

Flexural Behavior of Multi-Layer PUF Cored Sandwich Beams



Engineering

KEYWORDS : multi-layer core, layer density, polyurethane foam, sandwich beams, bending, FEM/ANSYS.

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ABSTRACT

Flexural behavior of PUF cored sandwich beams made up of multi-layered core of different layer density were studied numerically using most versatile analysis tool i.e. FEM/ANSYS. To rate the performance of these structures, many engineering parameters such as face sheet stress (σ_f), core shear (τ) beam deflection (y) were considered. To pursue this task, a three layered core model with different layer configurations was generated and analyzed under 3-point bending. All the models were simulated at constant beam length, width, mid span loading with similar and identical face sheets. Various layer configurations (layer density) were examined and an attempt was made to identify the best layer configuration that can perform better under flexural loading. Foremost of above, the analyzing tool i.e. FEM/ANSYS was validated using bench marks. From the present investigation it is evident that for a given multi-layer configuration, layers of foams of increasing densities from bottom to top face can perform better under flexural load.

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]. In its simplest form a structural sandwich which is a special form of limited composites is composed of two thin stiff face sheets and a thick light weight core bounded between them. The stresses and deflection induced under the action of external loads (flexural) and the overall structural performance of sandwich panels 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. J. Arbaqui et.al [8] has studied the mechanical behavior of sandwich beams with honeycomb multi-layer using 3-point bending and observed positive influence of multi-layer over the final mechanical properties. However in their studies, effect of multi-layer core & layer density on the other engineering parameters such as normal stress distribution in face sheets (σ_f), core shear (τ) and overall beam deflection(y) was not considered. Thus it is clear from the above reviews and references, the flexural behavior of sandwich structures can be improved to a large extent by modifying the core properties. In view of above fact, as an innovative idea to obtain the improved structural behavior, in the present study the conventional single layer soft core is replaced by a multi-layer core of different layer density. The multi-layer core is obtained by using several polyurethane layers of different densities and configurations. For the present investigation, a three layered core model with different layer density & layer configurations was generated and analyzed under 3-point bending using the most versatile numerical tool i.e. FEM/ANSYS. Number of finite element models was generated using various multi-layer configurations and the influence of layer density on performance parameters were studied with great care. All the models were simulated at constant beam length, width, mid span loading with similar and identical face sheets. Various layer configurations were examined and an attempt was made to

identify the best layer configuration that can perform better under flexural loading. The results so obtained were compared with the behavior of soft single layer core sandwich beam. Foremost of above, the analyzing tool i.e. FEM/ANSYS was validated using bench marks.

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 by 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 300mmx50mmx14.2mm 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

Mechanical properties of face sheets

Mechanical properties of core (PUF)

(Bi-woven glass /epoxy)

