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NUMERICAL STUDY OF HAIL IMPACT ON CORRUGATED STEEL PANELS

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Abstract. *Hailstones-induced impact on building envelopes causes severe damages and economic losses every year in Australia. Corrugated metal panel with different strength grade, dimension of sinusoid corrugation and thickness is commonly used for roof structure and wall cladding. However, Australian building codes provide no minimum standard for structural resistance to hail impact and there is no regulation governing roofing materials to hail resistance. Therefore, the research on the responses of building envelops against hail impact is essential for enhancing building resilience to severe hailstorm. This study assesses and quantifies the damage to corrugated metal panels subjected to hailstone impact by using numerical simulations and provide data for the design of hailstone-impact mitigation. The numerical model is validated by comparing numerical predictions and experimental results of corrugated panel under wind debris impact reported in previous study* [14]. *Parametric investigations into different hailstone impact scenarios assess the influence of impact location, hailstone size and velocity. Vulnerability curves and damage matrix are generated for the prediction of the perforation resistance of corrugated panel under diverse hail impact situations.*

1 INTRODUCTION

During service life, roofing structure may be subjected to natural disasters such as hailstorm, cyclone, and earthquake etc. The hailstorm is identified as the most expensive natural disaster to building assets with 34% of insured losses among all forms of natural disasters in Australia [1, 2]. For instance, both 1990 Sydney hailstorm and 2010 hailstorm occurred in Perth have caused over billion dollars in damage [3]. In particular, Sydney has experienced ten hailstorms with the diameters up to 80 mm per year over last 50 years [4, 5], and the recent recurrence of hail incidence is predicted to increase [5]. There is compelling evidence that hailstone impacts cause catastrophic damages to the roofs due to perforation and water ingress [4-10]. Corrugated metal panel is widely applied for roofing structures in residential and industrial buildings such as warehouses and commercial stores due to its lightweight and high strength. The specially configured corrugated profile aims at increasing stiffness and aesthetics by rolling and cooling flat metal sheets made up of Zincalume, Aluminium and Steel. In fact, roofing structure covered by metal sheets is vulnerable to hailstone damages[11, 12], the roof damages are exemplified in Fig 1. To date, four major building design codes require roofing structures such as roof-coverings or membrane to meet minimum resistance to hail and other impact loading due to windborne debris, etc [8]. A series of studies of various building envelops subjected to windborne debris impacts have been carried out [13-18]. However, Australian building codes have not provided a minimum standard for structural resistance to hail impact yet, nor provisions to govern roofing materials on hail resistance [19]. Therefore, Australian Building Codes Board (ABCB) is recommended to initiate the research program into hail damage with the purpose of developing standards that facilitate a better understanding of hail damage to building envelopes [19]. The existing experimental techniques provide various assessment approaches and criteria to determine hailstone resistance of roofing structure [8-10].The cost-effective numerical prediction on hail-caused damages needs to be developed as well. To conclude, hailstorm is one of the most catastrophic weather events in Australia, there is no regulation in place to govern building design against hailstone impact. There is also lack of cost-effective approach to examine the hailstone-caused damages on roofing structures under diverse impact scenarios.

This paper presents numerical study to determine the threshold sizes and deterministic impact velocity that cause damage to corrugated structural panels. The results provide designers with a convenient way for damage prediction or retrofitting work to minimise the hail impacts. The accuracy of this model is validated by comparing experimental results from the studies on windborne debris impact [13-15]. With the calibrated numerical model, intensive numerical simulations are conducted to build vulnerability curves and damage matrix of the G300 corrugated panel subjected to hailstone impact. The effects of quantitative parameters including hailstone diameter, velocity and impact location on the damage modes are discussed.

Fig 1: (L) Large Hailstone [20]; (M) Hail damage to roof; (R) Damage to roof panel [21].

2 PANEL DISCRIPTION

In this study, the dimension of the corrugated panel (0.76 m × 1.2 m) is used to simulate hail damage. The tested panels are made up of Zincalume AZ150 [14] with strength grades of G300/G550 (i.e. yield strength of 300 MPa and 550 MPa, respectively) and base thickness of 0.42 mm. The full height of sinusoid corrugation is about 16 mm. The schematic diagram of corrugated panel cross-section and simulated impact location are depicted in Fig 2 (a).

3 FINITE ELEMENT MODEL

The hailstone-caused damages are numerically simulated by using LS-DYNA. The accuracy and reliability of the numerical model is validated through the experimental results from windborne debris study [14]. After calibration, the model is updated by using hailstone-like projectiles for the assessment of hail damage. In this section, the failure modes and structural responses including effects of impact locations, hailstone diameters and hailstone velocities are assessed.

