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Hemp fibre woven fabrics / polypropylene based honeycomb sandwich structure for aerospace applications

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Abstract. Recently, natural fibre composites are widely used in aerospace industries due to their good specific mechanical properties, better acoustic properties, light weight, readily availability, biodegradability, recyclability, etc. In this study, the hemp fibre woven fabrics / polypropylene based honeycomb sandwich structure were proposed for aerospace applications. Firstly, the hemp fibre woven fabrics based honeycomb sandwich structures were manufactured and experimental mechanical tests (compressive and flexural) were performed in the laboratory. Numerical simulation was also performed and analysed to validate the proposed methodology. Different complex shaped aircraft part CAD models were created and numerical analysis was carried out in order to have a better understanding about the complex honeycomb sandwich structures.

Keywords: honeycomb sandwich structure; natural fibre composites; mechanical testing; numerical analysis

1. Introduction

Natural fibre composites were attracted by researchers and being widely used in aerospace, automotive, construction applications in the past decades. They provide good specific properties, better acoustic properties, lightweight, low cost, low density, less health risk while tooling, less energy consumption, etc. (Wambua *et al.* 2003, Malkapuram *et al.* 2009). Natural fibre composites manufactured using recyclable or bio resins can provide recyclability, renewability and biodegradability. Even though, it should be noted that natural fibre composites have several drawbacks such as high moisture absorption, lower durability, lower strength, higher variability of properties, adverse effect on temperature, water ageing effects, etc. compared to synthetic fibre composites (Pickering *et al.* 2016). Currently, researchers are focussing on overcoming these drawbacks and thereby increasing the potential of natural fibre composites in industrial applications. For instance, Joseph *et al.* (1996) improved the mechanical properties of natural fibre composite by chemical treatments and Maniruzzaman *et al.* (2012) were also able to improve the hydrophobic nature of natural composites by decrease the amorphous region of lignocellulose. The

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demand of the natural fibres is increasing day by day and as a consequence of this the price of the natural fibres are increasing. Hemp is an annual plant and its production is increasing every year. Hemp fibre is one of the cheapest natural fibre and the hemp fibre straw is produced in a so-called 'total fibre line' where the production of non-aligned technical fibres was done together. Flax fibre is a widely used natural fibre but the short and long fibre were produced separately in flax fibre processing, which provides an upper hand for hemp fibres in the automobile and aerospace industries where the production speed is key (Carus *et al.* 2013).

Honeycomb sandwich structures are generally fabricated by adding two thin composite skins on top, bottom and lower density sandwich core in the middle. The mechanical properties of honeycomb sandwich structures are mainly depending on the core material, the skin material, the thickness of the core and the skin material. Compressive and flexural are major mechanical properties in sandwich structures. These properties will be highly depended on the core properties (Akatay *et al.* 2018). The honeycomb sandwich core is considered as homogenous material in order to reduce the computational time and the equivalent material properties can be used in the aircraft part designing. Due to this, the equivalent material properties are significant (Cunningham *et al.* 2000).

In 1969, sandwich structure was used in Apollo project which reflects the potential of sandwich structure utilization in the aerospace field. They were able to construct lightweight and strong Apollo capsule and heat shield using this technology, which can sustain the stresses during the initial and the re-entry phase of the mission. In 1983, AIRBUS started to build large structures with composite material and they were managed to build composite honeycomb sandwich rudder for A310 aircraft. In 1985, Vertical Tail Plane for the A310 was also fabricated using composite honeycomb sandwich. Nowadays, sandwich structures are utilized in aircraft, ships, automobiles, rail cars, satellites, wind energy systems, and bridge construction widely (Herrmann *et al.* 2005). The main advantages of sandwich structures are better performance, lightweight structures, continuous distribution of stiffness, excellent damping behaviour, better crash behaviour, etc. (Vinson 2005). Earlier sandwich structures were used in manufacturing of non-loaded parts in aircraft structures. And in past years, the researchers have started using sandwich structures in dynamically loaded structural parts. A large number of parts of Airbus aircraft are made of composite sandwich structures recently (Herrmann *et al.* 2005). Nose landing gear doors, pylons / nacelles, spoilers / ailerons, cabin floor panels, wings, vertical tail plane, horizontal tail plane are the major parts fabricated using composite sandwich structures (see Fig. 1).

Some of the major issues for the aircraft structures are bird strike impact, hailstones, strike to some objects, etc. The thin outer skin and highly deformable sandwich core will provide low

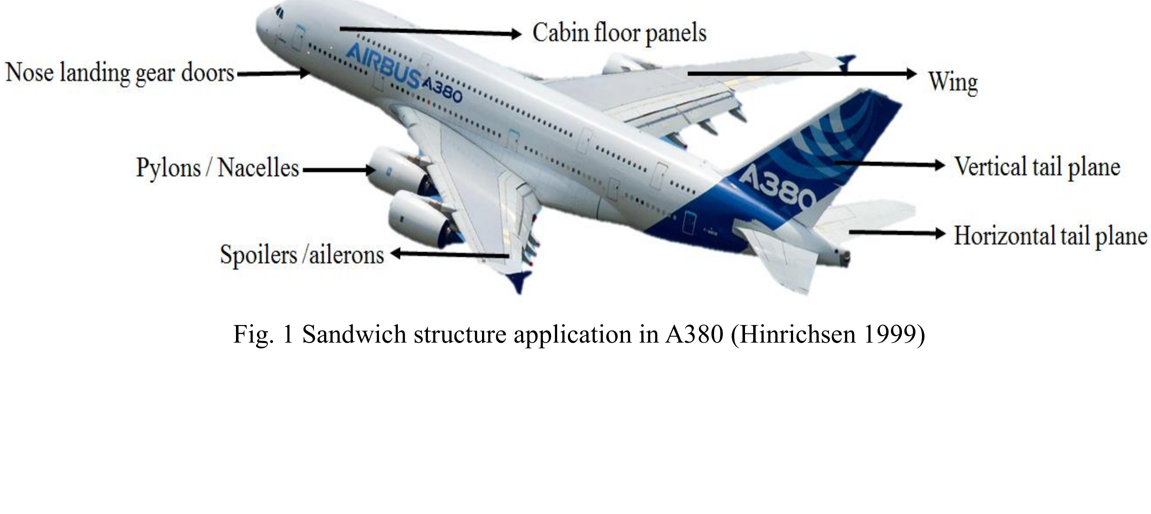

Fig. 1 Sandwich structure application in A380 (Hinrichsen 1999)

resistance to high velocity impacts. Matrix micro-cracking, fibre-matrix debonding and fibre failure are the major damages in composite materials. These initial damages will result in the skin fracture and the impact object may penetrate into the sandwich core. Sandwich structures will bend and damage slightly at low impact speed. And at high impact speed, the failure stress is reached quickly, which will result in the bending failure of the skin, interaction failure between the skin / core and compression failure of the core (Aktay *et al.* 2008, Abrate 2005). The failure of the core and the deformation are the major factor to estimate energy absorption capability of the sandwich structures (Aktay *et al.* 2005).

