FRAGILITY CURVES FOR CORRUGATED STRUCTURAL PANEL SUBJECTED TO WINDBORNE DEBRIS IMPACT

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ABSTRACT

With the climate change, more and more extreme wind events such as cyclone take place around Australia and the world, which cause tremendous loss and damage. The wind speed has been reported constantly increasing with the climate change, which imposes more threats to building environments. The building envelopes are vulnerable to the windborne debris impact in a form of creating an opening in wall, roof, door, windows and screens, which leads to internal pressure increase and results in roof lifting up. The capacity requirements of wall or roof panels to resist windborne debris impact in cyclonic regions has been substantially increased in the 2011 Australian Wind Loading Code (AS/NZS 1170.2:2011) as compared to its previous version. The performance of commonly used structural panels in Australian Building Industry under the increased design wind speed needs be evaluated. Intensive laboratory tests and intensive numerical simulations on performances of typical structural panels subjected to windborne debris impacts have been carried out. This paper presents the results of one panel type, i.e., corrugated panel. The vulnerability curves of the corrugated panel with respect to the debris mass and impact speed are simulated. These results can be used in probabilistic loss estimations of structural panels in extreme wind events.

KEYWORDS

Fragility curve, structural panel, windborne debris impact

INTRODUCTION

In Australia, tropical cyclone is considered one of the major natural hazards, especially in Northern regions of Western Australia and Queensland. With the climate change, the wind speed has been increasing in Australia and the extreme wind events occur more frequently than before, which cause devastating losses. The post-storm investigations found that strong wind events generated enormous amount of windborne debris and the windborne debris impact was highlighted as a major cause of damage to building envelope components such as wall, window and roof (Minor and Behr 1994). Strong wind might blow up the debris from damaged structures, roof tiles, rafter and timber shank, which might penetrate the building envelope, imposing threats to people inside the building. It might also create an opening on the building envelope, and the opening would increase the pressure differentials outside and inside the building, which makes the envelope more vulnerable to collapse or lift-up. Therefore, the windborne debris is considered as a crucial factor to the performance of the building envelope in strong wind events.

The performance of structural panels subjected to windborne debris impact is greatly affected by various uncertainties including random variations in parameters of the panel and windborne debris. The windborne debris impact fragility curves of building envelope components are developed to provide probabilistic description of the impact resistance capacity of panels. Fernandez et al. (2010) presented an experimental investigation of the performance of metal shutter systems designed to protect windows from windborne debris such as roof tiles. It was found that the deflection of the metal panel window protection system was highly sensitive to impact location and also to debris type and impact orientation. Borges et al. (2009) simulated the interaction of contact of windborne debris traveling at a specific velocity against the metal shutters. The permanent and maximum deformations and stresses were evaluated to determine the most detrimental behavior of the storm shutter assembly by means of parametric studies. Herbin and Barbato (2012) derived the fragility curves corresponding to different damage measures for aluminium storm shutters subjected to windborne debris impact. Monte Carlo simulation (MCS) was used in combination with the finite element method in the analysis. It was found that the projectile kinetic energy at impact is a sufficient intensity measure for building envelope components with ductile behavior subjected to windborne debris impact, and the performance of storm panels in terms of penetration of windborne debris is critically dependent on the details of the panels' installation.

To obtain the fragility curves of the structural panels to windborne debris impact, intensive testing or numerical simulations are needed for probabilistic statistics. With the development of computer technology, numerical simulations are effective and reliable to simulate experimental testing with the advantages of saving time and cost. In the previous study (Chen et al. 2014; Chen and Hao 2014), laboratory tests on structural panels were conducted to simulate the windborne debris impact by using a pneumatic cannon testing system. The test data were used to calibrate the accuracy of the numerical model developed in finite element code LS-DYNA. The calibrated numerical model can then be used to conduct intensive numerical simulations to obtain the vulnerability curves of the structural panels to windborne debris impact. The numerical simulations are conducted to assess if the structural panel fails or services the windborne debris impact with randomly generated impact location, impact angle, debris mass, panel boundary conditions, and material properties. Latin Hypercube Sampling method (LHS) is used to accelerate the simulation convergence. The statistical results are graphed to produce the fragility curves with respect to the impact velocity. Owing to the page limit, this paper only presents the generated fragility curves for the corrugated panel, which is commonly used in Australian building industry. The proposed fragility curves can be used in probabilistic loss predictions of corrugated structural panels in strong wind events.

