The Iraqi Journal for Mechanical and Material Engineering, Vol.22, No3, June.2023

INVESTIGATION OF VARIABLES GEOMETRY OF NOVEL PIN CORE-SANDWICH STRUCTURE ON UNSATURATED POLYESTER FLEXTURAL PROPERTIES

Meethaq M. Abed
meethaq.abed@atu.edu.iq
Karbalaa Technical Institute, Technical University of Al- Furat Al-Awsat, 56001, Karbala, Iraq.

ABSTRACT

Sandwich Structure with pin core is widely used in foam core for crushing, debonding and interfacial delamination prevention; this structure has manufactured by drilling foam core frequently. On the other hand, a novel method for manufacturing a pin core sandwich structure has been the aim of this research. Machinable wax panel was used to achieve cavities in form of pin within the core by drilling the wax panel by CNC-drilling machine then casting of thermoset resin (unsaturated polyester resin) into a wax mold, after that melting of the wax mold to get pin core sandwich structure. Complex structure can't be designed by conventional method but by this method allows to design such complex structures: spheres, pyramids, ellipse…etc. According to Response Surface Methodology method, fifteen specimens were achieved and three variables were investigated to get optimization and prediction model. The results show that 300% improvement of stiffness performance index with 40% weight reduction comparative to reference sample with 4.46 $GPa^{0.5}\ cm^{3}\ g^{-1}$ optimal value for the specimen ((High=11mm), (Diameter=9 mm) and (Pin-to-Pin distance=4.3 mm)). Strength performance index improvement is 126% and 50% weight reduction comparative to reference sample with 35.9 $MPa^{2/3}\ cm^{3}\ g^{-1}$ optimal value for the specimen ((High=11mm), (Diameter=6.115 mm) and Pin-to-Pin distance=1.5 mm)). ANOVA analysis shows that the pin height (H) is effective parameter on stiffness property. On the other hand, the height and diameter of the pin are effective parameters on strength property.

Keywords: **Pin-core structure, sandwich structure, composite materials, carving wax, lightweight structure, stiffness performance index.**

NOMENCLATURE

H	Height of cylinder
X	PIN-to-pin distance
DOE	Desig of experiment
D	Diamter of cylinder

ρr	Relative density of the pins
ρs	Cellular density (g/cm3)
ρ	Unsaturated polyester solid density (1.277 g/cm3)
w	Specimen weight (g)
ve	Specimen effective volume (cm^3)
Ϭf	Maximum bending stress (mpa)
p	Load at maximum (n)
l	Span length (mm)
b	Width (mm)
d	Thickness (mm)
e	Elastic modulus in bending, mpa,
b	Width of beam, mm
d	Depth of tested beam, mm.
m	Slope of the tangent to the initial straight-line-portion of the load-deflection curve, n/mm
r	Coefficient of determination
Anova	Analysis of variance

INTRODUCTION

Sandwich beams with tough stiff skins and core has low density , are generally used for applications that subjected to bending loads but at the same time it required weight reduction efficient. However, shear of core and wrinkling of skins are considered to be the most unconventional modes of failure of sandwich beams [Tagarielli V.L. *et al*, 2004]. Therefore, Composite materials are suggested and optimized for marine structures to provide high performance under such rigorous loading conditions. Beams with composite sandwich structure consisting of composite skins and foam core are employed in a way that covers marine applications which required lightweight [Gupta N. *et al*, 2019]. As a result, the researchers focused their attention to improve the performance of such structures.

