

New Concept for Optimal Application of Natural Fibre Reinforced Plastic (NFRP) in Building Construction

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Abstract — Natural fiber reinforced plastic (NFRP) has drawn more attention as an alternative materials, particularly when dealing with the concept of green or sustainable building. Although many efforts have been introduced, most results remain unsatisfied either structurally or economically. In this study, NFRP laminates were incorporated as the intermediate layer of hybrid structural insulated panels (hybrid SIPs). Two types of natural fibers, Jute and Hemp, were used to produce laminates for the intermediate layer. A total of 24 panels samples were tested using 4 point bending load scheme under half and full scale model followed by a statistical analysis of the results. The result shows the potential of using NFRP to improve the structural properties of hybrid SIPs.

Keywords-natural fibre reinforced plastics (NFRP); hybrid structure; building construction; SIPs

I. INTRODUCTION

The concept of green or sustainable building has now been a popular term in construction industry as the awareness of environment protection continues to rise. The key principles relate to the ecological sustainability of building are such as the use of raw materials based on renewable resources, products are easily recycled and are economic during the construction process (Berge, 2009). The concept of sustainable material integrates a variety of strategies during design, construction and site operation. The term of sustainable or sustainability has many definitions, adaptations and applications. The most common and widely accepted meaning can be adopted from the term of sustainable development which is defined as a meeting the needs of the present without compromising the ability of the future generations to meet their own needs (WCED in UN-Habitat, 2008).

In relation to the above principles of sustainability, natural fibers are a major renewable resource material throughout the world specifically in the tropics. According to the Food and Agriculture Organization (FAO) survey, natural fibers like jute, sisal, coir, and banana are abundantly available in developing countries such as India, Srilangka, Thailand, Indonesia, Bangladesh, Philippine, Brazil, and South African. Recent reports indicate that plant fibers can be used as reinforcement in polymer composite to replace more expensive and non-renewable synthetic fibers such as glass especially in low pressure laminating (Mathur, 2006).

Currently, natural fiber reinforced composites have drawn more attention as alternative building materials, especially as wood substitutes in the developing countries. The concept of using natural fiber in building components is not entirely new as it has been reported in the early seventies. The construction of cheap primary school building using jute fiber reinforced polyester in Bangladesh (1972-73) under the support of CARE and UNIDO is considered as a first effort in the use of natural fiber composite in developing countries. In the 80s, building panels and roofing sheets made from bagasse/phenolic were installed in houses in Jamaica, Ghana and Philippines. In another program, developmental work on low cost building materials based on henequen, palm and sisal fibers and unsaturated polyester resin had been undertaken as a co-operative research project between Government of Mexico and UNIDO for appropriate utilization of natural resources. In the 90s, UNDP in association with the government of India supported a program to develop jute based composite and moulded products as wood substitutes in packaging building sectors (Mathur, 2006). The use of natural fibers as reinforcement in a cement matrix has also been practiced for developing cheap building materials such as panels, claddings, roofing sheets and tiles, slabs and beams.

More recent efforts relating to the application of NFRP in building construction are as follows. Burgueno et al., (2004) reported their study which demonstrated that bio-composites could be used for load-bearing components by improving their structural efficiency through cellular material arrangements. Laboratory-scale periodic cellular beams and plates were made from industrial hemp and flax fibers with unsaturated polyester resin. Material and structural performance was experimentally assessed and compared with results from short-fiber composite micro-mechanics models and sandwich analyses. Short-term analytical evaluation of full-scale cellular bio-composite components indicated that they were compatible with components made from conventional materials. Dweib et al. (2006) manufactured a bio-based roof structure. Cellulose fibers were successfully mixed with soy oil-based resin to form composite structural panels. The cellular fibers were in the form of paper sheets made from recycled cardboard boxes. The panels were prepared using a modified VARTM process. The result provided from beam test shows that the stiffness and strength meet the requirement for roof construction. In addition, Uddin et al. (2011) developed a natural fiber

reinforced polymeric structural insulated panels (NSIPs) for panelized construction. This structural sandwich panel is made of jute reinforced polypropylene laminates skins separated by an expanded polystyrene (EPS) foam core. Structural characterizations were performed using flexural and low velocity impact (LVI) tests. Both test results show the potential of NSIPs concept to serve as an alternative to OSB SIPs and G/PP SIPs in structural application such as flooring and walls.

