THERMOPLASTIC COMPOSITE STRUCTURAL INSULATED PANELS (CSIPS) FOR BUILDING CONSTRUCTION

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ABSTRACT

Civil structures are often subjected to low and high velocity impacts. The interior panels (floor panels) of a building structure are subjected to low velocity impact (LVI) due to tool drops etc., while the exterior panels (wall panels) of a building are subjected to high velocity impact (HVI) during a wind storm due to high velocity wind borne debris. Traditional construction materials such as wood, brick and reinforced cement concrete (RCC) cannot withstand HVI if not properly designed to withstand such loads. This paper focuses on the impact behavior of the thermoplastic (TP) Composite Structural Insulated Panels (CSIPs). These panels can be used as modular segments for residential or commercial buildings in panelized construction system. In panelized construction system pre-designed, pre-fabricated lightweight sandwich composite panels are transported to the construction site and assembled according to the floor plan. These light weight panels possess high strength, stiffness and have better insulation properties compared to traditional construction materials. The CSIPs described here replace the oriented strand board (OSB) facesheets in the traditional Structural Insulated Panels (SIPs) with 70% bi-directional glass/polypropylene (PP) composite facesheets. The core of these CSIPs consists of $1.60 \times 10^7$ Mg/m$^3$ (1 pcf) density expanded polystyrene (EPS) foam. Weight saving of approximately 180% (per unit area basis) was achieved by replacing the OSB facesheets in traditional SIPs with TP facesheets. The aim of this work is to investigate the LVI and HVI response and the damage mechanisms of the proposed CSIPs. When tested under identical boundary and loading conditions the traditional SIPs failed at impact energy of 68 J with rupture of the facesheets and the core, while CSIPs were found to be intact at that energy. Limited description about the response of CSIPs for HVI loading is also covered in this paper.

KEYWORDS

Sandwich composite, Structural insulated panels, Modular construction technique, Expanded polystyrene

INTRODUCTION

Traditional construction materials such as steel, concrete and wood have come a long way in terms of design and applications. Though used in the construction industry for a long time these materials exhibit disadvantages in terms of being heavy (steel), corrosion prone (steel), subject to long processing times (concrete), generation of construction waste (concrete) and mold buildups (wood) to name a few. Polymer composites are widely used these days for the construction applications. About 30% of all polymers produced each year are used in the field of civil engineering and construction industries. Polymers offer many advantages over conventional materials because they are light weight, resilient to corrosion and easy to process. They can be combined with fibers to form composites which have enhanced properties, enabling them to be used as structural members and units. An article on the website (http://projects.bre.co.uk/composites/index.html (2007)) states that polymer composites can be used in many different forms ranging from structural composites in the construction industry to the high technology composites of the aerospace and space satellite industries. A form of polymer composite which is made up of two stiff and strong faces separated by a lightweight core is called as sandwich composite. The core of these panels act to separate the facesheets, increasing the moment of inertia of the panel, with little increase in weight, producing an efficient structure resisting bending and buckling load as stated by Moavenzadeh, F. (1990)
Structural Insulated Panels (SIPs) are high quality engineered components that combine to form several important systems of a building (The Engineered Wood Association (APA) Product guide, (1998)). SIPs are promoted by the U.S. Department of Energy (DoE) for their excellent insulating properties and are used in the panelized construction. These panels are in the form of sandwich composites in which the EPS foam core is sandwiched between two OSB facceheets (Figure 1(a)). Morley, M. (2000) proposed that the core of SIPs can be made from a number of materials, including molded expanded polystyrene (EPS), extruded polystyrene (XPS), and urethane foam. The EPS foam is widely used as the core in the SIP construction because of its excellent insulation properties. Advantages of using SIPs for panelized construction are multifold. Large size panels are factory manufactured which results in easy design, reduced construction time and strong structure. There is practically no construction waste as would occur in traditional construction techniques. Greater sound and thermal insulation can be achieved using SIPs which result in the higher energy conservation (Reported in Consumers guide by DoE (2007)). The proven superiority in transverse and axial loading capabilities and increased racking resistance over conventional framing make SIPs a stronger, safer alternative (Morley, M. (2000)).

