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An Optimum Sequence Configuration for Laminated Pressure Vessels Under Internal Pressure

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Abstract - Pressure vessels are leak-proof containers that contain fluids (liquids or gases) under high internal pressure. These vessels are made from different engineering materials (steel, aluminum, composite materials, etc.). For high pressure loading capacity of these vessels with weight saving, they are fabricated from thin multi shrink-fitted layers.
In this paper, an optimization work has been done to maximize the pressure loading capacity of the vessel through reducing the resulted stresses in the pressure vessel walls.Various laminated pressure vessels having different design aspects;including different number of laminated layers, different interference fits and different sequence of both layers'thickness sequence and shrink fit amount sequence have been manipulated and analyzed.
The results obtained from this study have showed that the best configuration for layers' thickness arrangement is the ascending sequence. Whereas, the best configuration for the fits-sequence between layers are the descending sequence (i.e. fits decreases towards the outgoing direction).
The study showed also thatincreasingboththe number of laminated layers forming the vessel and the interference-fit amounts between the fitted layers can increase the pressure loading capacity of the vessel.

KEYWORDS-Mechanical Design, Pressure Vessels, laminated Walls, Inside Liner and Hoop Stress.

I. LITERATURE REVIEW

In recent years, pressure vessels have found a lot of mechanical applications in different fields of industry as: steam boilers, pipelines, gas storages, gun barrels, hydraulic cylinders and else. Pressure vessels can have different forms, cylindrical, spherical, or elliptical shapes. These vessels are generally made from different engineering materials (metallic or composite materials). Since the material of the vessel is generally not fully utilized in longitudinal/meridional direction resulting in sometimes excessive weight. Instead of these traditional metallic materials, many techniques have been provided to increase the sustained internal pressure with decreasing their weights. For example, use of filament winding technique which can increase the vessel pressure capacity.Throughout this technique, fiber reinforced epoxy composites are used extensively for pressure vessels because they offer higher specific strength and higher moduli with tailorizing characteristics which result in reduction of weight of the structure. Another example is to fabricate these vessels from laminated fitted layers with certain interference fits to generate an external contact pressure applying on the vessel wall and so increasing its internal pressure loads.

Brownell and Young [1] have designed multilayer pressure vessels working under high pressure loading. They constructed a pressure vessel by a shrink fitting successive layers and compared their results with the traditional ones. A good agreement has been obtained.

Akash and Suwarna[2]have analyzed the stresses resulted in composite laminated pressure vessels. In that research paper, storage tanks are designed for storing chemical liquids. The main aim of that research is to optimize the design of a vertical cylindrical fiber reinforced plastic storage tanks by varying the thickness of the cylindrical shell. Laminated construction having alternate layers of chopped strand mat (CSM) and woven roving (WR) has been used for designing these cylindrical shells.They proposed fiber reinforced plastics (FRP) as a type of composite material for storage tanks' construction. They performed their numerical analysis by using ANSYS 19 software and the results of the FRP storage tank have been compared to a similar storage tank which was made of stainless steel.

Kumar and et al [3] have manipulated cylindrical pressure vessels, which are widely used for commercial, under-water vehicles and in aerospace applications. The outer shells of those vessels are made up of conventional metals like steels and aluminum alloys. They showed that using composite materials could improve the performance of the vessel and offered a significant amount of material savings. They presented a graphical analysis to find the optimum fiber orientation for given layer thicknesses. In thatwork, an analytical model has been developed for the prediction of the minimum buckling load with/ without stiffener composite shell of continuous angle ply laminas for investigation. Numerical and theoretical comparisons are made for two different approaches for those composite pressure vessels. He has presented a3-D finite element analysis by using ANSYS-14.5 version software, for static and buckling analysis on the pressure vessel collapse.