Wang B. *et al*, 2009 designed and manufactured a 3D sandwich structure composed of columns reinforced foam core. The composite columns density ranged (1, 1.5, 2, 2.5 and 4 columns/cm^2). Shear flexural and compression tests were accomplished for the different column densities samples. According to the results of these tests, an increasing of mechanical properties with increasing the columns density is shown. From studying of the failure modes by optical microscope, inclination and chain-like modes of failure represent the main mechanism of the failure. Abdi B. *et al*, 2013 focused their research on the polymer pin-reinforced foam core sandwich(PRFCS) behavior under compression and flexural loadings. Vacuum infusion process was used to manufacture panels of foam core sandwich (FCS) and PRFCS which composed of mat of glass/polyester for skins and foam of polyurethane as core. Effects of polyester pin reinforced core and different loading rates of flexural load were determined. Based on the obtained results, it was found that the cylindrical polymeric pins within the foam core significantly increases the compression and flexural properties of these sandwich structures. Furthermore, it was shown that polymer pins diameters had a significant influence compared to the moderate influence of loading rate.

Absorption energy of composite reinforced polyvinyl chloride (PVC) foam cores, which are used as lightweight impact-resistance sandwich structures, were investigated by J. Zhou et al, 2014. By accomplishing the compression test on foam cores of cross linked PVC with various densities (40 - 200 kg/m3) reinforced by carbon fiber and glass fiber rods have diameters: 2, 3 and 4 mm. Results of the study showed that the correct selection of foam density and arrangement of rods determines the optimized compression strength. Additionally, the dynamic performance of these structures was investigated by conducting the drop-weight impact tests. Here, it was found that as rods volume fraction was increased up to 2.5%, the measured SEA of these reinforced foam slitly affected. Compared to the unreinforced foam core (reference sample) the energy absorption, compression strength and impact resistance were found to be significantly increased.

There was an attempt for improving mechanical performance of sandwich with foam core by using a rather simpler method to reinforce the core. For that purpose, Yalkin H. E. et al 2015, used vacuum infusion process for manufacturing composite panels by only-perforated and perforated-stitched foams core with face sheet of multiaxial glass fabrics for epoxy resin. Based on the results of the conducted tests (shear, impact, bending and compression,) it was shown that the new proposed stitched core structures have superior mechanical performance compared to the plain core structure. In 2017, Icten B. M. *et* al, 2017 aimed to enhance the tensile and compressive performance of sandwich with foam core by modification of the core structure. At the same time, they took in consideration the time consumption and easy of application. Sandwich composites with single core perforated, divided core perforated, single core stitched, divided core stitched and plain core were tested and compared to each other. Results of this study show that the stitched and perforated core sandwiches have superior strength. Additionally, dividing the core is found to be very effective in term of performance enhancement compared to the plain core sandwich composite.

Meethaq M. and Mohammed H., 2020 innovated a new method to design and manufacture a complex sandwich structure such as Sphere Sandwich Structures (SSS) by using carving wax. Three geometry factors: skin thickness(K), distance between spheres(X) and diameter of sphere(D) had been studied. Specific fracture toughness was calculated by Izod test. The results showed that optimal geometry factors are 2 mm skin thickness, 8 mm distance between spheres and 6 mm diameter. ANOVA analysis showed that the greatest effective geometry factor was diameter of sphere(D) comparative to other factors.

This study aims to investigate the design and behavior of a novel lightweight pin core sandwich structure and optimize its three variables of core: the height of cylinder (H), Diameter of cylinder (D) and pin-to-pin distance(X). This pin core structure having self-bonded cylindrical pins to skins without adhesive between core and skins. Carving wax method was employed to fabricate these complex sandwich specimens and method of Box-Behenkin by Minitab 18 was employed to get optimal values and parameters modeling. According to Box-Behenkin method, 15 runs were obtained for three variables.

METHODOLOGY

Designing of experiments (DOE)

Carving wax (which is used for dentistry students training) from Dentirak company, China made, was used to make castings with (40*40*1.5 cm) dimensions. Fifteen specimens of waxy were made by CNC machine at 30-40 ◦C, with three principle variables, high cylinder (H), diameter cylinder (D) and pin-to-pin distance (X) as shown in figure 1. Table 1 showed experimental design with code of samples. All of these samples are designed according to the D790-03 ASTM standard for each tests, as shown in figure 2

Fabrication of specimen

After good fixing of the waxy sample and mixing unsaturated polyester resin with the hardener (1: 0.01 ratio mixing) at 30-50 ◦C and atmospheric pressure, very slowly pouring of the unsaturated polyester into the waxy sample was accomplished to allow unsaturated polyester resin to fill all designed cavities, as illustrated in figure 3.

