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# Vulnerability modelling of metal-clad industrial buildings to extreme wind loading

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## ABSTRACT

A vulnerability model was developed to predict the probability and extent of damage to metal-clad industrial buildings (industrial sheds) due to extreme wind loading. Structural reliability-based methods that describe the spatially distributed wind load and connection strengths probabilistically were used in this model. For the current paper failure of roof cladding was considered. This is a highly vulnerable failure mode due to extreme wind loading in industrial buildings. The load sharing effect due to fastener failure is also incorporated in this model. A vulnerability model of a hot rolled structural steel, metal-clad, gable-end, typical shed designed for cyclonic region C in Australia is presented. The results show the likelihood and extent of roof damage, and vulnerability curves are presented for 1%, 5%, 10%, 25% and 25-50% loss of roofing. The large variation in vulnerability of the shed with the incorporation cyclone washers and/or internal pressure (e.g. an open door) is highlighted.

## 1. INTRODUCTION

Wind vulnerability models are used to predict the damage to buildings and their contents due to wind loading. Vulnerability models play a key role in cost-benefit analysis which contributes to developing design procedures and other mitigation strategies to reduce economic losses due to severe wind events (e.g., Stewart et al. 2014, Stewart 2014). The models can be developed either by fitting curves to the actual damage data from historical wind damage records (i.e. empirical models and insurance data) or by using engineering knowledge to obtain the damage due to wind loading by investigating the behaviour of buildings and its components (i.e. engineering models).

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Industrial metal clad buildings are one of the building types that are vulnerable to extreme wind loading. In Australia, gable roof metal clad sheds are mostly used for manufacturing, storage and processing industries. Damages to these structures can result in huge economic loses. Therefore it is necessary to identify the vulnerability of such buildings and take actions to protect them against damage.

In the current study, an engineering vulnerability model is developed based on structural reliability, spatial, and probabilistic analysis for metal clad industrial buildings against wind loading. The dominant failure mechanism considered in this model namely; roof cladding pulling over fixing. Purlin failure (i.e. purlin to rafter connection failure and/or purlin buckling failure) is also a likely failure mode, but is an area for future research. The wind load probabilistic model developed by Holmes (1985) and Pham (1985) is used herein, and the component strengths probabilistic model is obtained from Australian data. The external pressure coefficients for the model are obtained from wind tunnel testing. Preliminary vulnerability curves for typical metal clad industrial sheds designed to current building standards in cyclonic regions in Australia (North Queensland) are generated considering the effect of roof cyclone washers and dominant openings.

## 2. MODEL DEVELOPMENT

A vulnerability model is developed for industrial buildings (sheds) with spans of 20 m to 40 m, lengths of 50 m or more, heights of 5 m to 10 m, and with gable-end low pitch roofs. The structural systems of these buildings generally consist of portal or pin-jointed frames, spaced at 4 m to 8 m along the length of the building (Fig. 1). Metal sheet cladding is attached to roof purlins and wall girts using fasteners with a spacing of 150 mm to 200 mm. Cross-bracing between the end frames resist longitudinal (i.e. in direction of ridge-line) wind loads. The possible failure modes in this type of buildings can be identified as; cladding pulling over fixing; cladding fastener failure; purlin to truss failure; purlin buckling; girt to column failure; girt buckling; support failure (foundation); collapse of the end wall (connections from gable end wall columns to portal frame); failure of roller doors; bracing failure of portal frames (diagonal cross bracing and/or compression in girts and purlins) and buckling/collapse of portal frame (failure at knee joint). For the current model, vulnerability of the roof envelope which is the most vulnerable structural assemblage against extreme wind loading is considered. To assess the vulnerability of the roof, the dominant failure mechanism is cladding pulling over fixing (Fig. 2).