Although many efforts have been introduced, most results remain unsatisfied either structurally or economically. A bio-based building component with higher structural performance is normally achieved at the expense of significantly higher cost as we need to provide a larger size. On the other hand, reducing the size to maintain normal cost will only produce building component with lower structural performance which may not be competitive with the conventional building materials. For instance, Singh et al. (2005) stated that manufacturing of single layered natural fiber based panels as the alternative for plywood has failed to possess desired properties as building materials. The specific strength, stiffness and dimensional stability were inadequate. In order to cope with this problem, a composite laminate from hybrid natural fibers was developed. This product can be prepared using different types of natural fibers such as sisal, jute, coir mats and unsaturated polyester, phenolic or polyurethane resins.

In order to deal with those shortcomings, Sarah et al. (2009) suggested modifying the shape of structural components to overcome the nature of large deflection performance of natural fiber composites due to their low modulus of elasticity, or involving hybridization at both the constituent and structural levels as advised by Drzal et al. (2004). This paper presents a new concept of applying NFRP in a building component namely hybrid structural insulated panels. The basic concept, manufacturing process and the results provided from experimental testing will be discussed thoroughly.

II. RESEARCH CONCEPT, SAMPLE FABRICATION AND TESTING PROGRAM

A. Research Concept

As an alternative to conventional brick and concrete construction, structural insulated panels (SIPs) have proven their ability for load bearing building construction. The nature of SIPs is a sandwich structure that consists of two skins separated by a thick-lightweight core. The current most employed skin is an oriented strand board (OSB) due to their ease of manufacturing and availability. Some advantages of SIPs with OSB skin are such as cost and energy efficient as well as require less construction and maintenance time. On the other hand they also have some drawbacks that limited their use. The organic nature of OSB skin laid them under the risk of mold build-up and termite attack and environment changes. The poor water resistance properties of OSB can lead them to be adversely affected by the presence of a flood. Following the hurricane Katrina in New Orleans in 2005, that damaged many houses built with OSB SIPs due to windborne missiles, several advancements were introduced to swap the conventional OSB skin using advanced composite laminates and metal. Laminates made of glass/polypropylene, carbon/epoxy or glass epoxy have been introduced which have excellent properties to

replace OSB (Vaidya et al., 2008). Other effort is the replacement of the OSB material with metal based skins such as steel and aluminium to produce more durable and tougher structural insulated panel that is known as metal SIPs (www.permatherm.net).

Both alternative materials for OSB replacement, composite and metal based skin, are actually excellent in terms of strength and durability. However, in building construction those two factors are not only the concern when it comes to the final production line due to many competing products have been released to the market. One important thing that needs to be concerned is a cost effective issue, a new product must have a competitive price with conventional products. The presence of glass and carbon fiber in composite laminates skin and aluminium or steel in metal skin are questionable when cost and environmental-friendly concern comes in to consideration. In addition, the presence of very thin skin in metal based SIPs for cost reduction reason creates a particular problem when combined with low density EPS core. For that reason, there is still a need to develop a new material for producing more durable, effective and efficient SIPs. In this work we employed a hybrid concept in developing new-hybrid structural insulated panels.

A combination of two or more materials in a predetermined geometry and scale, optimally serving a specific engineering purpose is called as a hybrid material. However, there is a certain duality about the way in which hybrids are observed. Ashby et al. (2003) mentioned that sandwich structure is an example of hybrid material that reflects duality, sometimes it is regarded as a structure that consists of two skins with a thick core layer in the middle, but occasionally it is also viewed as a bulk material that has its own density, stiffness and strength. The concept introduced in this work can be explained as follows. A natural fiber reinforced plastics (NFRP) laminate is placed as an intermediate layer in between aluminium skin and EPS core to produce a hybrid SIPs as shown in Fig. 1. Hence, this new structure is a combination of two components, SIPs with aluminium skins as an integrated sandwich structure and intermediate layer laminates made of NFRP that resulting in a hybrid structure. When we consider a monolithic panel made upon a homogenous material subjected to a loading scheme, the typical normal stress distribution is a straight diagonal line from the top surface to the bottom. The stress distribution, however, will have a considerable transform at the top and bottom interface between skin and core layers when the panel is in the form of sandwich structure. Many authors addressed this broadly gap as the causes of the structure's early failure. The idea of introducing intermediate layer, which has moderate properties between the skins and core, is likely to reduce this gap.

