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# Laboratory test and numerical study of structural insulated panel strengthened with glass fibre laminate against windborne debris impact

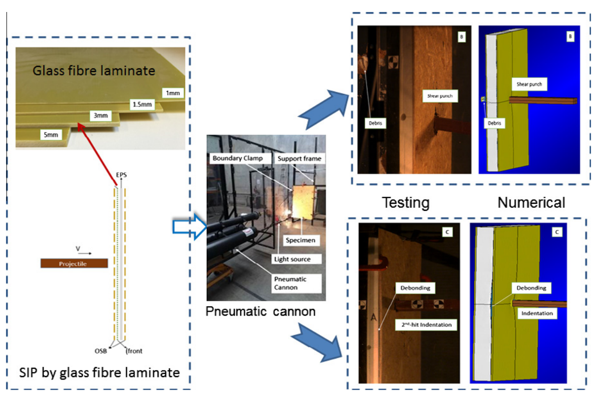
Qingfei Meng, Hong Hao, Wensu Chen *

*Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Australia*

## HIGHLIGHTS

- SIP strengthened with glass fibre laminate against debris impact was studied.
- Laboratory tests were conducted by using an air cannon system.
- Damage patterns of the specimens were observed and discussed.
- Impact resistance capacity of strengthened SIP under debris impact was studied.
- Numerical model was developed to generate SIP vulnerability curve.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Cyclone and tornado as common nature disasters have caused devastating damages and losses around the world. In such events loose objects might be lifted and propelled by strong wind as the windborne debris, which is a potential hazard to the building facade because windborne debris impact may create openings on the building envelop, threaten the safety of occupants inside the building and cause further damages to the structure. Some wind loading codes e.g., the Australian Wind Loading Code (AS/NZS 1170:2:2011) specifies the design requirements to address this issue. On the other hand, structural insulated panel (SIP) has been increasingly used in building constructions owing to the advantages of thermal insulation and easy to build, but it is vulnerable to windborne debris impact owing to its insufficient impact resistance capacity. This disadvantage prevents the wide applications of SIP in regions with strong winds, such as the Cyclone region C and D defined in Australian Wind Loading Code. In this study, glass fibre laminate was used to strengthen SIP with OSB (Oriented Strand Board) skins to improve its capacity to resist windborne debris impact. One unstrengthened and six strengthened SIP panels were manufactured and tested by using a pneumatic cannon system. Two high speed cameras were used to capture failure modes and dynamic responses. The effectiveness of glass fibre laminate strengthening was examined and compared in terms of the residual velocity of the projectile. A numerical model was also developed to simulate the laboratory tests. The accuracy of the model was calibrated by the test results. The validated numerical model was then used to conduct more numerical simulations to obtain vulnerability curves of OSB skin SIP panels against windborne debris impact.

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* Corresponding author.
*E-mail address:* wensu.chen@curtin.edu.au (W. Chen).

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## 1. Introduction

Strong wind events have caused devastating losses. As reported, Hurricane Bhola recorded as a moderate strength cyclone attacked East Pakistan, which resulted in uncountable economic losses and claimed more than 300,000 lives in 1900 s [1]. In Queensland and some western part of Australia, strong wind is considered as one of the major natural hazards. During a windstorm, loose objects such as roof tiles, broken tree trunks and gravels might be lifted and propelled in wind as windborne debris. The high speed wind would carry the debris flying at a high speed and impacting on the building envelope, which if penetrates through the building envelope, would threaten people inside the building. Furthermore, the internal pressure will increase as a result of wind blowing through the created opening. The increased internal pressure together with the external pressure and suction, might lead to structural failure such as roof lifting-up and wall collapse. Therefore, besides wind pressure on walls and suction on roofs, the windborne debris strike is another significant threat to the buildings in strong wind regions [2,3].

Many previous reconnaissance reports of strong wind events indicated the devastating effects of windborne debris impacts. For example, the post storm investigation found the hurricane created enormous amount of windborne debris and the windborne debris impact was highlighted as a major cause of damage to building envelope including wall, roof, door, window, window shutter and screen etc. [3]. Reports of Hurricane Alicia [4], Hurricane Hugo [5], and Hurricane Andrew [6] all cited windborne debris as a major contributor to loss totals. Sparks et al. [7] attributed most of the damages to the building envelope to windborne debris. The investigations following Hurricane Andrew also highlighted windborne debris as a major cause of property damage [8,9]. Typical windborne debris could come from less well-fixed building components and damaged members such as roof gravel, tiles, sheathing and framing members [10,11]. McDonald [12] found the timber with cross section of 100 * 50 mm in a mass between 5.4–6.8 kg is the most representative debris in tornados. As a result, timber debris is commonly considered in assessing the structure capacity to resist windborne debris impacts.