3.1 Model calibration

The corrugated panel model under windborne debris impact is simulated and compared with experimental results reported in [14]. Fig. 2 (M) and (R) show the numerical prediction and experimental observation of failure modes of panel after impacts. As show in Fig. 2, numerical model can predict the major failure modes. Different mesh sizes including 4mm, 2mm and 1mm are used for mesh convergence tests. It is found that the displacement time histories are very close with the difference of less than 15%. Although smaller mesh size (i.e. 1mm) gives more accurate prediction, the computational costs increases significantly comparing with 4mm mesh size. Therefore, 4 mm mesh size is used for achieving a cost-effective and reasonable numerical prediction in the subsequent simulations.

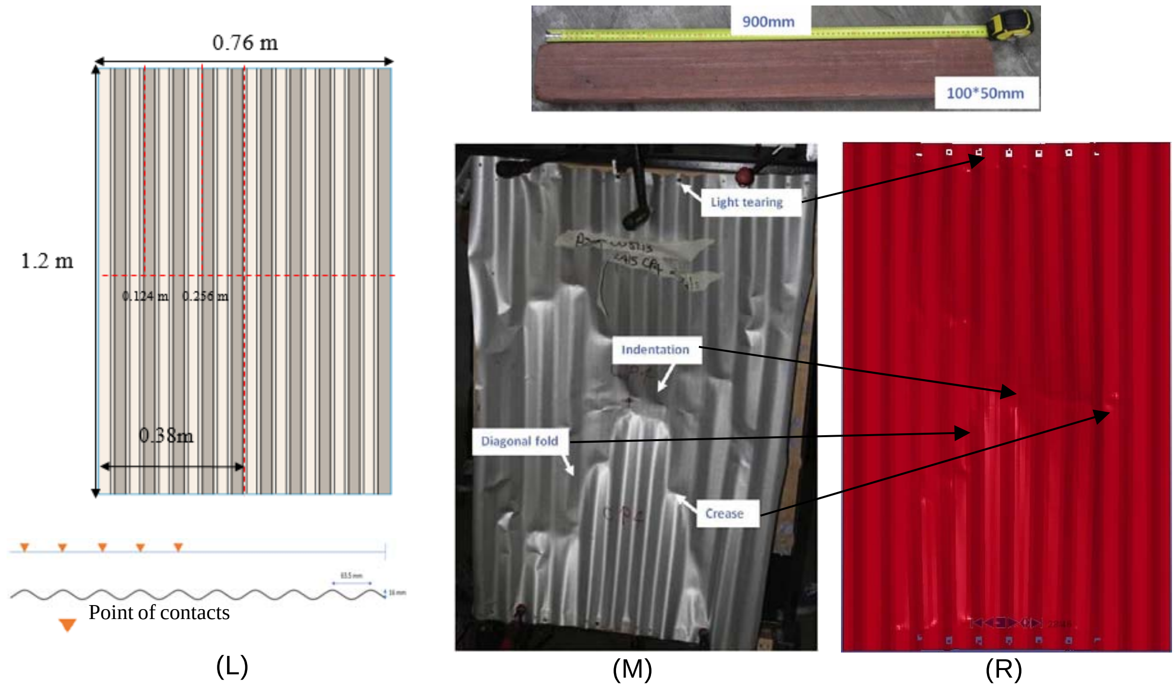

Fig 2: (L) Schematic diagram of corrugated panel and locations of hailstone impact; (M) Experimental observation of failure modes subjected to windborne debris impact from [14]; (R) Numerical prediction of failure modes.

3.2 Element and contact

The finite element model of the corrugated panel with thickness 0.42 mm is depicted in Fig. 3 (L). The shell element with ELFORM = 16 (i.e. fully integrated shell element) and NIP = 5 (i.e. number of through shell thickness integration points) is incorporated to model the corrugated panel. In this study, full model of the specimen with hailstone is modelled. Solid element with ELFORM=1 is used to model hailstone. The *CONTACT_ERODING_SURFACE_TO_SURFACE is used to simulate the contact between the hailstone and the corrugated panel. In addition, the contact is defined as segment based contact option (i.e. SOFT=2). SBOPT=3 & DEPTH=5 are defined to conduct edge to edge checking. The *CONTACT AUTOMATIC SINGLE SURFACE is used to define the contact of corrugated panel itself.

