ~45^{o}, ~135^{o}, ~225^{o} and ~315^{o}. Figure 5b shows that the girder truss experiences large peak hold down forces from wind directions θ of 0 ± 45^{o}. Thus it can be said that the general truss experiences large hold down forces from wind approaching from most directions.

The peak (i.e. design) hold-down force coefficients on the general truss and girder truss of the representative house obtained from the wind tunnel test data and Standards AS/NZS 1170.2 and AS4055 are given in Table 1. Loads calculated using the methods presented in this study that account for spatial and temporal variation in wind pressures are significantly smaller than those derived from the wind loading standards. However, It is assumed that the influence coefficients of load applied at Batten-truss connections remain constant over the sampling time. Henderson, Morrison et al. (2013) and Morrison and Kopp (2011) quantified the effect of progressive weakening of connections due to loads applied at batten-truss connections.

Ratios of design loads from the Standards to those measured in the wind tunnel can be defined. Design forces from AS/NZS 1170.2 are 1.20/0.86=1.40 and 1.64/1.05=1.56 times greater than those measured in the wind tunnel for the general truss and the girder truss respectively. Design loads determined from AS4055 are more conservative, being 2.08/0.86 = 2.42 and 3.00/1.05 = 2.86 times greater than those measured in the wind tunnel for the general and girder trusses respectively.

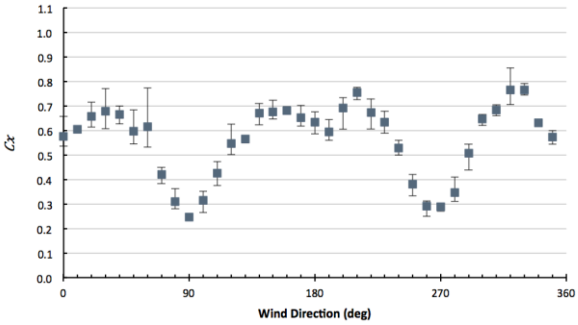

Figure 5a. Peak truss hold down C_x vs θ for the 1-storey general truss

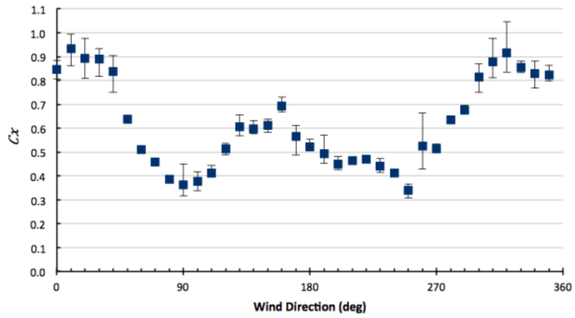

Figure 5b. Peak truss hold down C_x vs θ for the 1-storey girder truss

	AS/NZS 1170.2		AS4055		Wind Tunnel
Wind Directions ±45^{o}	0°, 180°	90°, 270°	0°, 180°	90°, 270°	All Directions
General truss	1.02	**1.20**	2.08	2.08	0.86
Girder truss	**1.64**	1.30	2.39	**3.00**	1.05

Table 1. Peak truss hold-down force coefficients C_x for the 1-storey house

2-Storey House

Similar to the 1-storey house, high hold down forces are experienced at a range of wind directions for the general truss, as shown in Figure 6a. However, it appears that wind moving over the lower storey garage roof induces higher suction pressures on the upper storey roof above, thus higher hold down forces are experienced for a wind approach angle of 50°. Here it can be said roofs at a lower level on the windward side of the house have increased suctions pressures on the roof and subsequently the truss hold down.

Critical wind directions for the girder truss occur due to cornering winds with the truss on the leeward side, as shown in Figure 6b. However, this occurred only from winds approaching within the range of $210° \leq \theta \leq 270°$ for both hold down locations. Large hold down loads were not observed for the complimentary range of angles from $45° \leq \theta \leq 150°$ due to shielding from the rest of the house. Thus, in this case, the asymmetry of the building footprint has reduced the number of critical wind directions for the girder truss.

As shown in table 2, design forces from AS/NZS 1170.2 are 1.09/1.3= 0.84 and 1.00/0.98=1.02 times those measured in the wind tunnel for the general truss and the girder truss respectively. Design loads determined from AS4055 are again more conservative, being 2.01/1.30 = 1.55 and 1.74/0.98 = 1.78 times greater than those measured in the wind tunnel for the general and girder trusses respectively.

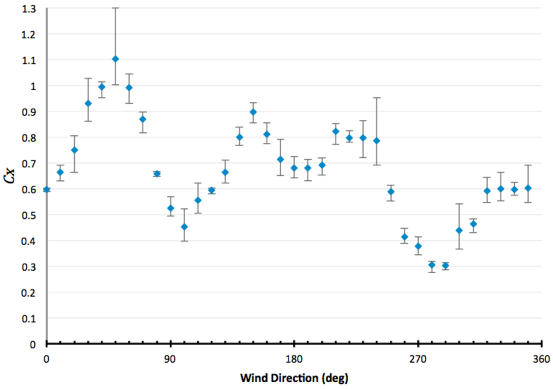

Figure 6a. Peak truss hold down C_x vs θ for the 2-storey general truss

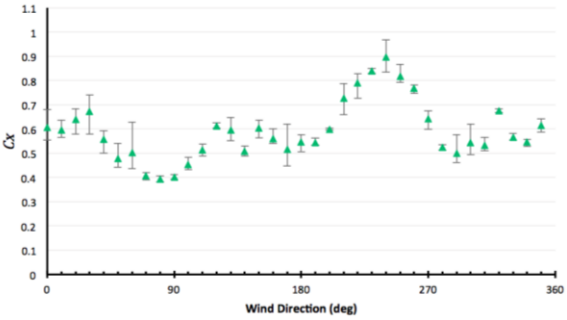

Figure 6b. Peak truss hold down C_x vs θ for the 2-storey girder truss

	AS/NZS 1170.2		AS 4055		Wind Tunnel
Wind Directions ±45°	0°, 180°	90°, 270°	0°, 180°	90°, 270°	All Directions
General Truss	0.91	**1.09**	**2.01**	2.00	1.30
Girder Truss	**1.00**	0.96	1.63	**1.74**	0.98

Table 2. Peak truss hold-down force coefficients C_x for the 2-storey house

Conclusions

Contemporary, 1-storey and 2-storey houses being built in the suburbs of Brisbane and Melbourne have been surveyed and representative houses determined. The wind loads determined from a 1/50 scale wind tunnel model study show that highly spatial and temporally varying external wind pressures act on the complex roof shapes of these houses.

In the case of the 1-storey house, the roof generally experiences smaller external pressures compared to values specified in standards such as AS/NZS 1170.2. However, peak suction pressures for cladding design higher than that specified in standards are measured in some local regions. The standards do not fully capture the spatial and temporal variation in pressures on the roof surface that result in smaller roof truss hold-down forces.

On the other hand, wind loads on the 2-storey house were equal or greater than those specified in AS/NZS 1170.2. It was observed that large suction pressures occurred on some upper storey roof edges that had a lower storey roof e.g. garage immediately below it.

Additionally, simplified velocity profiles in AS/NZS 1170.2 specify the same wind speed for structures 10m or less in height. This likely overestimates wind pressures on shorter structures such as the 1-storey house and underestimates pressures on the 2-storey house.

The study also found that the complex roof shape results in several critical wind directions that generate large truss hold down forces. This has implications for wind vulnerability modeling of structural performance.

Acknowledgments

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