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Influence of Core Density on Flexural Behavior of PUF Cored Sandwich Beams

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Abstract: ***The present investigation was mainly focus on the influence of high density polyurethane foam core on the flexural behavior of sandwich beams. To rate the performance of these structures, many engineering parameters such as face sheet stress (σ_f), core shear (τ) beam deflection(y) and the most important beam properties i.e. flexural rigidity (D) and Shear stiffness (S) were considered. In order to pursue this task, number of sandwich beam specimens of different core densities (ranged from 50Kg/m^3 to 300Kg/m^3) were fabricated & tested under both 3-Point and 4- point bending experimentally. The results of both 3-Point and 4- point bending were used to evaluate the mechanical properties using the most popular formulae proposed by Kuenzi (ASTM Standards, C393). Furthermore finite element analysis was performed by modeling the sandwich beams that were considered for experimental study using the validated FEM/ANSYS. From the present investigation it is evident that the performance of high density foams are better than conventional low density foams, because it was observed remarkable improvements on the most important beam properties i.e. flexural rigidity (D) and shear stiffness (S) of sandwich beams. It is also observed that the engineering parameters (σ_f, τ, y) decreases at constant load as core density increases which indicates that the load bearing capacity of the beam increases. From the present investigation it is evident that tremendous improvements can be achieved on flexural behavior of sandwich beams with the use of high density foam cores (ranged from 200Kg/m^3 to 250Kg/m^3). However the higher core densities (>300K/m^3) are unsuitable for cores because the results are nearly asymptote for densities higher than 300Kg/m^3.***

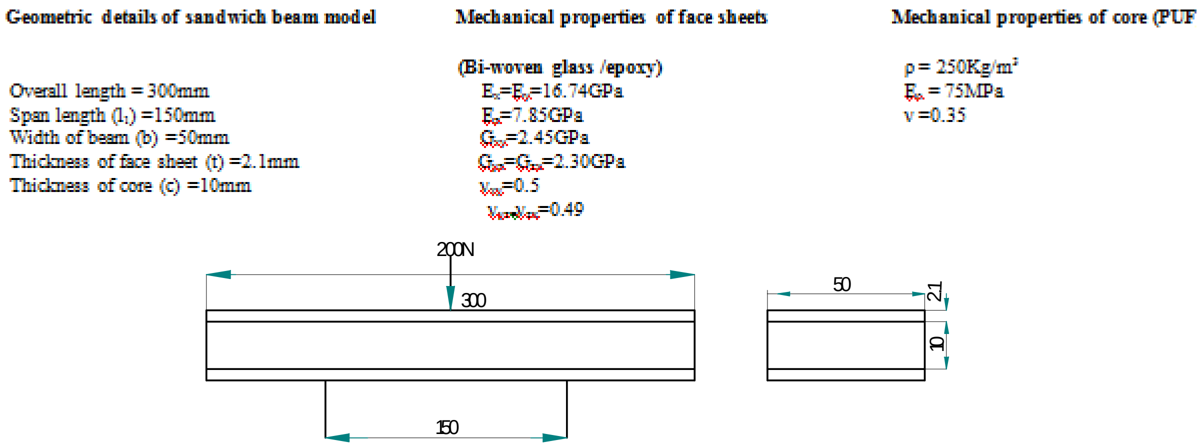
Keywords: Sandwich beams, High density foams, fabrication, FEM/ANSYS.

1. Introduction

The use of composite sandwich structure in aerospace and civil infrastructure applications has been increasing especially due to their extremely low weight and fuel consumption, high flexural and transverse shear stiffness and corrosion resistance [1-3]. The stresses and deflection induced under the action of external lateral load and the overall structural performance of sandwich beams is mainly depends on the geometries, physical and mechanical properties of the both facings as well as core materials [4, 5]. In several literatures it is reported that upon varying properties of core materials (exclusively its density) the flexural strength of sandwich beam can be alter to very large extent with a little weight compromise. R. Vijayalakshmi Rao et.al [6] and A Mizapur et.al [7] have studied the effect of core density of foam cored sandwich beams of on flexural strength for limited cases. They concluded that use of high density foam cores for sandwich structures, flexural strength can be improved to a very large extent. However in their studies, effect of foam core density on other engineering parameters such as normal stress distribution in face sheets (σ_f), core shear (τ) and overall beam deflection(y) was not considered. T.C.Triantafillou and L.J.Gibson [8] have studied the minimum weight design criteria for foam core sandwich panel for a given strength. They concluded that values of the face & core thickness and the core density play very important role for minimum weight design requirement of a sandwich panel. It is thus clear from the above reviews and references, the flexural behavior of sandwich composites can be characterized by two important factors, foremost the core thickness and other is variation of core density In view of above fact, the present investigation was mainly concern with the study of influence of core density on the most important mechanical properties of sandwich beams such as flexural rigidity (D) and Shear stiffness(S) and other performance parameters such as normal stress distribution in face sheets (σ_f), core shear (τ) and overall beam deflection(y).To pursue this task, number of sandwich beam specimens of different core densities (ranged from 50Kg/m^3 to 300Kg/m^3) were fabricated & tested under both 3-Point and 4- point bending. On the whole six sandwich beam specimens were fabricated as per ASTM (C393) standards and tested under both 3-point bending and 4 -point bending, in order to determine experimentally the most important mechanical properties of such as flexural rigidity (D) and shear stiffness(S). Furthermore in order to study the influence of high core density on other performance parameters such as face sheet stress (σ_f), core shear (τ) & beam deflection (y), finite element analysis was performed using the validated FEM/ANSYS by modeling the sandwich beams which were considered for experimental study. The mechanical properties of the sandwich beam specimens were calculated experimentally as well as numerically using the well known equations proposed by kuenzi (C393; ASTM standards). The theoretical estimates of the mechanical properties were obtained using analytical equations proposed by Allen H G in his book titled “Analysis and design of structural sandwich panels” Oxford Pergaman Press 1969.