3.3 Material model

The elastic-plastic material model *MAT PLASTIC KINEMATIC (*MAT_03) is used for corrugated steel. The material properties of G550/G300 steel such as density, Young's modulus, yield stress, Poisson's ratio and Hardening parameters are 7850 kg/m^3, 220 GPa, 550/300 MPa, 0.3 and 1, respectively, which are consistent with the previous study [14]. The strain rate parameters C and P used in this model are given as 100 s^{-1} and 10 [14]. The failure strain of steel material is set as 0.17 in accordance with a previous study by Chen et al. (2014) [14]. The material model *MAT_RIGID (*MAT_20) is used for hardwood projectile in model calibration where density and Young's modulus are 845 kg/m^3 and 10 GPa, respectively [14].

To model hailstone, MAT_ISOTROPIC_ELASTIC_FAILURE (*MAT_13) can be used as a non-iterative plasticity with simple plastic strain failure model. However, the calibrated parameters are needed for the model. In this study, conservative assumption is made by modelling hailstone as rigid body, in which *MAT_RIGID (*MAT_20) is used. The density and Young's modulus are 845 kg/m^3 and 9.3 GPa, respectively. It should be noted that the panel damage would be over-predicted by the assumption of rigid body.

3.4 Boundary condition

Boundary condition (BC) is defined as fixed. The corrugated steel panel is fixed along four edges by using *BOUNDARY SPC SET. The nodes along the panel edges are assumed being constrained on the both translational and rotational degrees of freedom (DOF).

3.5 Hail shapes, density, velocity and impact location

The hailstone diameters (D) including 20 mm, 45 mm, 50 mm, 60 mm and 90 mm are selected based on the previous studies [8-11, 22]. The hail density (ρ_{hail}) is 845 kg/m^3. Given the diameter of hail, the maximum vertical velocity known as the terminal velocity could be determined by using the following formula given by Macklin and Ludlam (1961) [6]:

$$V = \left(\frac{4g\rho_{hail}D}{3\rho_{air}C_D} \right)^2$$

where g (gravitational acceleration), ρ_{air} (air density), and C_D (drag coefficient) are 9.81 m/s^2, 1.2 kg/m^3 and 0.45, respectively.

In addition to the terminal velocity, wind-driven velocity is included to simulate impact scenario under strong windstorm events, which is essential to determine the resistance of sheet panel to hail impact. Therefore, 20 m/s wind velocity is used with accordance to ASTM E1038 where the wind component in horizontal direction is added through trigonometry [11, 23]. Fig. 3 shows the finite element model to simulate the hailstone impact and the resultant velocities of hailstone considering wind-driven effects. Furthermore, different impact locations on corrugated panels as shown in Fig.2 (a) are assessed to determine the impact resistance on different impact locations.