One of the major concerns with the traditional SIPs is that the OSB has a tendency to absorb moisture, thus causing the facceheets to swell and disintegrate, if the edges of the panels are not sealed properly. Special treatments are required for traditional SIPs to avoid mold buildup on the OSB facceheets, which can create unhygienic atmosphere and loss of millions of dollars in the flood prone areas. Along with the mold buildups flying debris referred to as windborne missiles generated during wind storms can cause severe damage to structures built with traditional SIPs. If wind speeds are high enough, missiles can strike building with enough force to penetrate windows, walls, or the roof of a structure. For example, an object such as a 5.1 cm x 10.2 cm (2 inch x 4 inch) wood stud weighing 67 N (15 lb), when carried by a 112 m/s (250 mph) wind, can have a horizontal speed of 44.7m/s (100 mph) and enough force to penetrate most common building materials used in houses today (Uddin et al. (2005)).

To overcome these issues the OSB facceheets in the traditional SIPs are replaced with TP composite facceheets in this study (Figure 1 (b)) and hence termed as CSIPs. Unidirectional glass/PP tapes can be produced using hot-melt impregnation process. These tapes can then be woven to obtain the bi-directional configuration. Layers of such woven preforms when consolidated, produce the TP facceheets of desired thickness. Weight savings of 183 % can be achieved by replacing OSB facceheets with the TP facceheets.

The core of CSIPs consists of closed cell EPS foam. Excellent insulation against heat can be achieved using SIPs as it makes use of closed cell EPS foam which has better insulation properties compared with the traditional fiberglass insulation. Table 1 describes the properties of the constituents of the CSIPs used in this study.

The focus of this paper is on the LVI and HVI response of SIPs having a reduced scale configuration (reduced scale panels consists of the EPS foam core thickness of 25.4 mm (1 inch)). Details of the experimental set up and the results obtained by testing these reduced scale panels are covered in the subsequent sections of this paper.
Table 1: Physical properties of the constituents of CSIPs

<table>
<thead>
<tr>
<th>Facesheet properties</th>
<th>Core properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal thickness</td>
<td>3.04 mm (0.12 inch)</td>
</tr>
<tr>
<td>Weight % of Glass</td>
<td>70%</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>414 MPa (60,000 psi)</td>
</tr>
<tr>
<td>Flexural modulus</td>
<td>13,790 MPa (2,000,000 psi)</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>317 MPa (46,000 psi)</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>15,169 MPa (2,200,000 psi)</td>
</tr>
<tr>
<td>Nominal density</td>
<td>$1.6 \times 10^7$ Mg/m$^3$ (1pcf)</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>1.2 - 1.5 Mpa (180-220 psi)</td>
</tr>
<tr>
<td>Flexural modulus</td>
<td>0.1 - 0.2 MPa (25-30 psi)</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>1.9 - 2.2 MPa (280-320 psi)</td>
</tr>
<tr>
<td>Shear strength</td>
<td>0.1 - 0.15 MPa (18-22 psi)</td>
</tr>
<tr>
<td>Reduced scale thickness</td>
<td>25.4 mm (1 inch)</td>
</tr>
<tr>
<td>Actual scale thickness</td>
<td>139.7mm (5.5 inch)</td>
</tr>
</tbody>
</table>

EXPERIMENTAL PROGRAM

Two sets of panels were tested under LVI type of loading namely traditional OSB SIPs and the proposed CSIPs. Both the type of panels were tested under similar loading and boundary conditions. For HVI loading CSIPs were tested under gas gun impact. All the CSIP specimens (for LVI and HVI testing) were prepared using a compression molding approach, while the traditional OSB SIPs were obtained from a SIP manufacturer. Specimen size of 101.6 mm x 101.6 mm (4 inch x 4 inch) was used for this study.

LVI Test Setup

The system used for LVI testing was an Instron Model 8250 drop-weight impact machine with an instrumented striker (tup) assembly (Fig.2(b)). The impactor used was 19.05 mm (¾ inch) hemispherical tup having the total weight of 6.15 kg. The reason behind selecting a hemispherical tup was to duplicate the impact condition similar to wind debris or tool drop. The specimens were sandwiched in between two aluminum plates to generate the fixed support condition. The aluminum plates had an exposed diameter of 72 mm (2.83 inch) through which the impactor could hit the specimens constrained between the plates (Fig.2 (a)). The tup contained a load cell, which was used to record the contact load between falling assembly and the specimen during the event of the impact. In order to achieve the desired impact energy height from which the impactor was dropped could be adjusted. The impact energy chosen in this study was 68 J, which was the maximum energy that could be achieved using above mentioned impactor and the experimental setup. The testing machine used DynaTup software to generate the data produced during impact loading. Impact loads, impact energy, velocity of impact and the energy of impact were measured directly from the software.

