Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME07-AM-68

FLEXURAL RESPONSE OF LIGHTWEIGHT SANDWICH PANELS FOR PANELIZED CONSTRUCTION

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ABSTRACT

Panelized construction technique is a method where the building is subdivided into basic elements that are typically fabricated in a manufacturing facility; shipped to the construction site and assembled into the finished structure. Thermoplastic (TP) composite materials are suitable for panelized construction as they possess advantages in terms of high strength to weight ratios, corrosion resistance, and better impact tolerance when compared with traditional construction materials. Two types of TP sandwich composite panels are proposed here which includes 3-D open core sandwich composite (OC) reinforced with glass fiber reinforced (GFRP) rebars and polyurethane (PUR) foam for internal partitioning walls and composite structural insulated panels (CSIPs), for external walls and floor of a structure. This paper includes structural characterization of these proposed panels in terms of static flexural loading. The results of CSIPs are compared with the traditional structural insulated panels (SIPs) comprising of oriented strand board (OSB) as facesheets.

Keywords: Panelized construction, Sandwich composites, Composite structural insulated panels (CSIPs)

1. INTRODUCTION

Structural design systems used in housing have historically developed into single purpose systems. Different layers of materials and structural components are brought individually to the jobsite and assembled with each other typically satisfying a single primary function. Different structural elements of a building such as beams, columns, floors and roof perform different functions in a traditional construction system. Modular building systems is a fast-growing modern form of construction gaining recognition because of its increased efficiency and ability to apply modern technology to the needs of the market place. In the modular construction technique single structural panel can be manufactured which can perform a number of functions such as providing thermal insulation, vibration damping along with providing strength to the structure and hence termed as multifunctional. These multifunctional panels can be prefabricated in a manufacturing facility and then transferred to the construction site. A system that uses prefabricated panels for construction is termed as a ‘panelized construction system’. Cost-effectiveness can be achieved through factory-based prefabrication of subcomponent assemblies where superior structural performance can be designed into the component [1]. Prefabrication can also provide new ways of resisting lateral loads in addition to improving affordability [2]. Pre-fabricated panels can incorporate better performance in terms of construction details, and remain economical due to the efficiency of their automated factory assembly.

The overall goal of this research work is to pioneer a new technology for the development of pre-engineered and pre-fabricated multifunctional building components that possess improved structural performance, have short processing times and can be installed quickly with limited skilled labor. This research proposes the use of thermoplastic (TP) sandwich composite panels for the panelized construction. Two types of TP sandwich composites are proposed in this research namely; (a) open core sandwich composite (OC): which are proposed for the internal wall segments and (b) composite structural insulated panels (CSIPs), which are proposed for the external load bearing walls, floors and roof panels (Fig.1). These panels have advantages of combining the structural performance with thermal, sound insulation, and fire-protection qualities. One of the major advantages of these panels is in terms of their resistance to impacts. Civil structures are often subjected to low and high velocity impacts. It is well known that under the impact events a typical mode of failure for sandwich composite is the delamination between facesheets and the core. In case of OC panels, issue of delamination is addressed by stitching the core piles to the facesheets of the sandwich. This method of connecting the core piles to the facesheets avoids delamination by creating a strong mechanical connection between the core and the facesheets. For CSIPs, the core consists of EPS foam which has low shear strength (0.1-0.15 MPa (18-22) psi). By using low density foam as core, the failure is engineered to the core thus protecting the interface of a sandwich.

This paper includes structural characterization of the proposed panels in terms of static flexural loading. Detailed description of these proposed panels is described in section 2 of the manuscript. The test setup used and the experimental results are covered in the subsequent sections of this manuscript.