$$\rho = 250 \text{Kg/m}^3$$

$$\text{Overall length} = 300 \text{mm}$$

$$E_x = E_y = 16.74 \text{GPa} \quad E_c = 75 \text{MPa}$$

$$\text{Span length } (l_1) = 150 \text{mm}$$

$$E_z = 7.85 \text{GPa}$$

$$\nu = 0.35$$

$$\text{Width of beam } (b) = 50 \text{mm}$$

$$G_{xy} = 2.45 \text{GPa}$$

$$\text{Thickness of face sheet } (t) = 2.1 \text{mm}$$

$$G_{yz} = G_{zx} = 2.30 \text{GPa}$$

$$\text{Thickness of core } (c) = 10 \text{mm}$$

$$\nu_{xy} = 0.5$$

$$\nu_{yz} = \nu_{zx} = 0.49$$

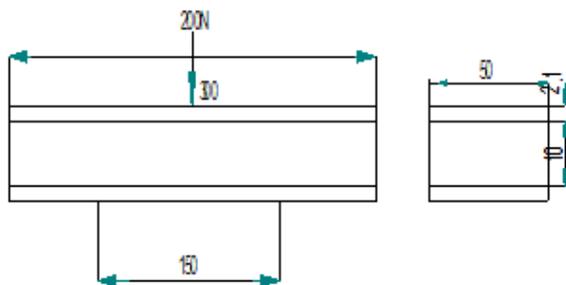


Figure1: Geometry of a sandwich beam under three -point bending

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

SX (AVG)
 RSYS=0
 DMX =.252348
 SMN =-6.089
 SMX =4.637

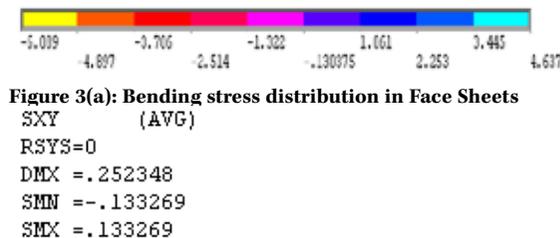
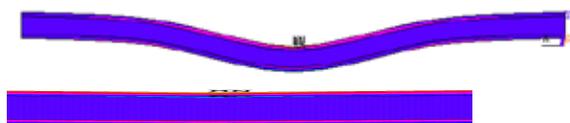


Figure 3(a): Bending stress distribution in Face Sheets (AVG)

RSYS=0
 DMX =.252348
 SMN =-.133269
 SMX =.133269

Figure 3(b): Shear stress distribution in Core (AVG)

Figure 3(c): Resultant deflection of sandwich beam

Table 1: Results of FEM/ANSYS under three-point bending

Bending stress (σ_f) MPa	Shear stress in core (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.

F=200N l=150mm b=50mm t=2.1mm d=12.1mm h=14.2mm
 $E_f=16740\text{MPa}$ $E_c=75\text{MPa}$ $\nu=0.35$ $G_c=26\text{MPa}$

Table2: Theoretical results from analytical formulae proposed by Allen H.G [5]

$M_b = Fl/4$ (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

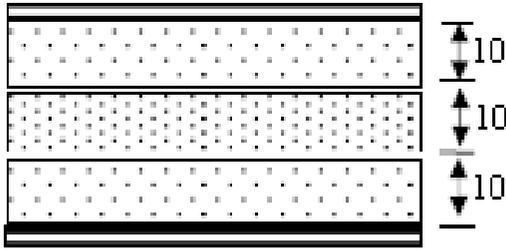
Table 3: Comparison of FEM/ANSYS & Analytical results

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

Flexural Behavior of Multi-layer PUF Cored Sandwich Beams

To study the effect of densities of multi-layer core on the flexural behavior of composite sandwich beam, a three layered core model of layer thickness 10mm each with different layer density

was chosen. The schematic view of sandwich beam with multi-layer core considered for present study is as shown in figure-4. In order to identify the best layer configuration that can perform better under flexural loading, number of finite element models of sandwich beams with different configurations of multi-layer core were generated as shown in table-4. All these models were analyzed under three point bending at constant mid span load (200N). Furthermore the span length, width and the thickness of face sheets remain constant for all the sandwich beam models. The contours of various post processing results so obtained from finite element analysis of all the multi-layer configurations is as shown in figures-5to 8



Top & Bottom facing (FRP) 2.1mm thick
 $(c=c_1+c_2+c_3=30\text{mm}; c_1=c_2=c_3=10\text{mm})$ where c_1 - thickness of layer-1

c_2 - thickness of layer-2

c_3 - thickness of layer-3

c - total core thickness

Figure-4: Cross sectional view of multi-layered Sandwich beam

$F=200\text{N}$ $l=150\text{mm}$ $b=50\text{mm}$ $t=2.1\text{mm}$ $c_1=c_2=c_3=10\text{mm}$ $c=30\text{mm}$
 $E_{c1}=15\text{MPa}$ $E_{c2}=30\text{MPa}$ $E_{c3}=45\text{MPa}$

