

Research Article

Manufacturing and Structural Feasibility of Natural Fiber Reinforced Polymeric Structural Insulated Panels for Panelized Construction

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Natural fibers are emerging in the fields of automobile and aerospace industries to replace the parts such as body panels, seats, and other parts subjected to higher bending strength. In the construction industries, they have the potential to replace the wood and oriented strand boards (OSB) laminates in the structural insulated panels (SIPs). They possess numerous advantages over traditional OSB SIPs such as being environmental friendly, recyclable, energy efficient, inherently flood resistant, and having higher strength and wind resistance. This paper mainly focuses on the manufacturing feasibility and structural characterization of natural fiber reinforced structural insulated panels (NSIPs) using natural fiber reinforced polymeric (NFRP) laminates as skin. To account for the use of natural fibers, the pretreatments are required on natural fibers prior to use in NFRP laminates, and, to address this issue properly, the natural fibers were given bleaching pretreatments. To this end, flexure test and low-velocity impact (LVI) tests were carried out on NSIPs in order to evaluate the response of NSIPs under sudden impact loading and uniform bending conditions typical of residential construction. The paper also includes a comparison of mechanical properties of NSIPs with OSB SIPs and G/PP SIPs. The results showed significant increase in the mechanical properties of resulting NSIP panels mainly a 53% increase in load-carrying capacity compared to OSB SIPs. The bending modulus of NSIPs is 190% higher than OSB SIPs and 70% weight reduction compared to OSB SIPs.

1. Introduction

The structural insulated panels (SIPs) have come forward as an excellent alternative to conventional brick and concrete construction. They are an excellent material for wall, partitions, flooring, and slabs. They possess numerous advantages over traditional wooden and concrete construction [1]. The main component of SIPs consists of two laminates or skin plates and a core as shown in Figure 1.

The laminates are used to carry tensile and compressive loads in the SIPs and core is used to carry the shear load [2]. The laminates in SIPs can be typically made up of oriented strand boards (OSB) that are adhered to the expanded polystyrene (EPS) foam core material to form SIPs. OSB SIPs are commonly used for the structural application due to their ease of manufacturing and ease of availability.

OSB SIPs are energy efficient, cost efficient, and require less construction and maintenance time. Significant weight reduction is possible with OSB SIP construction [2]. They provide several design choices, manufacturing alternatives, and also provide excellent aesthetic to the building structures [2]. They provide excellent bending properties and shear resistance along with excellent resistance to wind and seismic forces [3]. These mechanical properties play a key role for the structural applications such as wall panels, building panels, flooring, and slabs [4].

Although OSB SIPs have numerous advantages, they require wood for manufacturing the laminates in SIPs which results in large consumption of natural resources and reduces the greatly concerned resources. There are fire safety issues associated with the OSB SIPs [5]. OSB SIPs are of organic nature, so, to avoid the damages due to mold buildup and

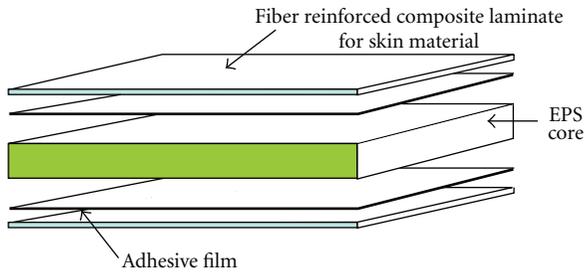


FIGURE 1: Typical layout of NSIPs.

termite attack, the special chemical treatment is needed to use OSB SIPs in the building construction [6]. The impact resistance of the OSB SIPs is always a major concern for their application in building industries. Windborne missiles can damage the OSB SIPs and may result in damage in the properties and even in the loss of life. One of the notable examples of this type of failure is hurricane Katrina in New Orleans which resulted in great loss of life and property damages [6]. OSB SIPs can have adverse effects of flood due to their poor water-resistant nature [7].