### *2.1 Limit state*

The limit state of roof failure is defined as exceeding the component/connection capacity by the wind load. Roof cladding pulling over fixing failure due to wind load occurs when the internal and external pressures are adequate to cause uplift of the roof cladding from the fastener. The limit state function *G(x)* is:

$$G(x) = R - (W - D) \tag{1}$$

where, *R* is the actual component strength of each failure mode, *W* is the actual wind load and *D* the actual dead load. Here the dead load is acting in favour of preventing the uplift due to wind load. To make a conservative assumption, deal load of the roof is neglected. Therefore the final limit state function is:

$$G(x) = R - W \tag{2}$$

Connection failure occurs when *G(x) < 0*. Event-based Monte-Carlo simulation methods are used in this model to obtain the probability of failure of each connection with increasing wind load.

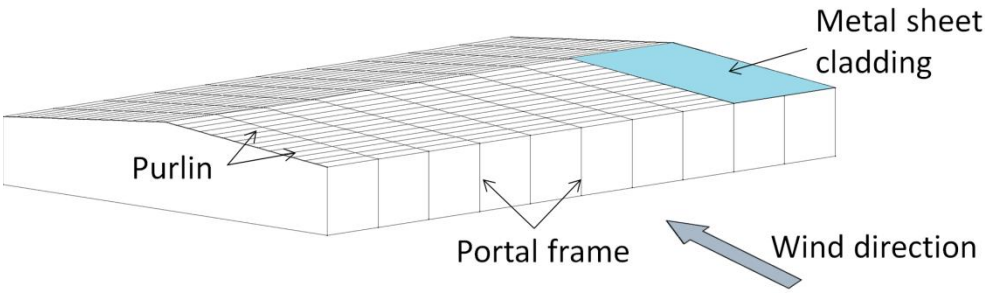



Fig. 1 Metal clad industrial building

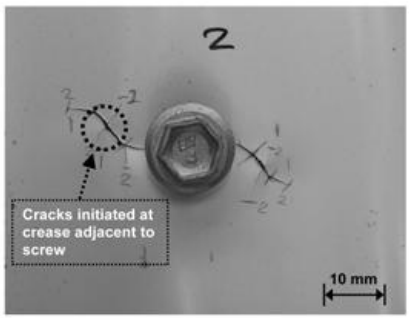



Fig. 2 Cladding pulling over fixing failure (Henderson et al. 2009)

### *2.2 Probabilistic model for wind load (W)*

The wind load (*W*) was calculated probabilistically as (Holmes 1985, Pham 1985):

$$W = BV^2 \tag{3}$$

where, *V* is the maximum 3s gust velocity at 10 m height in terrain category 2. The parameter *B* is:

$$B = \lambda . A . (C . E^2 . D^2 . G . \frac{\rho}{2}) \tag{4}$$

where, $C$ is the quasi-steady pressure coefficient, $E$ is a velocity height multiplier that accounts for the exposure and height of the building considered, $D$ is a factor for wind directionality effects, $G$ is a factor for gusting effects (related to $K_a$ and $K_l$), $\rho$ is the density of air, $A$ is the tributary area, and $\lambda$ is the factor accounting for modelling inaccuracies and uncertainties in analysis methods. The variables within brackets in Eq. (4) are directly related to the nominal values given in the Australian wind loading standard AS/NZS 1170.2 (2011).

In this vulnerability model, instead of quasi steady pressure coefficient ($C$) calculated from the design standard (AS/NZS 1170.2-2011), wind tunnel test data for external pressure coefficients were used (see Section 3.2 for more information). Internal pressure coefficients were included in the model and those values depend on whether the building has a dominant opening or not. The wind tunnel pressure coefficient data were assumed to have an Extreme Value Type 1 (Gumbel) probability distribution (e.g. Tieleman et al. 2008). All the other variables in Eq. (4) are assumed to have a log-normal probability distribution with estimated means and coefficient of variations (COV) given in Table 1 derived from Henderson and Ginger (2007) for their vulnerability model of Australian high-set houses. They deduced those data from surveys and other studies (Pham et al 1983, Holmes 1985). The subscript 'N' denoted in Table 1 is the nominal (design) value of the respective parameter obtained from the Australian wind loading standard AS/NZS 1170.2 (2011), and $A_N$ is obtained by calculating the effective tributary of each connection. The nominal air density is 1.2 kg/m$^3$.