Different ways to minimize the effective stress throughout radial position are studied by Kumar N. and et al [4] to show the stress behaviorin autofrettage pressures and shrink-fit multilayer pressure vessels. In their work, more effective ways of decreasing combined effect of autofrettage and shrink-fit in multilayer vessels is carried out. Combined effect of autofrettage (neglecting autofrettage) and shrink-fit is found to be much effective than shrink-fitted vessel. Introduction of autofrettageonsub-assemblyor final assembly reduces the net hoop stress. Combined effect of autofrettage, autofrettage and shrink-fit on fatigue is most effective than other ways of assembly.

In this research work, some design parameters have been analyzed to see their effect on the laminated vessel performance as: number of laminated layers, interference fit between layers and sequence configuration for both the layer thickness arrangement and fit amount sequencearrangement between layers.

Mojtaba Sharifi et al [5], have presented an analytical optimization methodfor an optimum design of multi-layers cylinders. They considered the maximum shear stress theory in their design. They minimized that shear stress which occurred at the inner surface of each layer. The formulae for obtaining the optimum values of layers' radii, contact pressures, and radial interferences are derived. A technique for interference-fitting of cylinders is also described and relationships for radial interferences and required temperature differences between cylinders for each step of the shrink-fitting process are derived using an analytical method. The results of that work showed that compound cylinders with more layers could give higher internal pressure capacity for a specified weight.

II. DESIGN APPROACH FOR LAMINATED PRESSURE VESSELS

As known that the design of pressure vessels depends on many factors like: the pressures applied inside and/or outside the vessel, the vessel material, the dimensions of the vessel and the manufacturing technique used for fabrication the vessel. In this study, the optimum design has been based on the multilayers cylindrical pressure vessels under internal applied pressure and fabricated from different shrunk-layers of different interference-fits and different thicknesses. The induced stresses in the laminated vesselsare affected by both the applied internal pressure and the contact pressures resulted from the effect of shrink-fit between the different layers [6]. The following subsections present the effect of shrink fit on the stresses resulted in the pressure vessels walls.

A- Thick-walled pressure vessels under internal and external pressures

Due to the applied internal and external pressures, the vessel wall will be subjected to three perpendicular stresses: tangential (hoop), axial (longitudinal), and radial stresses. These stresses vary throughout the wall thickness depending on the radial distance (r) from the vessel centerline.Since the maximum stress of these three stresses is the hoop stress, so it is used as the predominant stress in designing these vessels.

Equation (1) gives the hoop and radial stress resulted in cylindrical pressure vessels(Lame's equation) and shown graphically in figures 1& 2[6].

$$\sigma_h = \frac{P_i R_i^2 [1+(R_o/r)^2]}{(R_o^2 - R_i^2)} - \frac{P_o R_o^2 [1+(R_i/r)^2]}{(R_o^2 - R_i^2)} \quad \text{------} (1)$$

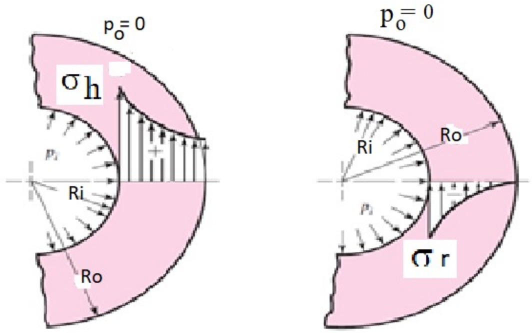

Fig. 1.Lame's stresses (hoop and radial) in thick-walledcylinder under internal and external pressure [6]

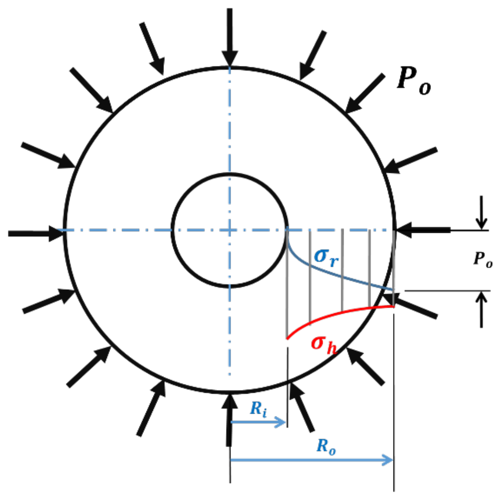

Fig. 2. Stress distribution along cylinder wall thickness under external pressure