Wax should be eliminated so the sample was heated to the melting temperature at (90-110 ◦C) and the same time curing of unsaturated polyester bulk was completed. Under the action of gravity, the molten wax flowed out of the unsaturated polyester sample and collected in adequate container to be reused for making another waxy sample, as shown in figure 4. After process finished, three set of samples designed were achieved according to the tables 1and the sets these samples were illustrated in figure 5. For comparing results with reference sample, bulk unsaturated polyester sample (1.5, 4, 20 cm) was prepared, as illustrated in figure 6.

Relative Density of the Pins (ρ_r):

One of the most important properties of lightweight structure is relative density, which express the material amount with respect to 100% dense solid. The relative density ranges from 0.02-0.9 depending upon the following equations (1) and (2) [Lehmhus D., 2013].

$$\rho_r = \frac{\rho_s}{\rho} \tag{1}$$

$$\rho_s = \frac{W}{V_e} \tag{2}$$

where is :

ρ_r :Relative density
ρ_s: Cellular density (g/cm^3)
ρ: Unsaturated polyester solid density (1.277 g/cm^3)
W : Specimen weight (g)
V_e : Specimen effective volume (cm^3)

Strength and Stiffness Performance Indices

The flextural strength test was done to calculated the index of strength and stiffness performance as shown in the following equations (3) , (5) [Tempelman E.et al, 2013]. Flextural test was according D790-03 ASTM to get maximum bending stress(MPa) and elastic modulus (MPa) as equations (4) and (6) by Universal Testing Machine, GUNT HAMBURG WP310 model at loading rate 2mm/min.

$$\text{Strength Performance Index} = \frac{\sigma_f^{2/3}}{\rho_s} \quad (3)$$

$$\sigma_f = \frac{3PL}{2bd^2} \quad (4)$$

where:

σ_f:Maximum bending stress (MPa)
P: load at maximum (N)
L: Span length (mm)
b: width (mm)
d: Thickness (mm)
ρ_s: Shape density (g/cm^3)

$$\textbf{\textit{Stiffness Performance Index}} = \frac{E^{0.5}}{\rho_s} \quad (5)$$

$$E = \frac{L^3 m}{4bd^3} \quad (6)$$

where is:

E= elastic modulus in bending, MPa,
L = span length, mm
b = width of beam, mm
d = depth of tested beam, mm.
m = slope of the tangent to the initial straight-line portion of the load-deflection curve, N/mm

RESULTS AND DISCUSSION

Minitab 18, Response Surface Methodology(RSM) method was used to analyze the values of indexes of strength and stiffness performance, then getting the optimization and prediction statistical models. The equation of model is full quadratic with 95% confidence level. The results of this work are presented in Table 2.

Strength Performance Index:

From obtained results (table 2) it is clear that 126% improvement of strength performance index with 50% weight saving, compared between reference sample (UPS Block) and maximum value of strength index (B-3) . The equation of optimization and prediction model with determination coefficient R^2 of 87% is given as below:

$$\textbf{\textit{Strength Index}} = -35.91-3.92H+24.38D-1.303X+0.3419H^2-1.9722D^2+0.0896X^2 \quad (7)$$

According to ANOVA analysis, all parameters model has P-value less than 0.05 so these are significant. From plot in figure 7 it is clear that (H) factor has significant effect by increasing strength index response with all values of factor (H) whereas (D) factor has low effect on strength index at nearly 6mm of diameter due to the diameter of pins work as stress stopper . On the other hand, (X) factor has significant effect distance but less thn (H) and (D) at 2 mm nearly due to the high (X) means allowing of cracks to diffuse in matrix highly.