This concept can be simply explained based upon the Hooke's law which implies that the stress is the function of material's modulus of elasticity. When the intermediate layers are placed in between, the gap between high and low stress configurations of skins and core can be reduced adequately because the elastic modulus of intermediate layers has the value between the two classical sandwich constituents. This material configuration, i.e. two layers of skins and intermediate layers at the top and bottom and the core in between, is

theoretically generating a higher flexural strength for the sandwich beam.

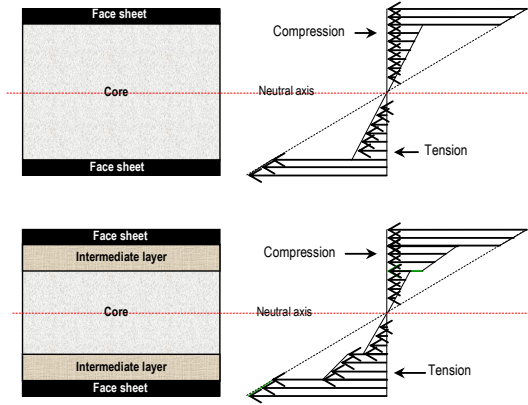


Fig. 1. Typical stress distribution in conventional SIPs (above) and hybrid SIPs (below)

The concept has been developed based on the previous work of Steeves et al. (2004) and Mamalis et al. (2008). The failure of a sandwich structure is a very complicated phenomenon. This complication may be due to various failure mechanisms in one of the materials that compose the structure. These failure mechanisms have been analyzed and tested and can be summarized as follows (Mamalis, 2008):

$$\text{Face micro-buckling} \quad : \frac{P}{b} = \frac{4t_f t_c \sigma_f}{L} \quad (1)$$

$$\text{Face wrinkling} \quad : \frac{P}{b} = \frac{2t_f t_c}{L} \sqrt[3]{E_f E_c G_c} \quad (2)$$

$$\text{Core shear} \quad : \frac{P}{b} = 2t_c \tau_c \quad (3)$$

$$\text{Indentation} \quad \frac{P}{b} = \sqrt[3]{\frac{\pi^2 E_f \sigma_c^2 t_f^3 t_c}{L}} \quad (4)$$

$$\text{or} \quad \frac{P}{b} = \sqrt{\frac{16E_f E_c t_f^3 t_c}{3L^2}} \quad (5)$$

where:

- τ_c : shear strength
- σ_f : compressive strength
- b : width of the sandwich panels
- E : elastic modulus
- G : foam core shear modulus
- L : span between supports
- P : load
- t : thickness

Subscripts

- f : face sheet
- c : core
- I : internal layer

It can be seen from the above equations that the materials can have a substantial influence to the failure of the sandwich structure. For instance, if a weak but cheap core is used, it is very likely that the beams will fail either due to core shear or due to indentation especially in three-point loading. The introduction of intermediate layer will not affect face micro-buckling (1) or core shear (3), which depends only on the skin and core properties, but it will improve face wrinkling (2) and

indentation (5) of sandwich structure. When intermediate layer placed between the face sheet and core, then equations (2) and (4) changes to:

$$\text{Face wrinkling} \quad : \frac{P}{b} = \frac{2t_f t_c}{L} \sqrt[3]{E_f E_i G_i} \quad (6)$$

$$\text{Indentation} \quad \frac{P}{b} = \sqrt[3]{\frac{\pi^2 E_f \sigma_i^2 t_f^3 t_i}{L}} \quad (7)$$

As the elastic modulus and compression strength of intermediate layer are higher than the core material, the failure limit loads for face wrinkling and indentation will increased significantly. This hybrid structure will have better structural performance at the expense of a slightly higher weight while maintaining or even reducing the cost. The cost of core materials is always a concern in manufacturing sandwich panel especially when metallic materials involved inside the structure. The use of intermediate layer provides a possibility of using a weaker and cheaper core which finally decreased the cost considerably.

