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Experimental and numerical study of composite lightweight structural insulated panel with expanded polystyrene core against windborne debris impacts

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A B S T R A C T

Natural disasters such as cyclone, hurricane, tornado and typhoon cause tremendous loss around the world. The windborne debris usually imposes high speed localized impact on the building envelope, which may harm people inside the building and create dominant openings. A dominant opening in the building envelope might cause internal pressure increasing and result in substantial damage to the building structures, such as roof lifting up or even collapse. To withstand the impact of such extreme event, the penetration resistant capacity of wall or roof panels to windborne debris impact should meet the requirements specified in the wind loading codes, e.g., the Australian Wind Loading Code (AS/NZS 1170.2:2011). In this study, a composite Structural Insulated Panel (SIP) with Extended Polystyrene (EPS) core sandwiched by flat metal skins that is commonly used in building industry was investigated. To study the structural response and penetration resistant capacity of the composite panel against windborne debris impacts, a series of laboratory tests were carried out by using a pneumatic cannon testing system. The effects of various specimen configurations, impact locations and debris impact velocities on their performance were investigated. The failure modes under various projectile impact scenarios were observed and compared by using two high-speed cameras. The dynamic responses were examined quantitatively in terms of the opening size, residual velocity of projectile, deformation and strain time histories on the back skin measured in the tests. The penetration resistance capacity of the panels subjected to windborne debris impact were examined and analyzed. In addition, numerical models were developed in LS-DYNA to simulate the response and damage of the composite SIP under windborne debris impact. Laboratory tested panels were first modeled. The test data was used to calibrate the accuracy of the numerical model. The validated numerical model was then used to conduct more numerical simulations to obtain more results such as energy absorption, impact force and vulnerability curve of the SIP against windborne debris impact.

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1. Introduction

Hurricane Andrew in 1992 was recorded by that time as the most destructive and expensive natural disaster in US history, which caused $25 billion damage and 65 deaths [2]. The post storm investigation found the hurricane created enormous amount of windborne debris and the windborne debris impact is highlighted as a major cause of damage to building envelope including wall, roof, door, windows shutters or screens etc. [3]. Windward wall is the most prone to debris impact among the building envelope. In a windstorm, unfixed objects or fixed objects such as roof tiles, roof gravel and rafter, which might turn loose under strong wind are the primary sources of potential windborne debris. The windborne debris can be classified into three types i.e. compact-like, rod-like and sheet-like [4]. Medium sized timber of 5.4–6.8 kg, 100 mm × 50 mm was found as the most representative of the windborne debris [5]. If wind speed is fast enough, the windborne debris might penetrate the building envelope, imposing threats to people inside the building. It also creates an opening. The opening in the envelope allows excessive amount of wind and rain to enter the building. Moreover, the opening might cause internal pressures increasing which results in more severe damage to the building such as collapse of the structural panel, entire roof lift-off, and total structure failure as illustrated in Fig. 1. Therefore, the windborne debris is a decisive factor to the performance of the building

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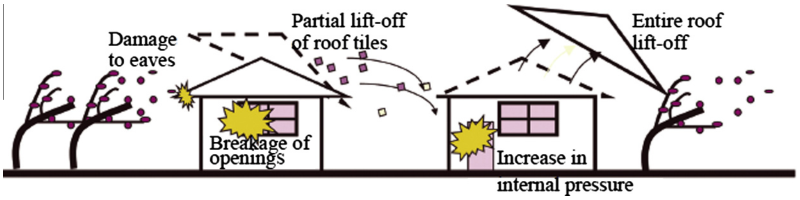

Fig. 1. Illustration of possible windborne debris damage to building [7].

envelope and the building envelope is crucial to the performance of buildings in windstorms [3,6].

To protect the structure, the US and Australia have developed national and regional guidelines and design standards to address the issue of windborne debris impact on the building envelope and its components. Since 1970's, extensive research work has been undertaken at the Wind Science and Engineering Research Center (WISE) of Texas Tech University (TTU), Florida A & M, University of Florida (UF) and Florida State University etc. in the US [8]. The research about the acceptance criteria of debris resistance of the building envelope has been adopted by the guidelines and codes [9–13]. Resisting the impact without perforation of a 4 kg lumber with a cross-section of 100 mm × 50 mm launched at a speed of 15 m/s is the most commonly used criterion in these codes. In Australia, the Design Guideline for Queensland Public Cyclone Shelters [14] provides a mandatory requirement for the windborne debris impact resistance for occupant protection. For all the ordinary buildings in cyclonic areas in Australia, Australian Wind Loading Code (AS/NZS 1170.2:2011) [1] specifies that the impact loading from windborne debris should be equivalent to (a) timber projectile of 4 kg mass with a nominal cross-section of 100 mm × 50 mm impacting end and impacting velocity of 0.4 V_R for horizontal trajectories and 0.1 V_R for vertical trajectories; and (b) Spherical steel ball 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 wind speed [1]. It should be noted that the Australian Wind Loading code of 2011 version increases the requirement of structural panel capacity to resist windborne debris impact. In particular, the debris impact velocity is increased from 15 m/s in the 2002 edition of the Australian Wind Loading Code to a velocity of 0.4 V_R, which could be 40 m/s in regions with the extreme wind velocity reaching 100 m/s. This substantial increment imposes great challenges for designing new penetration resistant panels to meet the acceptance criterion. It also raises the question regarding the safety of existing panels commonly used in construction industry designed according to the previous criterion.