Configuratio n-1	Configuration - 2	Configuratio n-3	Configuration -4												
Core layer order 1-2-3	Core layer order 3-2-1	Core layer order 2-1-3	Core layer order 3-1-2												
<table border="1"> <tr><td>Layer-1($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-2($\rho=100\text{kg/m}^3$)</td></tr> <tr><td>Layer-3($\rho=50\text{kg/m}^3$)</td></tr> </table>	Layer-1($\rho=50\text{kg/m}^3$)	Layer-2($\rho=100\text{kg/m}^3$)	Layer-3($\rho=50\text{kg/m}^3$)	<table border="1"> <tr><td>Layer-3($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-2($\rho=100\text{kg/m}^3$)</td></tr> <tr><td>Layer-1($\rho=50\text{kg/m}^3$)</td></tr> </table>	Layer-3($\rho=50\text{kg/m}^3$)	Layer-2($\rho=100\text{kg/m}^3$)	Layer-1($\rho=50\text{kg/m}^3$)	<table border="1"> <tr><td>Layer-3($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-1($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-2($\rho=100\text{kg/m}^3$)</td></tr> </table>	Layer-3($\rho=50\text{kg/m}^3$)	Layer-1($\rho=50\text{kg/m}^3$)	Layer-2($\rho=100\text{kg/m}^3$)	<table border="1"> <tr><td>Layer-3($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-1($\rho=50\text{kg/m}^3$)</td></tr> <tr><td>Layer-2($\rho=100\text{kg/m}^3$)</td></tr> </table>	Layer-3($\rho=50\text{kg/m}^3$)	Layer-1($\rho=50\text{kg/m}^3$)	Layer-2($\rho=100\text{kg/m}^3$)
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Layer-2($\rho=100\text{kg/m}^3$)															
Layer-3($\rho=50\text{kg/m}^3$)															
Layer-3($\rho=50\text{kg/m}^3$)															
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Layer-3($\rho=50\text{kg/m}^3$)															
Layer-1($\rho=50\text{kg/m}^3$)															
Layer-2($\rho=100\text{kg/m}^3$)															

Table-4: Various configurations of multi-layer cored sandwich beams

SX (AVG)
 RSYS=0
 DMX = .317453
 SMN = -7.505
 SMX = 7.036

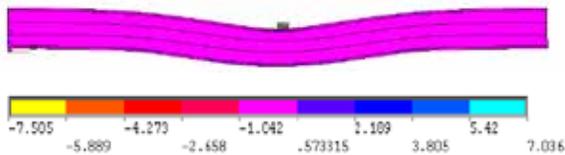


Figure 5(a): Bending stress distribution in Face Sheets

SXY (AVG)
 RSYS=0
 DMX = .317453
 SMN = -.122734
 SMX = .122734

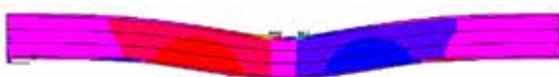


Figure 5(b): Shear stress distribution in Core

UY (AVG)
 RSYS=0
 DMX = .317453
 SMN = -.317389
 SMX = .061763

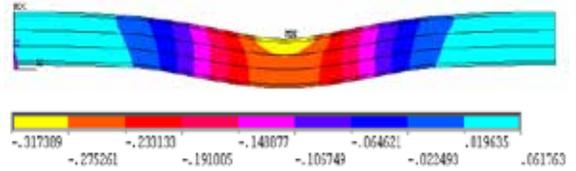


Figure 5(c): Resultant beam deflection of sandwich beam

Layer-1($\rho=50\text{kg/m}^3$)
Layer-2($\rho=100\text{kg/m}^3$)
Layer-3($\rho=50\text{kg/m}^3$)

Figure 5(d): Layer configuration-1

Figure 5: Results of flexural behavior of multi-layer sandwich beam of layer configuration -1