To overcome these issues, several advancements were carried to the OSB in the SIPs with more advanced composite laminates. Several fiber and matrix combinations can be used to manufacture the laminates such as glass-polypropylene, carbon-epoxy, and glass-epoxy. The research was carried out on application of glass/polypropylene (G/PP) which has emerged as an excellent material in the structural application to replace OSB laminates in SIPs [7].

G/PP shows excellent mechanical properties such as superior strength and stiffness which makes them an ideal material for manufacturing the SIPs [7]. Although they have superior mechanical properties, the main disadvantages with this material are their large energy consumption during manufacturing and their adverse effect on the manufacturing tools. They are manufactured in factory and so require significant manufacturing cost [8]. These issues direct the construction industry to a type of material which has higher strength than OSB and can be reproducible so as to reduce the environmental concerns and recyclability issues. These requirements can be well furnished by using natural fiber to replace the OSB and G/PP in the laminates.

Natural fiber reinforced polymeric (NFRP) composites are successfully being used worldwide in automobile parts such as doors, and body panels of cars [9] and in computer industry for manufacturing body panels [10]. Composites reinforced with these fibers are being studied worldwide for their low-cost application against other synthetic fibers such as glass and carbon fibers. There are wide ranges of natural fibers being used worldwide in composite applications such as bast, jute, sisal, cotton, coir, hemp, and kenaf. Natural fibers have numerous advantages which make them suitable to use as the structural material [11]. They require less energy for manufacturing and do not affect adversely the manufacturing tools. They are lightweight, cost efficient, recyclable, biodegradable, and possess a high specific modulus. In the current work the jute/polypropylene laminates along with

EPS foam core were selected for the manufacturing of NSIPs due to their excellent mechanical properties [12].

Jute fibers have high specific strength and stiffness, making them suitable as reinforcement in polymeric matrices. The advantages of agro-based jute fibers were their cost effectiveness, ease of availability, and nonabrasive nature. They allow high filling level and reduce the cost of the composite material. The cellular structure of jute fiber provides very good heat and noise insulation [13]. On the other hand the polypropylene (PP) possesses excellent mechanical properties such as tensile strength, fire resistance, and low price. PP is recyclable and so reduces the problems of waste disposal [14].

The primary goal of this work is to study the structural behavior of natural fiber reinforced structural insulated panels (NSIPs) for the structural application and their advantages over traditional OSB SIPs and advanced glass/polypropylene (G/PP) SIPs. To this end, flexural test was carried out on NSIPs to know the mechanical properties such as bending modulus, bending strength, shear strength, shear modulus, and the failure criteria. The flexural test was carried on NSIPs and comparison was made with OSB SIPs and G/PP SIPs as discussed in Section 4. The vulnerability of composite material against out-of-plane impact forces is always a major design concern for the laminated structural composites. To overcome the issue of low-velocity impact and to check the failure criteria, the LVI test along with flexural test was carried out on as described in Section 5. The LVI test results on NSIPs were compared with traditional OSB SIPs and G/PP SIPs in order to validate the use of NSIPs in building construction.

2. Pretreatments Given to Jute Fibers

The mechanical properties of jute fibers, such as density, tensile strength, and modulus, depend on their internal structure and chemical composition [15]. Jute fibers possess a lower tensile strength than glass fibers, and on the other hand a higher specific Young's modulus. The main disadvantage of jute in composite manufacturing is its hydrophilic nature, which affects the bonding with the PP materials. Therefore the mechanical properties such as strength and stiffness are highly affected. This limits the use of the polymer matrix to the low melting temperature plastics due to their low processing temperature. For the improvement of composite properties, several pretreatments such as mercerization, bleaching, and UV radiation may be given to the fibers prior to use them with PP.

The jute fibers consist of 50–60% cellulose, 20–25% hemicelluloses, and 12–15% lignin in their chemical composition [16]. These fibers consist of a long chain of cellulose molecules and lignin whereas the hemicellulose acts as cementing agent in giving strength and stability to the fibers. Lignin is the main ingredient of jute fibers which absorb moisture when exposed to the air. The fiber constitutes pendant hydroxyl and various polar groups which leads the fibers to the serious problem of moisture absorption. This moisture absorption ultimately leads toward poor interfacial bonding with resin. These fibers thus become unsuitable to use in

manufacturing NFRP laminates. To overcome this issues, in common practice, several treatments are given to the fibers prior to use them in NFRP composite manufacturing along with PP. These treatments includes bleaching, mercerization, and UV radiation treatment. But for the sake of brevity of this paper and based on ease of availability only bleaching treatment is given to the fibers for this study.

