EXPERIMENTAL CHARACTERISATION OF THIN SANDWICH PANEL OF POLYMER COMPOSITE

Prashant Kumar[1 *], Axay Kumar[2], Kamal.K. Kar[3] & J. Ramkumar[3]

[1]Professor, Department of Mechanical Engineering, IIT Kanpur 208 016, India,
[2]Scientist 'SC', ISRO Satellite Centre, Bangalore 560 017, India
[3]Asst. Professor, Department of Mechanical Engineering, IIT Kanpur 208 016, India

[*]Author to whom correspondence should be addressed
E-mail: jrkumar@iitk.ac.in

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ABSTRACT

A thin sandwich panel using 3 mm coremat and FRP skins of glassfibre chopped strand mat – epoxy was constructed through the hand lay-up technique. This kind of sandwich structure might replace a mild steel sheet enclosure used in many appliances and machines including auto bodies. The sandwich panels were characterized with three kinds of experimental investigation to find (i) flexural stiffness (ii) in-plane shear strength and (iii) impact-induced-damage by a low velocity foreign object. In comparison to mild steel, the sandwich panels were lighter with considerable saving in weight, the static strength was found to be attractively higher, flexural stiffness was better, and in-plane strength was reasonable. The impact-induced-damage and their mechanism of failure of these sandwich panels is also studied.

Keywords : Sandwich structure, chopped strand mat, impact induced damage, polymer composite, flexural stiffness

1. INTRODUCTION

Fibre polymer composites are now finding their applications, due to their attractive properties, in making thin enclosures or covers of many machines and appliances. The body cover of automobiles, washing machines, CNC machines, boats, railway coaches are some of the interesting applications to make them light weight, strong, attractive, less prone to environmental degradation, economical, etc. For several decades, the automotive companies have been making some components of exterior body from monocoque laminate of polymer composites. A thin structure of monocoque GFRP is usually thicker than 3 mm, its mass per unit area is not lighter than steel sheets and the cost of GFRP enclosure was considerably higher [1]. Automotive companies still use monocoque structure for a low production batch because the tooling cost is low.

A better alternative of FRP monocoque structure is a thin sandwich structure in which a very light weight core is sandwiched between two thin skins made of a high stiffness and high strength material. Very light weight honeycomb can be used as core material but are not suitable for many down-to-earth products because they are very expensive [2]. Rigid foams like polyurethane foam (PUF) are successfully used as the core material for many sandwiched structures but they are not suitable for thin composite sandwiched sheeting of thickness less than 5-6 mm. However, PUF or honeycombs are rigid enough to resist shear stresses generated due to transverse loads. Now, appropriate methods have been developed for joining the two skins of sandwich structure through inexpensive webs. Fig. 1 shows a thin sandwich structure in which a polyester foam (coremat) with regularly spaced holes is sandwiched between two FRP skins. The liquid resin is filled in the holes of the coremat and forms columns on curing. These columns join the two skins and act as webs. Thin sandwich structures, based on these kinds of web, have a high potential for their applications. There is a need to optimize the various parameters of thin sandwich structure made through webs.

Baker [3] tested very thin sandwich panel of 1.7 mm thickness to find in-plane shear strength. The sandwich panel was fabricated with polymethacrylimide foam core and Kevlar-epoxy skins. Mines et al. [4] fabricated sandwich panels using coremat of 8-10 mm thickness and various different kinds of FRP skins and tested them for static and impact behaviour. Approximate elastic-plastic analysis of static and impact behaviour of polymer

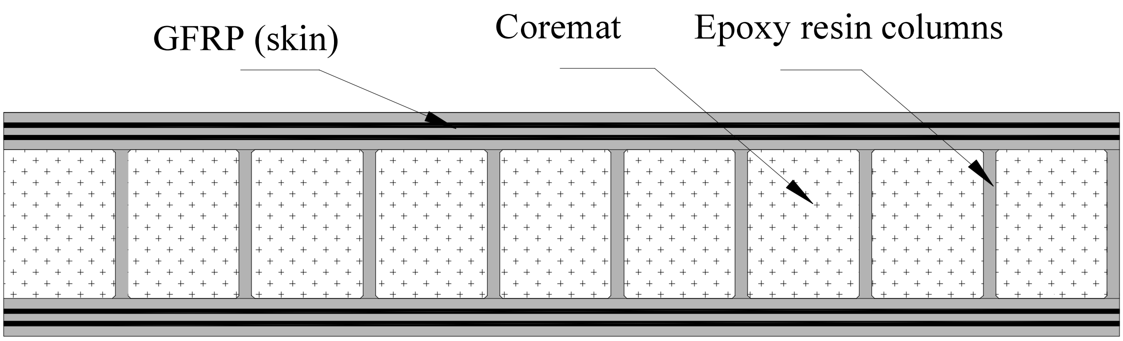

Fig. 1: Sandwich panel with GFRP skins, columns webs of epoxy resin and foamed core.

composite sandwich beams was carried out by Mines & Jones [5] using coremat of about 9 mm thickness. Low velocity perforation behaviour of polymer composite sandwich panel made of woven glass vinyl ester skins and coremat was studied with a drop test of an impact of up to 30 kg and a maximum impact energy of 882 J [6]. Numerical simulation was carried out to study the progressive collapse of polymer composite sandwich beams under static loading by Mines and Alias [7].