2. PROPOSED PANELS

The first type of panel proposed here is OC sandwich panel which is a special type of truss core sandwich composite in which the core consists of a number of vertical glass piles. Two bi-directional woven E-glass facesheets are mechanically connected with vertical woven piles. This produces a sandwich which has a pre-set space between the two surface decks. This arrangement prevents delamination between the core and the facesheets in the events of impacts, and increases the shear resisting properties of the sandwich. The core is hollow, which allows routing of wires, addition of fire retardants, and embedment of electronic components, among other advantages [3]. OC sandwich panels being multifunctional in nature, it is proposed that the internal walls of a structure would be designed in such a way as to provide better functionality in terms of fluid storage, sensor integration and storage of fire retardants to be used for protecting the internal structure. The OC sandwich panels can be impregnated with thermoset (TS) or TP matrix system. During the wetting-out process, the fabric has an inherent rebounding property, termed spring resilience, that forces the upper deck to spring back from the lower deck to a height dictated by the length of the vertical pile threads [3]. The length of the core piles of the OC panels used in this study was 22 mm. The resin system used for impregnation was TP polyurethane (PUR) and the specimens were manufactured using film stacking approach. To improve the in-plane load bearing capability of the OC sandwich panels, glass fiber reinforced polymer rebars of 6 mm diameter were inserted in the interstitial spaces of the OC and then PUR foam (density 61 kg/m^3) was impregnated under controlled vacuum. The panels reinforced with PUR foam only are referred to as OCF (Fig.2(a)) while the panels reinforced with the rebars and the foam are referred to as OCFR (Fig.2(b)) in this paper.

The second type of panel proposed for the external walls and the floors of a structure is Composite Structural Insulated Panel (CSIP). Traditionally SIPs consist of foam sandwiched between two oriented strand boards (OSB) facesheets (Fig. 3(b)). The core of SIPs can be made from a number of materials, including molded expanded polystyrene (EPS), extruded polystyrene (XPS), and urethane foam [4]. One of the major concerns with the traditional SIPs is that the OSB has a tendency to absorb moisture, thus causing the facesheets 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 facesheets, which can create unhygienic atmosphere and loss of millions of dollars in the flood prone areas. Flying debris referred to as windborne missiles generated during wind storms can cause severe damage to structures built with traditional SIPs. To overcome these issues this research illustrates the use of thermoplastic (TP) composites panels to replace the OSB facesheets in the traditional SIP construction (Fig. 3 (a)). Along with the weight savings of 180% (per unit area basis) the TP facesheets are stronger and thinner (30% thinner) than the OSB facesheets used in the traditional SIPs. These facesheets also have better penetration resistance against wind borne missiles during the events such as hurricanes and tornados. In this paper reduced scale configurations of traditional SIPs and CSIPs are tested under identical loading and boundary conditions. A reduced scale traditional SIPs consists of 1.60 x 10^7 Mg/m^3 density EPS foam sandwiched between 10.99 mm thick OSB facesheets, however the reduced scale CSIPs consists of 1.60 x 10^7 Mg/m^3 density EPS foam sandwiched between 3.04 mm TP facesheets.

3. TEST SETUP

It is well known that when a sandwich beam is loaded in flexure, the facesheets undergo tension and compression while the core undergoes shear and some degree of compression. The compression of the core is primarily below the loading point. In this study the panels were tested under three point bending to investigate the flexural strength and the flexural modulus of the panels according to ASTM C-393 [5]. The span length used was 558 mm. Tinius-Olsen, Universal Testing Machine (capacity 60,000 lbs (27215 N)) was used for flexural testing. The maximum load was attained in 5 minutes and a loading rate of 0.08 N/sec was used. Each specimen was loaded up to maximum deflection and then unloaded. The ultimate load carrying capacity was tested by loading the specimen to complete failure. A linear variable displacement transducer (LVDT) was used to measure the deflection at the geometric center of the specimen. Strain gauges were bonded to the beam specimens on the tensile side at their geometric center to record the longitudinal strains. Two samples of each type of panels namely OCF, OCFR, CSIPs and OSB SIPs were tested and the average results are reported here.

4. FLEXURAL BEHAVIOR OF THE FOCSC AND GFOCSC PANELS

Typical load versus deflection curves for the OCF and OCFR panels are shown in Fig.4. Failure of the FOCSC was mainly by the rupture of the tensile face of the panel. Along with the tensile face failure, shear cracks were developed in the foam core. The core piles however were seen to be intact. Once the load reached 50 N the shear cracks in the core were dominant and the panel ceased to take any further load. As seen from Fig 4, the initial behavior of both the types of panels up until a load of 10 N was similar. For OCFR however once the tensile face cracked, the GFRP rebars started bearing the load. As the bars were located very close to the bottom facesheet, the load was transferred to the bars from the faces through the rigid foam present in the core. The foam helped in creating a composite action and thus the stress transfer was possible amongst the various elements of the panel. The GFRP rebars cracked with the loud popping noise at an average load of 105 N. Figure 5 shows the rupture of the bottom facesheet and the cracked rebar. There was no delamination between the facesheet and the core for OCF and OCFR.