Table1. Parameters for wind loading

| Parameter | Mean | COV |
|---|---|---|
| $\lambda/\lambda_N$ | 1.00 | 0.05 |
| $A/A_N$ | 1.00 | 0.10 |
| $E/E_N$ | 0.95 | 0.10 |
| $D/D_N$ | 0.90 | 0.10 |
| $G/G_N$ | 0.95 | 0.10 |
| $\rho/\rho_N$ | 1.00 | 0.02 |

### *2.3. Probabilistic model for component and connection strength (R)*

The probabilistic model for roof cladding pulling over the fixing is obtained from expert judgment and component testing at the Cyclone Testing Station (CTS) at James Cook University. The mean connection strength for the failure mode of cladding pulling over fixing (with a cyclone washer) is assumed herein as 2500 N with COV of 0.30. This is assumed to have a lognormal probability distribution (Henderson and Ginger 2005). However, the mean capacity of 2500 N assumes that cyclone washers are installed. This is not always the case, and if they are not installed the mean capacity of the fastener reduces to approximately 1500 N. The statistics of these capacities are preliminary.

### *2.4 Load sharing*

Henderson (2010) found that when a particular fastener fails, its load is redistributed to the adjacent fasteners in percentages as shown in Fig. 3. This load redistribution mechanism is adopted in the current vulnerability model to share the failure load of a connection with adjacent connections. As shown in Fig. 3, when the fastener A fails, 90% of its load at the time of failure is shared with adjacent fasteners B and D, and 10% of its load is distributed to fasteners C and E.

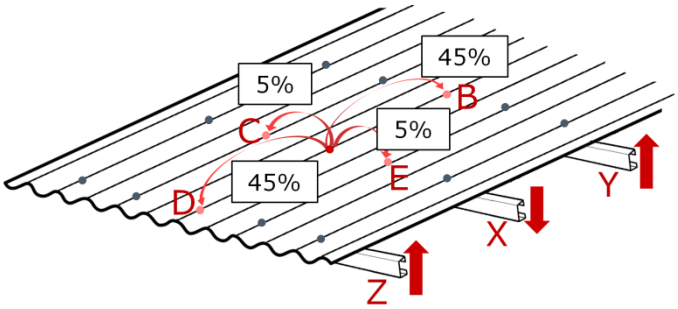



Fig. 3 Load sharing percentages

## 3. VULNERABILITY OF NEW INDUSTRIAL BUILDINGS IN CYCLONIC REGIONS IN AUSTRALIA

As a part of this study, vulnerability curves for a typical industrial building in a cyclonic region in Australia is developed using the above vulnerability model. The vulnerability curves are for one failure mode (cladding pulling over fixing) - results for the second failure mode (purlin buckling) are still in progress. The preliminary results to follow highlight the significant effect that cyclone washers and dominant openings have on wind vulnerability.

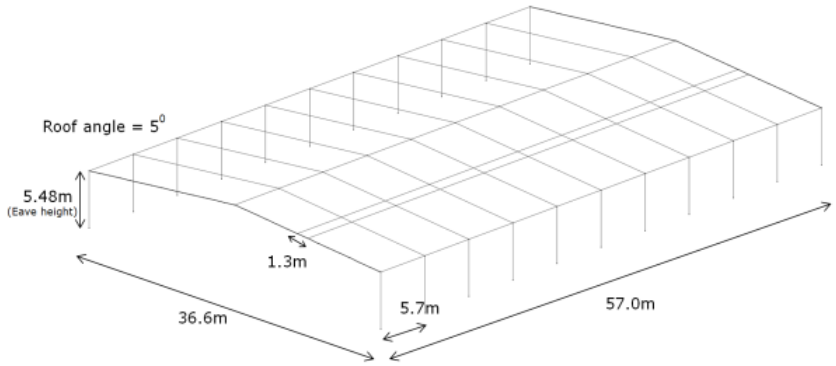
### *3.1 Shed data*

Details of the typical hot rolled structural steel low-pitch roof, metal-clad, metal-framed industrial building used in this study are shown in Fig. 4. The shed details were obtained from a survey carried out by the CTS described in Leitch et al. (2006).