Dai and Harn [8] found through three- point and four-point flexural tests that PVC foam core worked better than balsa wood core because of higher shear strength of the PVC foam. Shen et al. [9] developed correction factors for bending deflection of a soft transversely flexible core sandwich structure using higher order sandwich panel theory and compared the results with experimental ones. Petras and Sutcliffe [10] used higher order sandwich beam theory to analyze indentation behaviour of sandwich panel with honeycomb core and FRP skins. Xu and Qiav [11] developed a constitutive model to find elastic stiffness tensor for general honeycomb sandwich structure. Lambert et al. [12] found that in comparison to monolithic structures sandwich structures have better tolerances to hyper velocity impacts. Mouritz and Thomson [13] investigated the edge-wise compression shear and flexural properties of GFRP/PVC foam sandwich panels.

In this study, a thin sandwich panel was constructed using a 3 mm thick coremat and FRP skins made of chopped strand mat (CSM) of glassfibres and epoxy. The thin sandwiched structures were characterized with three tests, (i) flexural test, (ii) in-plane shear test, and (iii) low velocity impact-induced -damage.

2. SPECIMEN PREPARATION

Thin sandwich panels of size 250 mm x 250 mm were prepared by the hand lay up technique. For the skins, glassfibre CSM of area density 298 g/m^2 and with average fibre length of 50 mm was used as reinforcement; two mats were used per skin. An epoxy resin system was employed to make the sandwich structure. The constituents of epoxy system, resin Araldite LY556 (Ciba Giegy, Mumbai) and hardener HY 951 (Vantics Performances, Mumbai) were mixed in the ratio of 10:1 by weight.

For the core a low density polyester foam sheet, Lantor coremat XM of 3 mm thickness and manufactured by Lantor B.V., Netherland was employed. It was made of hexagonal structure of 4 mm (between opposite corners) size with porous walls (Fig 2). The porous hex-walls improved its drapability on the surface of a die with double

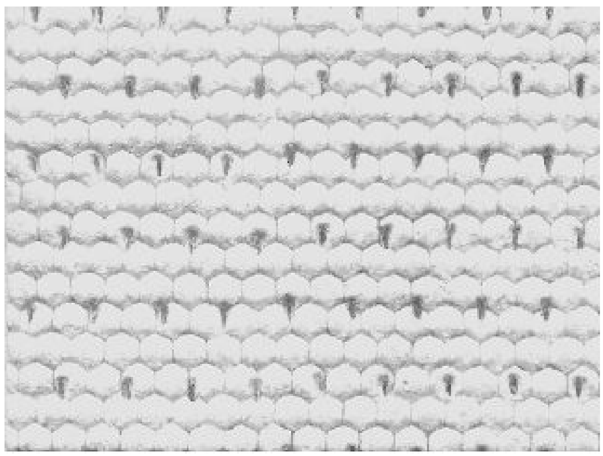

Fig. 2: Lamtor coremat XM, 3 mm thick with holes and hex structure.

curvatures and improved adhesion between skins and core. The coremat had a high microsphere contents of upto 55 % by volume. The density of the coremat was very low, about 40 kg/m^3 with area density of 118 g/m^2. The as-supplied coremat had interspaced holes which were approximate rectangles with average area of 1 mm x 3 mm. As shown in the figure the distance between holes in a row was 7 mm

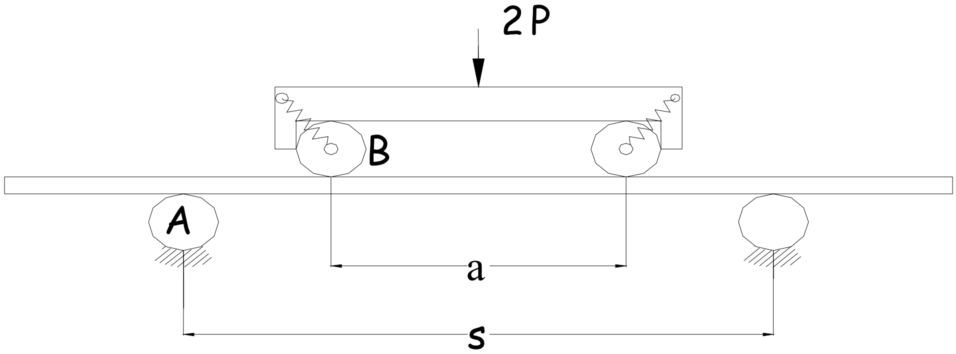

Fig. 3: Four point bend test with short span (84 mm) and long span (240 mm).

and the rows were separated by 10 mm.