The ultimate load carried by the OCFR was 110 N which was 300 % higher than the panels without the GFRP rebars. Hence, the rebars increased the stiffness of the OCF for 159% increase in corresponding weight.

5. FLEXURAL BEHAVIOR OF CSIPs and OSB SIPs

Traditional OSB SIPs and CSIPs were tested under identical boundary and loading conditions in this study. Similar test setup as described in section 3 was followed. Gradual increase in the load was observed till the peak load. The average peak load attained by OSB SIPs was 97.6 N (220 pounds) and a corresponding deflection for the peak load was 18.8 mm. A typical load versus deflection curve for OSB SIPs in shown in Fig. 6, while that of the CSIPs is shown in Fig. 8. Shear cracks were seen to have developed in the foam core once the load exceeded 27 N (65 pounds). The facesheet on the tensile face of the panel then started crushing. Figure 7 shows the damage conditions of the OSB SIP panels.

To compare the behavior of the traditional SIPs with the proposed SIPs, CSIPs were tested under the identical boundary conditions and loading rates. CSIPs reached an average peak load of 30 N (65 pounds) and the corresponding average deflection of 38.1 mm was recorded. A linear elastic behavior was observed till the load of 27.21 N (60 pounds) was reached. Shear cracks were seen to have developed in the foam core once the load exceeded 27.21 N (60 pounds) as seen from Fig. 9. These cracks were observed near the support and were oriented at 45^0 to the horizontal. The facesheets were seen to be intact and there was no sign of delamination between the core and the facesheets. There was an average permanent deformation of 6.35 mm observed for these panels during testing.

5.1 Comparison of Behaviors of Traditional SIPs and CSIPs

The average ultimate failure load attained by traditional SIPs was 100 N and that of the CSIPs was 30 N. The TP CSIPs deflected up to 35 mm at the load of 30 N, while the OSB SIPs deflected by 3.4 mm for the same load making them much stiffer as compared with the TP CSIPs. The failure strains attained by the OSB SIPs was 0.003814 (mm/mm) and that of the CSIPs was 0.002914 (mm/mm).

Bending stress values were normalized with the weight of each type of panel. Since the formula for finding the bending stresses is developed for beams whose material is homogenous, this formula cannot be applied directly to determine the normal stress in a composite beam [6]. This formula can be used by transforming the composite section into the section comprising of a single material. This can be done using transformation factor n.

$$n = \frac{E_1}{E_2} \qquad (1)$$

where E_1 and E_2 are the elastic modulii of the materials of the composite beams. The moment of inertia of the single material section can then be obtained which can be used for finding the maximum bending stress. In this study the bending stresses were obtained using the approach of transformed section and the stress values were normalized with the weight. The values are plotted in Fig. 10. 1100% stiffer configuration was obtained for the CSIPs against the traditional SIPs once the stress values were normalized. This stiffness was imparted due to the TP facesheets to the CSIPs.

The elastic modulus of the SIPs with OSB facesheets was found to be 1.52 x 10^3 MPa while the elastic modulus of the CSIPs was 2.265 x 10^3 MPa. As seen from Fig. 7 in the case of OSB SIPs the facesheets were seen to have fractured on the tensile as well as on the compressive side of the panel.

Delamination was observed amongst various layers of OSB which induced sudden cracking of the facesheets. Along with that the foam was also seen to have developed shear cracks. As against that for CSIPs the TP facesheets were seen be intact on the tensile as well as compressive side (Fig. 9). A ductile behavior of the panel was observed for CSIPs. The foam core was seen to have developed shear cracks as seen for the OSB SIPs. Thus the TP facesheets were seen to be more damage tolerant than the OSB facesheets for the applied flexural loads.

6. SUMMARY AND CONCLUSION

Structural characterization of two types of TP structural panels: OCFR panels for internal multifunctional walls and CSIPs for floors and exterior walls is presented in this research. The primary goal of these tests was to investigate the failure mechanisms of the proposed panels under the flexural loading.