METHODOLOGY

The fragility curves of corrugated structural panels subjected to windborne debris impacts can be developed by using stochastic finite element method (SFEM) (Liu 2008). SFEM is a hybrid method which combines finite element simulations with the probabilistic methods such as Monte Carlo simulation (MCS), Latin Hypercube Sampling method (LHS), Rosenblueth point estimate method, perturbation method, Neumann expansion, Taylor expansion, or reliability-based methods etc. (Ghanem 2008). Monte Carlo simulation (MCS) is the most widely used means for uncertainty analysis. It is straightforward to use and can give reliable estimations of statistical parameters. However, it is extremely time consuming and needs a large amount of computational effort to get the converged estimation. Latin Hypercube Sampling (LHS) is one variant of standard Monet Carlo method. It was developed to address the need for uncertainty assessment. The random variable distributions, consisting of all the uncertain parameters, are divided into an equal ordered number of segments, with each interval representing an equal probability (Wyss and Jorgensen 1998). One variable with normally distributed Probability Density function (PDF) and the other one with uniformly distributed PDF can be divided into five segments each of probability 1/5. Once the segments have been determined, a value within each segment is randomly chosen for all variables, and each value is used exactly once and in a random permutation with each of the other variables (Wyss and Jorgensen 1998). The method is used in applications which involve numerical simulations to reduce the number of simulations required to produce a result with minimal bias. Generally, LHS requires fewer samples than direct Monte Carlo sampling for similar accuracy, which will be demonstrated in the convergence test.

In this study, the methodology used is based on the combination of deterministic finite element analysis using LS-DYNA and Latin Hypercube Sampling method (LHS), which is applied to study the probability of the response by accounting for various uncertainties and random variations of the panel and debris parameters. The accuracy and reliability of using LHS method is verified by using Monte Carlo simulation results.

NUMERICAL SIMULATION

Numerical Models

A numerical model was developed and calibrated by using commercial software LS-DYNA in the previous study (Chen et al. 2014). The tested corrugated panels had dimension of 1200*762 mm and was subjected to a 4kg wooden projectile impact at different locations and velocities by using pneumatic cannon. The finite element model of the tested corrugated panel is depicted in Figure 1.

The Belytschko-Tsay shell element with mesh size of 4mm is utilized to model the corrugated panel. The elastic-plastic material model *MAT PLASTIC KINEMATIC is adopted to model cold rolled stainless steel. The strain rate effect is taken into account by using the Cowper-Symonds model. The steel material properties such as Density, Young's modulus, Yield stress, Poisson's ratio and Hardening parameter are given as 7.85g/cm^3, 220GPa, 550MPa, 0.3 and 1, respectively. The 4kg hardwood projectile is modeled as solid element with linear elastic material model *MAT RIGID. The contact between the projectile and the specimen is defined by using *CONTACT ERODING SURFACE TO SURFACE with segment based contact option (i.e. SOFT=2).

SBOPT=3 & DEPTH=5, which undertake edge-to-edge checking (LSTC 2010). The model was proven yielded reliable predictions of responses of corrugated panels subjected to windborne debris impacts.
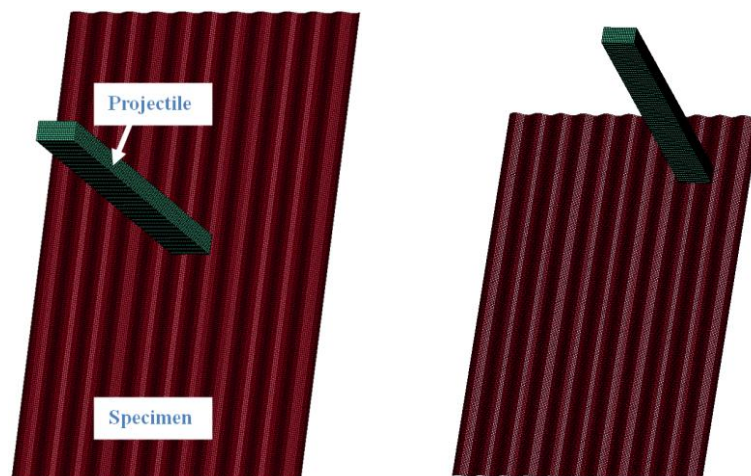

Figure 1 Numerical models (L) Impact at centre; (R) Impact at boundary

Parameters Considered

With the calibrated numerical model, parameters considered in the simulations to develop the fragility curves of corrugated panels include geometry of debris, debris mass, boundary conditions, impact angle, impact location and material properties of the panel, in particular the yield strength and Young's Modulus. All parameters are modeled as statistically independent random variables.