2. Validation of FE- Modeling for Static Analysis of Sandwich Beams under Flexural Load

Finite element method through the medium of general purpose program i.e. FEM/ANSYS offers a powerful tool for engineering analysis. However user of finite element analysis has to validate the elements, meshes and procedure employed using bench marks. This section is mainly concern with the validation of finite element modeling for static analysis of sandwich beams under three-point bending using analytical solutions of 2D-elasticity of sandwich beams. To pursue this task a sandwich beam model was chosen as per ASTM standards (C323) [9]of dimensions 300mm x 50mm x 14.2mm loaded in three- point bending with a span length of 150mm as shown in figure-1. It is assume that the composite sandwich beam consists of typically of two thin face sheets of 2.1mm thick made of bi-woven E- glass fiber-epoxy prepreg composite and a light weight thicker polyurethane foam core. The geometric details of chosen sandwich beam model, physical and mechanical properties of both face sheets and core are as follows



Geometric details of sandwich beam model

Overall length = 300mm
Span length (l_1) =150mm
Width of beam (b) =50mm
Thickness of face sheet (t) =2.1mm
Thickness of core (c) =10mm

Mechanical properties of face sheets

(Bi-woven glass /epoxy)
E_x=E_y=16.74GPa
E_z=7.85GPa
G_{xy}=2.45GPa
G_{yz}=G_{xz}=2.30GPa
ν_{xy}=0.5
ν_{yz}=ν_{xz}=0.49

Mechanical properties of core (PUF

ρ = 250Kg/m^3
E_c = 75MPa
ν =0.35

Figure1: Geometry of a sandwich beam under three -point bending

The face sheets and core were modeled using nonlinear SHELL 91(7 layered) and SHELL 93 elements respectively. The modeled structure was considered as a simply supported sandwich beam with overhanging loaded in three point bending. The relevant mechanical properties of both face sheet and core were carefully pre-processed. The schematic view of FE- modeling of sandwich beam so generated is as shown in figure-2 with necessary boundary conditions. After successful run of finite element program, various contour plots were extracted from the post files are as shown in figure-3 for reference. The various post processing results such as bending stress in face sheet(σ_f), shear stress in core (τ) and maximum beam deflection (y), obtained from numerical analysis are tabulated in table-1.