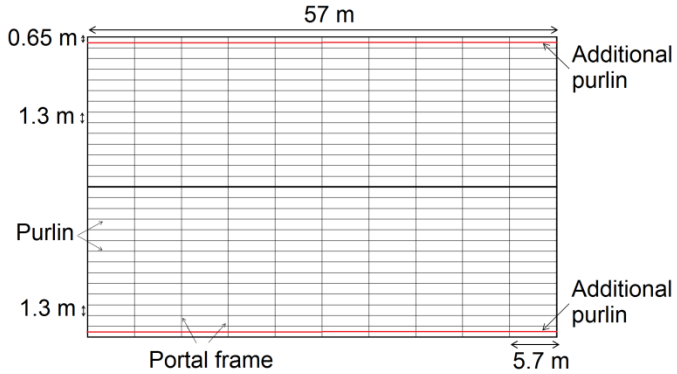
For this study, shed consists of eleven portal frames and the purlins used here were Z25019. Metal cladding of a thickness of 0.48 mm was used for the roof. Purlins were equally spaced with 1300 mm spacing (Fig. 4b) except the first span in each side of the roof. As an enhancement strategy against cyclonic loading, an additional purlin was introduced near each eave in between the first 1300 mm purlin spacing as shown in Fig. 4b.

Note that the current Australian wind loading standard allows the shed to be designed as a nominally sealed building if windows, doors and roof are designed for impact loading (e.g., a 4 kg piece of timber travelling at 28 m/s). Hence, the shed in this example is designed as a nominally sealed building. Experience in recent cyclones in

Australia suggests that some roller doors failed at their connections to the building, thus causing a dominant opening leading to damage of the building (Henderson and Ginger, 2008).




(a)



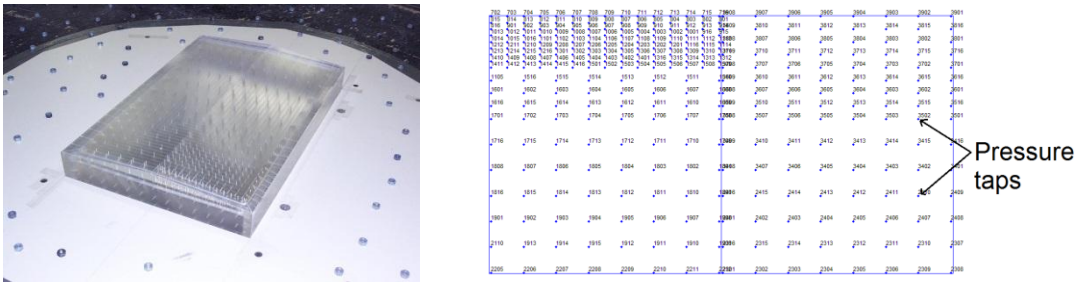

(b)

Fig. 4 Shed details (a) Overall dimensions (b) Plan view of the roof with purlin arrangement

### *3.2 External Pressure coefficients*

The external pressure coefficients ($C_{pe}$) were obtained from wind tunnel testing. Based on the analysis of the industrial buildings surveyed by the CTS, a representative wind tunnel model results for two different wind directions were obtained from the United States National Institute of Standards and Technology (NIST) aerodynamics database. The wind direction considered in this study is $90^0$ (Fig. 4a) as this produces the highest suction pressures and so dominates wind vulnerability. The NIST database provides time histories of external pressures measured on the roof and walls of a series of low-rise building configurations at a length scale of 1/100 in the wind tunnel at the University of Western Ontario, as described by Ho et al. (2005). Fig. 5 shows the wind tunnel model and the pressure tap locations of the wind tunnel model considered for the current study.