SX (AVG)
 RSYS=0
 DMX = .314574
 SMN = -7.151
 SMX = 6.586

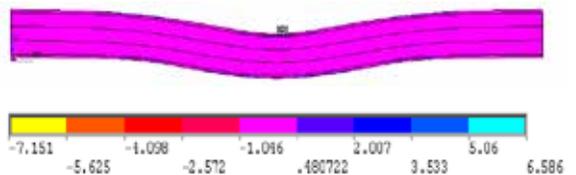


Figure 6(a): Bending stress distribution in Face Sheets

SXY (AVG)
 RSYS=0
 DMX = .314574
 SMN = -.11704
 SMX = .11704

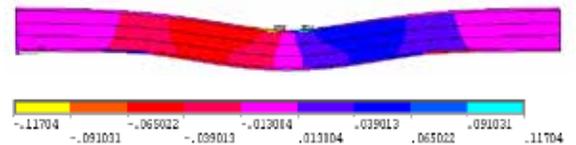


Figure 6(b): Shear stress distribution in Core

UY (AVG)
 RSYS=0
 DMX = .314574
 SMN = -.314548
 SMX = .058792



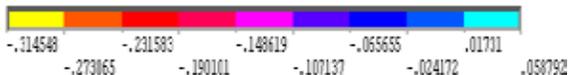


Figure 6(c): Resultant beam deflection of sandwich beam

Layer- 3($\rho=150\text{Kg/m}^3$)
Layer- 2 ($\rho=100\text{Kg/m}^3$)
Layer- 1($\rho=50\text{Kg/m}^3$)

Figure 6(d): Layer configuration-2

Figure 6: Results of flexural behavior of multi-layer sandwich beam of layer configuration- 2

SX (AVG)
 RSYS=0
 DMX = .319557
 SMN = -7.425
 SMX = 6.916

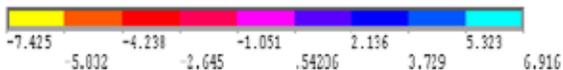


Figure 7(a): Bending stress distribution in Face Sheets

SXY (AVG)
 RSYS=0
 DMX = .319557
 SMN = -.120996
 SMX = .120996



Figure 7(b): Shear stress distribution in Core

UY (AVG)
 RSYS=0
 DMX = .319557
 SMN = -.3195
 SMX = .060029



Figure 7(c): Resultant beam deflection of sandwich beam

Figure 7(d): Layer configuration-3

Figure 7: Results of flexural behavior of multi-layer sandwich beam of layer configuration- 3

SX (AVG)
 RSYS=0
 DMX = .318663
 SMN = -7.306
 SMX = 6.761

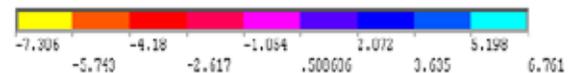


Figure 8(a): Bending stress distribution in Face Sheets

SXY (AVG)
 RSYS=0
 DMX = .318663
 SMN = -.118987
 SMX = .118987

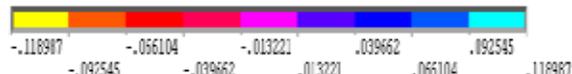


Figure 8(b): Shear stress distribution in Core

UY (AVG)
 RSYS=0
 DMX = .318663
 SMN = -.318632
 SMX = .059151

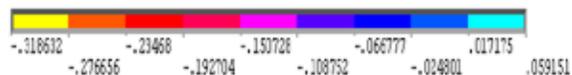


Figure 8(c): Resultant beam deflection of sandwich beam

Layer-3($\rho=50\text{Kg/m}^3$)
Layer- 1($\rho=50\text{Kg/m}^3$)
Layer-2($\rho=50\text{Kg/m}^3$)

Figure 8(d): Layer configuration-4

Figure 8: Results of flexural behavior of multi-layer sandwich beam of layer configuration- 4

Comparison of various engineering parameters such as face sheet stress (σ_f), core shear (τ) beam deflection (y) etc that were obtained from finite element analysis of all the multi-layer configurations that were analyzed under three point bending at constant mid span load (200N) is made as shown in table-5. In order to study the performance of multi-layer cored sandwich beams as compared to single layer low density ($\rho= 50\text{Kg/m}^3$) soft core sandwich beams, finite element analysis was performed on single layer core of thickness equal to the total thickness of multi-layer core. The contours of various post processing results obtained from finite element analysis for single layer sandwich beam is as shown in figures-9.

