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Effect of Carbon Nanotubes on Mechanical Properties of Honeycomb Sandwich Panels

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ABSTRACT

The present research paper discusses the effects of addition of carbon nanotubes on mechanical properties of hybrid honeycomb sandwich structure for high-tech applications. Hybrid honeycomb sandwich structure consists of aluminum honeycomb core sandwiched between multiscale Multi-Walled Carbon Nano-Tubes and Carbon Fiber (MWCNTs/CF) reinforced epoxy composite facing. Multiscale facing was fabricated through hand layup method followed by compression molding and curing. The sandwich panels were prepared through vacuum bagging technique and cured in an oven. Three point bend test and compression test were performed to evaluate the mechanical performance of sandwich panels. Flat-wise tensile test was performed to assess the bonding strength between core and facing. Quasi-static indentation test was conducted to assess the ability of sandwich panel against low velocity impact. Neat honeycomb sandwich panel was also prepared via similar process but without MWCNTs addition for reference. A comparative study has been made between both sandwich materials. Results depict that compressive strength and flexural stiffness improved by 21% and 28% respectively by the addition of 0.2% MWCNTs in comparison to neat sandwich panel. Energy absorption capability of CNT-filled sandwich panel was also enhanced by 10% with reference to neat sandwich panel.

1. Introduction

The cost of transportation and placement of satellite in orbit is very high and sometimes reaches 50% ($5-25K per kg of payload) of the overall mission cost [1]. Spacecraft designers therefore always strive to lower the mission cost by reducing the size and mass of the satellite by introducing new structural design concepts and multifunctional materials. Satellite structure experience high loads during launch phase (random vibrations, shocks, sound pressure, etc.) and uniquely harsh environment in orbit (high vacuum, intense radiations, thermal fluctuations, electromagnetic interferences, etc.). Therefore, the choice of the structural material for a satellite is vital and driven by the mission requirements, operational conditions and expected environment. These materials need to possess a number of unique properties to be effective in space. Traditionally, load bearing structures of satellite are made of space-grade aluminum alloy 6061-T6 (usually isogrid panel) because of its lower cost, good strength, ease of machining and availability. However recently, the use of advanced honeycomb sandwich structure has increased in spacecrafts because of high stiffness and incredibly lightweight features which makes this material economically viable for space missions. A saving of single kilogram of mass can cut down the cost of the launch by thousands of dollars.

The sandwich panel consists of two thin and stiff face sheets bonded to both sides of a lightweight core. Depending upon application and specific mission requirements, the face sheet can be of metal or composite material having high strength and stiffness. Core is usually fabricated from aluminum honeycomb or foam, nomex, etc. The benefits of using honeycomb sandwich structure over metallic structure are numerous including lightweight and durability, high specific strength and high bending stiffness. All these properties make it ideal for use in primary and secondary structure of satellites. Surrey Satellite Technology Ltd. (SSTL) is actively using honeycomb sandwich panels in developing small satellites in the 50-600 kg range like NigeriaSat-2 and Geostationary Mini satellite Platform-Transfer (GMP-T) [2]. Another example is that of Algerian microsatellite Alsat-1 (earth observation satellite) in which honeycomb sandwich panel has been used.

Despite the well-established technology of sandwich construction and extensive use in satellite structures [3-5], research efforts are still on-going for further improvement. The idea of using carbon fiber composite face sheet/aluminum (CFRP/Al) core sandwich panel in spacecraft is not new. The CFRP/Al honeycomb sandwich structure has been successfully used in RADARSAT2,