During the hand lay-up process, special care was taken to fill the holes in the coremat completely with epoxy with very small air entrapment. Once the coremat was placed on the wetted glassfibre CSM, it was pressed with a specially designed serrated roller so that a hole could be pressed between two adjacent ridges of the roller. This made the resin to rise up from below through the holes of the coremat and minimized the air entrapment within the resin columns. After the top reinforcement mat is placed, wetted and rolled, a low dead-weight pressure of 5 kPa was applied by placing a steel plate over it.. The specimen panel was cut using a diamond wheel splicer to prepare appropriate specimens for all the three tests.

3. FLEXURAL TEST

A transverse load on a sandwich structure generates bending moment and shear force. Both should be resisted for proper functioning of sandwich structure. In this study, a four-point-bend test was adopted and investigations were made in two phases. The results would be compared with behaviour of mild steel sheets commonly used for many enclosures of machines and appliances.

In the first phase, the experimental set-up was based on the lines of conventional flexural test of monocoque laminates with overall span length of 84 mm and centre distance between two loading point of 42 mm as shown in Fig. 3 (short span fixture). This test was addressed as short span bend test in this investigation. It was found that the specimen did not fail in the portion between the two centre load points which was subjected to pure bending moment and no shear force. The specimen failed through shearing of core between one of the end points and the corresponding centre load point. This set-up was similar to a short beam test characterizing the shear failure.

In the second phase, the test set-up was modified to increase the span length while maintaining the distance between the load points same as 42 mm. In this long span bend test, the overall span length was extended to 240 mm as shown in Fig. 3 (long span fixture) which increased the bending moment considerably and caused the failure of a skin in the specimen between the two centre loading points.

3.1 Short span bend test

The test set-up consisted of two fixed rods of 10 mm diameter as end supports and two load rollers of 10 mm diameters. Each load roller was tied to an upper load frame with a tensile spring as shown in Fig. 3. A MTS machine of 100 kN load capacity was used to load the specimen. The specimen with thickness lying between 5.0 and 5.2 mm was cut to length 120 mm and width 50 mm. The larger specimen width was chosen because there should be adequate number of columns joining the two skins between the load points.

The specimen works like a plate and deforms in plane strain. The plate, in fact, is a bi-material, FRP skin and coremat foam as core; each material can be treated as macroscopically isotropic for flexure analysis. The flexural stiffness per unit width, *D*, for this plate is determined using elementary theory [2] as:

$$D = \frac{E_s I_s}{1-\nu_s^2} + \frac{E_c I_c}{1-\nu_c^2} \qquad (1)$$

where subscripts *s* and *c* refer to skin and core, *E* is the modulus, *I* moment of inertia and ν the Poisson's ratio. For the material used in this study, $E_s/E_c \sim 15$ and for the very thin sandwich with skin thickness (*t*) of 1 mm and core of thickness (*c*) of 3 mm, $I_s/I_c = 3.6$ (Fig. 4). If ν_s and ν_c are taken to be of the same order, the second term is negligible. Then, *D* is expressed as:

$$D = \frac{E_s I_s}{1 - \nu_s^2} \tag{1.1}$$

The deflection, *u*, of the centre loads of four point bend test (Fig.3) was given by [14]:

$$u = \frac{(1-\nu_s^2)(s-a)^3(s+2a)P}{8D} \tag{1.2}$$

Knowing the relation between *u* and *P* from an experiment, flexural stiffness was determined.

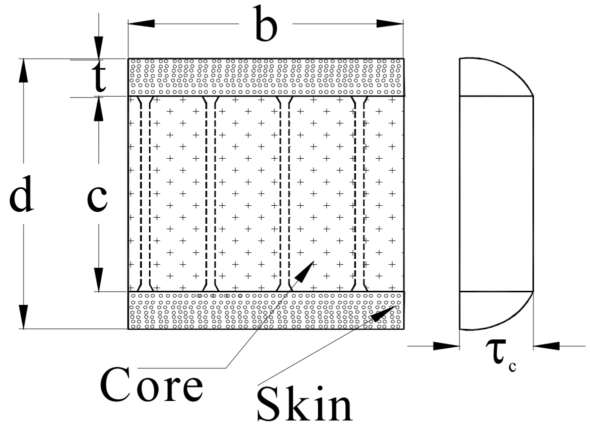

Fig. 4: Shear Stress Distribution through the thickness of the sandwich panel.