There is likely to be some correlation between adjacent pressure taps. In this case, the wind loading model utilises data from pressure taps located 5.7 m and 2.6 m apart (i.e. rafter spacing and double purlin spacing). A statistical analysis, using peak pressure coefficients ($C_{pe}$) of each pressure tap, reveals correlation coefficients of 0.10 - 0.97. The present analysis assumes a correlation coefficient of 0.5 for all pressure tap data used in the spatial probabilistic wind loading model.




(a) (b)

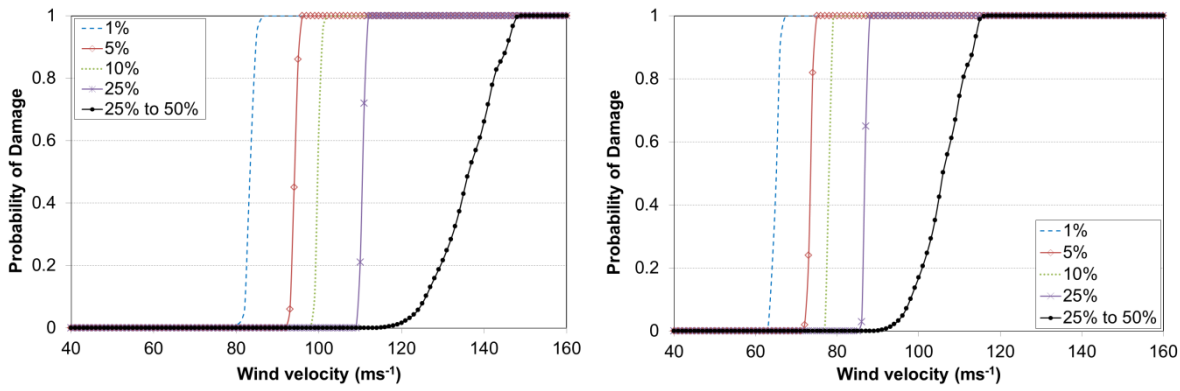
Fig. 5 (a) Wind tunnel model (b) Pressure tap arrangement (NIST 2008)

The internal pressure coefficients ($C_{pi}$) of +0.2 and +0.7 were considered for this model according to the AS/NZS 1170.2 (2011) for a nominally sealed building (no dominant opening case) and a building with a dominant windward wall opening respectively.

## 4. RESULTS AND DISCUSSION

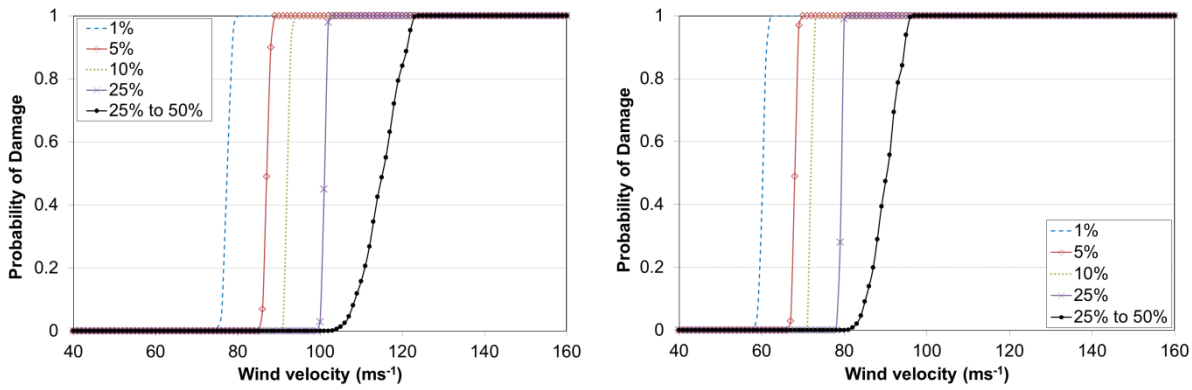
The vulnerability curves for a typical hot rolled structural steel, metal-clad industrial building in cyclonic region in Australia are obtained from the vulnerability model developed in this study. The failure criterion of the roof envelope of a building is that 25% to 50% of total connection failures is considered as 'total failure' of the roof. Hence, at this damage level is it assumed that structural damage is extensive enough to warrant complete roof replacement, and associated water ingress would cause significant damage to the contents in the building. However, the precise definition of damage levels is an area for further research.