There are several studies to investigate the mechanical behaviour of sandwich structures, to improve the quality of the structure, etc. Yamashita and Gotoh (2005) investigated cell shape effect and thickness of foil on the crush behaviour of regular hexagonal cells aluminium honeycombs. The results show that the crush strength is higher for smaller cell angle and it increases with foil thickness. And the maximum values at a regular hexagonal cell shape were obtained when the crush strength per unit mass of the foil material was evaluated. Gibson and Ashby (1999) studied the mechanical properties of honeycomb sandwich structures by experimental and analytical analysis under different parameters. The crushing behaviour of honeycomb sandwich structures was studied by Wu and Jiang (1997) under quasi-static and dynamic loading conditions by considering the effect of cell numbers, cell dimensions and material strength. It was observed that the structure with small cell size and mow core height provided high strength provided better energy absorption and impact behaviour.

Petras and Sutcliffe (1999) studied the mechanical behaviour of glass fibre reinforced plastic laminate skins and Nomex aramid paper honeycomb core sandwich structure and the failure mode map for skin and sandwich core under three-point-bending were detailed. It was observed that the load and failure mode were depended on the skin thickness to span length ratio and honeycomb relative density. Horrigan and Aitken (1998) studied the soft impact on Nomex honeycomb cored sandwich structure and it was observed that the impact test causes a shallow crush on the cores. And hard body impact causes deeper damage in the form of projectile shape. A numerical model was proposed and a good agreement with experimental studies were achieved for the core crushing depth and diameter of damage. Goldsmith *et al.* (1997) investigated the perforation characteristics of cellular sandwich plates in axial direction and observed that the ballistic limit of the structure was not remarkably affected by the cell size, cell type or wall diameter of composite as the major mechanism resisting perforation was piercing the facing plates. As a result, identical composite skins produce the same ballistic limit irrespective of the core type.

Meo *et al.* (2003) investigate experimental and numerical analysis to study the impact at low velocity and damage due to penetration on the aircraft sandwich structure by solid, round shaped impactors. Numerical models were proposed and achieved a good agreement in the calculation of dent depth and the delamination area. Nguyen *et al.* (2005) has developed an explicit finite element based simulation tool to predict sandwich structure damage under low velocity impact. The tool was able to generate the 3D shell models of honeycomb and folded structure core automatically. The results were validated with experimental test and analysis of aluminium honeycomb specimens from a fuselage panel of the F-111 aircraft. It was able to predict the size and depth of the indentation accurately and provided good correlation with force versus time. Chawla *et al.* (2003) investigated parametric study numerically to analyse the effect of element size, adhesive bonding between the neighbouring cells, variation in impact velocity, material model in crushing behaviour of aluminium honeycomb structure and achieved good agreement with the experimental results.

Mokhtari *et al*. (2018) investigated the dynamic behaviour of sandwich T-joint structure by experimental and numerical analysis. The studies were mainly focussed on the adhesive region and the effect of step graded behaviour of the adhesive zone on the dynamic behaviour were analysed. It was found that the step wise graded adhesive zone cases were changed and different arranges in the stepwise graded adhesive zone have remarkably affect the maximum stress.

In 2012, Rao *et al.* studied the mechanical behaviour of short sisal fibre composite hollow core sandwich panels. Shear and flexural properties were obtained from experiments and numerical analysis were performed. The mid span deflection was predicted and validated. The sisal fibre reinforced cores were able to provide twice specific strength compared to the unreinforced polypropylene cores, which raises the scope of natural fibre based sandwich cores in different applications. Zuhri *et al.* (2014) investigated the compressive properties of square and triangular honeycomb fabricated using co-mingled flax fibre reinforced polypropylene and polylactide. The structures were tested under compression and quasi-static rates of strain, strength, specific energy absorption characteristics were analysed. Finite element analysis was also performed and the results were predicted then validated. Stocch *et al. (*2014) introduced jute fabrics / vinyl ester honeycomb core and experimental test were performed. The elastic response of the composites was studied by finite element modelling and homogenization analysis. The homogenization analysis results were shown good agreement with the analytical results. These studies prove the potential of natural fibre based honeycomb sandwich structures in a large number of applications.

Aluminium and synthetic fibre composite hexagonal cores are largely used in the manufacturing of honeycomb composite structure in aircraft. One of the major objectives of the aerospace industries is to reduce the fuel consumption by 50% in 2020 and at least 70% less by 2025. Weight reduction of the aircraft to increase the payload is one of the major concerns. Replacing of hemp fibre based honeycomb sandwich structures in some of the interior parts of the aircraft can reduce the weight of the aircraft which will provide better fuel consumption and less pollution.

The aim of this study is to propose innovative hemp woven fabrics / polypropylene design sandwich structure based honeycomb for the aerospace applications. Initially, the moulds will be designed in CATIA CAD software with desired dimensions and fabricated using CNC machine. Later, the sandwich core will be manufactured using the hemp fibre woven fabrics / polypropylene under 190°C. Composite skins will be also manufactured and it will be attached to the cores using adhesive. The mechanical behaviour of the structure (compression and flexural) will be investigated and analysed. Numerical simulations will be also performed using ABAQUS FE software in order to have a better understanding about the behaviour of the structure. Finally, complex aircraft parts will be designed and simulate their behaviour under complex load. Comparison with aluminium structure will also be carried out to analyse the absorption energy capacity and material damage.

2. Manufacturing of hemp fibre woven fabrics / polypropylene sandwich structure

Hemp fibre woven fabrics / polypropylene composite sheets were initially fabricated by thermo-pressing manufacturing process. Hemp taffeta fabrics with an areal density of 290g/m^2 was stacked between two polypropylene sheets in a flat mould and the mould was allowed to heat in a curing oven for 2 hours 30 minutes under 190°C. Later, it is pressed using a thermal press that permits the polypropylene to melt and join with the fabrics. Composite sheets with 17.5% fibre volume fraction were produced (Fig. 2) and the estimated mechanical properties obtained from tensile tests for hemp taffeta fabrics, polypropylene, hemp taffeta composite were presented in Table 1. The composite sheets were cut into the required dimensions for skin and core parts. A mould for the honeycomb core was designed by CATIA CAD software and manufactured by CNC machine (see Table 2). Demould solvent was applied on the mould for the easy demoulding of the core structure. The composite sheet pieces were inserted into the mould precisely. The mould was allowed to heat for 2hrs and compressed in thermal press. This permits the polypropylene to melt and the composite sheet pieces to join together (Fig. 3). The mould was allowed to cool down in ambient temperature and honeycomb core was demoulded.