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GOCE, Herschel/Planck and BEPPO-SAX missions [6, 7]. Numerous research studies have been conducted on CFRP/aluminum honeycomb sandwich materials [8-10]. However, novelty of present research work lies in that we have introduced carbon nanotubes (CNTs) in the CFRP face sheet for making hybrid sandwich panel. Since their discovery, CNTs have gained extraordinary popularity and revolutionized almost all fields of science and technology due to their exceptional properties. But, very limited work has been done to date on using CNTs in honeycomb sandwich panels. Therefore, authors of this paper initiated extensive research in which hybrid sandwich panels were fabricated and effects of CNTs addition on electrical and mechanical properties were studied by performing experiments in laboratory. Electrical properties of this novel hybrid sandwich panel have been published earlier [11]. Here we present the results of mechanical tests conducted on CNT-CFRP/Al honeycomb panel. Results were also compared with the properties of reference CFRP/Al honeycomb panel without CNTs. The research findings demonstrated that the developed CNT filled hybrid sandwich panel outperformed the traditional honeycomb sandwich panel.

2. Materials and Methods

Multiwall carbon nanotubes (MWCNTs) were procured from Cheap Tube Inc. (USA), synthesized through chemical vapor deposition (CVD) method. Carbon woven fabric was used as reinforcement in this research work. Thermoset epoxy resin (Bisphenol-A) with diluent and hardener (Cycloaliphatic amine) was selected to form epoxy matrix in the weight ratio of 10:3.5. Aluminum alloy hexagonal honeycomb core was selected for the fabrication of sandwich structure. Araldite adhesive (Huntsman, Germany) was used for bonding skin sheets with honeycomb core. Specifications of raw materials used in this work are shown in Table 1.

Table1: Specifications of raw materials used in this work

Raw Material	Specification
MWCNTs	Purity level > 95%, Ash content < 1.5%, Specific area: 180-230 m^2/g, Bulk density 0.22 g/cm^3, Length: 10-30 µm, Outer diameter (OD): 10-20 nm
Carbon fabric	Weave style: satin 3, Tow: 3K, Thickness: 0.5±0.005 mm, Areal density: 325±5 g/m^2, Breaking strength in warp direction > 270 Kg/5cm
Honeycomb core	Aluminum alloy: AA 5056, Thickness: 25.4 mm, Cell density: 4.5 lb/ft^3, Cell size: 1/8 inch

2.1 Fabrication of Hybrid Sandwich Panel

Pristine MWCNTs (0.2 wt% of matrix) were mixed and dispersed in acetone through bath sonication to seperate the entangled CNTs. Epoxy resin was added to MWCNTs/acetone solution and magnetic stirring was performed to homogenize the solution. Solution was heated to 40°C with continuous magnetic stirring until acetone evaporates completely from the mixture. Stirring process was then stopped and solution was allowed to cool to ambient temperature. After cooling, hardener was added in the solution and magnetic stirring was performed for 15 min to properly mix the hardener in the solution. A metallic mold of cavity size (150 mm length and 75 mm width) was in-house developed to fabricate composite face sheets through compression molding, as shown in Fig.1. Carbon fabric was cut and impregnated with MWCNTs filled epoxy resin through applicator brush using hand layup technique. Total three layers of carbon fabric were impregnated and placed over each other in mold cavity. Male and female mold halves were fixed through guided pins and tightened in such a way that surplus resin drained out through drain holes. Mold was placed in oven for curing at 80°C and 120°C for 30 min and finally at 160°C for 2 h. Cured composite face sheet was removed from the mold and sides were trimmed. Further, composite face sheet surface was roughened through 80 grit silicon carbide paper for better adhesion with aluminum core. Adhesive layer of approximately 1mm thickness was applied on composite face sheet surface and core was placed over it. Vacuum bagging was employed to remove entrapped air during bonding under rough vacuum. Curing of adhesive was performed by heating the sandwich sample at 80°C for 2 h in an autoclave. Sandwich panels were fabricated in such a manner that the core was in longitudinal orientation. Similar methodology was adopted for fabricating neat sandwich panel without MWCNTs.

