

Structural Analysis of Multilayer Pressure Vessels for Different Shapes of Cross Sections by Using FEM

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ABSTRACT: Sandwich structures have been widely used in aerospace structures, ship building, infrastructure, etc. due to their light weight and high strength to weight ratio. Traditionally, light-weight core materials such as foam core, truss core, honeycomb core have been used in fabricating sandwich structures with limited success. The aim of this work is to evaluate the effect of core shape in sandwich panels. The different core shapes panels, namely Rectangular Core, Hollow Rectangular Core, Circular Core and elliptical core sandwich panels are taken into study and their mechanical behaviour is compare using simulations techniques. There are many applications based on sandwich structures, but in this project we have taken the pressure vessel as application. The core shape structures are placed in between the layers of the pressure vessel to improve the strength and to reduce the weight of the pressure vessel. To find out the best core shape sandwich structure we have used simulation techniques.

KEYWORDS: ANSYS, SOLID WORKS, Multi Layer Pressure Vessels.

I. INTRODUCTION

A sandwich structure is a fabricated material that consists of two thin, stiff facing sheets joined to either side of a low density core material or structure. The separation of the facing by a light weight core acts to significantly increase the second moment of area (and hence the bending stiffness) of the material cross section with only a small increase in weight. The construction is often used in light weight applications such as aircraft, marine applications, wind turbine blades, industrial platform sand floors. The face sheets of sandwich panels provide structural stiffness and protect the core against damage and weathering. During loading, the face sheet stake compressive and tensile loads and core is subjected to shear loads between the faces, thus providing high bending stiffness. Sandwich structures are used in applications requiring high stiffness to weight ratios, since for a given weight, the sandwich structure has a much higher moment of inertia compared to solid.

Steel sandwich panels : Metallic sandwich panels with top and bottom plates as well as the core made up of steel are called steel sandwich panels. The core structures are of different types according to core structures the steel sandwich structures are divided some of them are I-Core, O-Core, with rectangular beams ,with hat or corrugated sheets as a core, web core, round type of core and ellipsoid shape of material. Amongst all possible design concepts in composite structures, the idea of sandwich, The use of laminate composites as skins and low density cellular materials as cores in sandwich constructions has enabled a very good utilisation of the constituent material also providing structural components with high stiffness and strength to weight ratios Non metallic honeycombs are popular in high performance applications because of their good mechanical properties excellent resistance to hostile environments and better fatigue resistance than aluminium However because of the low stiffness of the core. They are susceptible to indentation failure The need to take into consideration the indentation. resistance of sandwich panels when optimising their design and the importance of having a robust computational tool to predict indentation failure in sandwich beams under bending have

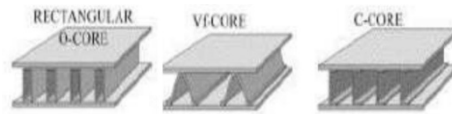
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been the main motivations for this thesis Sandwich panels are popular in high performance applications where weight must be kept to a minimum for example aeronautical structures high speed marine craft and racing cars in the most weight critical applications composite materials are used for the skins cheaper alternatives such as aluminium alloy, steel or plywood are also commonly used Materials used for cores include polymers aluminium wood and composites To minimise weight these are used in the form of foams honeycombs or with a corrugated construction .As well as mechanical requirements core.



II. LITERATURE REVIEW

- V.N. Scoping sky and A.B. Smetankin describes the structural model and stress analysis of nozzle connections in ellipsoidal heads subjected to external loadings. They used Timoshenko shell theory and the finite element method. The features of the structural model of ellipsoid-cylinder shell intersections, numerical procedure and SAIS special-purpose computer program were discussed. A parametric study of the effects of geometric parameters on the maximum effective stresses in the ellipsoid-cylinder intersections under loading was performed. The results of the stress analysis and parametric study of the nozzle connections are presented
- Drazan, Pejo, Fra V.N. Scoping sky and A.B. Smetankin describes the structural model and stress analysis of nozzle connections in ellipsoidal heads subjected to external loadings. They used Timoshenko shell theory and the finite element method. The features of the structural model of ellipsoid-cylinder shell intersections, numerical procedure and SAIS special-purpose computer program were discussed. A parametric study of the effects of geometric parameters on the maximum effective stresses in the ellipsoid-cylinder intersections under loading was performed. The results of the stress analysis and parametric study of the nozzle connections are presented
- Drazan, Pejo, Franjo and Darko (2010) considered influence of stresses resulting from weld misalignment in cylindrical shell circumferential weld joint on the shell integrity. The stresses estimated analytically by API recommended practice procedure and calculated numerically by using the finite element method
- njo and Darko (2010) considered influence of stresses resulting from weld misalignment in cylindrical shell circumferential weld joint on the shell integrity. The stresses estimated analytically by API recommended practice procedure and calculated numerically by using the finite element method