Figure (8) show the optimal values of geometry that it based on the model and denoted by Cur symbol, it's values are ((H=11mm), (D=6.115 mm) and (X=1.5 mm)). The optimal values had been experimentally investigated with 10% error.

Stiffness Performance Index:

From Table 2, the first most important result can be noted is the improvement. The maximum improvement percentage of stiffness performance index is up to 300% for sample A-1 with 40% weight saving compared to the reference sample (UPE Block). Equation 8 is optimizing and predict model of stiffness index with 70% coefficient of determination (R^2).

$$\textbf{\textit{Stiffness Index}} = -3.91+0.76H+0.22D+0.765X+0.0245H^2-0.0063D^2+0.0875X^2 \quad (8)$$

According to ANOVA analysis, only H parameter has P-value less than 0.05 so this is significant factor. Figure (9) show main effects plot for stiffness performance index, (H) factor has highly effect on strength index with all range and (D) factor has less than effect from (H) factor whereas increases from 3mm to 9mm. The (X) factor showed low effect. Figure (10) shows the optimization of the values of stiffness index to find out the optimal input values based on the model and denoted by Cur symbol, it's values are ((H=11mm), (D=9 mm) and (X=4.3 mm)). These input optimal values have been investigated experimentally with 20% error.

CONCLUSIONS

Geometrical parameters have been investigated at the novel pin core sandwich structure design by new manufacture process (carving wax method). From the obtained results and their discussion, the following conclusions can be summarized as below:

1- Maximum stiffness performance index value is 5.57 $GPa^{0.5}$ for specimen C-3 with 300% improvement percentage compared to the reference sample and 4.46 $GPa^{0.5}$ optimal value for specimen ((H=11mm), (D=9 mm) and (X=4.3 mm)).
2- Maximum strength performance index value is 34.53 $MPa^{2/3}$ cm^3 g^{-1} for specimen B-3 with 126% improvement percentage compared to the reference sample and 35.9 $MPa^{2/3}$ cm^3 g^{-1} optimal value for the specimen ((H=11mm), (D=6.115 mm) and (X=1.5 mm)).
3- The weight saving is 40-50% in C-3 and B-3 samples.
4- The high of cylinder is effective parameter in stiffness but in strength are high and radius.

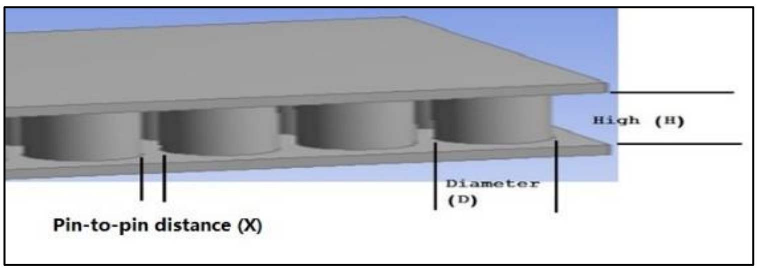

Fig 1**.** Pin-Core Sandwich Structure

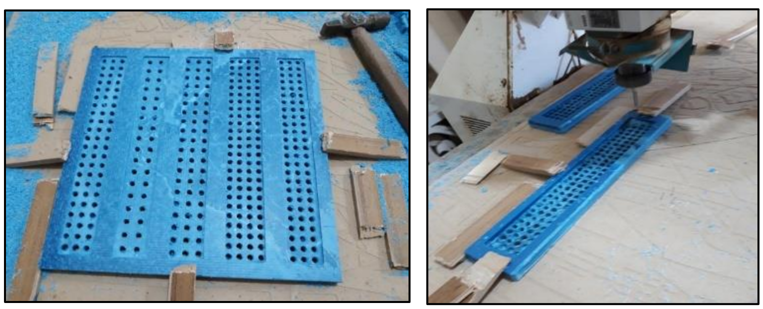

Fig 2: waxy specimens

Fig 3: sample shape after resin solidification (2-4 hour) within he waxy sample

Fig 4: wax eliminated by gravity under (90-110 ◦C) temperature condition.