Uniaxial tensile tests were performed using INSTRON 4411 machine with 5kN static load and a crosshead speed of 5mm/min at ambient temperature to estimate the mechanical properties of hemp taffeta fabrics / pp skin (longitudinal and transversal direction). Compression test was performed using INSTRON 4411 machine with 5kN static load and a crosshead speed of 5mm/min at ambient temperature to estimate the mechanical properties of hemp taffeta fabrics / PP core (Fig. 4). The core part is considered as an isotropic homogenous material. The mechanical properties of skin and core parts were calculated using the force versus displacement curve obtained from experiment and estimated cross-section area (see Table 3). The cross-section area of the skin and core part are 30mm^2 and 283.93mm^2 respectively. A comparison between the compressive strength of different honeycomb structures with respect to their geometry were presented (Table 4). Adhesives were applied on the core after, skins and the structures were pressed at ambient temperature (see Fig. 5).

The honeycomb structure was cut into 25mm x 25mm specimen for compression test and 150mm x 25mm for the flexural test. The compression test according to ASTM: C365/C365M and flexural test (4-points bending) according to ASTM: D790 were performed using INSTRON 4411 machine with static load 5kN and a crosshead speed of 5mm/min at ambient temperature. For compression test, the specimens were placed between the two jaws of the machine and compression force was applied. For flexural test, the specimens were placed on top of two cylinder shaped indenters with a support span of 100mm. Two cylinder shaped indenters with load span of 50mm were placed on top the specimen and flexural force was applied from the specimen top.

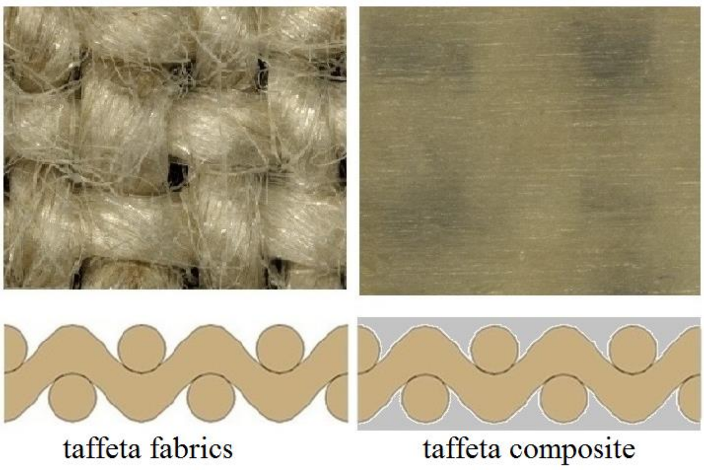

Fig. 2 Hemp fibre taffeta fabrics and taffeta composites

Table 1 Characteristics of hemp taffeta fabrics, polypropylene and composite

		Taffeta fabrics	Polypropylene	Taffeta composite
Volume density		0.815g/cm^3	0.91g/cm^3	0.90g/cm^3
Tensile modulus	Warp	1415±45MPa	975±15MPa	1143.50±45.38
	Weft	2125±55MPa		1356.81±33.61
Tensile strength	Warp	70±5MPa	21.75±2.25MPa	25.67±3.45
	Weft	72±6MPa		28.13±2.78

Table 2 Geometrical parameters of honeycomb sandwich structure

Cell size (D)	6mm
Core width (b)	25mm
Cell thickness (t)	2mm
Core thickness (H)	25mm
Skin thickness (h)	1.25mm
Distance between middle of skins (d)	26.25mm
Total thickness of sandwich (T)	27.50mm

(a) (b) (c)

Fig. 3 Honeycomb mould: (a) CAD, (b) Mould, (c) Sandwich core fabrication

Fig. 4 Tensile and compression test setup for skin and core part

Table 3 Experimental mechanical properties of core and skin

		Core	Skin
Strength (MPa)	Longitudinal	14±2.4	25.67±3.45
	Transversal		28.13±2.78
Young's modulus (MPa)	Longitudinal	385±7.3	1143.50±45.38
	Transversal		1356.81±33.61

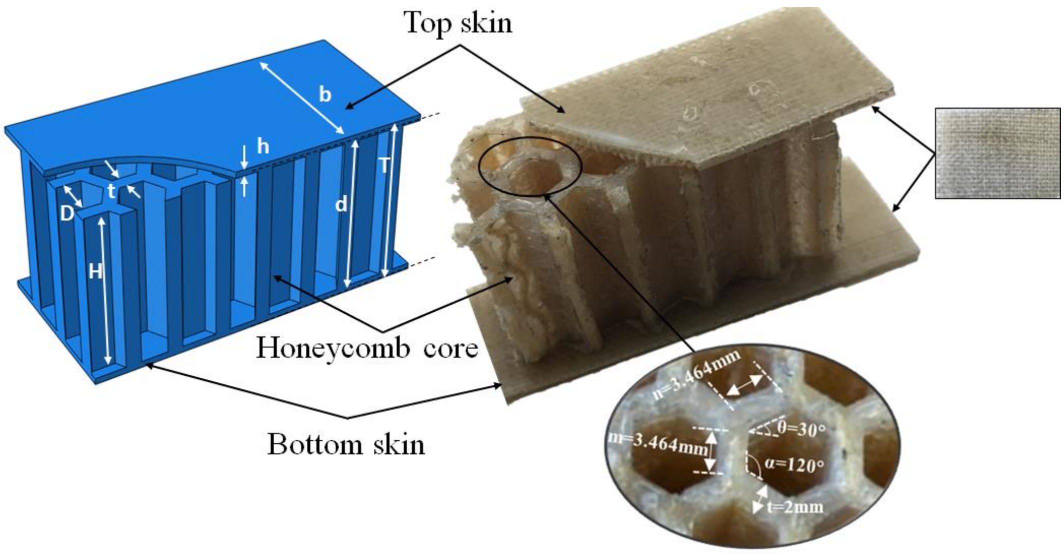

Fig. 5 CAD of honeycomb and sandwich structure

3. Result and discussion of honeycomb sandwich structure behaviour

Force versus displacement response of honeycomb sandwich structures in compression and flexural test (4-points bending) obtained from experiment is presented (Fig. 6). The compression test force versus displacement curve consists of mainly three stages. (A) The load increment linearly until the maximum load initially. (B) After this point, the buckling effect starts acting on the cell walls and the load drops suddenly. During this period, the cells starts folding and deform plastically. (C) Later, the cell wall start contact each other and the load start increasing, which is known as 'densification'. Similarly, the force versus displacement curve for 4-points bending also consist of mainly three stages. (A) Initially, the load increase linearly and (B) later some peaks and drops were appeared due to the sequential bucking and cracks in the core. (C) Finally, the cracks spread to the whole structure which lead to the catastrophic failure of the sandwich structure. Skin/core interface failure, skin failure and core failure were the main failure mode observed during the experiments (Fig. 7).