III. POST WORK

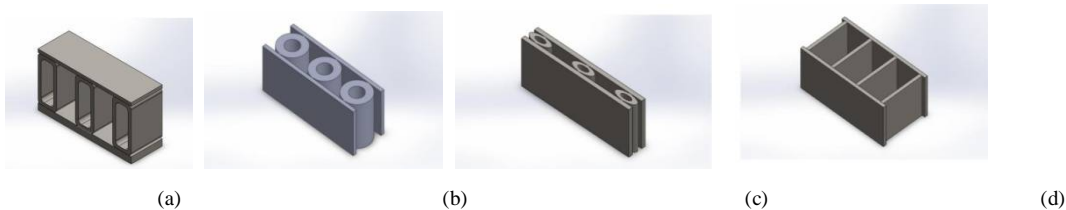


Fig. 2. Core Shape Structures (a) Hollow rectangular type of core structure (b) Hollow circle type of core structure (c) Hollow ellipse type core structure (d) Rectangle type core structure.

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Hollow Rectangular section :



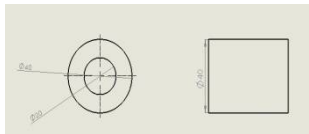
$$\begin{aligned} \text{Area} &= A_1 - A_2 \\ &= (70 \times 30) - (60 \times 20) \\ \text{Area} &= 900 \text{mm}^2 \end{aligned}$$

Rectangle section :



$$\begin{aligned} \text{Area} &= 70 \times 10 \\ &= 700 \text{mm}^2 \end{aligned}$$

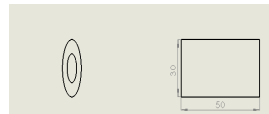
Circular section :



$$\begin{aligned} r_1 &= \frac{D}{2} = \frac{40}{2} = 20 \text{mm} \\ r_2 &= \frac{d}{2} = \frac{20}{2} = 10 \text{mm} \\ \text{Area} &= \pi r_1^2 - \pi r_2^2 \\ &= \pi(20)^2 - \pi(10)^2 \end{aligned}$$

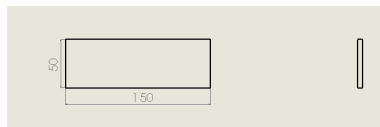
$$\text{AREA} = 942.47 \text{mm}^2$$

Hollow ellipse section :



$$\begin{aligned} \text{Area} &= \pi a_1 b_1 - \pi a_2 b_2 \\ &= \pi \times 30 \times 12 - \pi \times 15 \times 6 \\ \text{Area} &= 848.23 \text{mm}^2 \end{aligned}$$

Upper plate and lower plate :



$$\begin{aligned} \text{Upper plate Area } A &= 150 \times 5 \\ &= 750 \text{mm}^2 \\ \text{Lower plate Area } A &= 150 \times 5 \\ &= 750 \text{mm}^2 \end{aligned}$$

Calculation of weight of the whole bodies:

Material considered is Mild steel

$$\rho = 7.88 \text{g/cm}^3$$

Hollow rectangular structure:

W = volume * density * gravity

$$\begin{aligned} \text{Weight } W &= A * l * \rho * g \\ &= v * \rho * g \\ &= 0.9 * 0.05 * 788 * 9.81 \end{aligned}$$

$$w_1 = 347.86$$

$$w = w_1 + w_2 + w_3$$

$$w = 1043.58 \text{gm}$$

Weight of plate:

$$\begin{aligned} w_{p1} &= 0.75 * 0.05 * 788 * 9.81 \\ &= 289.88 \end{aligned}$$

$$w_p = w_{p1} + w_{p2}$$

$$w_p = 579.771$$

Total weight of structure W = w + w_p

$$W = 1043.58 + 579.771$$

$$W = 1.623 \text{kg}$$

Rectangular structure:

Weight of rectangular one $w_1 = A * L * \rho * g$

$$= 0.7 * 0.05 * 788 * 9.81$$

$$w_1 = 270.5598$$

$$w = w_1 + w_2 + w_3 + w_4$$

$$W = 1082.23 \text{gm}$$

Weight of the plate: - $w_{p1} = 0.75 * 0.05 * 788 * 9.81$

$$= 289.88 \text{gm}$$

$$w_p = w_{p1} + w_{p2}$$

$$w_p = 573.771 \text{gm}$$

Total weight of the structure body W = w + w_p

$$W = 1082.23 + 579.771$$

$$W = 1.66 \text{kg}$$

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Hollow circular structure:

$$\begin{aligned} \text{Weight of the Hollow circular one } w_1 &= A * L * \rho * g \\ &= 0.942 * 0.05 * 788 * 9.81 \\ &= 364.27 \\ w &= w_1 + w_2 + w_3 \\ w &= 1092.8 \text{ gm} \end{aligned}$$

$$\begin{aligned} \text{Total weight of the plates } w_p &= w_{p1} + w_{p2} \\ w_p &= 579.771 \end{aligned}$$

$$\begin{aligned} \text{Total Weight of the structural body} \\ W &= w + w_p \\ &= 1092.8 + 579.771 \\ W &= 1.67 \text{ kg} \end{aligned}$$

Hollow ellipse structure:

$$\begin{aligned} \text{Weight of the Hollow ellipse structure one} \\ w_1 &= A * L * \rho * g \\ &= 0.848 * 0.05 * 788 * 9.81 \\ &= 327.85 \end{aligned}$$

$$\begin{aligned} w &= w_1 + w_2 + w_3, \\ w &= 983.55 \text{ gm} \end{aligned}$$

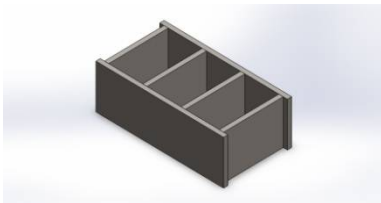
$$\begin{aligned} \text{Weight of the plates } w_p &= w_{p1} + w_{p2} \\ w_p &= 579.771 \end{aligned}$$

$$\begin{aligned} \text{Total weight of the structure body } W &= w + w_p \\ &= 1.56 \text{ kg} \end{aligned}$$

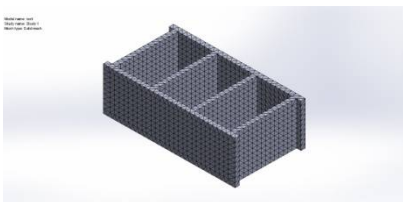
*Approximately Total Weight of the all core structure is 1.62kg

IV. EXPERIMENTAL RESULTS

Simulation of rectangle :



Mesh Information :



Resultant and Forces

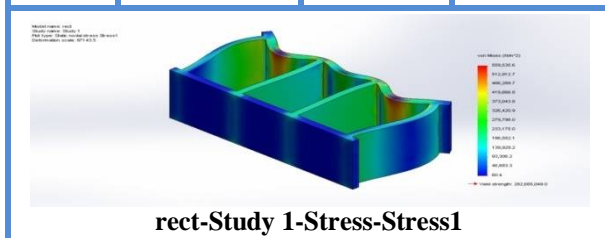
Reaction Forces :

Selecti on set	Uni ts	Sum X	Sum Y	Sum Z	Resulta nt
Entire Model	N	-0.0122099	-0.00219745	-149.966	149.966

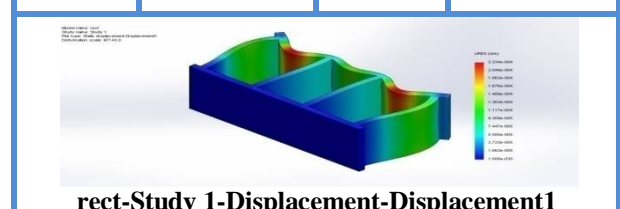
Reaction Moments :

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N·m	0	0	0	

Name	Type	Min	Max
Stress1	VON: von Mises Stress	60.3632 N/m ² Node: 5827	559536 N/m ² Node: 2330



Name	Type	Min	Max
Displacement 1	URES: Resultant Displacement	0 mm Node: 5049	0.000223408 mm Node: 3637