The flexural stiffness per unit width was found, based on six experiments, to be 86.7 ±11.1 Nm²/m. For comparison, monocoque specimen was also prepared using the same fibre reinforcement and epoxy resin but without the coremat. Its thickness was considerably smaller, only 2.04±0.06 mm against 5.92±0.2 mm of sandwich panel. Monocoque specimen was prepared with length and width same as these of sandwich panel specimens and tested using the same four-point-bend test. The stiffness of monocoque laminate based on six experiments, were found to be only 14.0 ± 1.1 Nm²/m. Thus, the flexural stiffness of sandwich structure was 6.2 times higher than flexural stiffness of monocoque laminate – a substantial gain. In fact, this is equivalent to the flexural stiffness of mild steel sheet of 1.65 mm thickness. Most steel sheet enclosures of machines/appliances are not thicker than 1.65 mm.

Another important parameter is area density to make sheet enclosures of light weight. The average area density of the sandwich structure was obtained as 5.46 ± 0.16 kg/m² which is much smaller than area density 12.9 kg/m² of 1.65 mm thick steel sheet. For another comparison, a mild steel sheet of 0.7 mm thickness was identified whose area density was same as that of the sandwich panel. The flexural stiffness of the sandwich panel was found to be 33 % higher.

There was another advantage of making an enclosure of a machine from the sandwich structure. The hand lay-up technique required only a single die as against matching die set required for conventional metal sheets. The cost of a single die was much less and thus sandwich structure enclosure was more

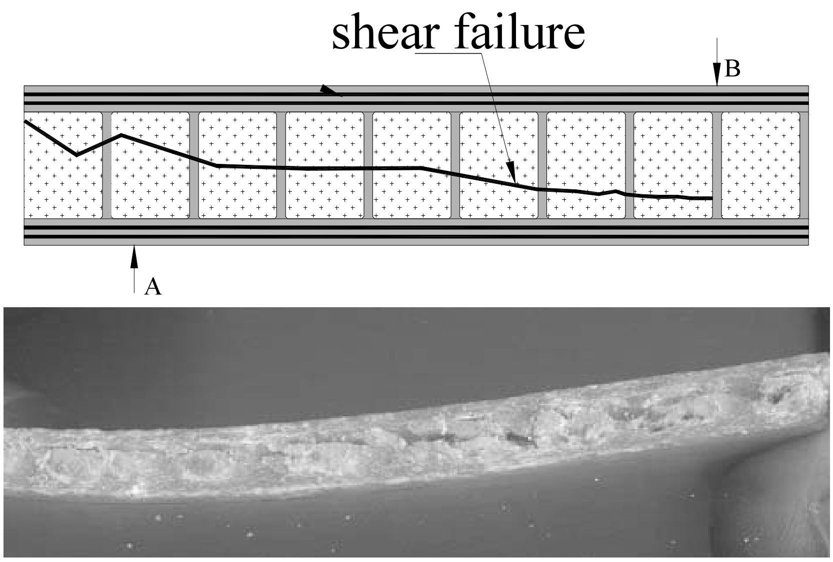

Fig. 5: Shear Failure between the end support at A and the corresponding centre load at B.

appropriate for low volume production of enclosures.

The failure of the specimen was initiated right under one of the centre loads and was extended towards the end support. As stated earlier no failure of specimen was observed between the two centre load points. The core failed with the shearing of columns as shown in Fig. 5. The short beam bend test determined the shear strength of the core.

Knowing shear force at a cross section of the plate, elementary theory of plate can be applied to bi-material of composite structure. The shear stress at distance y from the neutral plane was given by $\tau = VQ/I$ where V was the shear force per unit width of the plate and Q was the first moment of area beyond y. As discussed earlier (Eq 1) the contribution of I_c in I was negligible because the stress in the core was low and the entire core material was close to the neutral axis. Then the shear stress at the interface, τ_i, was given by:

$$\tau_i = \frac{Vt(c+t)}{2I_s} \qquad (2)$$

where

$$I_s = \frac{t}{6}(3c^2 + 6ct + 4t^2) \ .$$

The shear stress at the midplane of the sandwich panel was higher due to normal stress carried by the core. However, it was estimated for the thin core of this study and was estimated to be only 3.75 %, higher over τ_i. Thus, for all practical purposes, the variation of shear stress within the core was negligible it was taken to be constant as shown in Fig. 4.

The average shear strength of the web core was found to be 2.9 ± 0.13 MPa. The shear stress was also resisted by the hex-walls of the core. The contribution of hex-walls was difficult to assess as the hex-walls were very non uniform with holes at many spots. One can estimate the shear strength of the resin columns by assuming that hex-walls did not contribute and the entire shear force was resisted by resin columns only. The shear strength of column material was then found to be 107.2 MPa which is significantly higher than the shear strength of epoxy. Thus, hex-walls also contributed towards resisting the shear stress.