2.1. Bleaching. Bleaching is the most common method in which jute fibers are treated with oxidizing agents, such as sodium hypochlorite. A reaction takes place on the jute fibers in which the coloring agents get oxidized. Lignin is cementitious material which contributes mainly in the tensile strength of the fibers. The oxidizing agent mainly modifies the lignin from the fibers. Removal of lignin from the fibers provides jute fibers permanent white color, but simultaneously affects the tensile strength and young's modulus of fibers. To maintain the tensile strength of fiber the proportion of lignin should be retained as much as possible. The fibers are subjected to bleaching treatment using sodium hypochlorite (NaOCl). The raw jute fibers are soaked in 10% and 20% NaOCl for 4 hrs and washed with deionized water for 20 minutes to remove any chemicals present in it. The jute fibers are then allowed to air dry at room temperature [17]. NaOCl is the hypochlorous acid in which hypochlorite ions act as bleaching agent. Bleaching of jute fiber with NaOCl improves its brightness [17]. This deterioration of brightness of jute treated with alkali solution attributes to the removal of lignin from the structure of jute fibers. Bleaching of jute fibers, thus, results in reduction of tensile strength by 15%–20% due to the removal of lignin. The alkali treatment carried on jute fibers shows an increase in the elongation properties besides decreasing the tensile strength of the fibers [17]. In the bleaching treatment, the capillaries present in the fiber contract. The angle of contact increases due to the bleaching treatment. Young's modulus of jute fibers decreases after bleaching due to the removal of lignin [18]. The reduction of lignin from jute fibers improves their hydrophobicity, making them suitable for bonding with PP. Jute fibers treated with 10% NaOCl show greater moisture absorption than the jute fibers treated with a 20% NaOCl solution [9]. From the study, it is seen that the increase in NaOCl content also improves the resistance to humidity of the natural fibers [18]. The bleaching process affects stress strain curve and reduces the young's modulus of the fibers. It has been observed that there was a 220% increase in tensile strength of jute fibers treated with 10% NaOCl and 250% increase in tensile strength of jute fibers treated with 20% NaOCl to the raw jute fibers [18].

As the bleaching treatment demonstrated improved structural properties of the resulting laminate, the NFRP for the fabrication of NSIP panels for this study was manufactured using the bleached jute fibers.

3. Manufacturing of NFRP Laminates

Laminates can be manufactured using several methods such as extrusion blown molding, programmable powder perform process (P4), injection molding, film stacking, and

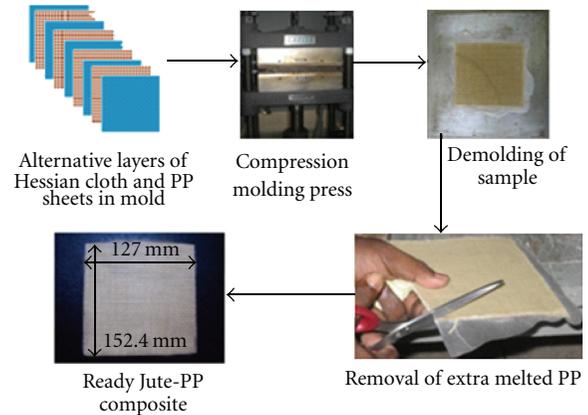


FIGURE 2: Detailed schematic of film stacking method for NFRP laminates.

hot melt impregnation method. In general, the laminate manufacturing process mainly governed by profit and loss ratio of particular production. All the processes vary according to the equipment cost and operating cost. The most suitable method for composite manufacturing is film stacking method [14]. This is a compression molding method in which fibers and matrices are subjected to predefined temperature and pressure. This method is cheaper than any other method used for manufacturing the laminates due to its low initial investment [14]. The fibers of desired size and desired directional orientation can be used for manufacturing the laminates. In this method the alternate layers of fibers and matrices are placed in position. This whole assembly is treated under predefined temperature and pressure up to the melting point of the matrix for certain time period and then allowed to cool at room temperature. Due to the melting of matrix it penetrates through the fibers. This penetration results in wetting of fibers and thus forming strong bond between fiber and matrix. After cooling the matrix the whole assembly turns into stiff and stable compound called as laminate.