Many standards and guidelines have been made for structure designs to resist strong wind, e.g., FBC (Florida Building Code) [13], FEMA (US Federal Emergency Management Agency) [14], AS/NZS (Australian/New Zealand Standard) [15], ASTM (American Society for testing and Materials) [16], and SBC (US Standard building Code) [17] give specific requirements in structural designs for impact resistance. The USA Federal Emergency Management Agency (FEMA) requires a structure under extreme conditions should be able to resist impact from a timber projectile of 15 Ibs (i.e. 6.75 kg) with a horizontal velocity of 44 m/s and vertical velocity of 30 m/s [18]. As one of the requirements in FBC code, the structure should be able to resist the impact loading by a timber projectile of 4 kg with a speed of 34 mph(15.2 m/s) [13]. In Australia, the AS/NZS 1170.2:2011 [15] requires the structure being able to resist the debris impact equivalent to (a) a timber member of 4 kg mass with a nominal cross-section of 100 mm * 50 mm impacting end and impact velocity equal to 0.4 $V_R$ for horizontal trajectories and 0.1 $V_R$ for vertical trajectories; and (b) a spherical steel ball of 8 mm diameter (approximately 2 g mass) impacting at 0.4 $V_R$ for horizontal trajectories and 0.3 $V_R$ for vertical trajectories, where $V_R$ is the regional design wind speed. Therefore, the projectile impact velocity could be over 40 m/s in region D defined in AS/NZS [15] with $V_R$ more than 100 m/s under the extreme wind condition.

Effects of windborne debris on building structures have been intensively studied [19,20]. Fernandez et al. [11] studied the performance of metal shutter systems for window against windborne debris impact. It was found that the deflection of window protection system was sensitive to the impact location. Ginger et al. [21] studied the effects of strong wind and debris impacts on domestic house and gave recommendations on the house design and construction. Chen and Hao [22,23] conducted impact tests of windborne debris on different structural panels with different impact velocities and different impact locations. The impact resistance capacities of common structural panels or envelop used in Australian building constructions have been assessed through the impact tests and numerical simulations [22–26].

Prefabrication in house construction in Europe and North America has been gaining popularity due to its low cost and construction efficiency. The OSB skin SIP panel is identified as one of the representative structural panels used in the prefabrication construction [27]. As reported by Porter [28], the SIP has good physical characteristics such as light weight, thermal insulation and fire resistance. The SIP is usually made of EPS (Expanded Polystyrene) foam core covered with two skin layers of various materials on both sides. Chen and Hao [22–25] tested a series of SIP panels with different skins against windborne debris impacts. The SIP panels showed different failure modes. The impact caused large global plastic deformation on the ductile steel skins SIP panel, while the SIP panels with rigid OSB skins suffered localized damage with indentation or penetration due to punching shear failure. It was concluded that SIP with OSB skin was more susceptible to shear punch failure as compared to those made of ductile materials. As observed from the previous testing [23], typical OSB skin SIP panels used in the Australian building industry were penetrated or experienced boundary failure by the 4 kg timber projectile impact at a velocity of 18 m/s, These test results indicate the structural panel could not be used in regions that require structural panels to resist windborne debris impacts at higher velocities, e.g., under extreme wind conditions, the structural panel needs to satisfy the requirement of resisting the impact up to 40 m/s as defined in Australian code [15]. Therefore, the OSB-skin SIP panels need be strengthened in order to be used in strong wind regions to satisfy the design requirements.

Fibre Reinforced Plastic (FRP) laminate has been intensively investigated and applied in practice to strengthen reinforced concrete and steel structures. For instance, Triantafillou [29] strengthened the reinforced concrete (RC) beam with FRP, and proved as an effective technique to improve the shear resistance of the RC beam. FRP laminate strengthening was also reported as an effective method to enhance the capacities of RC structures to resist blast [30–32] and impact loadings.

Among different types of FRPs, glass fibre is a light weight, strong and robust material [33]. It is also cheaper and less brittle as compared to carbon fibre. Kawata et al. [34] found the impact absorption capacity of GFRP is higher than CFRP. Sun et al. [35] found that protective covering with epoxy adhesive interlayers can effectively protect concrete against projectile impact. As shown in Fig. 1, glass fibre laminate is a composite material by impregnating the glass fibre with epoxy resin under proper pressure and heat. In the research by Meng and Werasak [36], applying glass fibre laminate could enhance the mechanical performance of the structural insulated panels under compressive loads. However, there is no study that has been reported in the open literature of using glass fibre laminates to strengthen structural insulated panels to improve the impact resistance capacities of the panel, and no study of the performance of glass fibre laminate to strengthen OSB skin SIP panels subjected to windborne debris impact.

This paper studies the performance of glass fibre laminate strengthened OSB skin SIP panels against windborne debris impact. Six strengthened SIP panels and one referencing panel without

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