B. Sample Fabrication Using Vacuum Bagging Method and Testing Program

A vacuum bagging process was used for preparing natural fibre laminates. In a manual to the principle s and practical application of vacuum bagging for laminating a composite materials published by West System® Epoxy, vacuum bagging (or vacuum bag laminating) is defined as a clamping method that uses atmospheric pressure to hold the adhesive or resin-coated components of a lamination in place until the adhesive cures. Vacuum bagging uses atmospheric pressure as a clamp to hold fiber and matrix together within an airtight envelope. More simple description about vacuum bag moulding is the process that combines manual method using hand-layup or spray-up on the open mould to produce a laminated component followed by a vacuum process after covering the laminated using polymeric sheet (Kaynak et al., 2001). The current available modern adhesives that can be cured at room temperature have helped to make vacuum bag laminating techniques economically available by eliminating the need for much of the sophisticated and expensive equipments required for laminating in the past. This method offers many advantages over others available method such as the possibility of controlling matrix content, produce custom shapes and allows to complete the laminating process in one efficient operation. It also delivers a firmly and evenly distributed pressure over the entire surfaces regardless of the nature or amount of material being laminated.

The procedures for vacuum bagging process that used in this experiment are as follows.

1) This process was started by preparing all the materials to be laminated. Jute woven and hemp mat were cut into required shape and placed in the mold. In the same time, a release fabric, breathe material and vacuum bag were also cut to size. The vacuum bag was cut 20% larger than the mold dimensions.

2) The second step was applying the mold release to the mold and shelf surface followed by applying mastic sealant to the mold perimeter. The sealant was firmly pressured and overlapped to avoid the existence of gaps.

3) The surface of the mold base then wetted out with the matrix (mixed epoxy resin and hardener) and the first layer of fiber mat was put on the top of it. The matrix then poured on the top of the fiber mat and firmly spread out prior to place the subsequent fiber mat. This process was repeated several times until the required thickness had achieved. This process needs to be done carefully since once the epoxy mixed the time limit for the entire process is established.

4) The excess epoxy was then squeezed from each layer after it was wetted out. The excess epoxy on the fibre mat was rolled out to make sure there had no puddles of epoxy or air pocket under the fibre mat. When properly wet out, a puddle of epoxy will appear around the edges of a thumb print after a few pounds of pressure with a roller.

5) A layer of release fabric was then placed over the laminate followed by a layer of breathe material. The release fabric will peel off the cured laminate leaving a fine textured surface. It will also absorb the excessive epoxy that can be removed after curing. The breathe material, a polyester blanket, that placed above the release fabric allows the air to pass through the fibres to the port and absorbs excess epoxy that passes the release fabric.

6) The vacuum bag was then placed over the mold and sealed to the mold perimeter. The protective paper was then peeled from the mastic sealant starting at the corner of the mold. The edge of the bag has to be firmly pressed on to the mastic sealant while pulling the bag taut enough to avoid wrinkles. Since the bag perimeter is larger than the mold, we need to create several folds of excessive material as the bag sealed around the mold.

7) The folds of excess bag were then sealed with a strip of the fold. This process was repeated wherever the fold exists around the mold.

8) The next process was connecting the vacuum line to the bag with a vacuum port. The vacuum port used here was basically a suction cup with a hole through it, attached to the end of the line. A small hole was punctured and the port was attached to the bag over the hole. Breather fabric provides a path to the port inside the bag over a wide area. We need to place an extra layer or two of breather under the port.

9) After all the previous procedures done, the vacuum pump was then turned on to begin evacuating air from the bag. If necessary, temporarily shut off the vacuum to reposition laminate or adjust the bag. As the air is removed from the bag, we need to listen for leaks around the bag perimeter, particularly at the folds in the bag, laps in the mastic and at the vacuum line or port connection.