Table 5: Comparison of performance parameters for various multi-layer configurations

Configuration no	Face sheet stress(σ_f) (MPa)	Core shear(τ) (MPa)	Maximum deflection(y) (mm)
1	7.5	0.112	0.317
2	7.15	0.117	0.314
3	7.42	0.120	0.319
4	7.30	0.118	0.318

SX (AVG)
 RSYS=0
 DMX = .44421
 SMN = -8.6
 SMX = 8.14

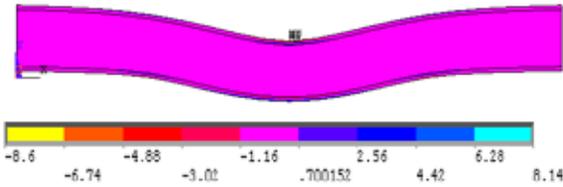


Figure 9(a): Bending stress distribution in Face Sheets

SXY (AVG)
 RSYS=0
 DMX = .44421
 SMN = -.0901
 SMX = .0901

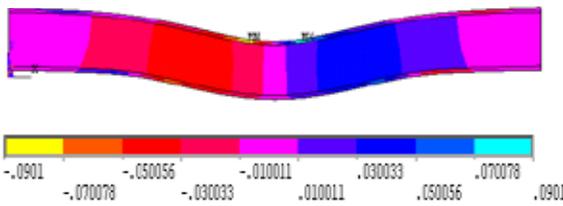


Figure 9(b): Shear stress distribution in core

UY (AVG)
 RSYS=0
 DMX = .44421
 SMN = -.444173
 SMX = .118587

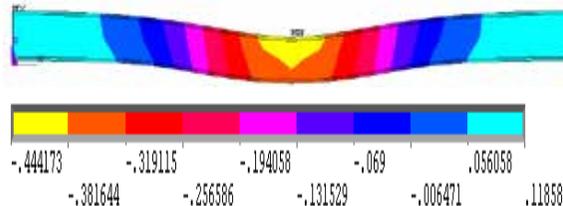


Figure 9(c): Resultant beam deflection of sandwich beam

Bending stress (σ) MPa	Shear stress in core (τ) MPa	Max deflection (y) mm
8.6	0,0901	0.444

Figure 9(d): Single Layer core

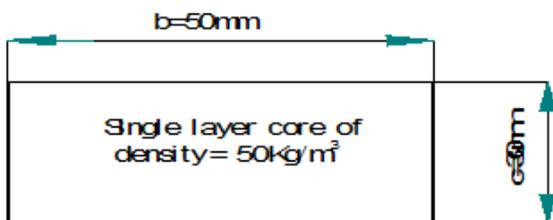


Figure 9: Results of flexural behavior of single layer core sandwich beam

Results and Discussions

The present investigation was mainly focus on the flexural behavior of multi-layer cored sandwich beams made up of composite face sheets (Bi-woven E-glass/epoxy resin) and cores of polyurethane foams of different layer densities using most versatile numerical tool i.e. FEM/ANSYS. As an innovative idea sandwich beams are modified by replacing the conventional single layer low density ($\rho= 50\text{Kg/m}^3$) soft core with multi-layer core of different densities in order to overcome the most common problem of sandwich structures i.e. material properties mismatch. The problem for the study was mainly concern with the study of influence of multi-layer core on flexural behavior of sandwich beams. To rate the performance of these structures, three engineering parameters of the sandwich beams under flexural load such as face sheet stress (σ_f), core shear (τ) and beam deflection (y) were considered. A three layered core model of layer thickness 10mm each with different layer density was chosen. The schematic view of sandwich beam with multi-layer core is as shown in figure-4. In order to identify the best layer configuration that can perform better under flexural loading, number of finite element models of sandwich beams with different multi-layer core configurations were generated as shown in table-4. All these models were analyzed under three point bending at constant mid span load (200N). Furthermore the span length, width and the thickness of face sheets remain constant for all the sandwich beam models. Foremost to this task, the numerical procedure (FEM/ANSYS) was validated using 2D-elasticity solutions. For validation process, a sandwich beam model was chosen as per ASTM standards (C323) [9] of dimensions 300mmx50mmx14.2mm loaded in three- point bending with a span length of 150mm as shown in figure-1. Finite element analysis was performed successfully by analyzing the beam model under three- point bending with a constant mid span load of 200N. The various post processing results obtained from numerical analysis are tabulated in table-1. 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 agreement between numerical and theoretical results were generally good.