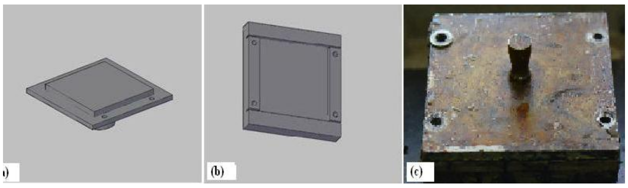


Fig. 1: Schematic of metallic mold (a) Male part, (b) Female part and (c) Picture of the fabricated mold

2.2 Mechanical Tests

Flat-wise compression test was conducted to assess the compressive strength of sandwich panel according to ASTM standard C 365-94. Specimen of square cross-section (50 x 50 mm) were tested at a cross-head speed of 1 mm/min. Load was applied on to the specimen through loading block to evenly distribute the load over entire surface. Testing was performed on 3 specimen of each type (Fig. 2a) and average results are reported here.

Three-point bend test was conducted on three sample of each type in accordance with ASTM standard C 393-94, as seen in Fig. 2b. Short beam (mid span) specimens were prepared having overall 150 mm length, 60 mm width and 29 mm sandwich thickness. Span length was kept 100 mm and test was carried out at cross-head speed of 6 mm/min. Load-displacement curves were recorded and analyzed for determination of various parameters (i.e. core shear strength, facing bending strength, panel flexural stiffness and total beam mid span deflection of sandwich panel).

Flat-wise tensile testing was performed on sandwich specimens in accordance with ASTM standard C 297-94 to determine the bond strength between the skin and core. In this test, sandwich specimen was subjected to tensile load perpendicular to the plane of sandwich construction. During test, load was transmitted to the sandwich through thick loading blocks which were bonded to skin of the sandwich panels with strong adhesive (Fig. 2c). Specimen size for this test was 50 x 50 mm (square cross section) and speed of testing was 1 mm/min. All mechanical tests were performed at Universal testing machine (Tinus Olsen, UK) of capacity 150 kN at room temperature and photos of test setups are shown in Fig. 2.

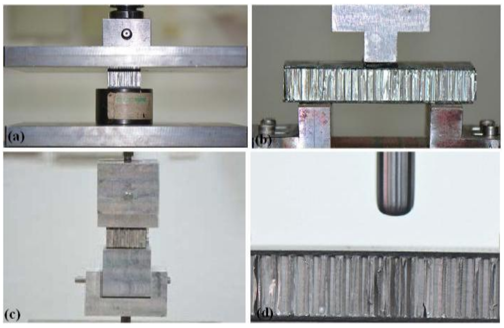


Fig. 2: Photos of test setups (a) Flatwise compression test (b) Flexural test (c) Flatwise tensile test (d) Quasi-static indentation test

Knowledge of the damage resistance properties of a sandwich structure is very important not only for design purposes but equally useful for product development and material selection. Low-velocity impact events are expected to occur during the manufacturing and service life of sandwich panels. Quasi-static indentation test was therefore performed on sandwich panels in accordance with ASTM standard D6264-12 to assess the damage resistance in case of low velocity impact. In this test, edge supported configuration (using especially fabricated support fixtures) is used to test the flat square shape specimen having dimensions 150 mm length, 60 mm width and 29 mm thickness. Damage was imparted on supported specimen by slowly pressing a blunt, hemi-spherical steel indenter (15 mm diameter) on sandwich skin and exerting concentrated out-of-plane force (Fig. 2d). The cross-head speed was 1.25 mm/min during the test. Load Vs. displacement data was recorded and energy absorption was calculated from area under the curve up to maximum load. The values were also compared with those obtained on neat sandwich panel to study the effect of CNTs addition on energy absorption. The indented specimen was cut and damage was examined to characterize its size and type.