CAD design model of honeycomb sandwich is used to simulate the behaviour of these structures using ABAQUS software. Frictional interaction properties were applied between the core and skin parts by tie constraint. The material properties obtained from the experiments were assigned for each part. FE simulations were performed in ABAQUS/Explicit analysis and predicted displacement field in each displacement load:

- In compression test, two discrete rigid plates were attached on the top and bottom of the sandwich structure. The bottom plate is fixed and displacement of u = 5 mm is applied to the top plate. The honeycomb sandwich core was meshed with 29419 quadratic tetrahedral finite elements (C3D10) and the skin parts were meshed with 384 linear hexahedral elements with reduced integration (C3D8R).

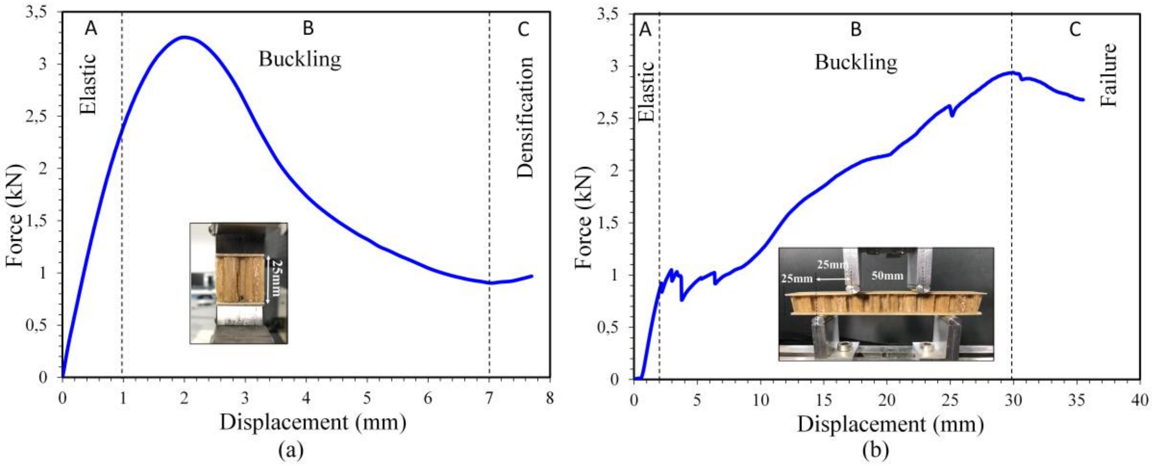

Fig. 6 Experimental force versus displacement (a) Compression test, (b) Flexural test

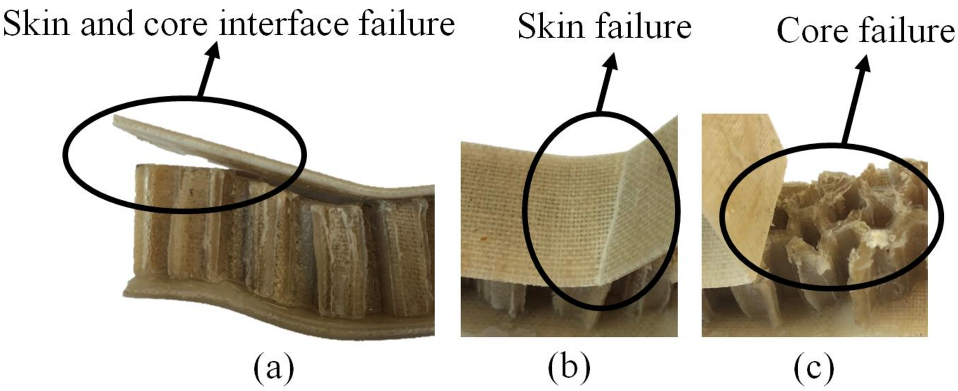

Fig. 7 Failure mechanisms (a) Skin/core interface failure, (b) Skin failure, (c) Core failure

Table 4 Comparison of geometrical and compressive strength data of honeycomb (Stocch *et al*. 2014)

Core	Cell size (d) (mm)	Cell thickness (t) (mm)	Core height (H) (mm)	Compressive strength (σc) (MPa)
Hemp/PP honeycomb	6	2	25	6.51
Jute/VE honeycomb	6	1.43	10	14.99
Aluminium plascore	6.4	0.1	15.8	9.37
Stainless steel plascore	9.5	-	12.7	2.41
Euro composite	6.4	-	12.7	1.4
Hexcel HRH 10 Nomex	4.7	0.15	19	0.9

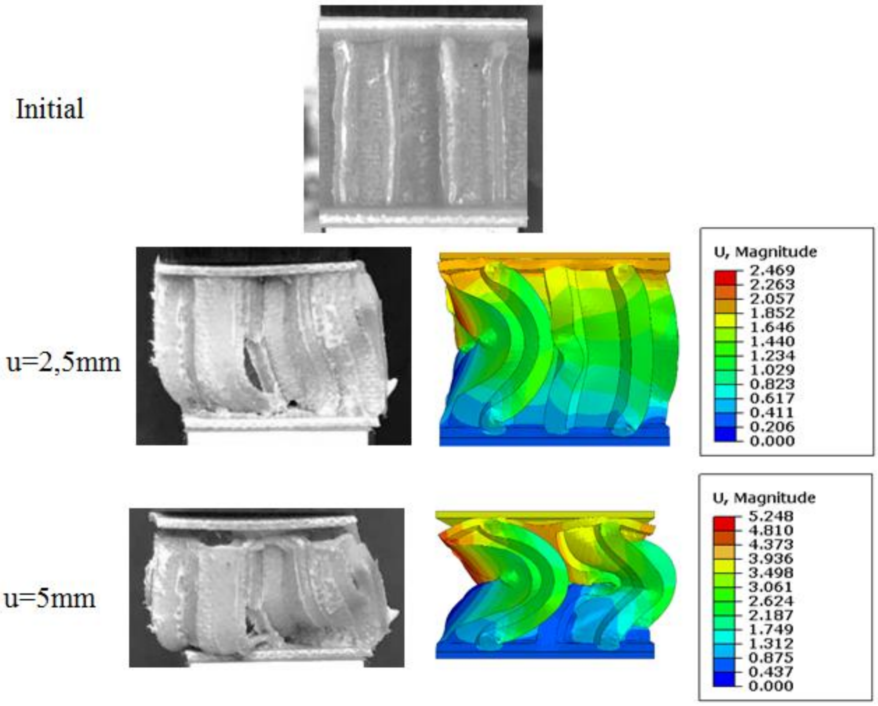

Fig. 8 Comparison of experimental and predicted compression deformed sandwich structure

- In 4-points bending test, two discrete rigid cylinders were attached to the top and two cylinders were attached on the bottom of honeycomb sandwich structure in desired distance. The bottom cylinders were fixed and displacement u = 20 mm were applied to the top cylinders. The honeycomb sandwich core was meshed with 34956 quadratic tetrahedral finite elements and the skin parts were meshed with 2304 linear hexahedral elements.