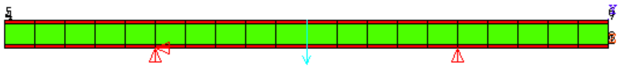


Figure 2: Finite element model of sandwich beam

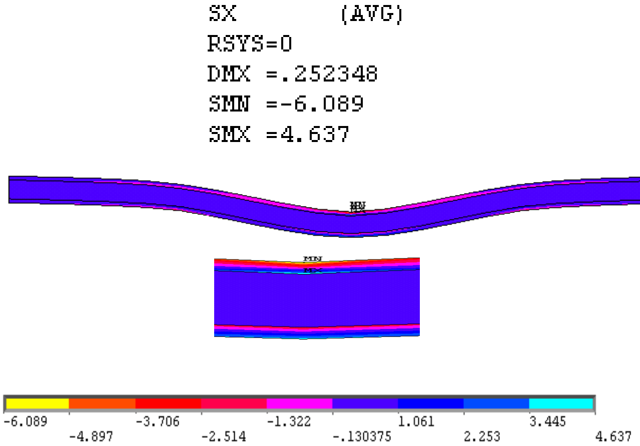


Figure 3(a): Bending stress distribution in Face Sheets

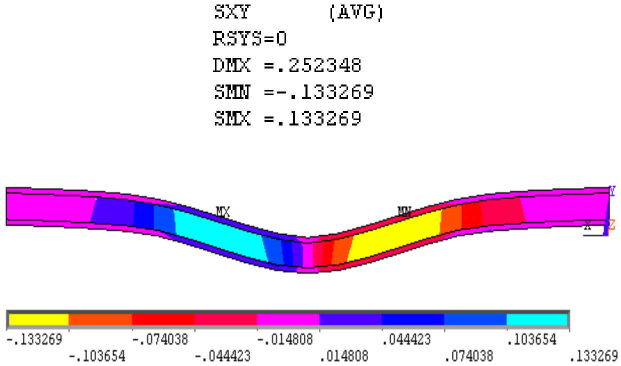


Figure 3(b): Shear stress distribution in Core

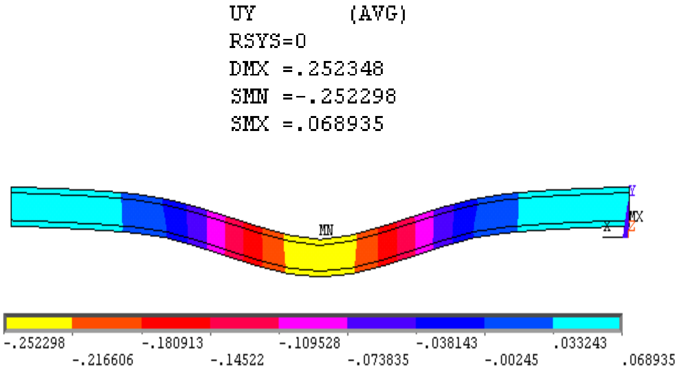


Figure 3(c): Resultant deflection of sandwich beam

Figure 3: Contours of post processing results under three-point bending

Table 1: Results of FEM/ANSYS

Particulars	*FEM/ANSYS*	*Theoretical*
Bending Stress (σ_f) MPa	**6.1**	**5.9**
Shear stress (τ) MPa	**0.133**	**0.16**
Max deflection (y) mm	**0.253**	**0.286**

Table 2: Comparison of FEM/ANSYS and Analytical results

Bending stress (σ_f) MPa	Core Shear (τ) MPa	Max deflection (y) mm
6.1	0.133	0.253

The theoretical calculations were obtained using 2D elasticity solutions proposed by H. G. Allen [5] for the above sandwich beam model is as shown in table-2. Comparison between theoretical & numerical results obtained using FEM/ANSYS are shown in table 3. The agreement was generally good and hence it can be applicable for the study of flexural behavior of sandwich panels. The validated numerical tool was successfully applied to study the flexural behavior of sandwich beams of high density polyurethane foam cores.

Table 3: Theoretical results from analytical formulae proposed by Allen H.G [5]
F=200N l=150mm b=50mm c=10mm t=2.1mm h=14.2mm E_f=16740MPa E_c=75MPa ν= 0.35 G_c=26MPa

$M_b = Fl/4$ (N-mm)	$\sigma_f = M_b/(btd)$ (MPa)	d= (c+t) (mm)	$D = E_f btd^2/2$ (N-mm^2)	$S = bdG_c$ (N)	$\tau = F/2bd$ (MPa)	$y=(FL^3/48D)+(FL/4S)$ (mm)
7500	5.9	12.1	128.67x10^6	15730	0.16	0.286

2.1 Fabrication Testing and Analysis of Sandwich beams

Sandwich beams specimens were fabricated using thin skin composite face sheets of thickness 2.1mm made of bi-woven-glass cloth reinforced plastic (epoxy resin) and thick light weight core of thickness 30mm made of polyurethane foam using suitable adhesive materials. A systematic procedure was followed. First of all the polyurethane foam cores of density 200Kg/m^3 were cut to the required size and bonded to the facings by using an adhesive made from a mixture of AY103 resin and HY951 hardener in properties of 100:10 by weight. The surfaces were thoroughly cleaned in order to ensure that they were free from oil dirt etc., before bonding at room temperature and pressure. The specimens were allowed to cure for about 24 hours and were kept under slight pressure by dead weights placed on them. On the whole six similar & identical specimens were fabricated with constant overall length of 310mm in order to provide sufficient overhang and support. Out of six, three specimens were tested under 3-point bending with a span length of 150mm and remaining three specimens were tested under 4-point bending with a span length of 250mm.The fabricated Sandwich beam specimens were loaded as simply supported beams and tested under 3- point & 4-point bending separately in a universal testing machine. Special flexure test rig was fabricated for specimens tested under four point bending. A dial gauge was used to measure the deflection of the specimen under load. Figure 4(a) and 4(b) shows the photographs of 3-point and 4-point bending test setup used for experimental studies represents the best two of three tests performed on identical specimens under 3P&4P bending respectively