3.1 Long span bend test

The span of the flexural test was extended from 84 mm of short span to 250 mm of long span. This reduced the shear stress and made the specimen fail under bending moment between the centre load points.

The flexural stiffness, *D*, of five experiments was found to be 93.3 ± 11.1 Nm^2/m which is, as expected, was same as of short beam span test within the error bands. The critical moment, which caused failure of the specimen between the two central load points, was determined as 341.5 ± 83.5 Nm/m. Since shear stress in the core was smaller no failure was observed due to shearing of webs between a load point and the corresponding end point.

The failure mechanism in these tests was bending

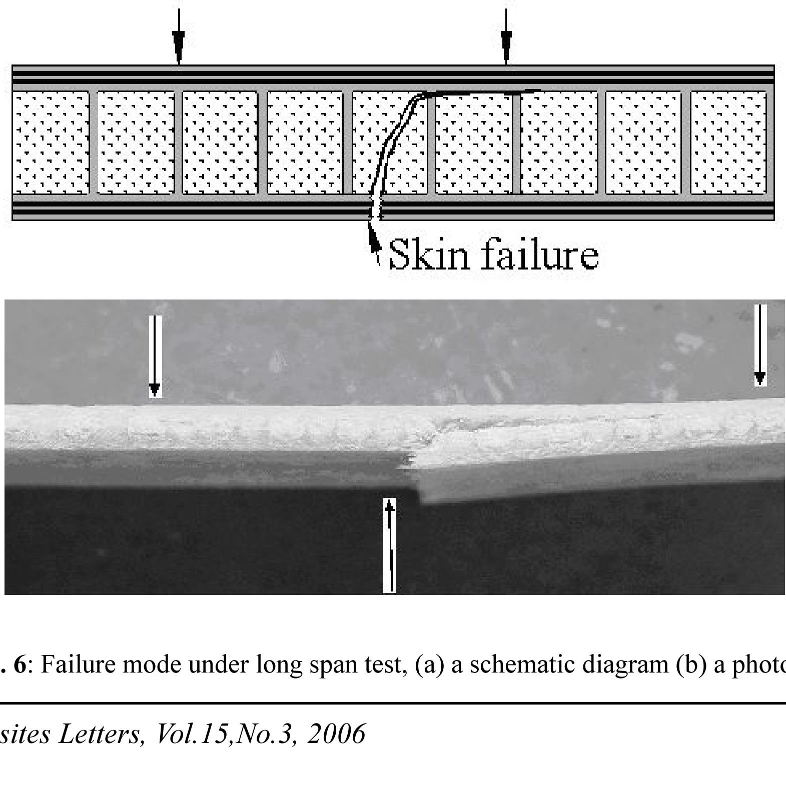

Fig. 6: Failure mode under long span test, (a) a schematic diagram (b) a photograph

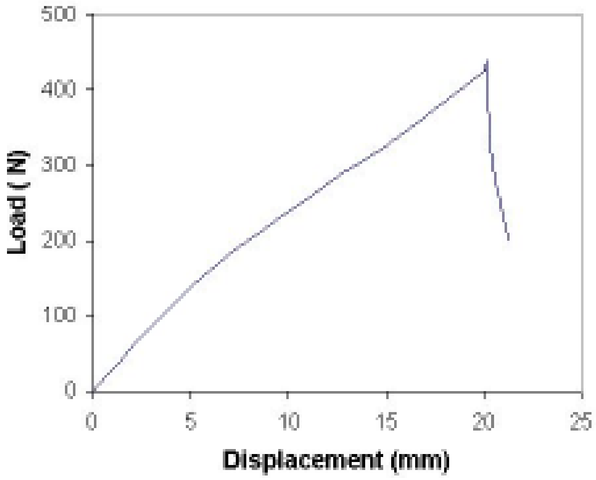

Fig. 7: Load Deflection Curve of a long span bend test

dominated. The skin on the tension side was found to break and eventually separate as shown in Fig. 6. The crack ran into the coremat till it reached the top skin. Since the crack could not enter easily into the FRP top skin, it turned and moved along the interface breaking the web columns. This was similar to transverse cracks generated in the rear ply of an angle ply laminate when it was impacted with a foreign object; the transverse cracks meeting the next ply with different fibre angle turned sideways into the interface. Also, the skin on the compression side was found not to be buckle unlike in sandwich structure based on foamed cores. The webs (columns) were integral parts of the entire sandwich panel and adhesive bonding between the skins and the core did not ply a dominant role. Thus, the failure did not take place by the separation of the skin on the compressive side from the core and buckling of the skin. Once the skin on tension side was broken, the interface separated out fast and the specimen failed catastrophically as shown in Fig. 7.