In order to manufacture the NFRP laminates, bleached jute fibers were used along with polypropylene (PP). The alternate layers of fibers and PP films were used for manufacturing the laminates. Figure 2 shows the step by step illustration for manufacturing NFRP laminates.

NFRP laminates were manufactured at processing temperature 180°C and processing time 20 minutes at the applied pressure of 10 Tons [14].

4. Flexure Test of NSIP Samples

The main goal of flexure test was to check the suitability of NSIPs in flooring, and slab application to provide better alternative to the traditional OSB SIPs. Flexure test was carried on NSIPs to check the behavior of the specimen under different loading conditions and to check the deflection and failure types of the specimens. The prefabricated NFRP laminates with of 6.25 mm thickness were taken for manufacturing the NSIPs along with expanded polystyrene foam (EPS) with 25.4 mm thickness and $1.6 \times 10^{-5} \text{ g/mm}^3$

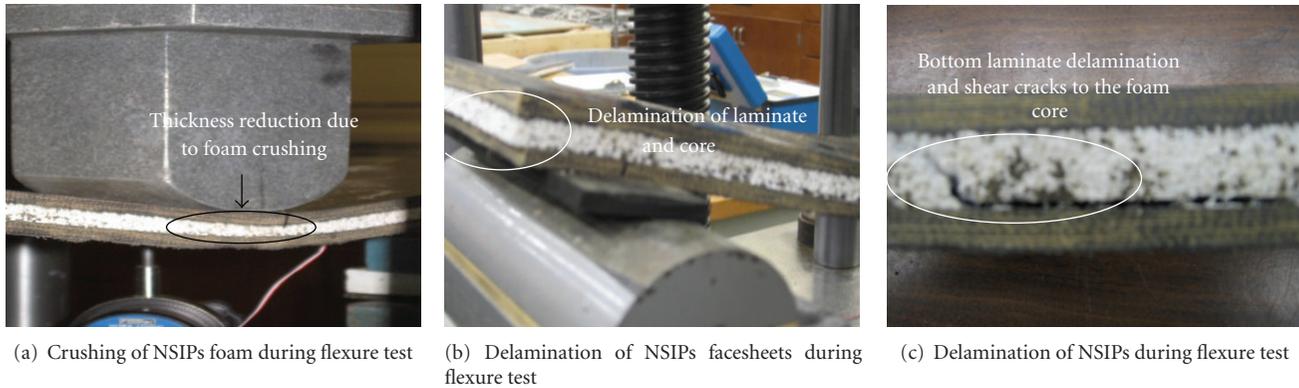


FIGURE 3: Failure modes of NSIPs during flexure test.

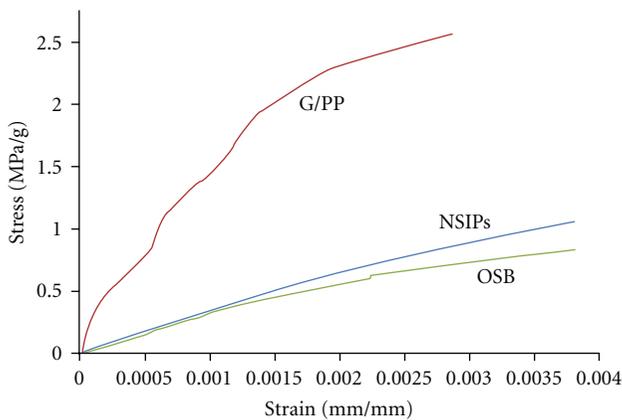


FIGURE 4: Comparison of normalized stress strain curves for different SIPs.

density for the core using hot melt spray adhesive to bond the NFRP with EPS [19].