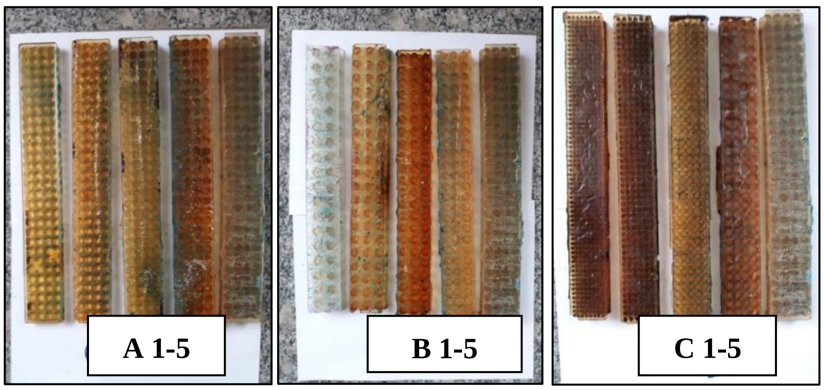

Fig 5 : Three specimens groups

Fig 6 : bulk unsaturated polyester sample

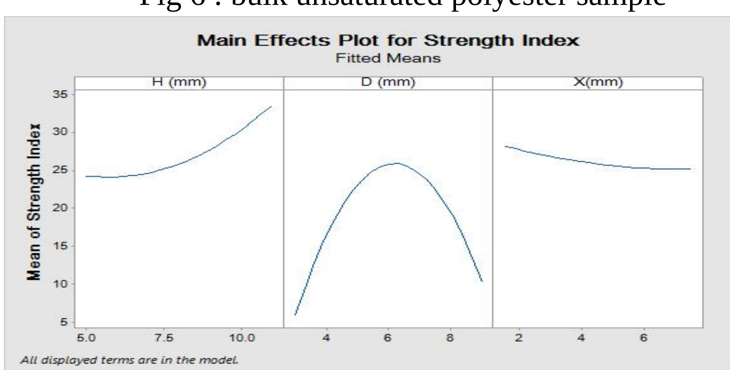

Fig 7 : The plot of main effects between strength index and H,D,X .

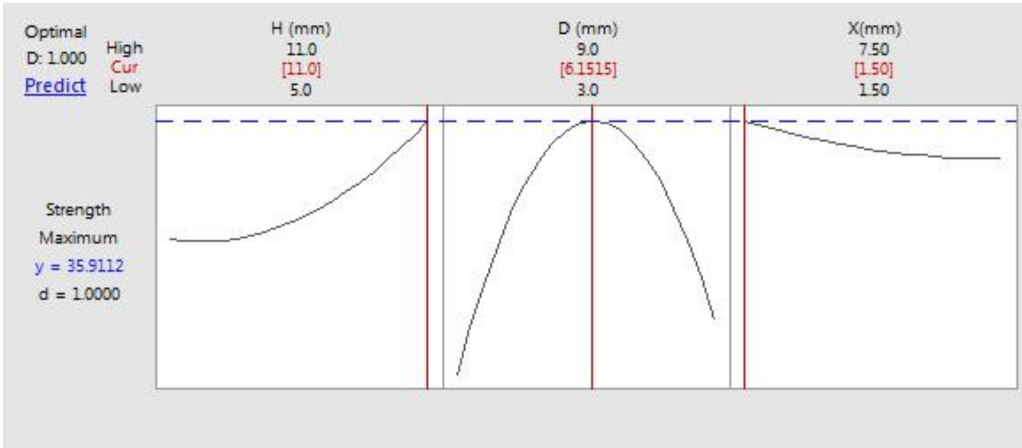

Fig 8: The optimal value of strength index with H,D,X variables.