Two kinds of comparison were made with conventional mild steel sheets. First, a mild steel plate of 1.65 mm was identified whose flexural stiffness was same as of sandwich panel. The area density of the sandwich panel was only 42 % of that mild steel sheet; the critical bending moment was 5.1 times higher. Second, a mild steel of 0.7 mm was identified whose area density was same as of composite panel. The flexural stiffness of sandwich panel was found to be 37 % higher and critical bending moment was 12.3 times higher. It was therefore inferred that the sandwich structural panel, considered in this study, was superior to steel as far as area density, flexural stiffness and critical bending moments were concerned under static testing.

4. IN-PLANE SHEAR TEST

In thin sandwich structures, prepared using a coremat, shearing of the core is one of the dominant failure mechanisms. Resin columns whose cross-section was small, were not able to resist high shear force acting on a cross-section. Thus, an experimental set-up and the specimen were specially designed to determine shear strength of the core of thin sandwich structures. It is a modified form of Rail shear test [15].

4.1 Experimental Set-up

The schematic diagram of the test fixture is shown in Fig. 8 and the specimen in Fig. 9. The ends of the specimen were prepared by retaining only a skin on each end as shown. The central portion of 45 mm x 28 mm was subjected to pure shear during the test. Both skins of the specimen were made rough using an emery paper and bonded to upper and lower plates as shown. In some preliminary experiments, the bond strength was found not to be high enough to transfer the load from the plates to the specimen. Thus, skins of the specimen were extended so that each could be tightened, besides the bonding, to the plate with three M6 screws. On each end, pulling load was applied to the plate with a hinge as shown to avoid bending on the specimen. The tests were made on a 100 kN MTS machine with a low pulling rate of 2 mm/min appropriate for quasistatic tests. The specimen failed in shear and a typical load vs. deflection is shown in Fig. 10.

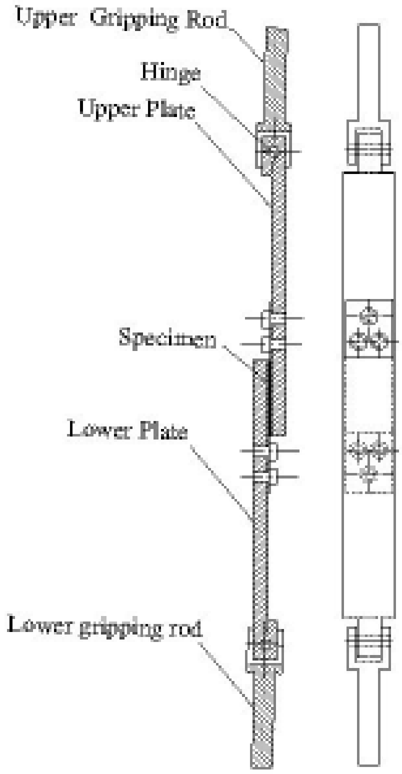

Fig. 8: Setup for in-plane shear test with hinges at each end.

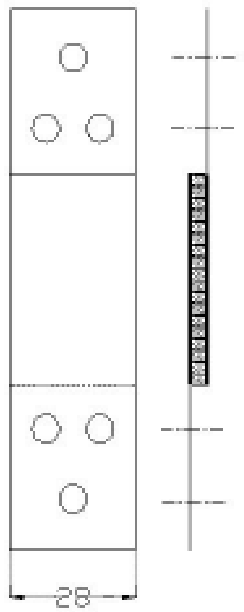

Fig. 9: Specimen with extended skins.

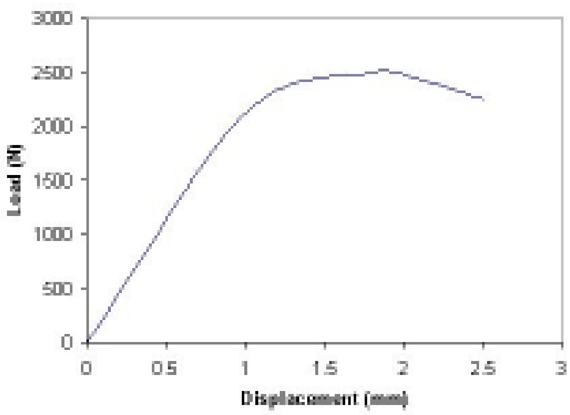

Fig.10: Load vs deflection plot for In- plane shear test.

4.2 Results and Discussion

The shear strength of core, based on eight specimen, was found to be 2.3 ± 0.6 MPa. The scatter was high probably because the performance of columns varied from each other. The shear strength of the core, determined through short span beam test, was 2.6 MPa. Within the experimental error band, the two values of in-plane shear were similar.