10) After the laminate curing thoroughly, the vacuum bag breather and release fabric were entirely removed from the mold. The laminate was separated from the mold by inserting small wooden or plastic wedges between the edge of the laminate and the mold.

Once the laminates ready, they were cut into required size to make SIPs samples for structural testing. The experimental testing in this study was aimed at providing the information whether introducing natural fiber composite laminates as the intermediate layer would or would not significantly improve the structural properties of hybrid structural insulated panels. Hence, the testing program was designed as a single factor

experiment with 3 levels in which two different types of natural fibre laminates were employed as the intermediate layer of SIPs with aluminium skin and EPS core. Each type of intermediate layer has played the role for a variable or factor in the experimental design which is called a qualitative factor. Those two variables or factors were compared to a control which was a conventional SIP without intermediate layer. The size of the samples was produced into two categories or scales; full scale and a half scale while maintaining its aspect ratio. The full scale model refers to as the minimum size of metal SIPs that currently available in the market. The testing results were then analyzed using statistics software Minitab 15. For the purpose of analysis, those factors were leveled as 0, 1 and 2 as required by Minitab software. For a half scale model, level 0 was the SIPs without intermediate layer or control level while level 1 and 2 refer to as Hemp fiber composite (HFC) and Jute fiber composite (JFC), respectively. In full scale scheme, level 1 and 2 refer to as Jute fiber composite (JFC) and Medium Density Fibre (MDF) while level 0 was control factor which is the SIPs without intermediate layer. The beam SIPs samples were fabricated in accordance with ASTM C 393-00 which is a standard test method for flexural properties of sandwich constructions. The equipments for vacuum bagging process used in this study are as shown the Fig. 2.



Fig. 2. The equipments for vacuum bagging process

In half scale model, the samples were cut and shaped into a span length of 450 mm and the size of 550 x 50 x 22 mm for

length, width and thickness, respectively. Aluminium sheet with the thickness of 0.5 mm was used as the skins for all samples. They type of intermediate layers were varied with the same thickness of 3 mm. The thickness of EPS core for control level was 21 mm and 15 mm for all factor levels to maintain a constant overall thickness of 22 mm. Each level was replicated 4 times; hence the total of samples tested was 12 beams. The beams were tested using four-point bending load scheme. The testing set-up for this experiment is as presented in the Fig. 3. For the full scale model, the samples were cut and shaped into a span length of 1150 x 100 x 52 mm for length, width and thickness, respectively. The similar materials with the half scale model were used for the skins and the core. Aluminium sheet with the thickness of 1.0 mm was used as the skins for all samples. They type of intermediate layers were varied with the same thickness of 6 mm. The thickness of EPS core for control level was 50 mm and 40 mm for all factor levels to maintain a constant overall thickness of 52 mm. Each level was also replicated 4 times and tested using four-point bending load scheme. The testing set-up for this experiment is presented in the Fig. 3.



Fig. 3. Testing set-up for four point bending test

III. RESULT AND DISCUSSION

Fig. 4 shows the average maximum load carrying capacity and deflection against the type of intermediate layer for a half scale model. The average maximum ultimate load for hybrid SIP with HFC and JFC intermediate layer was 591.50 N and

396.25 N, respectively. Whilst the average value for conventional panel was 305.75 N. It can be noted here that the load carrying capacity of hybrid SIPs is significantly higher than the conventional SIPs. The percentage of improvement was 93.46% for hybrid SIPs with HFC and 29.60% for JFC intermediate layer. In addition, those two hybrid SIPs can endure a large deflection before reaching the failure load as shown in the Fig. 5. This figure plots the load-deflection curve of structural insulated panels tested in this experiment. The average maximum deflection for hybrid SIPs with HFC and JFC intermediate layer was 40.19 mm and 55.44 mm, respectively. The correspond value for conventional SIPs was 11.80 mm which is 240.49% and 370.25% less than those of hybrid structural insulated panels with HFC and JFC intermediate layer, respectively.