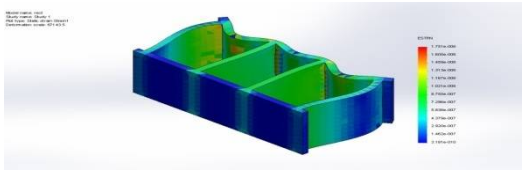
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Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.18091e-010 Element: 4499	1.75067e-006 Element: 402



rect-Study 1-Strain-Strain1

Similarly, by using ANSYS the stress, strain and displacement are found for Hollow Rectangle, Hollow Ellipse and Hollow Circle and the results are tabulated below:

Results obtained from the respective core shapes:

S NO	Structure	Strain	Stress	Displacement (mm)	Factor of Safety	Weight (N)
1	Rectangle	1.75067×10^{-6}	559536 N/m^2	0.000223408	505.52	2.88387
2	Hollow Rectangle	8.7131×10^{-7}	246640 N/m^2	9.0047×10^{-5}	1146.85	2.88487
3	Hollow Ellipse	4.72003×10^{-6}	$1.65431 \times 10^6 \text{ N/m}^2$	0.000521869	170.96	2.88487
4	Hollow Circle	3.33632×10^{-6}	$1.038 \times 10^6 \text{ N/m}^2$	0.000383581	272.50	2.88487

Pressure Vessels

Pressure vessels are used to store and transmit liquids, vapour, and gases under pressure in general. The pressure of these fluids will exert pressure equally in all directions on the walls and ends of pressure vessels. Because of the internal loading, stresses are induced on certain sections of the cylinders (pressure vessels) wall. The pressure vessels (cylindrical or spherical) are generally used in engineering to store fluid under pressure. Major uses of pressure vessels are as follows:

- Pressure vessels are used in steam boilers.
- Pressure vessels are also used in storage of chemicals in chemical plants.
- Used in storage of petroleum products (petrol, diesel etc.).
- It is also used in engine cylinders.

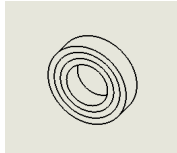
Model of Pressure Vessels with various core shapes:



Fig. 3. (a) Hollow Circular core type vessel (b) Hollow ellipse core type vessel (c) Hollow Rectangular core type vessel (d) Rectangular core type vessel

PRESSURE VESSEL CALCULATIONS :

Calculations on pressure vessels:



layers pressure vessel

Diameters of the 3layers pressure vessel 100,130,160,190(in mm) In pressure vessel majorly the failure occurs due to circumferential stress (σ_c)
Calculating the hoop stress on layer one:-
For layer one the inner and outer diameters are 100mm and 130mm

$$d_1 = 100mm$$

$$d_2 = 130mm$$

$$r_1 = \frac{d_1}{2} = 50mm$$

$$r_2 = \frac{d_2}{2} = 65mm$$

Circumferential stress or hoop stress:

$$\sigma_c = \frac{p_1 r_1^2}{r_1^2 - r_2^2} \left[\frac{r_2^2}{r_1^2} + 1 \right]$$

$$K = \frac{r_2}{r_1}$$

$$p_1 = \text{applied pressure}$$

$$\sigma_c = \frac{30 \times 50^2}{65^2 - 50^2} \left[\frac{65^2}{50^2} + 1 \right]$$

$$\sigma_c = 43.47 [2.69]$$

$$\sigma_c = 116.93N/mm^2$$

Longitudinal stress :

$$\sigma_l = \frac{p_1 r_1^2}{r_1^2 - r_2^2}$$

$$\sigma_l = \frac{30 \times 50^2}{65^2 - 50^2}$$

$$\sigma_l = 43.47N/mm^2$$

Maximum principal stress :

$$\sigma_r \left[\frac{k^2+1}{k^2-1} \right] \leq \sigma$$

$$K = \frac{r_2}{r_1} = \frac{65}{50} = 1.3$$

$$\sigma = \text{allowable stress}$$

$$\sigma_r = \text{radial stress (or) Internal pressure}$$

$$\sigma_r = 30N/mm^2$$

$$30 \left[\frac{1.3^2+1}{1.3^2-1} \right] \leq 260$$

$$116.95 \leq 260$$

Maximum principal strain :

$$\sigma_r = \frac{\sigma_c}{E} + \frac{\sigma_r}{mE} - \frac{\sigma_l}{mE}$$

$$\frac{1}{m} = 0.3$$

$$\sigma > \sigma_r \left[\frac{k^2+1}{k^2-1} + \frac{1}{m} \left[\frac{k^2-2}{k^2-1} \right] \right]$$