Under the shear stress, foam of coremat failed differently from the epoxy columns. Within a hexagonal pocket, the foam column failed under a tensile load which was at 45° to the load – axis. At places several parallel failure planes were observed which made the foam protruding out as lips. Resin hex-walls were prominent and thick at places and almost non-existent at some other places.

Resin columns were found to fail through several mechanisms. Most columns failed close to one of the two interfaces probably because the stress concentration was high. Also, the fractured plane of the failed columns were found to be within 0° and 30° from the plane of the sandwich panel. However, in a few columns, higher angle of the fractured plane was also observed. It was felt that walls of the holes in the core mat were not smooth which, in turn, made the walls of resulting resin column rough with intrusions and extrusions. One of the intrusion in a column became critical and broke the column. The intrusion along 0° was favoured to fail in Mode II but based on length and orientation, a crack would become critical and grow under mixed Mode I and Mode II conditions.

In some cases, a column was uprooted out from the reinforcement plane of a skin. It was worth noting that strands of the chopped mat were flattened to a width ranging between 0.5 and 0.9 mm. If a strand ran parallel to the long side of a column's cross-section with width of only 1 mm, the strand overlapped on a major portion of the foot of the column. Then, the interfacial bond between the fibres and resin became critical and the resulting debonding caused the uprooting of the column through Mode II failure.

A few columns failed due to entrapment of an air bubble within a column during the fabrication. Although a care was taken to minimize the air entrapment it was difficult to avoid it completely. However, such failures were less than 10%.

In short, resin columns which played important roles in resisting shear and maintaining required distance between skins, were found to fail through several mechanisms; failure of columns close to one of skins was observed to be the dominant mechanism.

5. IMPACT TEST

Monocoque polymer composite laminates are known to be susceptible to foreign body impact although they work well under static loading. In case of sandwich structure, impact –induced –damage might be more acute as the core with thin resin columns were likely to fail under impact loading.

If a thin sandwich structure were explored to replace conventional metal enclosure of various machines and gadgets, it should resist various impact loads like tool dropping, impact during handling and transportation, hail storm if enclosures were used out doors, etc. The damage caused by a low velocity foreign body should not be large , otherwise the performance of the structure was affected. In fact, aerospace structures were often designed to have a barely visible damage when impacted by a foreign object [16].

In this impact study, a panel of sandwich structure was impacted with a foreign cylindrical projectile with three impact levels, 3, 6 and 9 J. Resulting damage area and failure modes were investigated.

5.1 Experimental Technique

A panel of sandwich structure of 120 mm x 120 mm size was impacted with cylindrical steel projectile of 12.6 mm diameter and about 16 mm length. The impacting end of the projectile was shaped spherical and the projectile weighed about 4.4 g. The projectile was made hallow from its rear end to reduce the mass. Its mass was determined very accurately using Sartorius electronic balance before the impact.

The projectile was accelerated in an air gun with a smooth and stainless steel barrel of high accuracy bore 12.65 mm diameter and length of one meter. The air gun stored compressed air in the chamber of the Breech End and a Solenoid valve of 10 mm diameter triggered the air gun. The velocity of the projectile was measured using a laser beam, a photodiode, a suitable electronic circuit and a digital oscilloscope. The time taken by the projectile to cross the laser beam was monitored as a pulse on the oscilloscope. Knowing the mass and velocity of the projectile, the incident impact energy of the projectile was determined within 1 % accuracy.

The panel was supported on its all four edges in a rigid specimen mount with central unsupported area of 80 mm x 80 mm. As mentioned earlier, the panels were impacted with three energy levels 3, 6 and 9 J. In the set up, desired impact energy levels could not be achieved exactly. Just prior to an impact experiment, the projectile was fired several times by varying pressure of compressed air without the specimen to determine likely pressure that would yield impact velocity close to the desired level. Also, it was found that for a low energy impact of 3 J, controlling the pressure was not giving consistent projectile velocity. Therefore, firing pressure was not altered but the initial portion of the projectile within the barrel was varied. The projectile velocity of 3, 6 and 9 J energy levels were close to 36, 52 and 64 m/s respectively.

5.1 Results and Discussion

The impacted specimens clearly showed visible damage area at the front and rear of the panel. Fig. 11 shows the damage on the impact and rear skin for an experiment with impact energy of 6.3 J. Table 1 shows average damage area on impact and rear skins.

The damage area near the front skin increased marginally with impact energy. Also, the damage area was much smaller than the corresponding damage area on the rear skin, within 4 %. The damage area near the rear skin increased from 28.7 cm^2 for 3 J impact energy to a very high value of 91.1 cm^2 for 9 J impact energy.

Near the centre of the impact on the front skin, there was indentation with local failure of the skin. The skin failed with mechanisms like fibre breakage, debonding of fibres, fibre pull out. Also the columns of core were found to be crushed under compressive impact loads. Fig. 12 shows the failure mechanisms.