Structural Insulated Panel (SIP) is a lightweight composite structure which is used in a wide range of commercial, industrial and residential building industry. It consists of insulating polymer foam sandwiched by two layers of structural skins. Two layers of skins can be metal sheet, fiber cement sheet, plywood sheet and oriented strand board etc. The foam can be either Extended Polystyrene (EPS), extruded polystyrene foam (XPS) or polyurethane foam (PU), etc. The SIP panels are considered as sustainable, economical, easy to install, ultra-lightweight, thermal insulated, moisture resistant, acoustic insulated, and flame retardant panels. The performances of some SIP have been investigated. Mousa and Uddin [15] studied a composite structural insulated panels (CSIP) made of thermoplastic orthotropic glass-PP (i.e. glass/polypropylene) laminate as skins and EPS as core. Its global buckling behavior was investigated when it was subjected to concentric and eccentric in-plane loadings. Smakosz and Tejchman [16] studied the strength, deformability and failure mode of the CSIP which consists of glass-fiber reinforced magnesia cement boards as skins and EPS as a core. It was found CSIP has potential as load–bearing elements in buildings such as roofs, floors and walls with respect to their high strength. However, no investigation into the SIP subjected to windborne debris impact has been found in the literatures.

Various testing facilities including drop weight, pendulum, catapult, Hopkinson pressure bar and gas gun have been utilized for impact testing [17–21]. In accordance with the above mentioned testing guideline [10] and FEMA P-320/361 [9,13], large projectile cannon facilities have been developed at TTU and UF to simulate windborne debris impacts. A large amounts of structural components or assemblies of buildings including metal panel, CMU (i.e. concrete masonry unit), concrete wall, stud wall, hollow core slab, weatherboard, cladding, glazing and shutter etc. have been tested by using pneumatic cannon facility [22,23]. However, no study of SIP subjected to projectile impact has been found in the literatures.

In the above mentioned testing, the acceptance criterion that a test can be considered a pass is the projectile being rejected by the specimen without perforation. Perforation implies the projectile passed through the specimen while penetration means the projectile made an indention or embedded itself into the specimen but not through [13]. A review on penetration and perforation of plates and cylinders by free-flying projectiles has been conducted by Corbett et al. [24]. Backman and Goldsmith [25] reported a comprehensive survey of the mechanics of penetration of projectiles into targets and identified eight possible occurring failure modes for thin or intermediate targets including fracture, spalling, scabbing, plugging, petaling in the back and front plates, and fragmentation. The failure modes vary for different targets with different target thickness and material, projectile geometry and velocity. The behavior of steel plates impacted by blunt-nose cylindrical projectiles has been studied and all steel plates failed by shear plugging [26]. Polyurea coasted composite aluminum plates subjected to high velocity projectile impact was studied. The polyurea coating was found effective in reduction of the residual velocity of projectile and energy absorbing [27]. The damage of sandwich panels are characterized as front skin failure, core failure and back skin failure [28,29]. Shear failure occurs when the relatively thick skins do not experience large deformation and the membrane forces are not well developed. Tensile failure takes place when the relatively thin skins experience large deformation and the tensile forces are developed. The back skin usually deforms in shear-bending form and the core experiences shear failure [30]. Finite element analysis of penetration of aluminum plates impacted by titanium impactor was conducted by using LS-DYNA to simulate the uncontained engine debris impact on fuselage-like skin panels [31]. The EPS foam subjected to multiple loading and unloading has been modeled by using low density material model in LS-DYNA and calibrated using test results [32].

In this study, composite SIP with EPS core sandwiched by flat metal skins currently commonly used as building envelopes were analyzed. To investigate the structural response and impact resistance of the SIPs subjected to the timber projectile and steel ball impacts as specified in Australian Wind Loading Code (AS/NZS 1170.2:2011) [1], a series of laboratory tests were carried out by using pneumatic cannon testing system. The influences of

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