The obtained deformed specimens at each displacement (u = 2.5 and u = 5 mm) is compared to the predicted displacement in the case of compression test (Fig. 8). Noting that, the qualitative numerical simulation is agreed with the observed damaged specimen. The step by step progression of experimental displacement field in the 4-points bending test is also compared to the numerical analysis in Fig. 9. The flexural stiffness EI considering each component (core and skin) of composite structure can be expressed as (Styles *et al.* 2007):

$$\mathrm{EI} = \frac{bh^3}{6}E_s + \frac{bhd^2}{2}E_s + \frac{bH^3}{12}E_c \qquad (1)$$

where E_s is the modulus of skin (1250MPa), E_c is the modulus of core (35MPa), b is the width of the sandwich beam (25mm), h is the thickness of the skin (1.25mm), d is the distance between the middle of the skins (26.25mm), H is the thickness of the core (25mm). The flexural rigidity (EI) of hemp fibre woven fabrics / polypropylene sandwich structure is estimated using equation 1 as 22.55 Nm^2.

The flexural deflection of sandwich structure Δ in four points bending (bending + shear) can be calculated as (Matta *et al.* 2017):

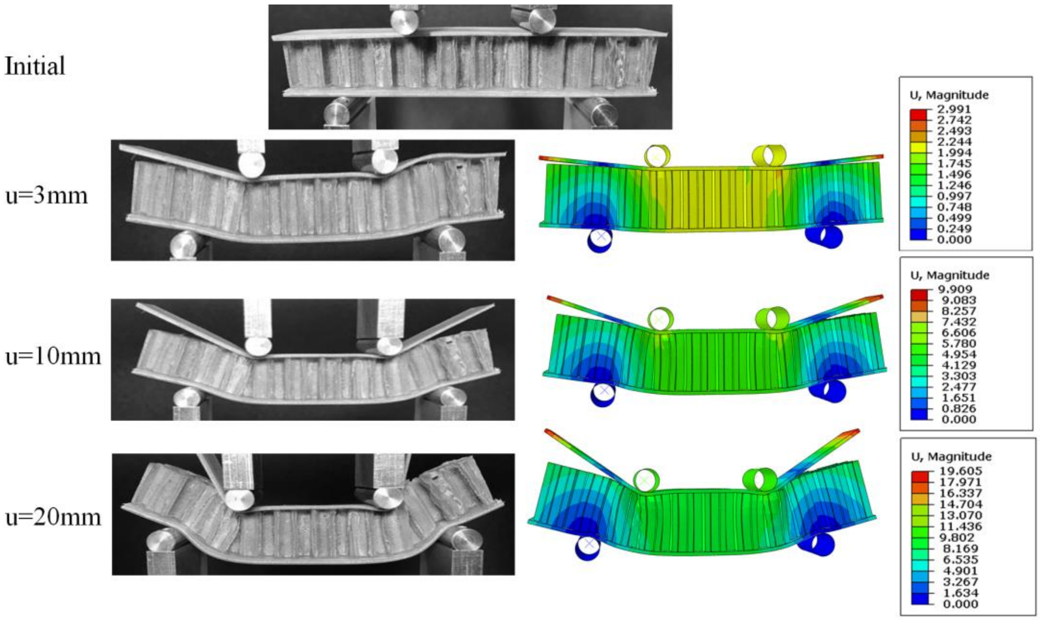

Fig. 9 Comparison of experimental and predicted 4-point deformed sandwich structure

$$\Delta = F\frac{(2S^3 - 3SL^2 + L^3)}{96EI} + F\frac{(S-L)}{4U} \tag{2}$$

where F is the imposed force, S = 100mm is the length of support span, L=50mm is the length of load span and U is the transverse shear rigidity estimated as 42.78MPa with (Gibson and Ashby 1999):

$$U = E_c\left(\frac{t}{n}\right)^3 \frac{{}^m/_l + \sin\theta}{({}^m/_n)^2(1 + 2{}^m/_n)\cos\theta} \tag{3}$$

where $n = 3.464mm, m = 3.464mm, t = 2mm \; and \; \theta = 120°$ (Fig. 5)

- Core shear stress maximum can be determined as (Styles *et al.* 2007):

$$\tau_{max} = \frac{F_{max}}{EI}\left(\frac{E_s\,hd}{2} + \frac{E_c}{2}\frac{H^2}{4}\right) \tag{4}$$

Where F_{max} is the maximum load.

- Stress maximum on the core (σ_c) can be estimated as:

$$\sigma_c = \frac{M_f\,.\,z}{EI}E_c \quad with \quad z = \frac{c}{2} \tag{5}$$

- Stress maximum on the skin (σ_s) can be estimated as:

$$\sigma_s = \frac{M_f\,.\,z}{EI}E_s \qquad with \qquad z = \frac{H}{2} + \frac{1}{2}\left(\frac{d+h}{2} - \frac{H}{2}\right) \tag{6}$$

where M_f is the maximum bending moment defned as:

$$M_f = \mathrm{F}_{max}\frac{(L-S)}{4} \tag{7}$$

From the above equations, the mechanical properties of the hemp fibre woven fabrics / polypropylene sandwich structure are: τ_{max} = 5.87MPa, M_f = 36250Nmm, σ_c= 7.74MPa and σ_s= 19.29MPa.

4. Numerical analysis of honeycomb sandwich aircraft structures

Honeycomb structures are being used in the fabrication of different complex parts in automobile and aircraft industries. Hemp fibre woven fabrics / polypropylene based honeycomb sandwich in projectile, spline, dome and cabin wall shaped structures were studied numerically. The material properties obtained for hemp sandwich structure was applied to each models. Numerical simulations for compression and flexural behaviour of each sandwich aircraft honeycomb structures were performed in ABAQUS/Explicit and results were analysed and compared with aluminium structures.