B- Press and shrink fits

The press or shrink fit is used when a tube or cylinder is mounted around another one to increase its pressure capacity. Due to the press fit, the inside tube or shaft will be subjected to external contact pressure (Pc) and the outer tube will be subjected to internal contact pressure of same value P_c. The contact pressure between two shrink-fitted tubes can be computed from the following equation (3)and shown in Fig. 3 [6].

$$P_c = \frac{\delta E}{2R_c}\left[\frac{1}{\left[\left(\frac{k^2+1}{k^2-1}\right)_o+\left(\frac{k^2+1}{k^2-1}\right)_i\right]}\right] \quad (2)$$

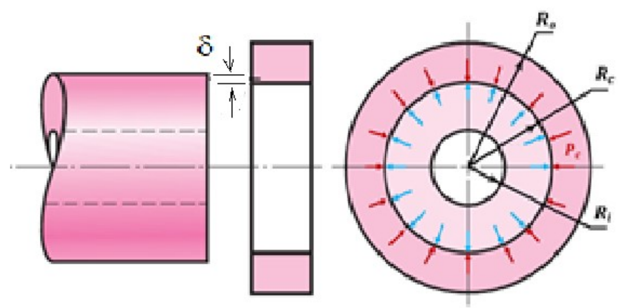

Fig.3. Contact pressure due to shrink-fitting [6]

Where;
δ = interference fit value

R_c = contact (mating) radius
$k_o = R_o / R_c$, $k_i = R_c / R_i$
E_i = modulus of elasticity of the inner tubematerial
E_o = modulus of elasticity of the outer tube material
ν_i= Poisson's ratio of the inner tube material
ν_o= Poisson's ratio of the outer tube material

The stresses distributions through the wall thickness of both the outer and inner tubes (due to the shrink-fit contact pressure are shown in the attached Fig. 4.

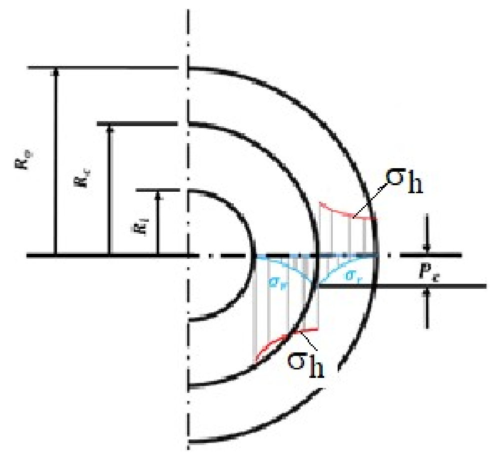

Fig. 4. Stress distribution in a shrink-fitted cylinder

III. MULTI-LAYERS LAMINATED PRESSURE VESSELS CONFIGURATION

Many factors affecting the design of laminated pressure vessels. Some of these factors are related to vessel material properties as: strength, modules of elasticityand poison's ratio. Some other factors are related to the dimensions of the vessel as: the inside diameter and wall thickness.Other factors are related to vessel shapeand fabrication technique of the vessel as: filament winding technique andlaminationtechnique.

As known that shrinking two cylinders or tubes one inside the other with certain type of interference fit will produce radial contact pressure between the two fitted cylinders. This contact pressure will apply as an external pressure around the inside cylinder. That contact pressure is mainly influenced by many factors as: the type of layers' material, the dimensions and the amount of interference fit between layers.