The mechanism of failure near the rear skin was same as the separation of last ply in an angle ply laminate impacted by a foreign body. Right after the impact,

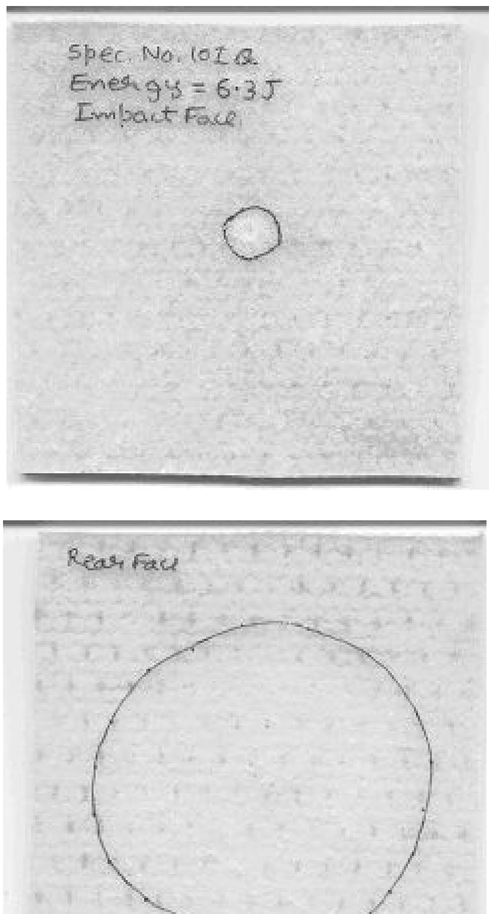

Fig.11: Impact damage, (a) Impact face and (b) Rear face.

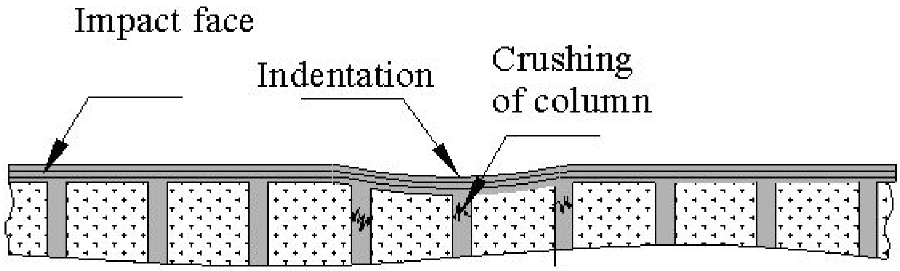

Fig.12: Failure near impact face.

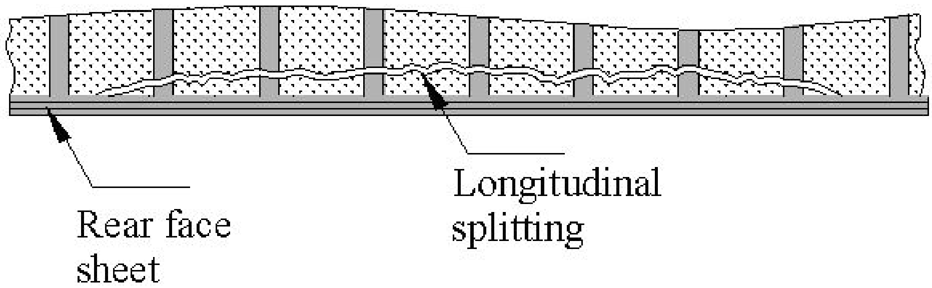

Fig.13: Failure near rear face.

compressive wave front propagated from the front skin to core columns to rear skin. This was reflected from the rear free surface of the panel and turned into tensile wave front. Columns being made of unreinforced resin and of thin cross section failed under the tensile load. The impacted specimens were dissected and the failure of the column were examined. Fig. 13 shows the nature of the failure of column close to the rear skin.

6. CONCLUSIONS

In order to replace mild steel enclosures of many machines and appliances including auto bodies a light weight sandwich structure was constructed using a 3 mm thick coremat and chopped strand mat of glass fibres reinforcing epoxy resin. The thin sandwich panel was characterized with three tests, (i) four point flexural test (ii) in-plane shear test and (iii) low velocity impact-induced-damage.

In comparison to mild steel sheets, the sandwich panel showed encouraging results with smaller area density, higher flexural stiffness and higher flexural strength. A short beam flexural test was also conducted to determine shear strength of the structural panels. An appropriate test set-up was developed, based on the lines of Rail test, to determine in-plane shear strength directly. The strength was found to match with shear strength determined through the short span four point bend test. The low velocity impact tests on the sandwich panels showed a large damage near the rear skin of the panel due to tensile reflection.

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