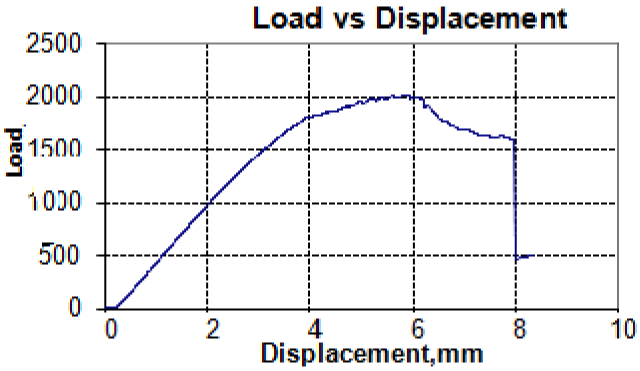


Figure 5(a): Graph of F v/s y for 3-Point bending

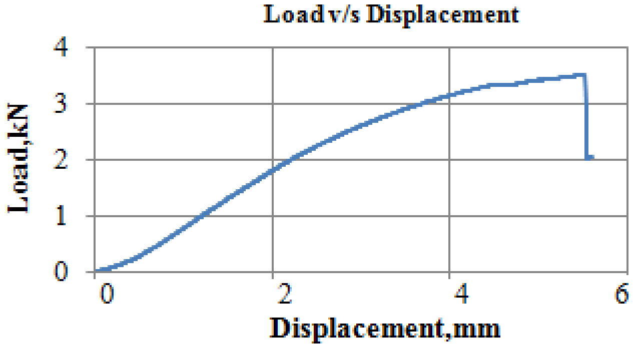


Figure 5(b): Graph of F v/s y for 4-Point bending

Finite element analysis was performed on the geometric models of sandwich beams which were fabricated for experimental study. Similar test conditions were imposed and analyzed under 3-Point & 4-Point bending using static solver. Finite element models were generated by descritization of geometric modeling of the beam. The schematic view of FE-modeling of sandwich beam for 3-Point bending and 4-Point bending is as shown in figure 6(a) and 6(b). The contours of deflections of beams under constant load of 200N as obtained from post processing results are as shown in figure 7(a) and 7(b). A graph of load v/s deflection from the results of both 3-Point bending and

4-Point bending tests using finite element analysis was plotted as shown in figure 8(a) and 8(b).