Three-point bending setup was used for carrying out the flexure test on NSIPs and the stress-strain and load-deflection curves were obtained for these NSIPs. The load was applied at the center of specimen through rounded edge steel bars at constant rate of 2 mm/min as per ASTM C 393 [19]. The maximum load and deflection were recorded for all specimens. The load deflection curve was plotted to determine the sandwich stiffness. Four specimens of average dimensions 590 mm × 101 mm × 25.4 mm and average weight of 700 gm were used for the test and average stress strain curve was plotted for all specimens. For measuring the central deflection, dial gauge was placed at the bottom side of center of specimen. The strain gauge was placed at the center of specimen in order to record the strain induced. Figures 3(a)–3(c) shows different failure modes of NSIPs obtained during flexure test.

During the flexure test it was observed that the NSIPs failed due to shear failure of core and delamination of the facesheet and core as shown in Figure 3. From the flexure test on the NSIPs various parameters were obtained

using numerical formulae given in ASTM C-393 [19]. Normalization of stress strain curves were carried out by dividing obtained stresses by the final weight of the specimen tested in order to validate the comparison of specimens with respect to weight. Figure 4 provides normalized average stress strain relationships for NSIPs, OSB SIPs, and G/PP SIPs obtained from three-point flexural test.

From Figure 4 it can be observed that the average stress-strain curve for NSIPs is higher than that of traditional OSB SIPs. The NSIPs shows more a consistent curve than OSBs. Failure observed was due to slippage of specimens from the supports due to excessive bending without any crack to the laminates. The shear cracks and delamination of laminates were observed during flexure test on NSIPs. Table 1 summarizes the results of flexure test for NSIPs, OSB SIPs, and G/PP SIPs.

From the Table 1 it has been observed that the bending modulus of NSIPs was more than traditional OSB SIPs by 190%. Also the bending stress at the extreme fibers of facesheet was 189% more than OSB SIPs and 80% of G/PP SIPs. The overall deflection obtained for NSIPs was 64% less than G/PP SIPs. On the other hand the average weight of NSIPs was 30% less than the traditional OSB which results in great reduction of weight of components.

5. Low-Velocity Impact (LVI) Test

The objective of low-velocity impact (LVI) test was to represent the resistance offered by the NSIPs under LVI conditions such as impact of hammer, tool drops, and nails as well as thrown object from outside that damage the skin material of wall. LVI test were carried on NSIPs to investigate the dynamic deformation, failure mode, and the response of sandwich composites against sudden weight drops. The LVI test provides knowledge regarding damage-resistant properties of NSIPs that are very useful for design and material selection [8]. The usual tendency of composite structures against small impact results in delamination of stronger and stiffer facesheet from the comparatively less strong core material. The common mode of failure in LVI