4.1. Projectile shaped honeycomb sandwich aircraft structure

The projectile shaped honeycomb sandwich structure with a length of 132mm and width of 100mm were created. The core structure was meshed with 129560 quadratic tetrahedral elements, and the top of skin is meshed with 6968 linear hexahedral elements and the bottom of skin is meshed with 4824 linear hexahedral elements. Rigid plates were attached at the top and bottom of the structure and compression test were carried out by applying a displacement of u = 10mm from the top while the bottom plate is fixed. Flexural 4-points test was performed by attaching two rigid rods at the top and two rigid rods at the bottom of the structure. The bottom rigid rods are fixed and displacement of u = 10mm was applied on the top rigid rods (Fig. 10). The displacement field for compression and flexural test were analysed and plotted in Fig. 11.

4.2. Spline shaped honeycomb sandwich aircraft structure

The spline shaped honeycomb sandwich structure with a length of 100mm and width of 100mm were created. The core structure was meshed with 90742 quadratic tetrahedral elements and the top and the bottom skins were meshed with 4100 and 2600 linear hexahedral elements respectively (Fig. 12). Due to the curve shape of the structure, only one rod from the top and one rod from bottom was connected to the structure initially. The displacement field for compression and flexural test were analysed and plotted in Fig. 13.

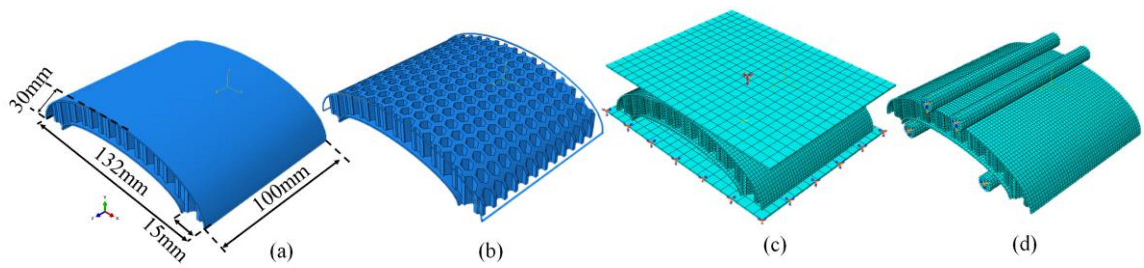

Fig. 10 Projectile shaped honeycomb (a) Geometry (b) Core (c) Compression (d) Flexural

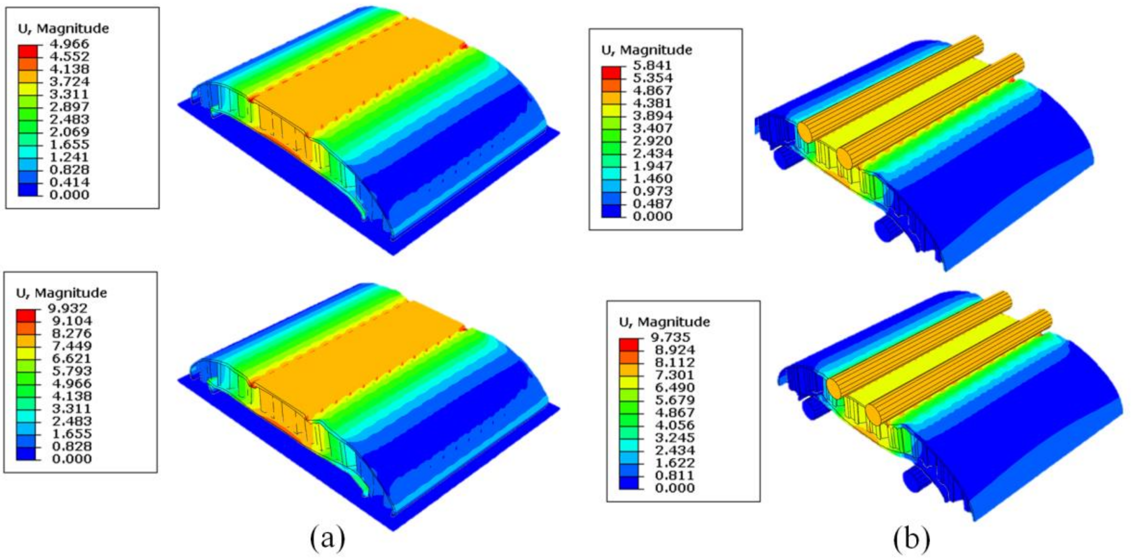

Fig. 11 Deformed projectile shaped honeycomb (a) Compression (b) Flexural

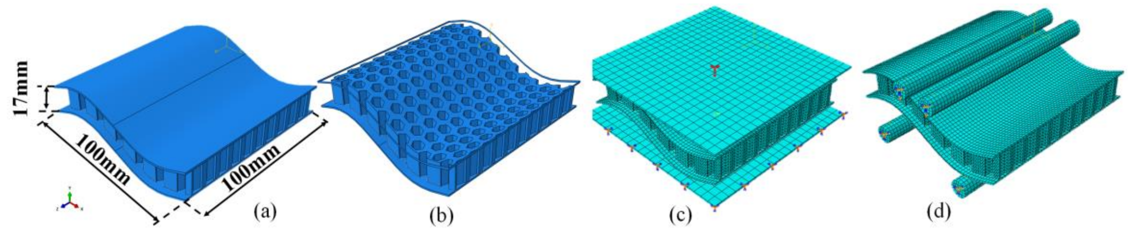

Fig. 12 Spline shaped honeycomb (a) Geometry (b) Core (c) Compression (d) Flexural