The findings of this study can be summarized as follows:

1. The OCF panels failed by rupture of the tensile face and shear failure of the foamed core. In the case of OCFR panels, failure occurred by breakage of the reinforcing bar along with rupture of the bottom facesheet. The foam within the core supported the glass core piles and helped to transfer the load from facesheet to reinforcing bars. The foam thus helped to create a composite action. The ultimate load carried by the OCFR panels was 110 N which was 300 % higher than the OCF. Hence, the rebars increased the bending stiffness of the TP open core sandwich for 159% increase in the weight.
2. Weight savings of 183% can be achieved by replacing the OSB skins in the traditional SIPs with TP skins thus reducing the total dead weight of the various structural panels.
3. The primary mode of failure under three point bending for CSIPs was the shear failure of the foamed core which resulted in developing shear cracks in the foam core. The facesheets were seen to be intact in the case of CSIPs.
4. The primary mode of failure of the traditional SIPs was however the rupture of the OSB facesheet on the tensile as well as compressive side of the panel. Along with this the foam was also seen to have

undergone shearing and resulted in development of shear cracks.

5. Though the load carrying capacity for the OSB SIP was seen to be more than that of CSIPs, 1100% stiffer configuration was observed once the stress values were normalized with the weigh of the individual panels.

8. FIGURES

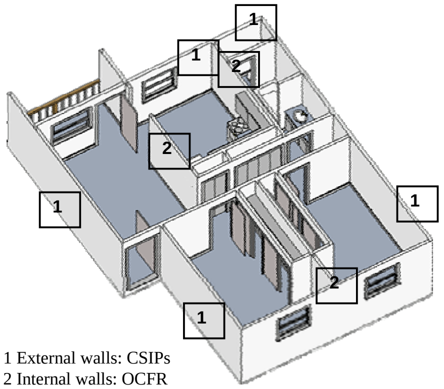
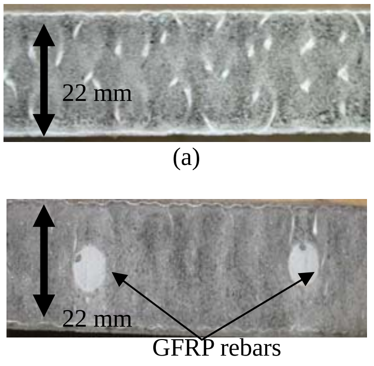


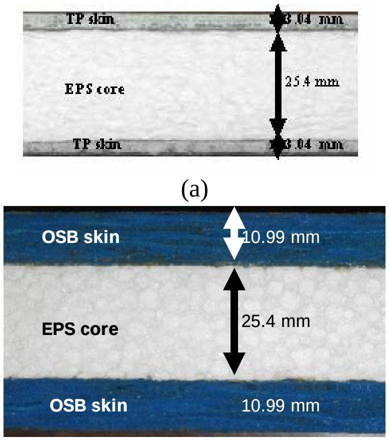
Fig 1: Locations of proposed panels; (Modified from [4])



(a)

(b)

Fig 2: Internal wall panels (a) open core foamed panels (OCF), (b) open core foamed panels with rebar (OCFR)



(a)

(b)