Behavior of Traditional OSB SIPs

A typical load and energy vs. time curve for OSB SIPs is plotted in Fig. 3. The curves in Fig. 3 can be used to investigate the impact response of traditional OSB SIPs. During the impact event energy was transferred from the impactor to the top facesheet, once the impactor struck the specimen. Impacted OSB facesheet being weak in shear could not resist the applied impact energy and impact energy was used up in penetrating the top OSB facesheet. The first load drop (in OSB SIP curve) in Fig.3 corresponds to the response of the top facesheet to the applied impact energy. Delamination between various layers of the top OSB facesheet was observed at this instance. Once the impactor penetrated the top facesheet completely (seen from Fig 4 (a)), the impactor came in contact with the low shear strength (0.1-0.15 MPa (18-22 psi)) EPS foam core. The foam being extremely weak in resisting the shear loads, the impactor easily penetrated through the core. After the impactor penetrated the foam core, large amount of impact energy was already used up in damaging the top OSB facesheet and the foam core. The second peak in the load- time curve for traditional OSB SIP corresponds to the response of the bottom facesheet to the impactor. It can be observed that the width of the second load peak for OSB SIP in Fig 3 was greater than the first peak which signifies that the amount of time required for the impactor to damage the bottom facesheet was greater than that required for damaging the top facesheet.
The maximum load attained by the second peak was 2 kN which was 266.67 % greater than the peak load for the first load peak (0.75 kN). This can be attributed to the fact that the impact energy was used up in damaging the top facesheet and the foam and also was used up in the friction between the various components of the sandwich. Also at the end of the impact event the impactor stuck in the bottom facesheet and the extent of delamination in the bottom facesheet was less as compared with the top facesheet. The large drop in the energy curve for the OSB SIP in Fig. 3, at the end of the impact event signifies that the OSB SIP was not able to absorb the impact energy and all the impact energy was dissipated in damaging the OSB SIP.

**Behavior of Proposed CSIPs**

Figure 3 shows a typical load and energy vs. time curves for the CSIPs. A peak load of 8 kN was observed for the CSIPs. The first peak observed in load curve for CSIPs was the response of the top composite facesheet for the applied impact load. Once the impactor came in contact with the top face, impact energy was transferred to the sample through the top face. The contact stiffness (which is the slope of the load vs. time curve in Fig. 3) for CSIPs was seen to be higher than that of the OSB SIPs. Energy absorbing mechanisms of the OSB SIPs and the CSIPs were observed to be different for the same amount of impact energy. For OSB SIPs the impact energy was dissipated in delaminating various layers of the OSB facesheet, while in CSIPs, the glass/PP facesheets absorbed the applied impact energy. The extent of damage of the CSIPs can be seen from Fig. 4 (b). In case of CSIPs impactor could not penetrate through the top facesheet but left an indentation on the top facesheet spreading the damage over a larger area on the top facesheet. As against that for OSB facesheets in traditional SIPs the damage was highly localized and impactor punched through the top facesheet and the core of the SIPs.

**HVI Testing**

After testing the OSB SIPs and the CSIPs for the LVI type of loading, it was observed that traditional OSB SIPs were not able to withstand the LVI loading and failed completely at impact energy of 68 J. So the HVI testing was performed only on the proposed CSIPs to check their suitability for HVI loading.

The HVI was generated using a laboratory scale gas gun. A standard developed by Texas Tech (Texas Tech University Wind Engineering Research Center (1998)) was used a basis for this study which made use of energy balance equation to calculate equivalent energy of impact recommended by Federal Emergency Management Agency (FEMA (2000)) for the design of storm shelters against high velocity wind. Using this energy balance, the velocity required for a gas gun sabot to produce the same amount of energy as a 66.7 N (15 lb) wood of size
5.1 cm x 10.2 cm (2 inch x 4 inch) traveling at a speed of 44.7 m/s (100 mph) can be achieved using a 5.1 cm (2 inch) long, 3.8 cm (1.5 inch) diameter aluminum sabot traveling at 291 m/s (652 mph). Based on this study the CSIPs were tested under the HVI using blunt object impactor. The impactor was 5.1 cm (2 inch) long, 3.8 cm (1.5 inch) in diameter 6061 grade aluminum sabot. The velocity of travel was 135 m/s (302 mph) (which was nearly 50% of the velocity recommended by Texas Tech standard to produce equivalent velocity of the 66.7 N (15 lb) wood 5.1 cm x 10.2 cm (2 inch x 4 inch) traveling at a speed of 44.7 m/s (100 mph). The samples were sandwiched between the two steel plates and were secured with the help of bolts (Fig.5(a)). This boundary condition was a typical of actual wall scenario where the wall panels are constrained along the edges.