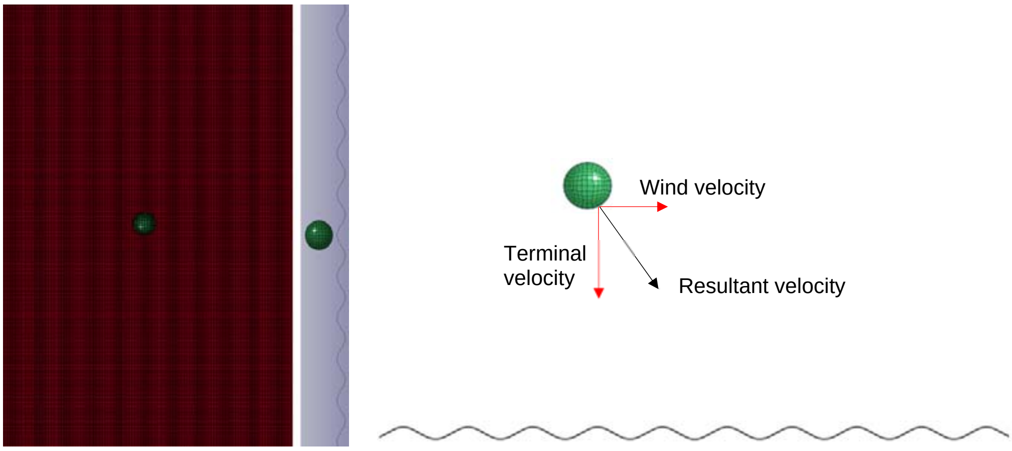

Fig 3: (L) Finite element model; (R) Hail velocity

4 RESULTS AND DISCUSIONS

The corrugated panels with strength grade of G300 and G550 and 0.42 mm, 0.48 mm and 0.6 mm base metal thickness are assessed under hail impact. It is found the G300 corrugated panel with 0.42 mm thickness is the most vulnerable to hail impact. Therefore, the G300 0.42 mm-thick corrugated panel is assessed to determine the threshold velocity and size of hailstone, which cause penetration or perforation of panel. It is found that high stress occurs at the impact location and near the boundary edges. In addition, the 45 mm hailstone with the wind-driven speed of 36.3 m/s causes detrimental localized damages as shown in Fig 4 (L), where there is no surface rupture or tearing occurred. Moreover, the terminal speed for 70 mm hailstone impact (non-wind driven) is around 37.9 m/s, which causes plastic deformation and indentation on the surface crest as shown in Fig 4 (M). As shown in Fig 4 (R), the hailstone with 90 mm diameter acting on the G300 panel causes severe damage of perforation with 253 mm tearing opening owing to excessive steel rupture. Fig 5 shows the Von Mises (V-M) stress distributions of panel under 90 mm wind-driven hailstone.

Based on the numerical results, the edge of the panel is the most vulnerable area. The threshold velocity (average) for 50 mm hailstone causing perforation is around 38.4 m/s with a standard deviation of 1.1 m/s. Table 1 summarizes the numerical results including the thresholds of the integrations of hailstone size, wind-driven effects and impact location to perforate the panel, where ‘‘P’’ represents perforation, “I” represents indentation, ‘‘N’’ stands for no perforation and “B” stands for boundary damages.

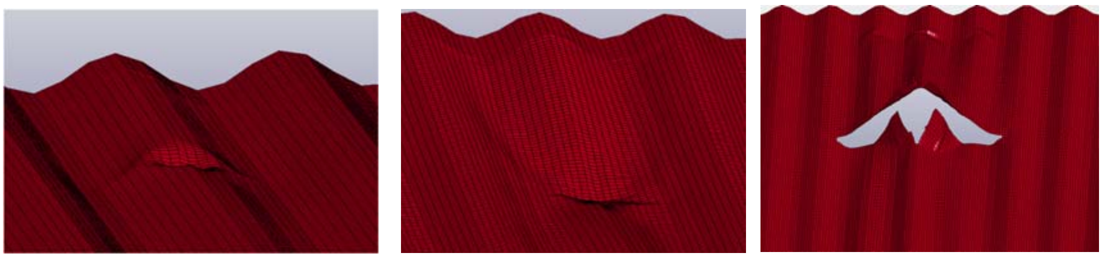

Fig 4: Typical failure modes (L) Indentation; (M) Edge holes; (R) Tearing.

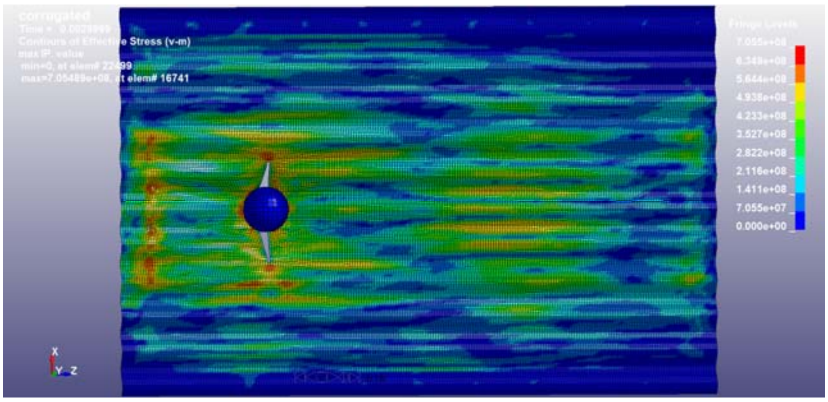

Fig. 5: Von Mises stress contour of 0.42 mm-thick G300 panel under 90 mm wind-driven hailstone.

Hail Diam.(mm)	Centre; No wind-driven	Quarter; No wind-driven	Quarter; Wind-driven	Hailstone terminal velocity (No-wind driven)	Hailstone resultant velocity (Wind driven)	Threshold velocity causing failure
20	N	N	I	20.2 m/s	28.4 m/s	78.0 m/s
30	I	I	I	24.7 m/s	31.8 m/s	44.0 m/s
40	I	I	I	28.6 m/s	34.9 m/s	38.0 m/s
45	I	I	I	30.4 m/s	36.3 m/s	38.0 m/s
50	I	I	O	32.0 m/s	37.7 m/s	38.0 m/s
60	O	O	O/B	35.1 m/s	40.3 m/s	36.0 m/s
70	O	O	O/B	37.9 m/s	42.8 m/s	36.0 m/s
80	O	O	O/B	40.5 m/s	45.1 m/s	34.0 m/s
90	O	P/B	P/B	42.9 m/s	47.4 m/s	33.0 m/s

Note: N-no damage*; ***I-indentation; O-opening; P-penetration; B-Boundary damage*

Table 1: Damage matrix for different impact locations and wind cases for 0.42 mm-thick G300 corrugated panel.