$$\sigma > 30 \left[\frac{1.3^2+1}{1.3^2-1} + \frac{1}{0.3} \left[\frac{1.3^2-2}{1.3^2-1} \right] \right]$$

$$260 \leq 115.35$$

Maximum shear stress :

$$\frac{\sigma_c + \sigma_r}{2} = \frac{\sigma_r}{2} \left[\frac{k^2+1}{k^2-1} + 1 \right]$$

$$= \frac{\sigma_r}{2} \frac{2k^2}{k^2-1}$$

$$= \frac{30}{2} \frac{2(1.3)^2}{(1.3)^2-1}$$

$$\tau = 73.47N/mm^2$$

Layer two:-

Diameters: - $d_2=130mm$

$d_3=160mm$

Radius: - $r_2 = \frac{130}{2} = 65mm$

$r_3 = \frac{160}{2} = 80mm$

Hoop stress

$$\sigma_c = \frac{p_1 r_2^2}{r_2^2 - r_3^2} \left[\frac{r_3^2}{r_2^2} + 1 \right]$$

$$\frac{r_3}{r_2} = k$$

$$= \frac{30 \times 65^2}{80^2 - 65^2} \left[\frac{80^2}{65^2} + 1 \right]$$

$$= 58.27 [2.51]$$

$$\sigma_c = 146.27N/mm^2$$

Longitudinal stress :

$$\sigma_l = \frac{p_1 r_2^2}{r_3^2 - r_2^2}$$

$$= \frac{30 \times 65^2}{80^2 - 65^2}$$

$$\sigma_l = 58.27N/mm^2$$

Max principal stress :

$$\sigma_r \left[\frac{k^2+1}{k^2-1} \right] \leq \sigma$$

$$K = \frac{r_3}{r_2} = \frac{80}{65} = 1.23$$

$$\sigma = \text{allowable stress}$$

$$\sigma_r = \text{radial stress (or) Internal pressure}$$

$$\sigma_r = 30N/mm^2$$

$$30 \left[\frac{1.23^2+1}{1.23^2-1} \right] \leq 260$$

$$146.98 \leq 260$$

Maximum principal strain :

$$\sigma_r = \frac{\sigma_c}{E} + \frac{\sigma_r}{mE} - \frac{\sigma_l}{mE}$$

$$\frac{1}{m} = 0.3$$

$$\sigma \geq \sigma_r \left[\frac{k^2+1}{k^2-1} + \frac{1}{m} \left[\frac{k^2-2}{k^2-1} \right] \right]$$

$$\sigma \geq 30 \left[\frac{1.23^2+1}{1.23^2-1} + \frac{1}{0.3} \left[\frac{1.23^2-2}{1.23^2-1} \right] \right]$$

$$260 \geq 30 [4.899 - 0.284]$$

$$260 \geq 138.46 \text{ safe}$$

Maximum shear stress:

$$\tau = \frac{\sigma_c + \sigma_r}{2} = \frac{\sigma_r}{2} \left[\frac{k^2+1}{k^2-1} + 1 \right]$$

$$= \frac{\sigma_r}{2} \frac{2k^2}{k^2-1}$$

$$= \frac{30}{2} \frac{2(1.23)^2}{(1.23)^2-1}$$

$$\tau = 88.49N/mm^2$$

Layer three:-

Diameters: - $d_3=160mm$

$d_4=190mm$

Radius: - $r_2 = \frac{160}{2} = 80mm$

$r_3 = \frac{190}{2} = 95mm$

Hoop stress

$$\sigma_c = \frac{p_1 r_3^2}{r_4^2 - r_3^2} \left[\frac{r_4^2}{r_3^2} + 1 \right]$$

$$\frac{r_4}{r_3} = k$$

$$\sigma_c = \frac{30 \times 95^2}{95^2 - 80^2} \left[\frac{95^2}{80^2} + 1 \right]$$

$$= 73.14 [2.41]$$

$$\sigma_c = 176.27N/mm^2$$

Longitudinal stress:-

$$\sigma_l = \frac{p_1 r_3^2}{r_4^2 - r_3^2}$$

$$\sigma_l = \frac{30 \times 80^2}{95^2 - 80^2}$$

$$\sigma_l = 73.14N/mm^2$$

Maximum principal stress :