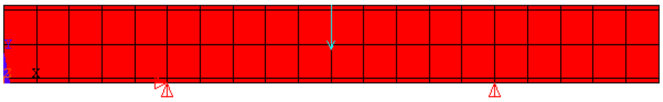


Figure 6(a): FE-modeling for 3P- bending

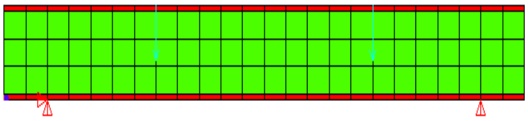


Figure 6(b): FE-modeling for 4P-bending

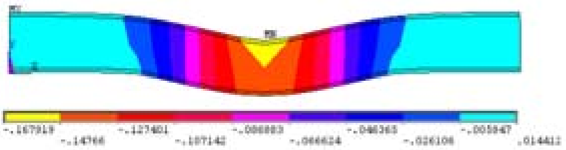


Figure 7(a): Deflection contour of 3P- bending

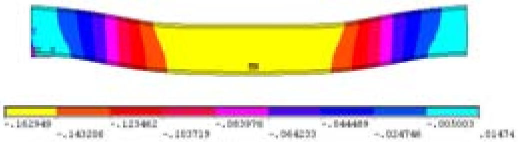


Figure 7(b): Deflection contour of 4P- bending

Table 4(a): Post processing results of 3-Point bending

Load(F) N	200	400	600	800	1000
w_1(mm)	0.167	0.334	0.501	0.668	0.835

Table 4(b): Post processing results of 4-Point bending

Load(F) N	200	400	600	800	1000
w_2(mm)	0.163	0.326	0.489	0.652	0.815

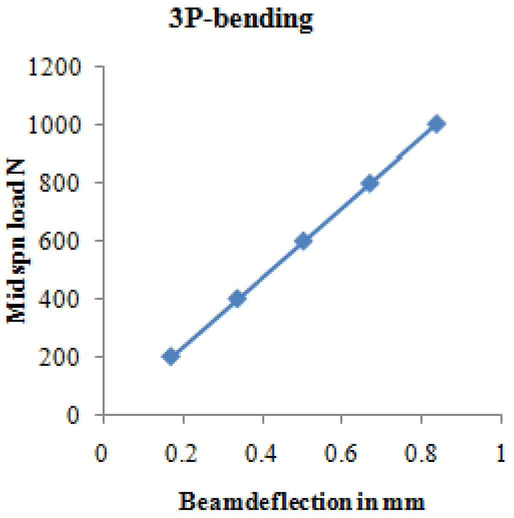


Figure 8(a): Graph of F v/s w_1 for 3P- bending

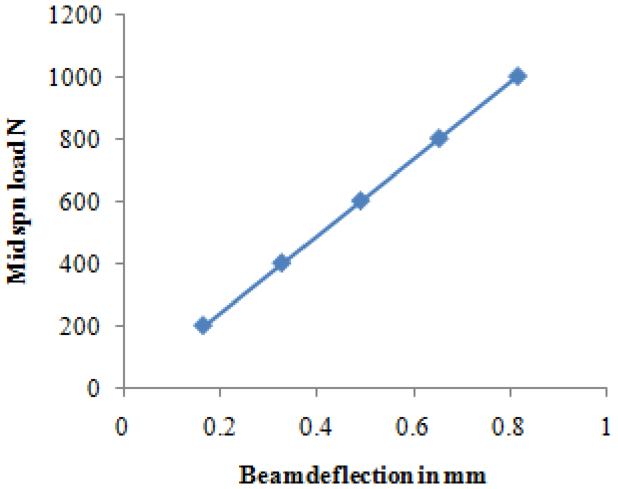


Figure 8(b): Graph of F v/s w_2 for 4P- bending

2.2 Evaluation of Mechanical properties of sandwich beams

In this section the most essential mechanical properties of the sandwich beams under flexural load such as flexural rigidity (D) and shear stiffness(S) were calculated using all the three methods i.e. theoretically, experimental and numerical. The theoretical calculations were obtained using beam geometry and physical properties of beam materials proposed by Allen H G [5] as tabulated in table-5. In experimental method, the plot of load versus deflection recorded from independent tests of the three-point and four-point bending on the similar specimen were used to evaluate the mechanical properties using the most popular formulae proposed by Kuenzi (Standards,C393). These equations (eq1,2&3) as shown below are modified in terms of slopes of loads v/s deflections (θ_1& θ_2) and ratio of span lengths (l_1& l_2)to get an average effect.

$D = (l_1^3\ \theta_1)/48\ [2.821/\ \{2.4\ (\theta_1/\ \theta_2)\}-1]$ (1)
$G = 3\ \theta_1 c\ /\ (h+c)^2\ [0.7383/\ \{1-0.6284\ (\theta_1/\ \theta_2)\}]$ (2)
$S = bdG$ (3)

Table 5: Theoretical estimation of beam properties

$D= E_f btd^2/ 2$ (N-mm^2)	$G = E_c /2(1+\nu)$ (MPa)	$S = bdG$ (N)
0.905 x10^9	22.23	0.358x10^5

The geometric and material properties of sandwich beams tested under flexural load are as follows

E_f=16740MPa ρ_c=200Kg/m^3 E_c=60MPa l_1=150mm l_2=250mm b=50mm c=30mm t=2.1mm d=32.1mm h=34.2mm

Table 6(a): Beam properties using Experimental results

θ_1 (N/mm)	θ_2 (N/mm)	$\theta_1/\ \theta_2$	D (N-mm^2)	G (MPa)	S (N)
1197	1227	0.976	0.176x10^9	49.93	0.8 x10^5

Table 6(b): Beam properties using FEM/ANSYS results

θ_1 (N/mm)	θ_2 (N/mm)	θ_1/θ_2	D (N-mm^2)	G (MPa)	S (N)
500	833.34	0.6	0.225×10^9	12.93	0.21×10^5

Table 7: Comparison of Beam properties using various solutions

Mechanical properties	Theoretical	Experimental	Numerical
Flexural rigidity (D) (N-mm^2)	0.905×10^9	0.225×10^9	0.176×10^9
Rigidity modulus (G) (MPa)	22.23	12.93	49.93
Shear stiffness (S) (N)	0.358×10^5	0.21×10^5	0.801×10^5

2.4 Influence of Core density on Flexural Behavior of Sandwich Beams

The mechanical response in general and flexural behavior in particular of a sandwich beam depends upon various parameters such as constituents of face sheets, geometric and material properties of cores, the adhesive bonding the cores to the skins and type of external load. To design an efficient sandwich structure, it is vital to understand the behavior of each element/layer and the complete structural integrity of the structure due to the variation of constituents. In this section some studies were undertaken to understand the influence of core density variation on the flexural behavior of sandwich beams. To pursue this task various set of sandwich beam specimens (6 specimen/set) were fabricated with different core density ranged from 50Kg/m^3 to 200Kg/m^3 and tested under both 3P & 4P bending. Similar test conditions were imposed as discussed in previous section. The plot of load versus deflection recorded from independent tests of three-point and four-point bending for various specimens of different core density is as shown in figure-10. Finite element models were generated and analyzed them in similar way as discussed in previous section for the entire set of sandwich beam specimens that were tested experimentally. The deflection contours of FEM/ANSYS results are as shown in figure-9.