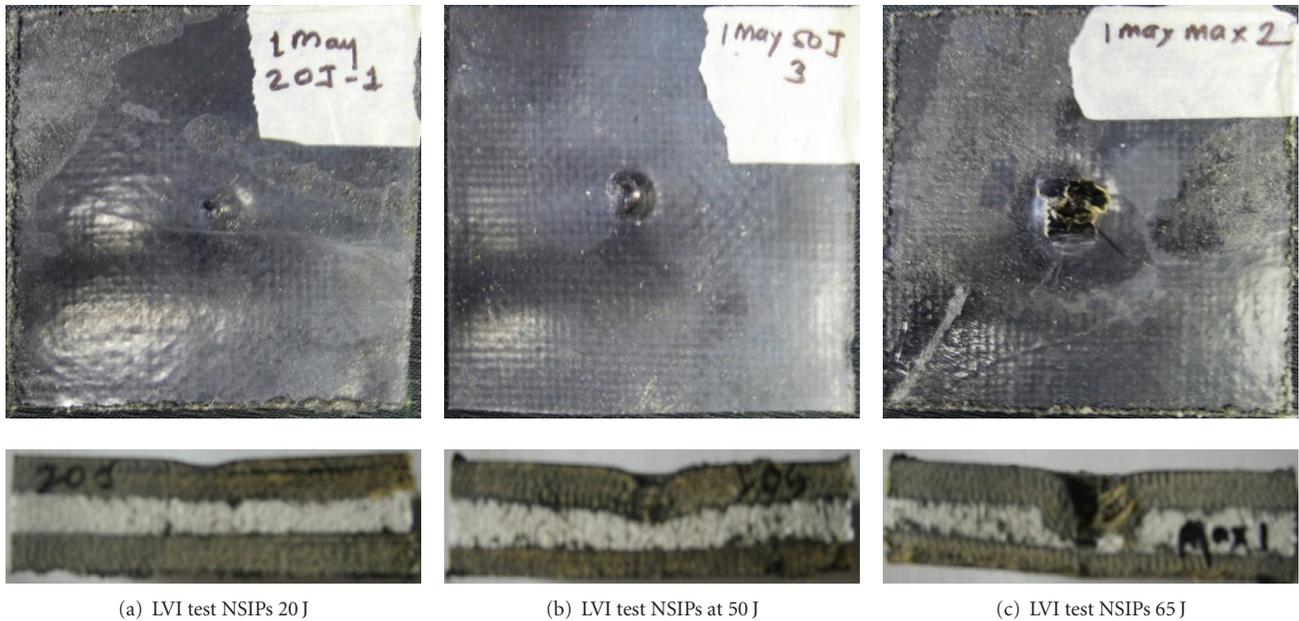


FIGURE 5: LVI failures of NSIPs at energy of 20 J, 50 J, and 65 J.

TABLE 1: Parameter obtained from flexural test on NSIPs, G/PP SIPs, and OSB SIPs.

Description	Load at failure (N)	Deflection obtained (mm)	Bending modulus (MPa)	Maximum bending stress (MPa)	Weight of material (gm)
NSIPs	511.52	27.83	1.71E3	5.41	518.4
OSB SIPs	978.56	18.84	0.90E3	2.86	732.8
G/PP SIPs	266.88	43	9.74E3	6.78	379.6

were surface cracking, laminate buckling, and debonding between laminate and core.

To know the LVI response, the impact tests were performed on NSIPs using a drop tower device with a free-falling mass. The damage was imparted through out of plane, concentrated impact perpendicular to the laminate using Instron 8250 drop-weight impact machine with instrumented striker assembly. Impacts of mass were carried out at the center of NSIPs, sufficiently away from the edges to avoid interaction of stresses at the edges and stresses at the impact location during damage formation. Damage resistance of composite depends on several factors such as thickness of plate, stiffness of material, mass, and boundary conditions.

NSIPs with variable laminate thickness were cut into piece of $101.6\text{ mm} \times 101.6\text{ mm}$ size for the test. These specimens were placed in the fixture with two-plate assembly used to hold the specimens in perpendicular direction to the freely falling mass. The fixture was then tied with screws in order to prevent the specimen movement and provide fixed end conditions. The drop weight impactor was then raised to the desired height and allowed to fall freely on the specimen in order to create required impact force on the specimen.

All data such as force at the time of impact and break and velocity of hammer was recorded with data acquisition software. The specimens were subjected to impact energy of 20 J, 50 J, and 65 J. From the LVI test various parameters such as impact energy absorbed by specimens, peak load at the time of failure, total energy, and impact velocity were calculated. Figure 5(a)–5(c) shows failures observed on NSIPs during LVI test.

From Figure 4, various failure modes were observed for the NSIPs. At energy of 20 J, the NSIPs showed indentation to the top laminate without any damage. On the other hand, at 50 J and 65 J, the top laminates were damaged due to impact. A crushed core and slight indentation to the bottom laminates have been observed at 65 J. The LVI test were also carried out on OSB SIPs and G/PP SIPs in order to compare the results obtained in all cases so as to replace the NSIPs with OSB SIPs and G/PP SIPs. Figure 6(a)–6(c) shows load versus time and energy versus time curve at 20 J, 50 J, and 65 J.