Fig 6 shows the vulnerability curves developed to assess hailstone damages with the diameter ranging from 20 to 90 mm. The relationships between hailstone velocity and diameter, terminal velocity and the wind driving speed are interpolated. No perforation occurs when the combination of velocity and diameter (blue line) is on the left and below the curve while perforation occurs when it is on the right and above the curve. It is found the panel tends to be perforated when it is subjected to higher velocity and small diameter hailstone than larger dimeter of hailstone with low impact velocity. In addition, there is a dramatic decrease of impact velocity between the data points for the 20 mm and 30 mm diameter hailstones followed by a linear gradual decline. With the increase of hailstone diameter, the influence of hail velocity becomes less critical. In general, both the hailstone diameter and impact velocity play the essential roles in the penetration resistant capacity. Furthermore, the vulnerability curve is used for the assessment of capacities to prevent the hailstone penetration, which might be useful for the design of the panel against the hailstone impact. Based on the numerical results, it is found that the hailstones with the diameter greater than 30 mm can cause different levels of damage for G300 panel (0.42 mm base thickness), but only the hailstones of greater than 50 mm diameter can create the opening and cracks.

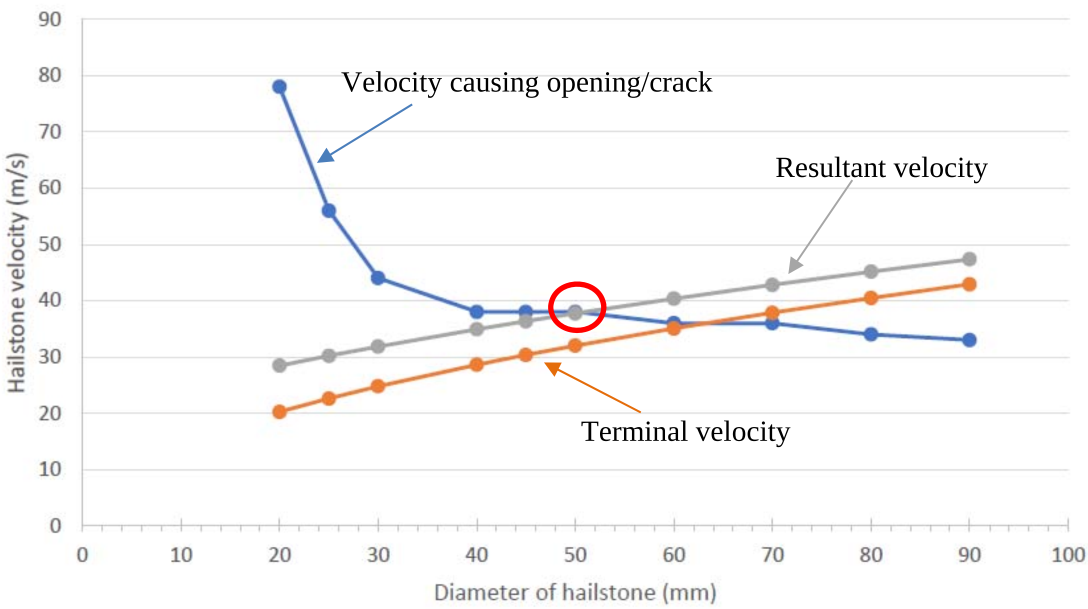

Fig 6: Vulnerability curves for 0.42 mm-thick G300 corrugated panel subjected to hailstone impact.

5 CONCLUSIONS

In this study, numerical model is developed to simulate the response of corrugated metal panel subjected to hailstone impacts by using LS-DYNA. The numerical model is validated by comparing with numerical predictions and the experimental results from windborne debris studies [14]. The validated numerical model is used to predict the impact resistance and performance of the corrugated panel under hailstone impact. It is found that the corrugated G300 steel panel with 0.42 mm thickness cannot survive under the impact of wind-driven hailstone greater than 50 mm in diameter at the speed of 38.4 m/s. In addition, the calibrated numerical model is used to generate vulnerability curve and damage matrix. The influence of hailstone parameters (i.e. diameters ranging from 20 mm to 90 mm) and wind-driven velocities on the performance against hailstone impacts are developed, which will be useful for the assessment and design of panels under strong hailstorm events.

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