After successful validation process, as an innovative idea to obtain an improved structural behavior, in the present study an attempt was made to replace the conventional single layer soft core of density (ρ) by a multi-layer core of different layer density ranged from 50Kg/m^3 to 150Kg/m^3 . The multi-layer core is obtained by using several polyurethane layers of different densities and configurations. In the present investigation, a three layered core model with different layer densities & configurations was generated and analyzed under 3-point bending using the most versatile numerical tool i.e. FEM/ANSYS and the influence of layer density on the performance parameters (σ_f, τ, y) were studied with great care. All the models were analyzed at constant beam length, width & mid span loading with similar and identical face sheets. Various layer configurations were examined and an attempt was made to identify the best layer configuration that can perform better under flexural loading. The contours of various post processing results so obtained from finite element analysis of all the multi- layer configurations is as shown in figures-5 to 8.

In order to identify the best layer configuration that can perform better under flexural loading, the various post processing results of all the multi-layer core configurations under flexural loading are shown graphically in figure-10. The analysis of graphs shows that the performance of layer configuration-2 is better as compared to other layer configurations.

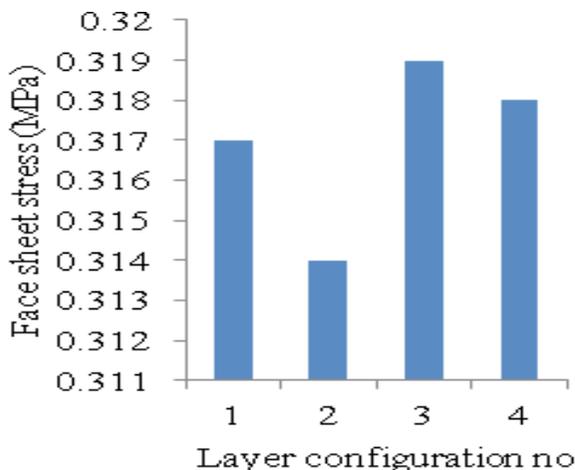


Figure10(a): σ_f v/s configurations

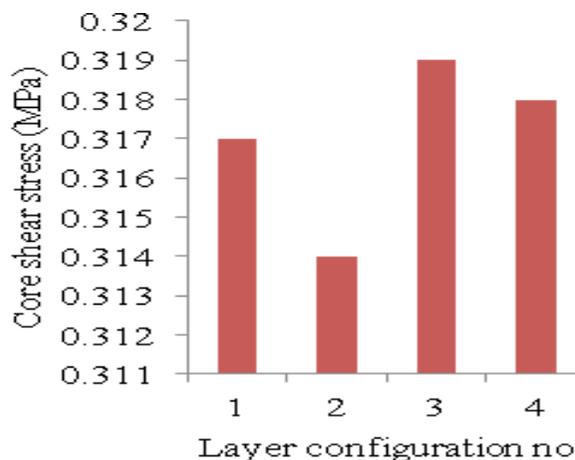


Figure10(b): τ v/s configurations

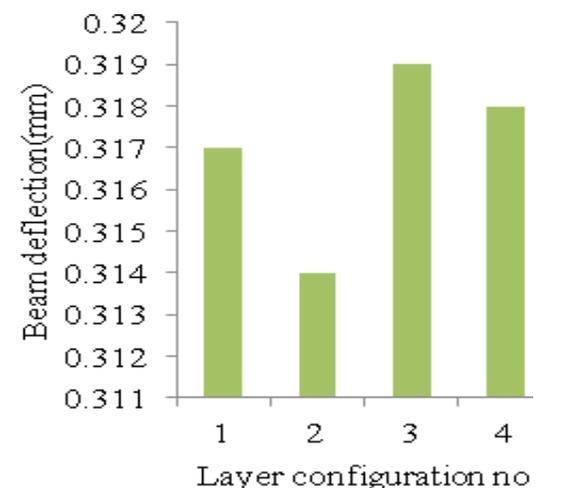


Figure10(c): y v/s configurations

Figure10: Performance parameters v/s multi-layer configurations

In order to study the performance of multi-layer cored sandwich beams as compared to single layer low density ($\rho= 50\text{Kg/m}^3$) soft core sandwich beams, finite element analysis was performed on single layer core of thickness equal to the total thickness of multi-layer core. The contours of various post processing results obtained from finite element analysis for single layer sand-