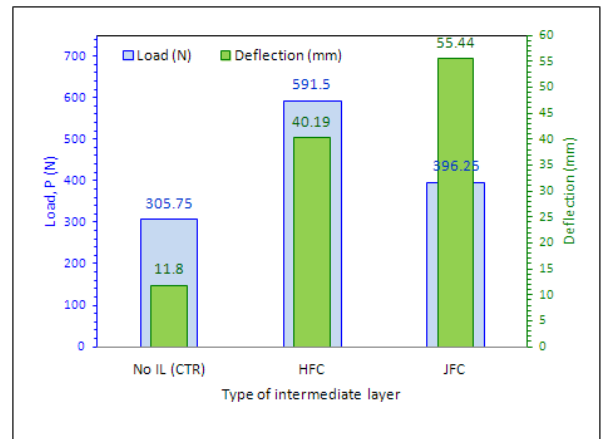


Fig. 4. The maximum average load and deflection of SIPs against type of intermediate layer used for half-scale model

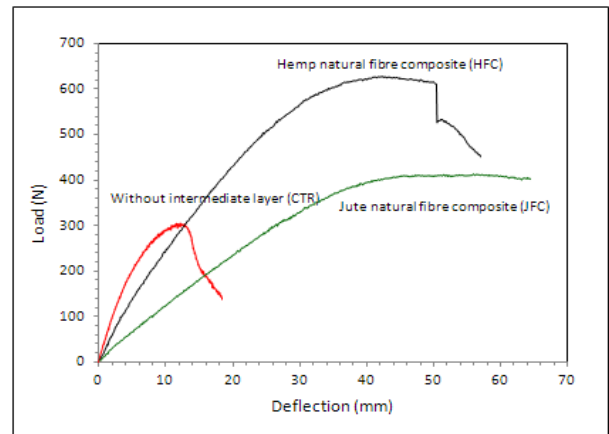


Fig. 5. Load-deflection curve of structural insulated panels for half-scale model

The advantage of using natural fiber composite as the intermediate layer of hybrid SIPs is also shown by the full scale testing scheme. As can be observed from Fig. 6 which shows the load carrying capacity and deflection against the type of intermediate layer for a full scale model, the average maximum ultimate load for hybrid SIP with JFC intermediate layer was

807.25 N. This value is 62.58% higher than the conventional SIPs with the average maximum load of 496.5 N. The ultimate load of conventional SIPs was also far lesser than those of hybrid SIPs with lignocellulosic composite intermediate layer, namely medium density fiber (MDF), which was 1333.5 N.

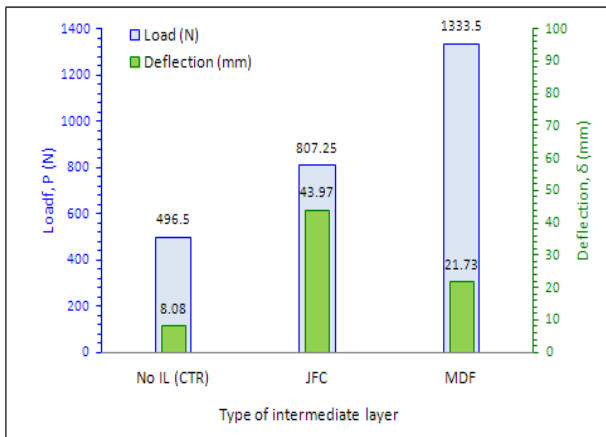


Fig. 6. The maximum average load and deflection of SIPs against type of intermediate layer used for full-scale model

Similarly to the data of deflection in half scale model, the full scale model also shows that the hybrid SIPs with natural fiber intermediate layer could withstand a large deflection before reaching its peak load. The average maximum deflection for hybrid SIPs with JFC intermediate layer was 43.97 mm compared the maximum deflection of conventional SIPs which is 8.08 mm. The average maximum deflection of hybrid SIPs with MDF intermediate layer is also higher than this value which is 21.73 mm. The load-deflection curve of structural insulated panels tested in full scale is presented in the Fig. 7.