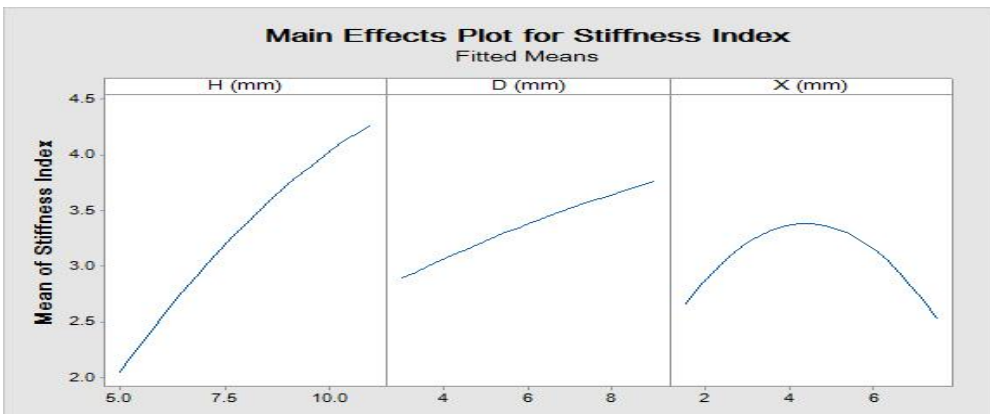

Fig 9 : The plot of main effects between stiffness index and H,D,X.

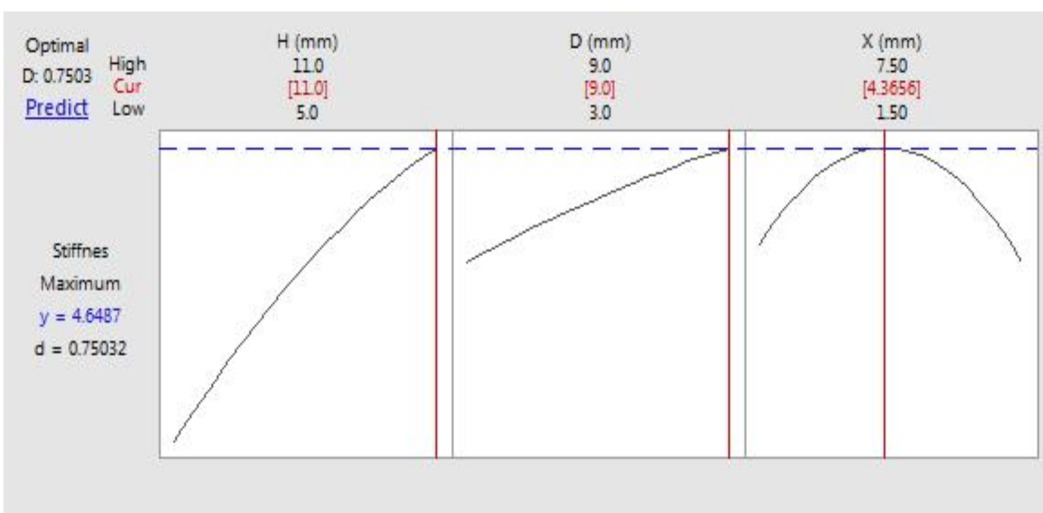

Fig 10: The optimal value of stiffness index with H,D,X variables.