**Behavior of CSIPs**

Figure 5 shows the undamaged and the HVI tested CSIPs. The major mode of failure in this case was fiber breakage of the impacted facesheet. The impactor left an indentation on the impacted facesheet of the CSIP (Fig.5(b)). Delamination amongst various layers of TP facesheet was also observed.

Whenever a panel is subjected to impact loading, the panel undergoes flexure, with the bottom facesheet subjected to tension and the top (impacted) facesheet subjected to compression. This flexing helps the panel to absorb large amount of impact energy. This flexing highly depends on the ductility of the panel being tested. If the panels being tested are rigid, the failure is by a brittle manner, and the impactor would punch through the panels.

Earlier studies by Vaidya et al. (2007) on the flexural response of CSIPs concluded that there is a large degree of ductility observed in CSIPs. This ductility is imparted due to the PP matrix used for impregnating the glass fibers and also due to the low density EPS foam core. In this case due to large amount of flexing, the back facesheet was damaged by fiber breakage and the foam was damaged by compression. The flexing also helped in deflecting the impactor away from the panel and there was no penetration through the CSIP panel.

![Figure 5: Extent of damage for HVI tested CSIP panels](image)

**SUMMARY**

Reduced scale configuration of traditional OSB SIPs and the proposed CSIPs were tested under the LVI and HVI in this study. The impact energy of 68 J for LVI testing duplicated a typical scenario of a tool drop on the floor panel, while the impact energy of 1300 J used for HVI testing was based on the standard based on the Texas Tech. The results of the tests can be summarized as follows:

- Weight saving of approximately 180% was achieved by replacing the OSB facesheets with CSIPs of equivalent stiffness.
- Under LVI loading, the OSB facesheets failed under the impact energy of 68 J. The impactor penetrated through the top facesheet and the core. For CSIPs however the impactor left an indentation on the top facesheet, and there was no penetration through the top facesheet. The foam core was also seen to be intact.
- For HVI loading fiber breakage on the impacted face was the predominant mode of failure for CSIPs. There was no penetration through the CSIP panel, but the impactor was deflected away from the panel due to large degree of flexing.
• In all the tests, the bond between the facesheets and the foam was intact and there was no delamination between the facesheet and the foam, proving excellent adhesion between the facesheets and the foam for OSB SIPs as well as CSIPs.

• By replacing the OSB facesheets of the traditional SIPs with equivalent stiffness TP facesheets, light weight panels were obtained which had better penetration resistance and better energy absorption under LVI and HVI scenarios than traditional SIPs.

• Future work would include testing of full scale (139.7 mm (5.5 inch) EPS foam sandwiched between 3.04 mm (0.12 inch) glass/PP facesheets) CSIPs and full scale (139.7 mm (5.5 inch) EPS foam sandwiched between 11.11 mm (7/16 inch) OSB facesheets) traditional OSB SIPs with the impact energy of 2600 J, which is the equivalent energy of 66.7 N (15 lb) wood 5.1 cm x 10.2 cm (2 inch x 4 inch) traveling at a speed of 44.7 m/ s (100 mph), based on the standard developed by Texas Tech, to duplicate a typical wind borne debris impact on building panels.

REFERENCES

Company literature: Crane Composites, Inc. - A Crane Co. Company 23525 W Eames Channahon, IL 60410 U.S.A.

Company literature: Universal Packaging, Inc.- 2216 Greenspring Drive Lutherville, MD 21093


Web article: http://www.r-control.com/SIPs/benefits.asp (Visited on December 20, 2006).


Web article: http://projects.bre.co.uk/composites/index.html (Visited on May 1, 2007)