$$\sigma_r \left[\frac{k^2+1}{k^2-1} \right] \leq \sigma$$

$$K = \frac{r_4}{r_3} = \frac{95}{80} = 1.1875$$

$$\sigma = \text{allowable stress}$$

$$\sigma_r = \text{radial stress (or) Internal pressure}$$

$$\sigma_r = 30N/mm^2$$

$$30 \left[\frac{1.1875^2+1}{1.1875^2-1} \right] \leq 260$$

$$176.28 \leq 260$$

Maximum principal strain:

$$\sigma_r = \frac{\sigma_c}{E} + \frac{\sigma_r}{mE} - \frac{\sigma_l}{mE}$$

$$\frac{1}{m} = 0.$$

$$\sigma > \sigma_r \left[\frac{k^2+1}{k^2-1} + \frac{1}{m} \left[\frac{k^2-2}{k^2-1} \right] \right]$$

$$\sigma > 30 \left[\frac{1.1875^2+1}{1.1875^2-1} + 0.3 \left[\frac{1.1875^2-2}{1.1875^2-1} \right] \right]$$

$$260 > 30 [4.899 - 0.284]$$

$$260 > 163.35$$

Maximum shear stress:

$$\tau = \frac{\sigma_c + \sigma_r}{2} = \frac{\sigma_r}{2} \left[\frac{k^2+1}{k^2-1} + 1 \right]$$

$$= \frac{\sigma_r}{2} \frac{2k^2}{k^2-1}$$

$$\tau = \frac{30}{2} \frac{2(1.1875)^2}{(1.1875)^2-1}$$

$$\tau = 103.142N/mm^2$$

Considering as a three layer in to single layer:-



single layer pressure vessel

Diameters: - $d_1=100mm$

$d_2=190mm$

Radius: - $r_1 = \frac{100}{2} = 50mm$

$r_2 = \frac{190}{2} = 95mm$

Hoop stress

$$\sigma_c = \frac{p_1 r_1^2}{r_2^2 - r_1^2} \left[\frac{r_2^2}{r_1^2} + 1 \right]$$

$$\frac{r_2}{r_1} = k$$

$$\sigma_c = \frac{30 \times 50^2}{95^2 - 50^2} \left[\frac{95^2}{50^2} + 1 \right]$$

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$$\sigma_c = 52.98 N/mm^2$$

Longitudinal stress

$$\sigma_l = \frac{p_1 r_1^2}{r_2^2 - r_1^2}$$

$$\sigma_c = \frac{30 \cdot 50^2}{95^2 - 50^2}$$

$$\sigma_l = 11.49 N/mm^2$$

Maximum principal stress:

$$\sigma_r \left[\frac{k^2+1}{k^2-1} \right] \leq \sigma$$

$$K = \frac{r_2}{r_1} = \frac{95}{50} = 1.9$$

$\sigma =$ allowable stress

$\sigma_r =$ radial stress (or) Internal pressure

$$\sigma_r = 30 N/mm^2$$

$$30 \left[\frac{1.9^2+1}{1.9^2-1} \right] \leq 260$$

$$52.98 \leq 260$$

Maximum principal strain:

$$\sigma_r = \frac{\sigma_c}{E} + \frac{\sigma_r}{mE} - \frac{\sigma_l}{mE}$$

$$\frac{1}{m} = 0.3$$

$$\sigma > \sigma_r \left[\frac{k^2+1}{k^2-1} + \frac{1}{m} \left[\frac{k^2-2}{k^2-1} \right] \right]$$

$$\sigma > 30 \left[\frac{1.9^2+1}{1.9^2-1} + 0.3 \left[\frac{1.9^2-2}{1.9^2-1} \right] \right]$$

$$260 > 30 \left[1.766 + 0.3 \cdot \frac{1.61}{2.61} \right]$$

$$260 > 58.53 \text{ safe}$$

Maximum shear stress:

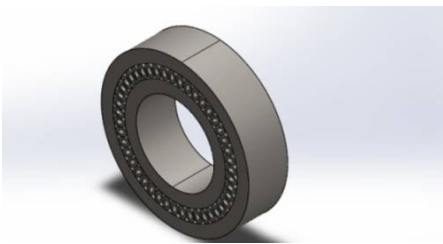
$$\tau = \frac{\sigma_c + \sigma_r}{2} - \frac{\sigma_r}{2} \left[\frac{k^2+1}{k^2-1} + 1 \right]$$

$$= \frac{\sigma_r}{2} \frac{2k^2}{k^2-1}$$

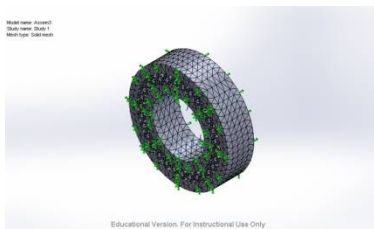
$$= \frac{30}{2} \frac{2(1.9)^2}{(1.9)^2-1}$$

$$\tau = 41.49 N/mm^2$$

Circular core type pressure vessel :



Mesh Information :



Resultant Forces

Reaction Forces

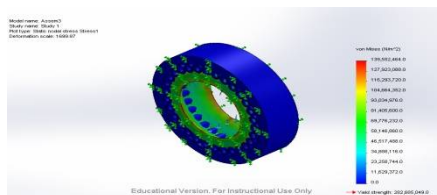
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-1.68723	0.129002	-4.28174	4.60398

Reaction Moments

Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N·m	0	0	0	0

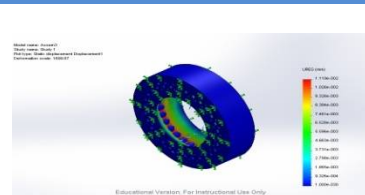
Study Results :

Name	Type	Min	Max
Stress1	VON: von Mises Stress	0 N/m ² Node: 1	1.39552e+008 N/m ² Node: 20097



Assem3-Study 1-Stress-Stress1

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0 mm Node: 1	0.0111916 mm Node: 19797



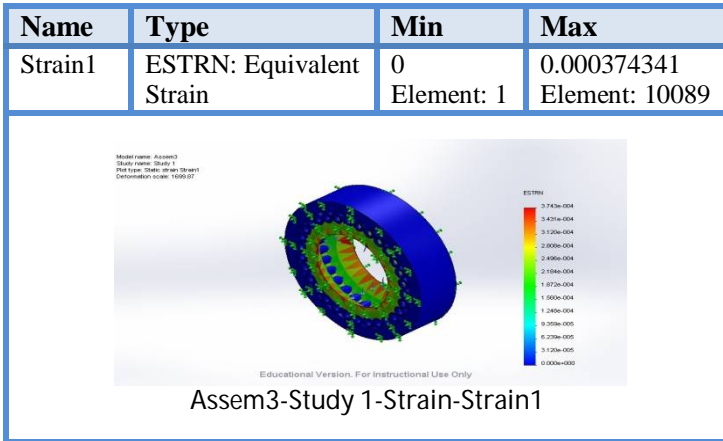
Assem3-Study 1-Displacement-Displacement1

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Similarly, by using ANSYS the stress, strain and displacement are found for Hollow Rectangle Core Type Vessel, Hollow Ellipse Core Type Vessel and Hollow Circle Core Type Vessel and the results are tabulated below:

Results obtained from the respective core shapes:

S NO	Material	Structure	Strain	Displacement (mm)	Factor of Safety	Weight (Kg)
1	SS1035	Rectangle	0.00026	0.00692	2.68	6.13
2	SS1035	Hollow Ellipse	0.00047	0.01139	1.68	6.92
3	SS1035	Hollow circle	0.00037	0.011916	2.025	6.92
4	SS1035	Hollow Rectangle	0.000302	0.085	2.53	5.91

V. CONCLUSION

In this project the different core shaped structures, namely Rectangle Core, Hollow Rectangular Core, Hollow Circular Core and Hollow ellipse core sandwich panels are taken into study and their mechanical behavior is compared, For evaluating mechanical behavior of the core sandwich Structures, on the basis of simulations techniques. Compare to all stress values, The Hollow circular cross sections have less stress at same weight and same load. So, at this circular cross section is suitable for application for members subjected to compressive loads. For considering the multilayer sandwich pressure vessels subjected to same pressure at different cross sections, Stresses induced in this cross sections hollow rectangle type is compared to remaining. So, this cross section is suitable for pressure vessels. So by using this kind of cross sections the weight reduces and strength increases. Finally based on the results of the analysis, we observed that hollow rectangular shape has got the optimum values like factor of safety, weight, deformation, stress and strain values

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