Table 1. Design of Experiments

No	High(H) mm	Diameter(D) mm	Pin-to-pin distance(X) mm	Code
1	11	9	1.5	A-1
2	9.5	9	1.5	A-2
3	8	9	1.5	A-3
4	6.5	9	1.5	A-4
5	5	9	1.5	A-5
6	11	9	1.5	B-1
7	11	7.5	1.5	B-2
8	11	6	1.5	B-3
9	11	4.5	1.5	B-4
10	11	3	1.5	B-5
11	11	9	1.5	C-1
12	11	9	3	C-2
13	11	9	4.5	C-3
14	11	9	6	C-4
15	11	9	7.5	C-5

Table 2: Results of the pin core structure

No	Code	ρ_r	Strength Index $MPa^{2/3}cm^3g^{-1}$	Stiffness Index $GPa^{2/3}$ cm^3 g^{-1}
0	UPS Block	1	15.33	1.37
1	**A-1**	0.656526	20.37	4.15
2	**A-2**	0.685529	14.80	3.62
3	**A-3**	0.672346	12.35	3.30
4	**A-4**	0.728846	11.99	2.00
5	**A-5**	0.837137	10.46	1.88
6	**B-1**	0.656526	20.37	4.15
7	**B-2**	0.535108	33.30	2.90
8	**B-3**	0.504209	34.53	3.64
9	**B-4**	0.49458	31.28	4.06

10	**B-5**	0.383734	15.71	2.68
11	**C-1**	0.656526	20.37	4.15
12	**C-2**	0.624683	18.62	3.50
13	**C-3**	0.588987	17.83	5.57
14	**C-4**	0.506808	17.82	4.17
15	**C-5**	0.515778	17.07	3.76

REFERENCES

Abdi B., S. Azwan, M. R. Abdullah, A. Ayob, Y. Yahya, and L. Xin, "Flatwise compression and flexural behavior of foam core and polymer pin-reinforced foam core composite sandwich panels," Int. J. Mech. Sci., vol. 88, pp. 138–144, 2014.https://doi.org/10.1016/j.ijmecsci.2014.08.004

Gupta Nikhil, Steven Eric Zeltmann, Dung D. Luong and Mrityunjay Doddamani, "Marine Composites: Design and Performance", Woodhead Publishing, Chapter 7, 2019.

Icten B. M., Yalkin H. E. and T. Alpyildiz, "Tensile and compressive performances of foam core sandwich composites with various core modifications," J. Sandw. Struct. Mater., vol. 19, no. 1, pp. 49–65, 2017.https://doi.org/10.1177/1099636216650819

Lehmhus D., M. Busse, A. S. Herrmann, and K. Kayvantash, Structural Materials and Processes in Transportation. 2013.

Meethaq M. Abed and Mohammed H. Al-maammori2 "Optimization of Novel Sphere Sandwich Structure for Impact Requirements," Annales de Chimie - Science des Matéria., vol. 44, no. 4, pp. 49–65,Augest 2020. https://doi.org/10.18280/acsm.440403

Tagarielli V.L. , N.A. Fleck and V.S. Deshpande, "Collapse of clamped and simply supported composite sandwich beams in three-point bending", Composites: Part B : Engineering , vol 3 , Issue 6-8, pp:523–534,2004. https://doi.org/10.1016/j.compositesb.2003.07.001

Tempelman E., Lightweight Materials, Lightweight Design, Elsevier, 2013.

Wang B., L. Wu, X. Jin, S. Du, Y. Sun, and L. Ma, "Experimental investigation of 3D sandwich structure with core reinforced by composite columns," Mater. Des., vol. 31, no. 1, pp. 158–165, 2009. https://doi.org/10.1016/j.matdes.2009.06.039

Yalkin H. E., B. M. Icten, and T. Alpyildiz, "Enhanced mechanical performance of foam core sandwich composites with through the thickness reinforced core," Compos. Part B Eng., vol. 79, pp. 383–391, 2015. https://doi.org/10.1016/j.compositesb.2015.04.055

Zhou J., Z. W. Guan, W. J. Cantwell, and Y. Liao, "The energy-absorbing behaviour of foam cores reinforced with composite rods," Compos. Struct., vol. 116, no. 1, pp. 346–356, 2014. https://doi.org/10.1016/j.compstruct.2014.05.025