Debris geometry (rod; sheet; compact)

When built a model for describing the damage that might be put on to buildings by windborne debris, Wills et al.(2002) classified windborne debris into three types: compact-like (3D), plate-like (2D) and rod-like (1D) according to their shapes and dimensions. Lin et al. (2007) gave the examples for compact-like (e.g. roof gravels), plate-like (e.g. plywood, roof tile and roof shingle) and rod-like debris (e.g. timber shank). The classification has been accepted in many literatures that study the motion and effects of windborne debris. In addition, shingle was found among the most common source of debris in cyclones (Gao and Fatt 2013). Roofing tiles were observed to be the major windborne debris in Hurricane Andrew (1992). However, a projectile of 2 by 4 inches timber is still recommended as representative debris due to the difficulties to define a representative roof tile in modelling the windborne debris (Lin 2005). Numerical simulation results, which are not shown here owing to page limit, indicate that the panel is most vulnerable to rod-type debris impact among the three debris geometries. Since rod geometry is also the only, besides small steel ball which was found not critical to structural panels, debris geometry specified in the Australian Wind Loading code for assessing the safety of structural panels, in the present study, only rod type debris geometry is considered.

Debris mass (1 kg ~ 6 kg)

The windborne debris can be categorized as light-weight, medium-weight and heavy-weight according to their damage performance (Wright-Patterson Air Force Base, Ohio1976). Light-weight debris includes roof gravel, sheet metal panel and tree branches. Medium-weight debris includes timber planks and posts. Heavy debris includes poles, storage tanks and even automobiles. Minor (1994) identified the most prevalent windborne debris as small debris (such as roof gravel) and large debris (such as framing timbers). As specified in the Australian and American Standard (AS/NZS 2011; FEMA 2008; Florida Building Code 2010; ASTM2009), 4kg rod-type projectile with cross section of 2 by 4 inches has been widely used in design and testing of product qualification. It has been also used in the previous laboratory testing and the numerical model calibration. To create the fragility curves with random debris impacting, the rod-type debris mass varied between 1kg and 6kg (i.e. 1kg, 2kg, 4kg and 6kg) are initially considered. The projectile's lengths are changed accordingly. In this study, the debris mass is considered as a deterministic parameter, and fragility curves corresponding to the different debris masses are generated.

Boundary conditions (pinned or fixed)

The boundary condition is considered as pinned or fixed around the perimeter of the panel. It is also considered as deterministic with the fragility curves corresponding to each boundary condition independently generated.

Impact angle (0 ~ 90 degree; uniform distribution)

The impact angles are considered randomly varying in the range of 0 ~ 90 degree with a uniform distribution. The projectile is rotated about both the X and Z axes, i.e., in each simulation, two random angles are generated and used.

Impact location (region 1~9; uniform distribution)

The X and Y coordinates of the projectile impact location, defined as the impact location of the geometric center of the section of projectile, are modelled as uniformly distributed random variables. The impact location has been split into 36 regions, with 4 major regions and 9 sub-regions each, as shown in Figure 2. The debris impact location is randomly picked among the 36 sub-regions. For each region, the centre of the debris impacts the centre of each of the sub-regions. Since the panel is symmetrical, random impact regions can be shifted to one major region. For example, the effects of debris impacting region 1 would be the same as impacting regions 11, 21 and 31, which greatly simplify the simulation.
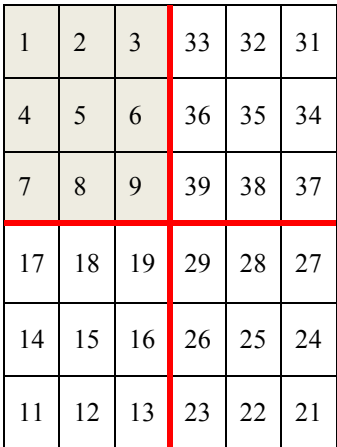
1	2	3	33	32	31
4	5	6	36	35	34
7	8	9	39	38	37
17	18	19	29	28	27
14	15	16	26	25	24
11	12	13	23	22	21

Figure 2 Diagram of regions of the panel

Material properties (yield strength and Young's Modulus; normal distribution)

The Young's modulus and yield strength of corrugated panel are considered as normally distributed random variables, while the Poisson's ratio and other mechanical properties are modeled as deterministic quantities. Due to the lack of statistical information regarding the material properties, the probability distribution and variance are selected based on the engineering judgment as shown in Table 1. They are assumed statistically independent of each other.