From Figure 6(a) it can be observed that G/PP SIPs and OSB SIPs followed the same energy and load paths. The maximum load attained by them was 2.04 kN and 2.09 kN respectively, whereas, in case of NSIPs the maximum load

TABLE 2: Comparison of Impact response of NSIPs with OSB and G/PP SIPs.

Impact energy (J)	20			50			65		
Velocity (m/s)	2.6			4.0			4.7		
Impact height (m)	0.33			0.82			107		
Specimen	NSIP	G/PP	OSB	NSIP	G/PP	OSB	NSIP	G/PP	OSB
Total energy (J)	16.6	13.8	14.9	44.3	30.4	6.97	68.6	42.7	20.3
Energy at yield (J)	18.5	2.13	0.89	—	0	0	—	0	−13.6
Energy at failure (J)	17.4	14.8	15.5	46.2	34.8	6.90	69.1	48.8	20.0
Maximum load (KN)	3.2	2.04	2.09	4.9	6.57	0.74	5.0	8.23	2.03
Load at yield (KN)	3.1	0.73	1.44	0.02	0	−0.02	0	0	−0.85
Load at failure (KN)	0.6	0.40	0.40	0.9	1.30	0.13	0.9	1.62	0.39
Defl. at max. load (mm)	14.0	17.5	10.9	19.7	20.8	12.5	22.7	23.5	61.0
Defl. at yield (mm)	13.4	3.98	1.20	—	0	0	—	0	45.8
Defl. at failure (mm)	11.4	11.0	8.67	19.1	15.0	21.0	28.8	18.4	74.1
Total deflection (mm)	7.5	5.64	5.71	11.8	6.04	22.3	27.5	7.86	75.6

attained by specimen prior to failure was 3.2 KN which is 57% higher than G/PP and 53% higher than OSB SIPs. The energy absorbed by NSIPs was 16.6J which is 20% higher than G/PP and 11% higher than OSB SIPs. It can be observed from Figure 6(b) that the total energy attained by NSIPs was 44.3J which is 45% higher than G/PP SIPs. Also at 65J as shown in Figure 6(c), maximum load attained by the NSIPs was 5 KN which is 246% higher than OSB SIPs. The maximum energy absorbed by NSIPs is 68.6J which is 60% higher than G/PP SIPs. From the LVI results and the curve plotted the information was obtained, as summarized in Table 2.

From the LVI tests on NSIPs, it can be concluded that the NSIPs showed comparable results in terms of energy absorption with G/PP and OSB SIPs. The LVI test was carried out on NSIPs manufactured using bleached jute fiber, considering their superiority over other type of treated fibers. The LVI test was also carried out on G/PP and OSB SIPs in order to compare the NSIPs with traditional OSB and G/PP SIPs. The following are the conclusions obtained from NSIPs, OSB SIPs, and G/PP SIPs LVI tests.

- (1) The total energy absorbed by NSIPs at 20 J was 12% higher than G/PP SIPs and 11% higher than OSB SIPs.
- (2) The energy absorbed by NSIPs at 50 J was 45% higher than G/PP and 64% higher than OSB SIPs.
- (3) The energy absorbed by NSIPs at 65 J was 60% higher than G/PP.
- (4) The maximum load taken by NSIPs was higher in all cases in which it showed an increase of 53% increase in maximum load at 20 J and 146% at 65 J compared to OSB SIPs.

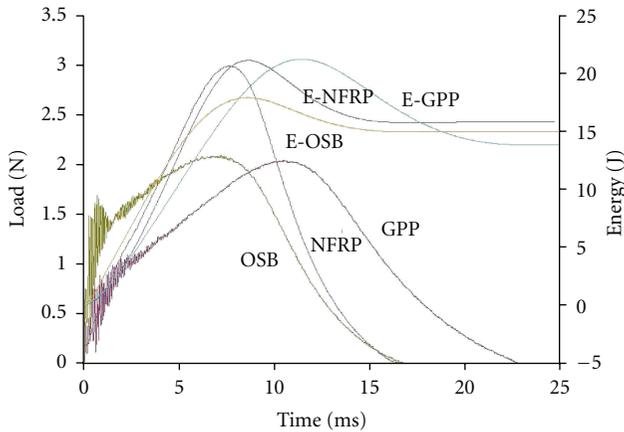
The overall performance of NSIPs in all cases resulted in a significant improvement in the energy absorption as well as

mechanical properties of NSIPs compared to traditional OSB SIPs and G/PP SIPs.