ρ_o= 50Kg/m^3 c=30mm t=2.1mm h=(c+2t)=34.2mm

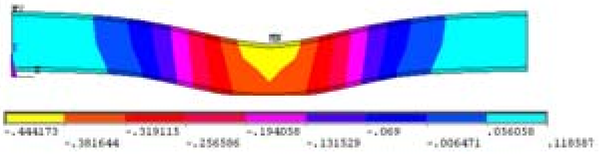


Figure 9(a): 3P- Sandwich beam of core density 50Kg/m^3

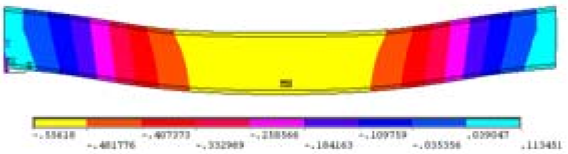


Figure 9(b): 4P- Sandwich beam of core density 50Kg/m^3

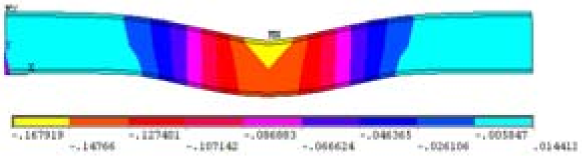


Figure 9(c): 3P- Sandwich beam of core density 200Kg/m^3

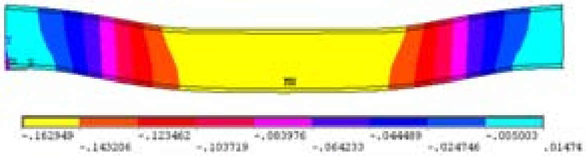


Figure 9(d): 4P- Sandwich beam of core density 200Kg/m^3

Figure 9: Contours of deflection of sandwich beam models under 3P &4P bending at 200N load

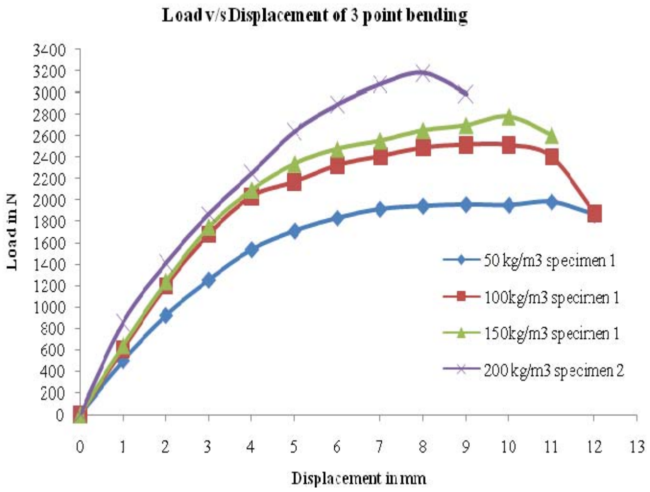


Figure 10(a): Graph of F v/s y for 3P-Bending

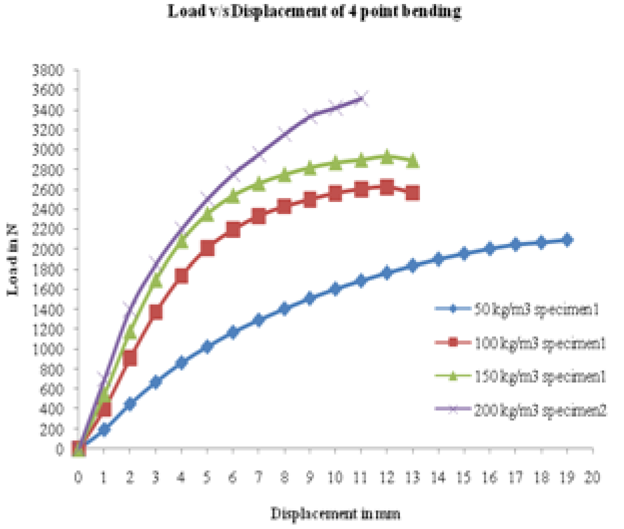


Figure 10(b): Graph of F v/s y for 4P-Bending

Figure 10: Comparative graph of sandwich beams of different core density (Experimental results)

Table 8: Post processing results of 3P-bending of sandwich beam model

ρ_o (Kg/m^3)	50	100	150	200
σ_f(MPa)	8.6	6.72	5.73	5.1
τ(MPa)	0.0901	0.073	0.062	0.05
y(mm)	0.444	0.287	0.209	0.167