Table 1 Statistical characterization of material parameters

Zincalume AZ150 G550	Units	Mean	COV	Distribution
Density	Kg/m^3	7850	-	Deterministic
Poisson's Ratio	-	0.3	-	Deterministic
Young's Modulus	GPa	220	10	Normal
Yield Strength	MPa	550	10	Normal

Note: COV (coefficient of variance)

Convergence test

To verify the Latin Hypercube Sampling (LHS) method, a total of 120 stochastic FE simulations have been conducted by using the Monte Carlo (MC) method, followed by a number of 72 simulations by using the LHS method under the same conditions. As shown in Figure 3, the LHS method yielded a result of P (Failure) equal to 82% and the MC method yielded a result of P (Failure) equal to 79% and both approaches converged. Although LHS yielded a slightly different failure probability, it required less number of simulations, which

greatly saves computational time. Therefore, the LHS method is used to develop the fragility curves in the present study.
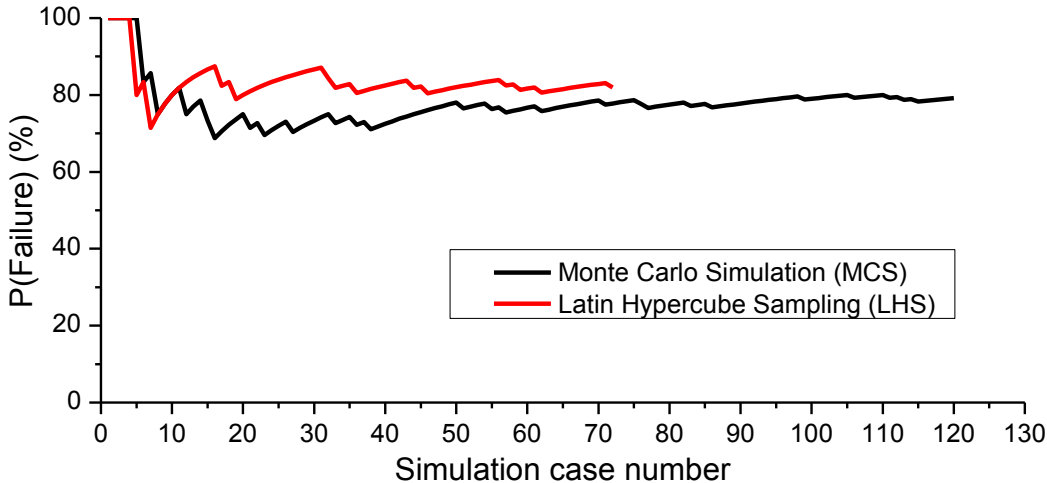

Figure 3 Convergence test results for MCS and LHS method

RESULTS AND DISCUSSIONS

During the intensive numerical simulations, two types of failure modes are observed, including debris penetrating the panel at center and torn failure at the boundary as shown in Figure 4. Intensive simulations have been conducted for corrugated panels with two boundary conditions subjected to impacts of debris of mass 1 kg, 2 kg, 4 kg and 6 kg at different impacting velocities. The simulation results are assessed based on either the panel failing or surviving, i.e., no opening is created, the impact. The convergence of each data point is checked to ensure the validity of the numerical data.
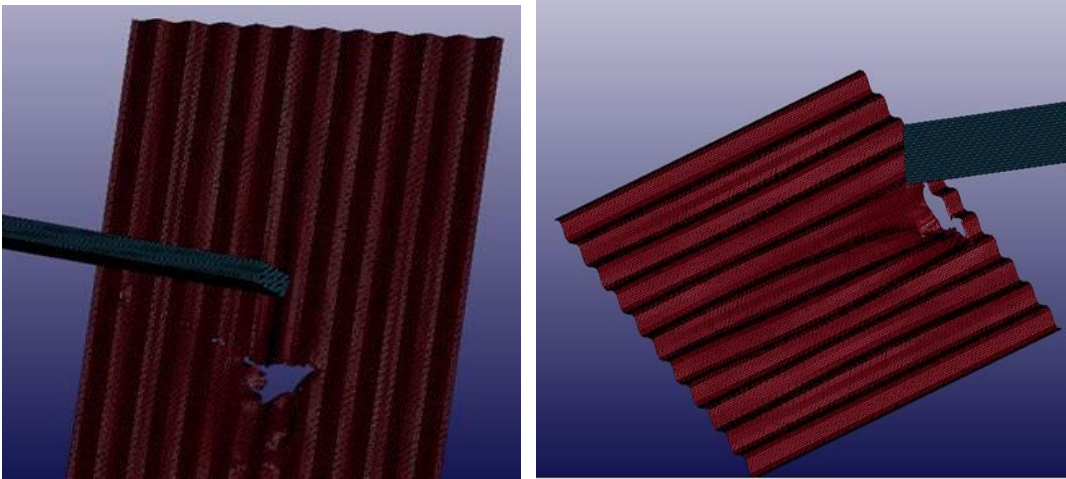