3. Results and Discussion

3.1 Flexural test

Three-point bend test was carried out to investigate the flexural behavior of sandwich panels. Fig. 3a shows the typical load-displacement curve for hybrid and neat sandwich panel. Each curve depicts initial elastic behavior up to maximum load after which curve declines and load value becomes almost stable. The flexural properties were calculated using equations given in the ASTM C-393-94 and are listed in Table 2. Results show that the addition of MWCNTs into the sandwich panel has imparted slight increase in the facing bending stress of about 5%. However, flexural stiffness of the panel was significantly improved by 35% in comparison to neat sandwich panel. Since pristine MWCNTs have been used in present work,

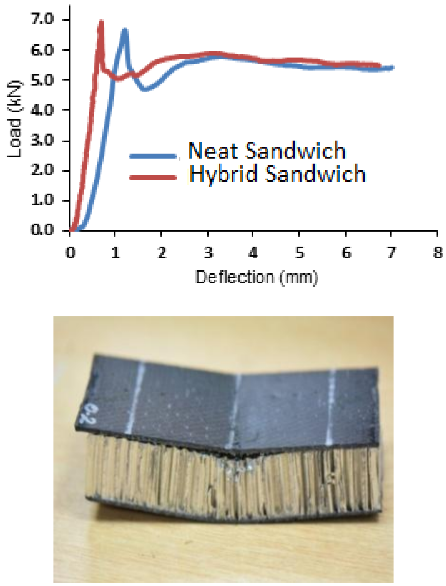


Fig. 3: (a) Load-deflection curve (b) failed sandwich sample after 3-point bend test

therefore, enhancement in all flexural properties is not very attractive. Core shear strength is almost the same in both types of sandwich panels i.e. without CNTs and with CNTs. Total beam mid span deflection was 1.4 mm for neat sandwich sample which decrease to 1.1 mm in case of hybrid sandwich panel. This decrease is obvious since the panel stiffness was increased. Figure 3b show a photograph of flexural sample after test. In most cases, de-bonding of core from face sheet and core buckling is observed in failed samples (Fig. 3b). It was noted that face sheet was de-bonded from one side only i.e. the region at which the load was applied. Beside this, core shear failure is also observed in few samples. Failure was initiated near loading point (contact point of cross-head) due to core indentation which then progress and resulted in de-bonding of face sheet from core and core shear failure.

Table 2: Flexural properties of sandwich panels

Sample	Core shear strength (MPa)	Facing Bending Stress (MPa)	Panel flexural stiffness (MN-mm^2)	Total beam mid span deflection (mm)
Neat sandwich panel	2.23	55.67	115	1.4
Hybrid sandwich panel	2.28	58.74	160	1.1

3.2 Compression Test

Fig. 4 represents the compression test results in the form of bar graph. Results illustrate that the MWCNTs filled hybrid sandwich panel has higher compressive strength than the neat sandwich panel. Hybrid panel showed peak compressive strength of 5.43 MPa (on average) while average compressive strength of 4.26 MPa was attained in neat sandwich panel. Improvement of about 21% was calculated in compressive strength by the introduction of MWCNTs. MWCNTs provide an additional source for energy absorption. This behavior of MWCNTs on nanoscale has been reflected as enhancement in compressive strength on macro scale in the composite.

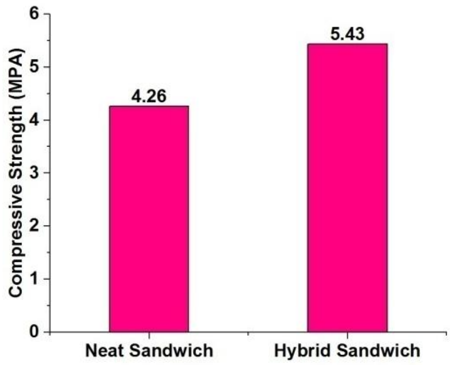


Fig. 4: Compressive strength comparison of neat and hybrid sandwich panel

3.3 Flat-wise Tensile Test

Results of flat wise tensile tests on sandwich panel samples are shown in Fig. 5. Both sandwich panels showed similar kind of flat wise tensile strength because same adhesive was used in both cases. It was found that the adhesive (Araldite 2011, Huntsman, Germany) used in this work is not suitable for metal-to-composite bond, therefore both sandwich samples showed inferior flat wise tensile strength. The quality of the adhesion between face sheet and core determines how much force a sandwich structure can bear as one piece so it is crucial to carefully select the appropriate adhesive for joining core with face sheet. Incorporation of MWCNTs in adhesive between composite face sheet and aluminum core is expected to increase the interfacial bonding and ultimately flatwise tensile strength. However, this assumption has not been confirmed through experimentation in this work and authors have planned further experiments.