wich beam is as shown in figure-9. The results so obtained were compared with the results of multi-layer core (Configuration-2) graphically as shown in figure-11. From the comparative graphs it is observed that the magnitude of face sheet stress and beam deflection induced in multi-layer core case are less compared to that of single layer core sandwich beams. This indicates that the load bearing capacity and flexural stiffness of multi-layer core sandwich beams are higher as compared to that of single layer soft cored sandwich beams of same core thickness.

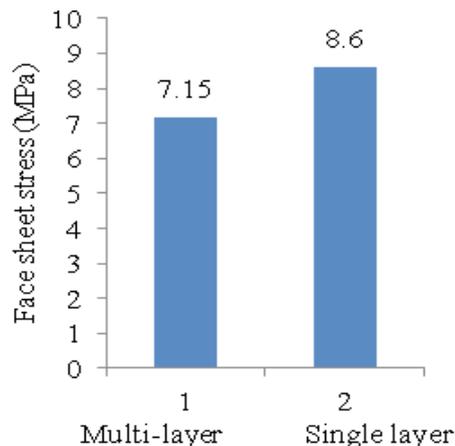


Figure 11(a): σ_f v/s sandwich cores

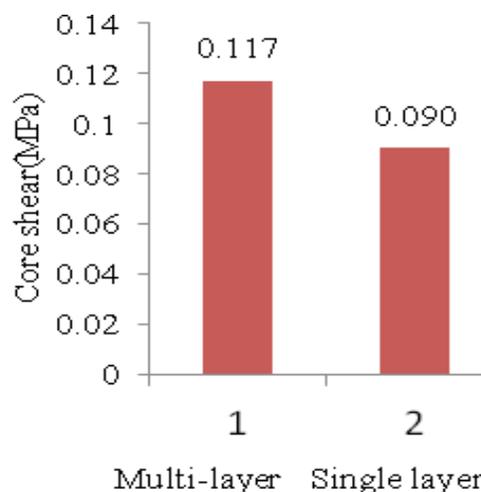


Figure 11(b): τ v/s sandwich cores

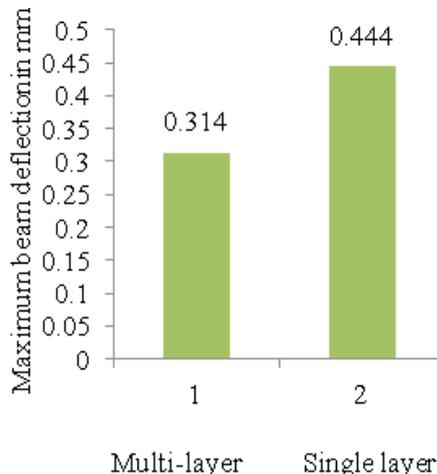


Figure 11(c): y v/s sandwich cores

Figure11: Comparative graphs of performance parameters

v/s sandwich cores

From the present investigation it is evident that the performance of multi-layer configuration-2 i.e. core layers arranged in order lower density to higher density from bottom layer to top layer that means denser layer adjacent to face sheet under compression & softer layer adjacent to face sheet under tension is most suitable solution to the problem of replacement of conventional single layer core sandwich beams.

Conclusion

Flexural behavior of multi-layer PUF cored sandwich beams were studied numerically using the most versatile numerical tool i.e. FEM/ANSYS. The present analysis shows the positive influence of multi-layer core over the performance parameters such as face sheet stress (σ_f), core shear (τ) and beam deflection (y) as compared to single layer core. The multi-layer core is obtained by using several polyurethane foam layers of different densities and configurations. Various layer configurations were examined and the influence of layer densities on above said engineering parameters of the sandwich beams was studied with great care. In the present investigation major attention was paid to the arrangement of layers with their densities. All the analyses were carried out at constant static load. Thus for future work it is recommended to study the behavior experimentally under higher loads in order to understand the peak loads at which beams fail.

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