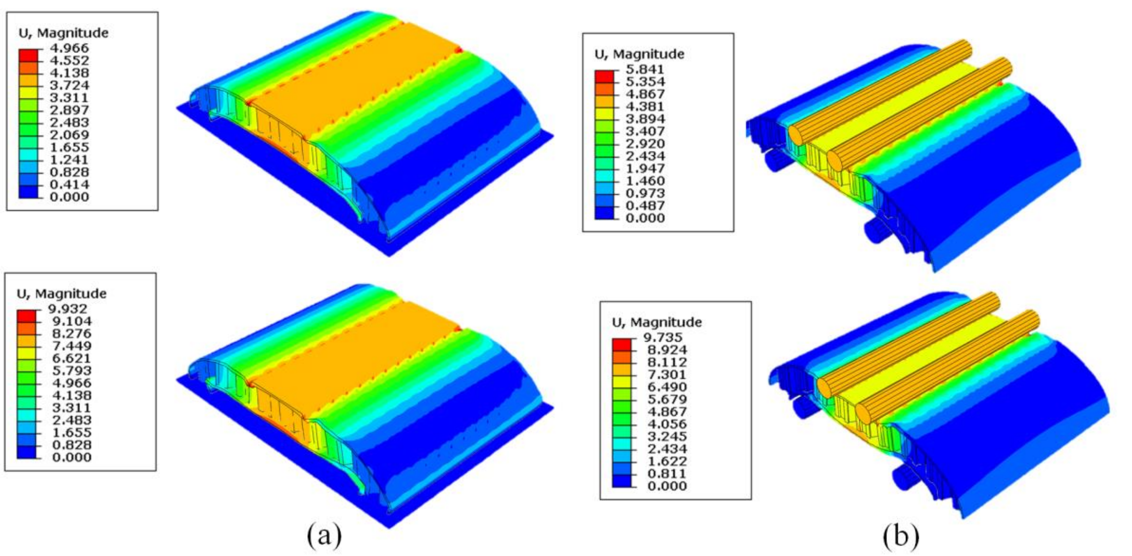

Fig. 13 Deformed spline shaped honeycomb (a) Compression (b) Flexural

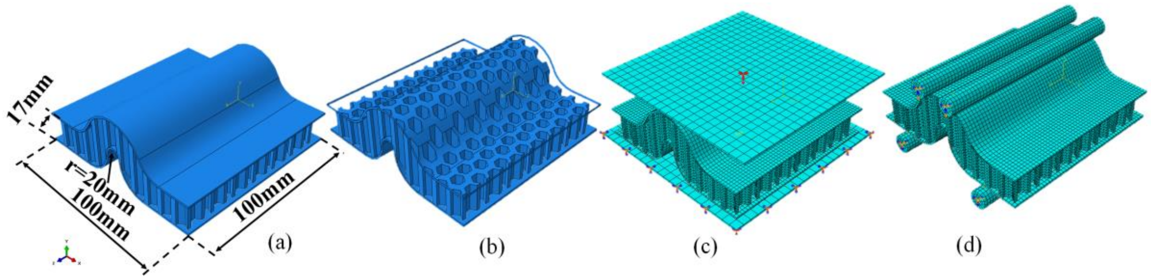

Fig. 14 Dome shaped honeycomb (a) Geometry (b) Core (c) Compression (d) Flexural

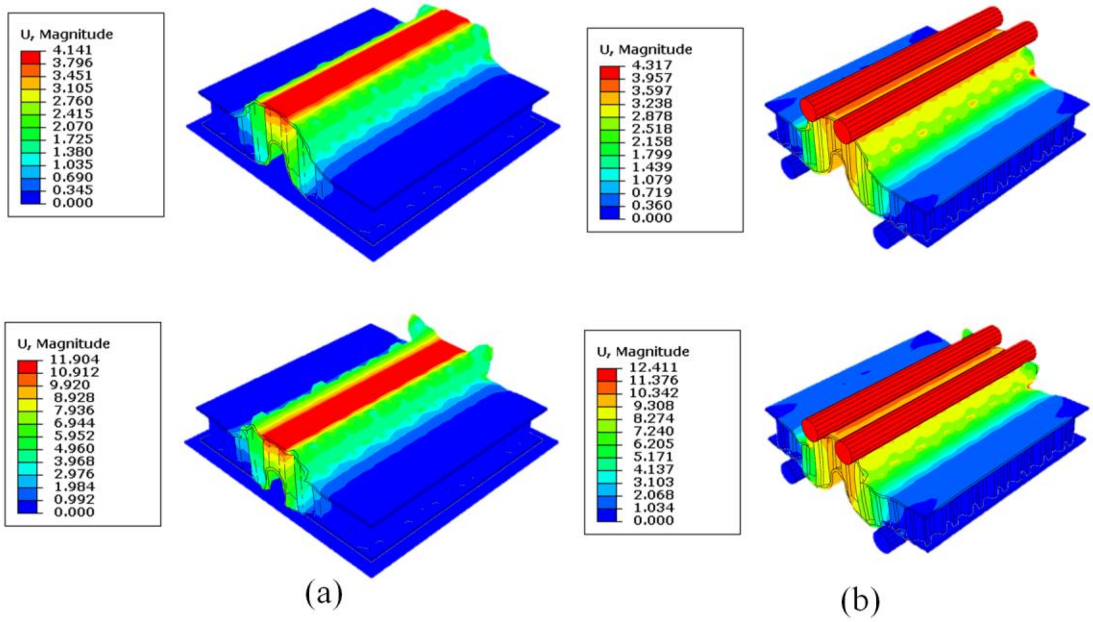

Fig. 15 Deformed dome shaped honeycomb (a) Compression (b) Flexural

4.3. Dome shaped honeycomb sandwich aircraft structure

The dome shaped honeycomb sandwich structure with a length of 100mm and width of 100mm were created. The core structure was meshed with 122643 quadratic tetrahedral elements and the top and the bottom skins were meshed with 3800 and 3750 linear hexahedral elements respectively (Fig. 14). The displacement field for compression and flexural test were analysed and plotted in Fig. 15.

4.4. Cabin wall shaped honeycomb sandwich aircraft structure

The cabin aircraft wall shaped honeycomb sandwich structure with a length of 150mm and width of 75mm was created. The core structure was meshed with 117990 quadratic tetrahedral elements and the top and the bottom skins were meshed with 10801 and 9793 quadratic tetrahedral elements respectively (Fig. 16). The displacement field for compression and flexural test were analysed and plotted in Fig. 17.

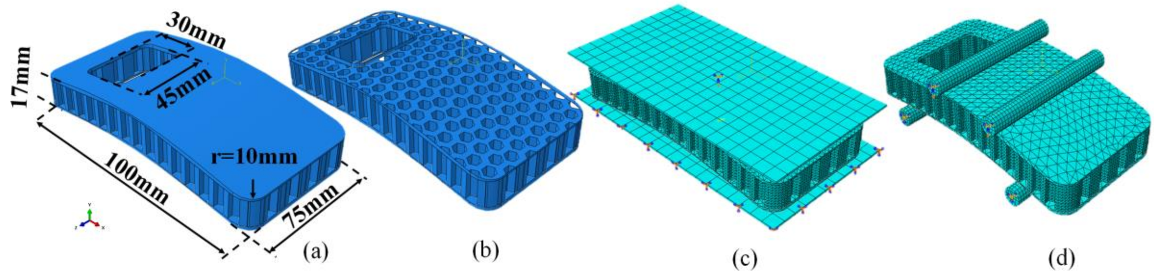

Fig. 16 Cabin wall shaped honeycomb (a) Geometry (b) Core (c) Compression (d) Flexural