Figures 6(a) and 6(b) show the vulnerability curves for a nominally sealed building with and without cyclone washers, at a wind direction of $90^0$. Further, figures 7(a) and 7(b) show the vulnerability curves for a building with a dominant opening, at a wind direction of $90^0$. The results presented here confirm that the vulnerability is high when a roof has no cyclone washers for both sealed buildings and buildings with dominant openings. A comparison of the total failure (25% to 50% of total connection failures) of roof with and without cyclone washers for both types of buildings is shown in Fig. 8. Results also show that roof damage vulnerability is high for the buildings with a dominant opening.




(a) (b)

Fig.6 Vulnerability curves for sealed building (a) with cyclone washers (b) without cyclone washers, for extent of damage of 1% to 50%




(a) (b)

Fig.7 Vulnerability curves building with dominant opening (a) with cyclone washers (b) without cyclone washers, for extent of damage of 1% to 50%

## 5. CONCLUSIONS

A wind vulnerability model was developed to predict the probability and extent of damage to metal-clad industrial buildings due to extreme wind loading. The model considered the spatial probabilistic characteristics of wind load and component strength, and load sharing of failed components for the roof envelope. Results were described for hot rolled structural steel, metal-clad, gable-end, typical shed designed for cyclonic regions in Australia, and designed to current Australian building standards. One wind direction ($90^0$) was considered in this study to obtain the results. The preliminary results show the likelihood and extent of roof damage, and vulnerability curves for 1%, 5%, 10%, 25% and 25-50% loss of roofing. It was found that omission of cyclone washers increases wind vulnerability considerably. It was also found that large internal pressures caused by a dominant opening result in a lower wind vulnerability.

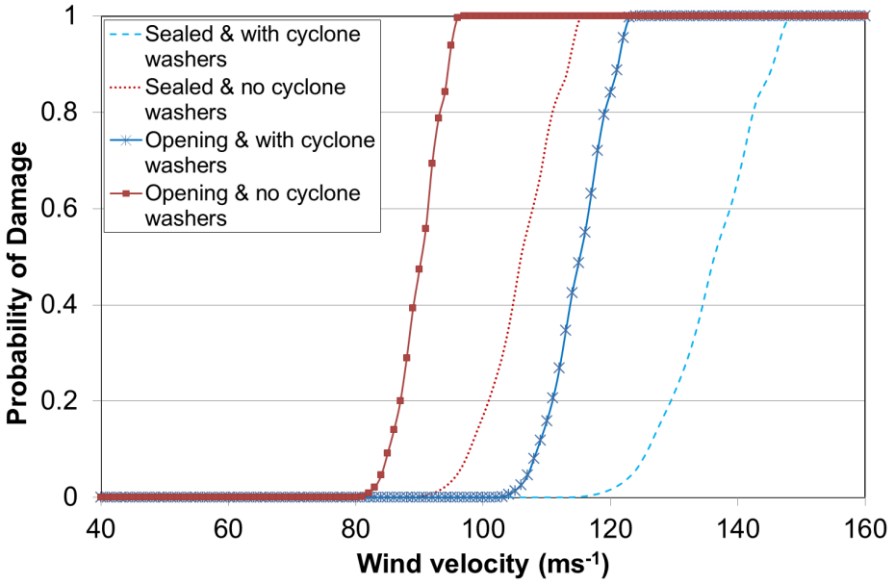



Fig.8 Comparison of Vulnerabilities for 'Total failure' (extent of damage is 25-50%)

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