Fig 3 External walls and floor panels (a) OSB SIPs (b) CSIPs

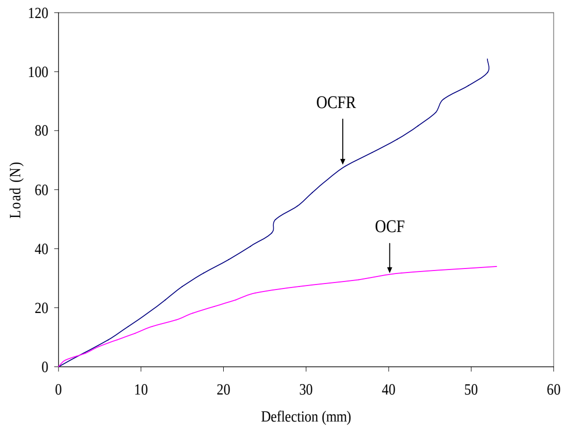


Fig 4: Typical load versus deflection curves for OCF and OCFR

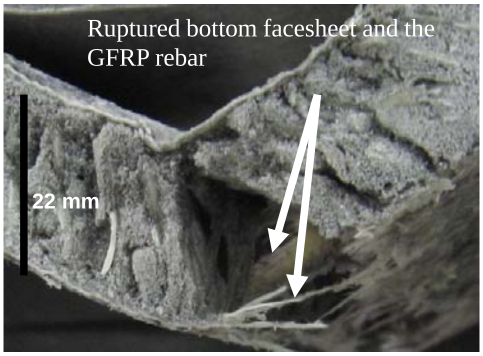


Fig 5: Failure of GFRP rebar for OCFR at maximum deflection

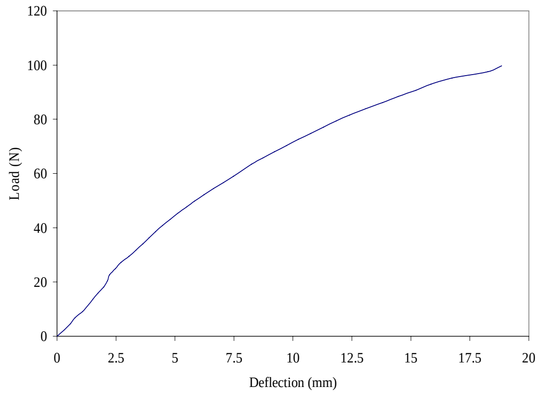


Fig 6: A typical load versus deflection curve for the OSB SIP.

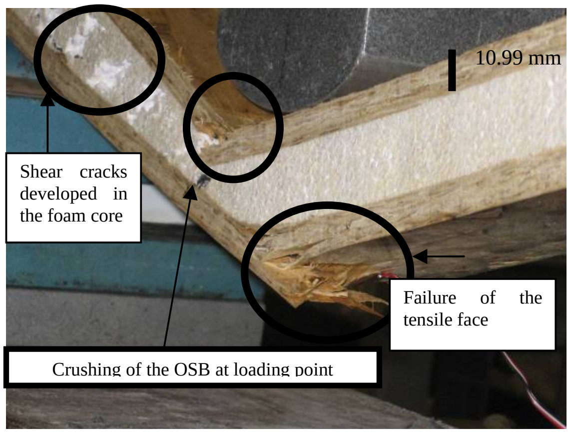


Fig 7: Failure of the OSB SIPs

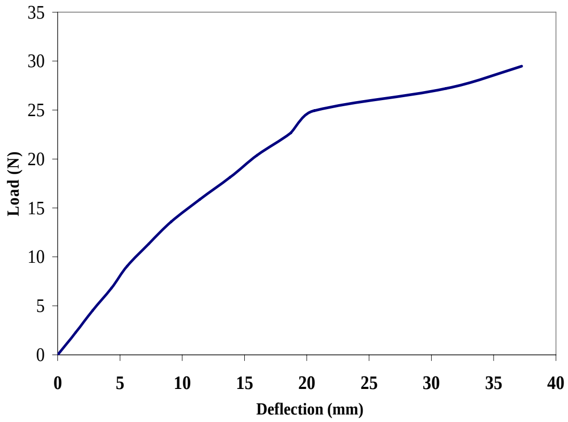


Fig 8: Typical load-deflection curve for CSIPs

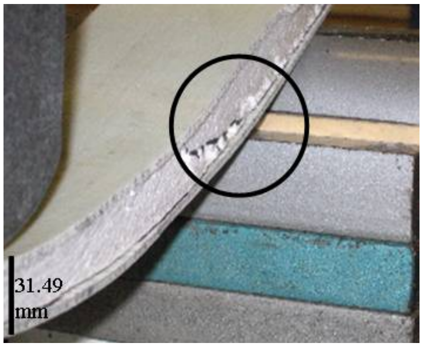


Fig 9: Shear cracks developed in the foam core but intact facesheets of CSIPs

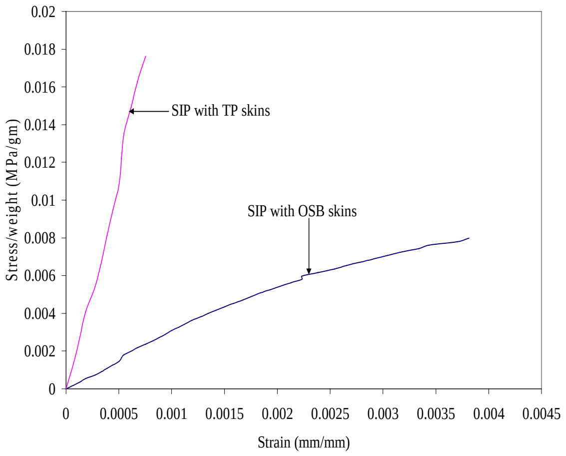


Fig 10: Normalized value comparison for SIPs

9. REFERENCES

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10. NOMENCLATURE

Symbol	Meaning	Unit
n	transformation factor	(Dimensionless)
E_1	Elastic modulus of the core	(MPa)
E_2	Elastic modulus of the facesheet	(MPa)