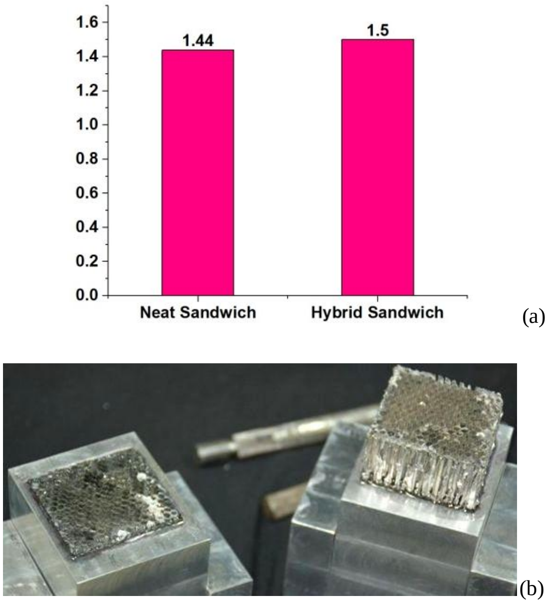


Fig. 5: a) Flatwise tensile strength comparison between neat and hybrid sandwich panels, b) photograph of failed sandwich sample showing adhesive failure

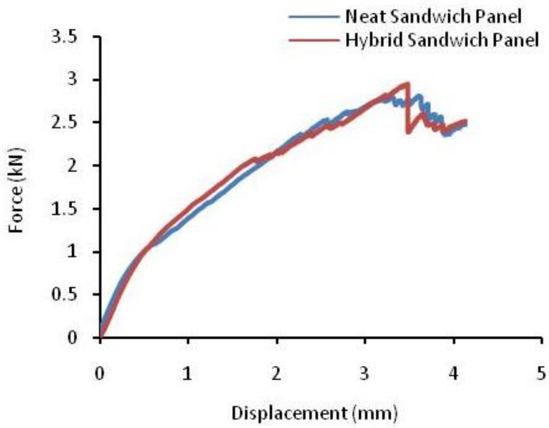
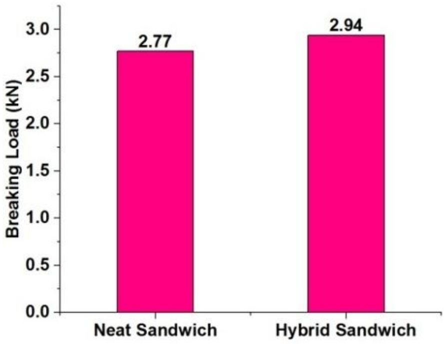


Fig. 6: Force-Displacement curve of both sandwich panels captured during quasi-static indentation test