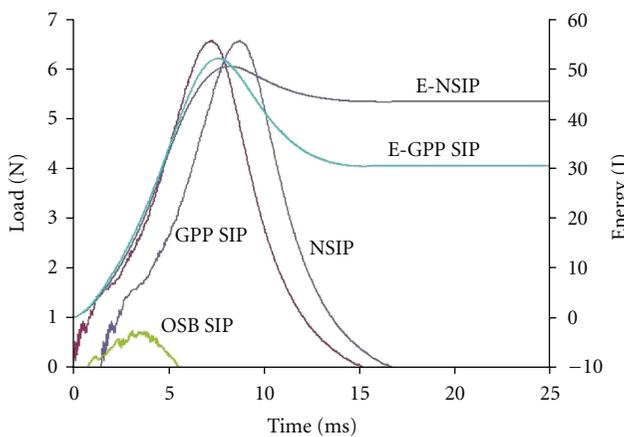
6. Summary

Flexural strength tests and low-velocity impact tests were carried out on the reduced scale NSIP panels to determine the behavior of NSIPs in bending and impact conditions. The EPS foam with 25.4 mm thickness was used for the core along with NFRP laminates in the resulting manufacture of the NSIPs. Structural characterization of innovative, reduced scale NSIPs was presented in this paper, and the following conclusions were drawn from this study.

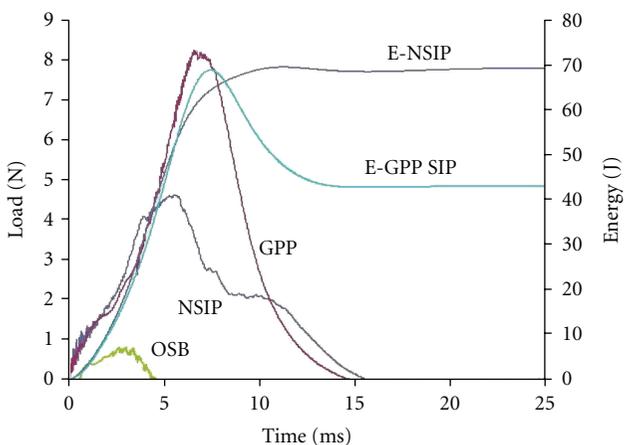
- (i) Bending modulus of NSIPs is 190% higher than OSB SIPs. Also the bending stress at the extreme fibers of facesheet is 189% more than OSBs and is 80% of G/PP SIPs.
- (ii) There is great savings in the material as the weight of NSIPs is 30% less than the weight of OSB SIPs.
- (iii) G/PP SIPs and OSB SIPs followed the same energy and load path in which the maximum load attained by them was 2.04 KN and 2.09 KN.
- (iv) The maximum load attained by NSIPs prior to failure was 3.2 KN which is 57% higher than G/PP and 53% higher than OSB SIPs.
- (v) In case of 20 J impact energy, The energy absorbed by NSIPs was 16.6 J which is 20% higher than G/PP and 11% higher than OSB SIPs. In case of 50 J impact energy, total energy attained by NSIPs was 44.3 J which is 45% higher than G/PP SIPs. Also in case of 65 J impact energy, the maximum load attained by the NSIPs was 5 KN which is 246% higher than OSB SIPs. The maximum energy absorbed by NSIPs is 68.6 J which is 60% higher than G/PP SIPs.



(a) Load versus time and energy versus time curve at 20 J



(b) Load versus time and energy versus time curve at 50 J



(c) Load versus time and energy versus time curve at 65 J

FIGURE 6: Load versus time versus energy curve for NSIPs, G/PP, and OSB SIPs at 20 J, 50 J, and 65 J.

Hence it can be concluded that the NSIPs can be used as a better alternative to OSB SIPs and G/PP SIPs in structural applications such as flooring and walls.

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