3. Results and Discussions

The present investigation was mainly focus on the influence of high density polyurethane foam cores on the flexural behavior of sandwich beams made up of polyurethane foams and composite face sheets (Bi-woven E-glass/epoxy resin). To rate the performance of these structures, the most important beam properties i.e. flexural rigidity (D) and Shear stiffness (S) and the engineering parameters such as face sheet stress (σ_f), core shear (τ), beam deflection(y) of the sandwich beam were considered. For the present study, these properties were obtained using all the three methods such as analytical, experimental and numerical using FEM/ANSYS. First of all, the numerical procedure (FEM/ANSYS) was validated using 2D-elasticity solutions. To pursue this task, a sandwich beam model of dimensions 300mmx50mmx14.2mm loaded in three- point bending was chosen as per ASTM standards (C323) [9] with a span length of 150mm as shown in figure-1. Finite element analysis was performed and analyzed under three- point bending with a constant mid span load of 200N. To be more confident on the FE- modeling and its results, analytical verification using 2D-elasticity of sandwich beam were carried out as shown in table-2. A comparison of FE-analysis results and analytical solutions are tabulated in Table-3. The agreements between numerical and theoretical results were generally good.

In order to study the most important mechanical properties of sandwich beams such as flexural rigidity (D) and Shear stiffness (S) experimentally, on the whole six sandwich beam specimens were fabricated as per ASTM (C393) standards and tested under both 3-point & 4 -point bending as shown in figure-4.The results of both 3-Point & 4- point bending were used to evaluate the mechanical properties using the most popular formulae proposed by Kuenzi (ASTM Standards, C393). Furthermore finite element analysis was performed by modeling the sandwich beams that were considered for experimental study using the validated FEM/ANSYS. The theoretical estimates of the mechanical properties were also obtained using analytical equations proposed by Allen H G in his book titled "Analysis and design of structural sandwich panels" Oxford Pergaman Press 1969 as shown in table-5. Finally the results so obtained using all the three methods were compared as shown in table-7. The agreement between numerical and experimental results was generally good.

In order to study the influence of core density on the flexural behavior of sandwich beams, number of sandwich beam specimens of different core densities (ranged from 50Kg/m^3 to 300Kg/m^3) were fabricated & tested under both 3-Point and 4- point bending. The plot of graphs of load v/s deflection for all the cases studied experimentally is as shown in figure-10. It was observed that as the density of core increases, the stiffness of beam increases, which in turn the load bearing capacity of the beam increases. It was also observed that the increasing of core density in PUF cored sandwich beams is more or less similar to the phenomenon of increasing of carbon content in steel alloy. Furthermore in order to study the influence of high core density on other performance parameters such as face sheet stress (σ_f), core shear (τ) & beam deflection (y), finite element analysis was performed using the validated FEM/ANSYS by modeling the sandwich beams which were considered for experimental study. From the present investigation it is evident that the performance of high density foams in PUF cored sandwich beams are better than the conventional low density foams, because remarkable improvements was observed on the most important beam properties i.e. flexural rigidity (D) and shear stiffness (S) of sandwich beams with the use of higher density foams as shown in figure-12. Influence of core density on three important parameters of sandwich beams such as (σ_f, τ, y) were observed during FE-analysis as shown in figure-13. From the results so obtained, it was observed that all the three engineering parameters such as face sheet stress (σ_f) transverse shear stress (τ), as well as resultant beam deflection (y) decreases drastically as core density increases to certain limit (ρ=300Kg/m^3) and attains to nearly asymptotic for further increase in core density thereafter.

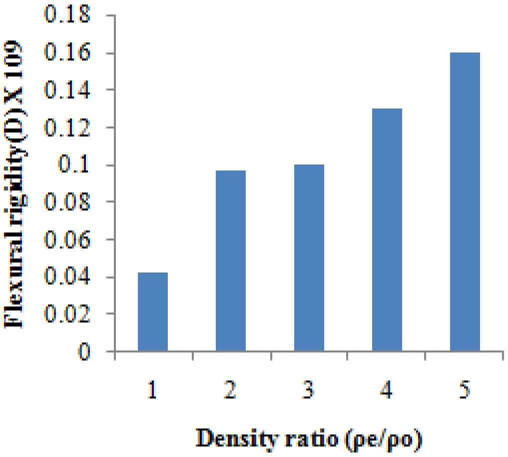


Figure 12(a): Graph of D v/s (ρ_e/ρ_o)