3.4 Quasi-static Indentation Test

The force-displacement curves of sandwich panels are shown in Fig. 6. It was seen that the force (load) increases linearly in the initial region up to the maximum force. After upper face sheet fracture, the force value drops by a small amount, and then remains constant over a short flat plateau due to collapse of the cells. After this plateau, the force increases again due to core densification and consolidation. The test was stopped after penetrating the indenter up to 6 mm depth; since we were interested only in assessing the affect of MWCNTs on face sheet resistance to indentation. Highest breaking force (load) was attained in hybrid sandwich sample which means better static indentation resistance of MWCNTs containing face sheet. Fig. 7 shows the breaking load and energy absorption of both sandwich panels after quasi-static indentation test. It was observed that the breaking load for hybrid sandwich panel was enhanced by 6% by the addition of 0.2% MWCNTs. Maximum breaking load of 2.77 kN and 2.94 kN was measured for neat and MWCNTs hybrid sandwich panels respectively, (Fig. 7a).The improved resistance to penetration in hybrid sandwich panel is visible by comparing the absorbed energy during indentation. Total energy absorption for the sandwich panel is defined as the area under the load–displacement curve up to the maximum load. Maximum energy absorption of 1.4 J was calculated for hybrid sandwich panel while neat sandwich showed energy absorption of 1.27 J (Fig. 7b). The incorporation of MWCNT in the face sheet resulted in 10% improvement in energy absorption due to excellent energy absorption capability of CNTs. Enhancement in the resistance to low velocity impact is attributed to the fact that presence of MWCNTs in the matrix effectively transfers the load from weak polymeric matrix to strong



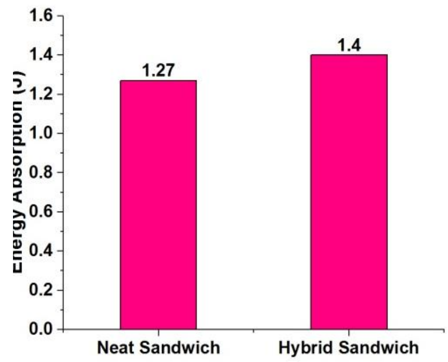


Fig. 7: Quasi-static indentation test results (a) breaking load and (b) energy absorption

reinforcement and contributes as a load carrying members along with micron size carbon fibers. Both sandwich samples were cut to observe the damage zone (Fig. 8). It was seen that the damage was almost similar in both cases. Matrix cracking and fiber breakage were observed in the deformed upper face sheet, as visible in Fig. 8a. Fiber and matrix fracture appear randomly oriented and saturate the area of damage. After face sheet failure and complete penetration, the core started yielding, densifying followed by crushing, creating a cavity in core (Fig. 8b).

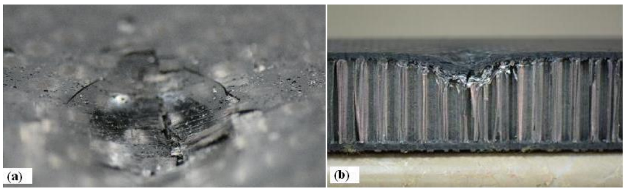


Fig. 8: Photo of indentation damage in sandwich panel after quasi-static indentation test showing (a) fiber breakage and cracking in face sheet and (b) core crushing and local buckling in cross sectional view

4. Conclusions

Present study was conducted to investigate the effect of MWCNTs addition on the mechanical performance of honeycomb sandwich panel. Series of mechanical tests were performed on developed sandwich panels and results were compared with reference neat sandwich panel. On the basis of experimental results, following conclusions are drawn:

i. Hybrid sandwich panel showed 28% improvement in flexural stiffness while increase in facing bending stress was not significant on addition of 0.2 wt% MWCNTs.
ii. Compression test results depicts that the incorporation of MWCNTs has increased the compressive strength by 21% as compared to neat sandwich panel.
iii. From the flatwise tensile test, it was observed that bonding strength of adhesive was quite low therefore composite face sheet failed at very low loads and cannot be used for space applications. However, in our opinion the MWCNTs addition in adhesive can improve the bonding between core and facing, which will be carried out in future work.
iv. Quasi-static indentation test was conducted to simulate low velocity impact. Both breaking load and energy absorption were found to be increase by 6% and 10% through the incorporation of MWCNTs in sandwich structure.
v. To sum up, hybrid sandwich panel is mechanically superior than neat sandwich panel and this improvement is attributed to beneficial effect of MWCNTs. Moreover, functionalized MWCNTs can be used in place of pristine to further augment the mechanical properties.

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