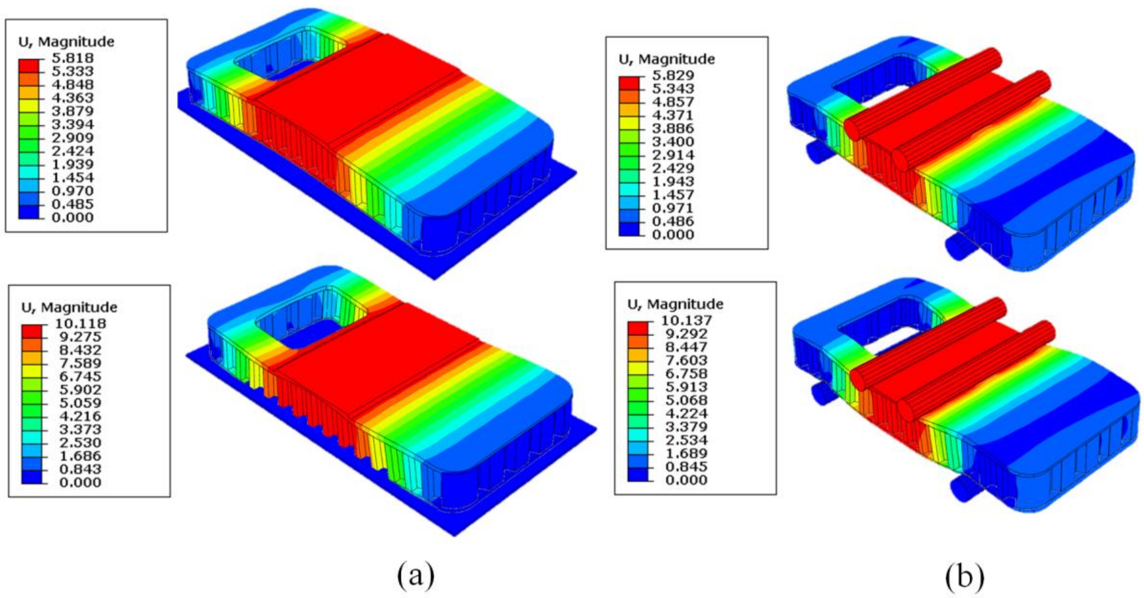

Fig. 17 Deformed cabin wall shaped honeycomb sandwich structure (a) Compression (b) Flexural

Table 5 Comparison of hemp composite and aluminum honeycomb sandwich aircraft structures

Shape		Mass (g)	Compression				Flexural			
			Max Disp (mm)	Energy absorption (kN.mm)	Max force (kN)	Max stress (MPa)	Max Disp (mm)	Energy absorption (kN.mm)	Max force (kN)	Max stress (MPa)
He	Projectile	113	10	150	23	752	20	840	84	867
	Spline	113	15	412	47	386	20	235	94	1231
	Dome	92.9	10	875	182	1465	10	390	78	2328
	Cabin wall	113	10	85	17	370	10	175	32	882
Al	Projectile	305	10	455	91	1097	20	4020	402	4135
	Spline	306	15	1939	277	4058	20	2950	295	6641
	Dome	251	10	1920	384	4658	10	720	144	4383
	Cabin wall	306	10	260	54	2321	10	530	106	1835

*He: Hemp honeycomb structure; Al: Aluminium honeycomb structure; Disp: Displacement

Numerical simulation results obtained for each shape were analysed and compared in Table 5. It is noted that the dome shaped structure have the maximum force and stress in both compression and flexural cases due to the high complex shape. Dome shaped structure achieves a maximum force of F=182kN and a maximum stress of σ=1465MPa in compression and maximum force of F=78kN and a maximum stress of σ=2328MPa in flexural test at u=10mm displacement. The surface area of the structure is higher due to the dome shape and other parts except the dome is flat which gives a good support to the structure. The projectile shaped structure has a maximum force of F=23kN, maximum stress of σ=752MPa in compression at a displacement of 10mm and maximum force of F=84kN, maximum stress of 867MPa in flexural at a displacement of 20mm. Similarly, the spline shaped structure has a maximum force of F=47kN, maximum stress of σ=386MPa in compression at a displacement of 15mm and a maximum force of F=94kN, maximum stress of σ=1231MPa in flexural at a displacement of 20mm. The cabin wall shaped structure has a maximum force of F=17kN, maximum stress of σ=370MPa in compression and maximum force of F=32kN, maximum stress of σ=882MPa in compression at displacement of 10mm. The energy absorption of each structure in compression and flexural tests were also calculated.

Numerical simulations were also performed with aluminum skin material A5083-H321 (E=70000MPa, Density=2.7g/cm^3) and aluminium foil honeycomb core material A3003-H19 (E=540MPa, Density=0.055g/cm^3) (Paik *et al.* 1999). It is observed that aluminium honeycomb has better performance comparatively due to their high mechanical properties. And it was noted that, the mass of the aluminium honeycomb structure was about 3 times greater than the hemp composite honeycomb structure. The better performance of the hemp based honeycomb structures could be obtained by improving the mechanical property of the fabrics by chemical treatment, using better resin, etc. Handmade academic level manufacturing process may also have affected the mechanical performance adversely and this can be improved by machine manufacturing technics in industrial level. The obtained results suggest that hemp based honeycomb structure has good potential to be a substitute to commercially available honeycomb core in different applications. The interior walls, doors, panels which are made of plastic can be replaced with hemp based honeycomb structures which will provide better mechanical performance and reduce the weight of the whole structure. Further studies to improve and optimize the mechanical performance can also be conducted and thereby utilization of natural fibre based honeycomb structure can be expanded.

5. Conclusion

In this study, a novel Hemp fibre woven fabrics / polypropylene (PP) based honeycomb sandwich structure was introduced. A mould for honeycomb core with desired dimensions was created in CATIA CAD software and fabricated. Hemp fibre woven fabrics based skin and core was manufactured by thermal press and the structures were tested experimentally. Hemp / PP cores with a cell size of 6mm, cell thickness 2mm, core height of 25mm provided a compressive strength of 6.51MPa. Compressive strength of different commercially available honeycomb core was compared and it is observed that hemp / pp honeycomb structures have good performance. Compression and flexural tests were performed experimentally in static loading. Elastic, buckling, densification stages were observed in compression test and elastic, buckling, failure stages were observed in flexural test. CAD of honeycomb structure was created in CATIA and numerical simulations of compression and flexural tests were performed in ABAQUS/Standard FE software. Material properties of conventional aluminium based honeycomb structures were applied in the same structures and results were compared to hemp composite aircraft structures. The results obtained show the good potential of hemp based honeycomb structure to be used in many applications in aircraft or automotive interior parts such as interior walls, doors, panels, etc.

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