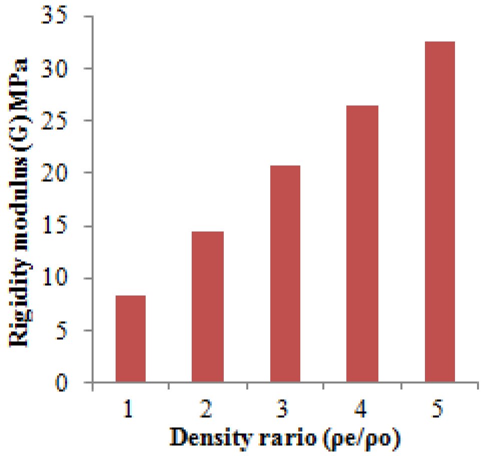


Figure 12(b): Graph of G v/s (ρ_e/ρ_o)

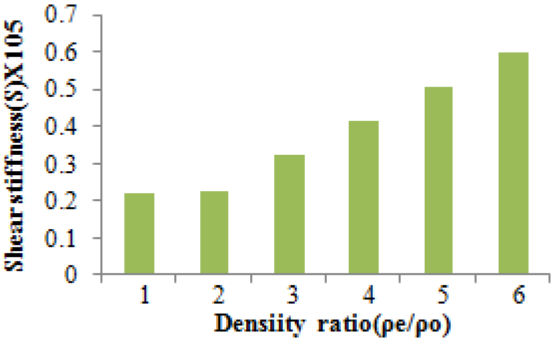


Figure 12(c): Graph of S v/s (ρ_e/ρ_o)

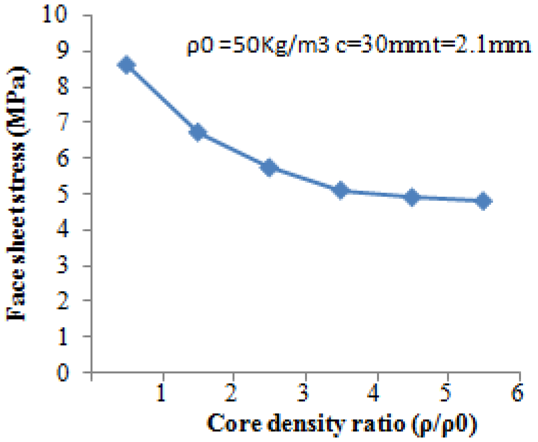


Figure 13(a): Graph D v/s (ρ_e/ρ_o)

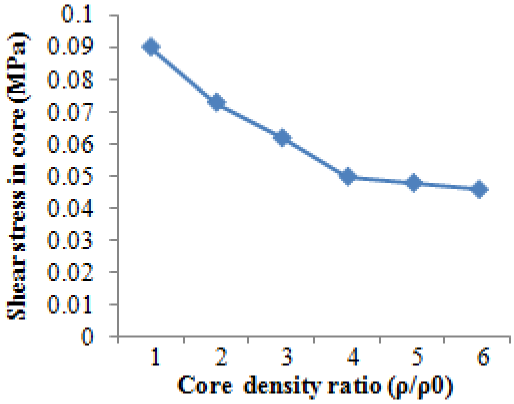


Figure 13(b): Graph G v/s (ρ_e/ρ_o)

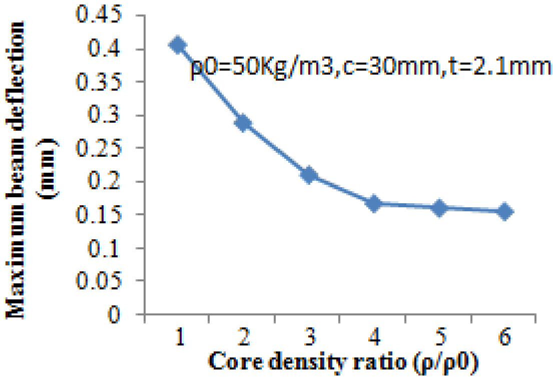


Figure 13(c): Graph S v/s (ρ_e/ρ_o)

Figure 13: Effect of core density on Engineering parameters (σ_f,τ,y)

4. Conclusions

To rate the peformance of high density PUF cored sandwich beams, number of sandwich beam specimens of different core densities (ranged from 50Kg/m^3 to 300Kg/m^3) were fabricated & tested under both 3-Point and 4- point bending experimentally. Effect of core density on most important beam properties i.e. flexural rigidity (D) and Shear stiffness (S) were studied experimentally as well as numerically. Experimental studies on the engineering parameters such as face sheet stress (σ_f), core shear (τ) of sandwich beams under flexural load is quite expensive and time consuming. Instead a prior validated most versatile numerical tool i.e. FEM/ANSYS, was successfully used for the purpose. From the present investigation it is evident that use of high density foams (ranged from 200Kg/m^3 to 250Kg/m^3) for cores has tremendous improvements on complete sandwich construction, However the density higher than 300K/m^3 are unsuitable for cores because the results are nearly asymptote for all densities higher than 300K/m^3.

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