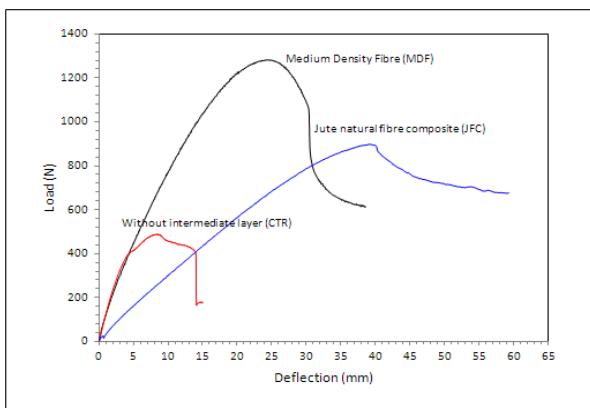


Fig. 7. Load-deflection curve of structural insulated panels for full-scale model

The typical failure patterns of structural insulated panels tested in this experiment are shown in Fig. 8. It is clearly demonstrated that the introduction of intermediate layer has prevented the existence of premature failure modes. The typical failure mode of conventional SIPs was a localised delamination between core and top skins in the maximum

flexural zone in compression which is known as wrinkling of the skins in compression due to a sudden local buckling of the top skin. The addition of NFRP laminates as the intermediate layer provide some additional strength to hybrid SIPs to endure more load and then collapsed under other types of failure mechanism such shear failure of the core or and late delamination after experiencing large displacement which finally resulted in higher load carrying capacity. The typical failure patterns of some specimens are as illustrated in the following figure.

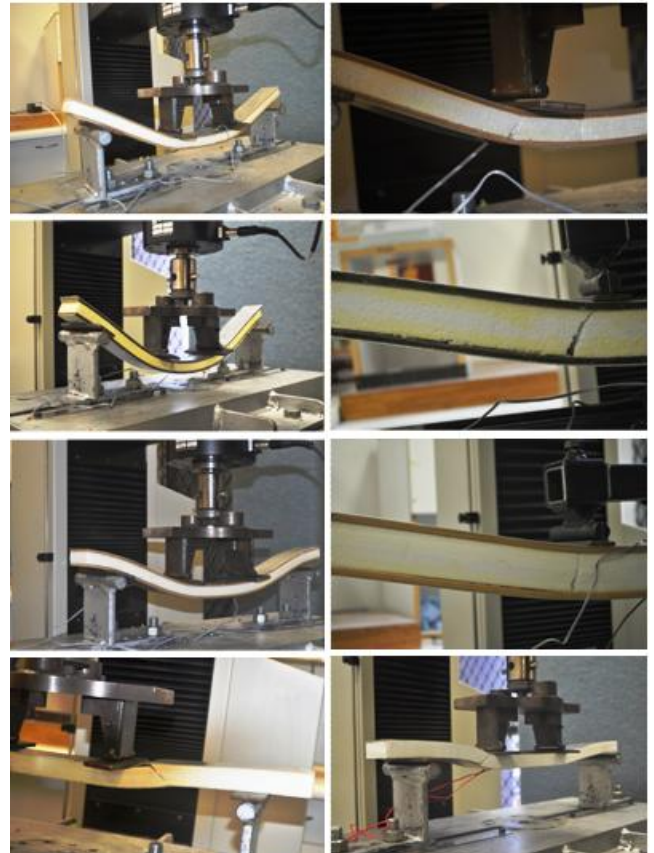


Fig. 8. Typical mode of failures of SIPs tested

The primary objective of this study was actually to find out how significant the improvement given by the introduction of NFRP composites as the intermediate layer of hybrid SIPs. In order to achieve the objectives of the research, the work was designed as a single factor experiment in which one variable is varying during the experiment and all the rest variables are fixed. The type of natural fiber used for intermediate layer laminates was varied while all other materials as well as the shape and size were fixed. A single factor analysis is a process of analyzing data obtained from experiment with different levels of a factor, usually more than two levels of factor. This experimental design is the most common approach employed by many researchers to explore the difference among more than two levels of a factor. The results of experiments were then analyzed using analysis of variance (ANOVA). As the name implies, this analysis tool attempts to evaluate the variation in a set of responses and

that the null hypothesis should be rejected and it can be concluded that the level means differ. The difference of the means of the factors confirms that the introducing of NFRP composite laminates for the intermediate layer significantly affects the load carrying capacity of SIPs.

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