Figure 4 (L) Penetration failure at centre; (R) Torn failure at boundary

Figure 5 shows four fragility curves, each of which corresponds to different masses of rod type debris impacting a fixed panel. Figure 6 shows four fragility curves, each of which indicates the probability of failure of pinned corrugated panel subjected to impacts of debris with different masses. Since the largest possible impact velocity is about 44 m/s as defined in Australian Wind Loading code for region D with a 10,000 years return period (AS/NZS 2011), the simulations stopped at 45 m/s even 100% failure is not reached. As shown in Figure 5, the failure probability is about 84% and 95% when the fixed panel is subjected to the 1kg and 2 kg projectile impact at 45 m/s, respectively.
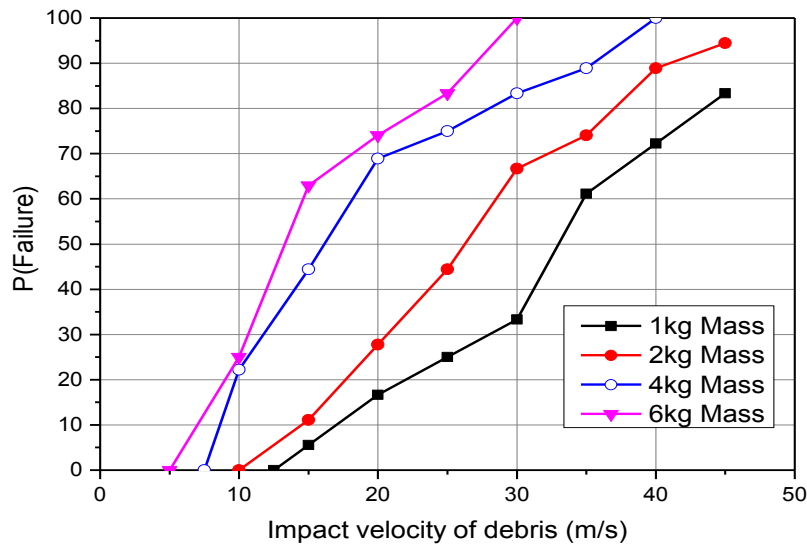
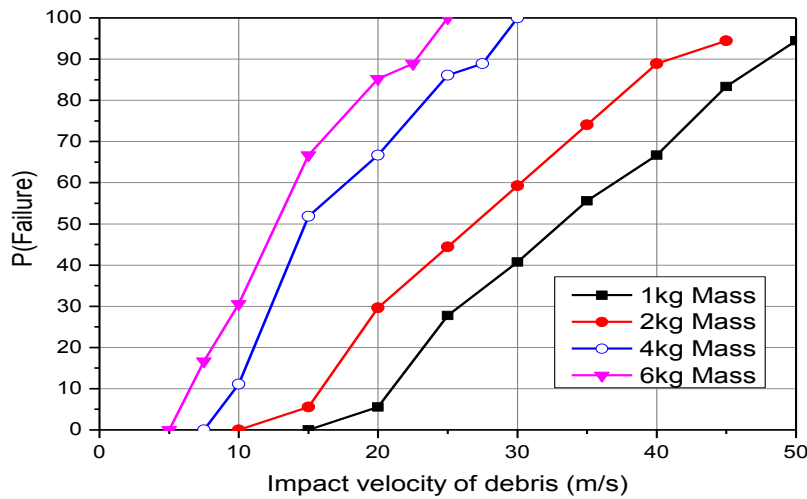Figure 5 Fragility curve for a fixed panel subjected debris impact

Figure 6 Fragility curve for a pinned panel subjected debris impact

CONCLUSIONS

This paper presents the development of fragility curves of corrugated structural panels subjected to windborne debris impacts. Finite element method together with Latin Hypercube Sampling (LHS) is used to perform intensive numerical simulations to construct the fragility curves of corrugated panels with either fixed or pinned boundary conditions subjected to impacts of debris of different masses with different velocities. Debris impact location, impact angle, as well as the panel material strength and elastic modulus are considered as random in the simulations. The results demonstrate that

1) The probability of failure increases with the debris mass and impact velocity as expected;
2) The impact location is a significant factor that affects the survivability of the panel. The panel is more vulnerable when impacted at locations closer to its boundary than at its center;
3) The fixed-boundary panel is more vulnerable than the panel with pinned boundary;

The fragility curves developed in this study can be used in the reliability analysis of corrugated panels subjected to windborne debris impact.

ACKNOWLEDGMENTS

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