In this paper, the laminationmethod is used as a fabrication technique to generate an external pressure around the vessel inside layer and so increasing the internal pressure load capacity of the vessel. In this technique the wall of the vessel is fabricated from certain number of layers (up to four layers), each layer is shrunk around the inside layer (s) by certain type of interference fits: δ1, δ2 and δ3 which are taken interchangeably as: 10, 20 and 30 μm. The vessel has 100 mm inside radius and the total wall thickness is taken as 10% of the inside radius (thin layers). The layers arrangement has been selected in four manners: equal-thickness-layers sequence, descending sequence, ascending sequence and randomly sequence, as shown in Fig. 5.

The maximum induced stresses (hoop and radial)resulted in the vessel wall will be focused on the inside layer, which considered as the critical layer in the vessel wall layers. These stresses areinfluenced by both the internal pressure and the contact pressure generated between the different fitted layers.

Various factors are affecting the resulted stresses in that inside layer as: the amount of interference fit between the fitted layers, the number of these layers and the sequence of these layers (with respect to both thickness and shrink fit amount). In the following subsections, the effect of these fabrication factors is studied in details based on 10 MPa as an internal applied pressure.

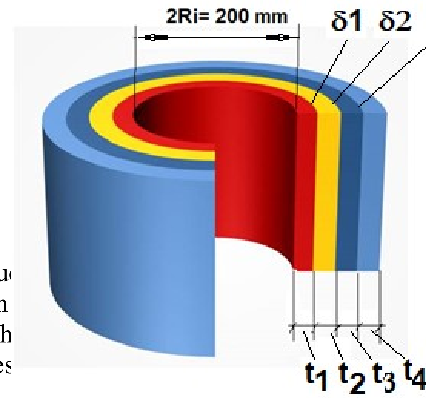

Fig. 5. Vessel laminated layers layout and dimensions

A- Effect of inferencefit

Increasing the interference fit between the laminated layers could redu
pressure vessels by a significant amount which means that the vessel can
vessel having same whole thickness. Figure 6 shows the reduction in th
liner wall due to increasing the amount of fit between two fitted layers ves

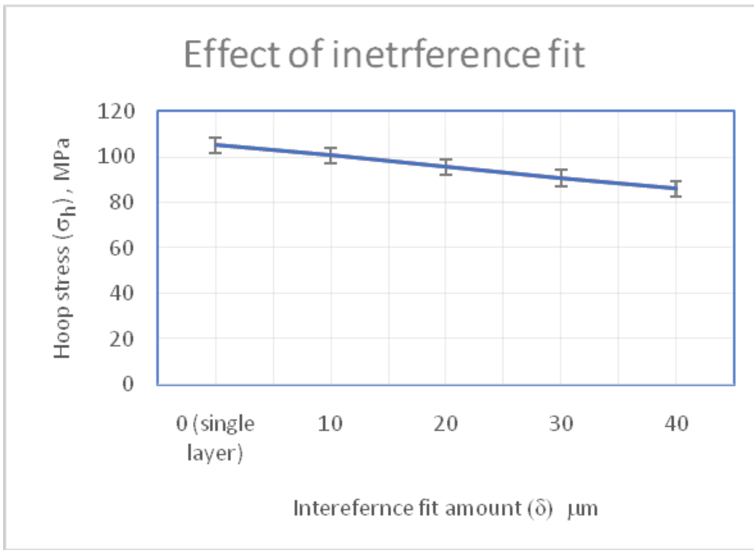

Fig. 6. Effect of inference fit between layers on the hoop stress in the inside layer

B- Effectof number of laminated-shrunk layers

Increasing the number of laminated shrink vessels could increase the pressure capacity of the vessel, where it reduced the resulted stresses in the wall of the vessel. Figure 7 shows the reduction in the resulted hoop stress in four vessels having same whole wall thickness but with different number of layers. Making the wall thickness having four-layers could decrease the resulted stress by a ratio of 10% lower than that of single wall layer having same whole wall thickness.

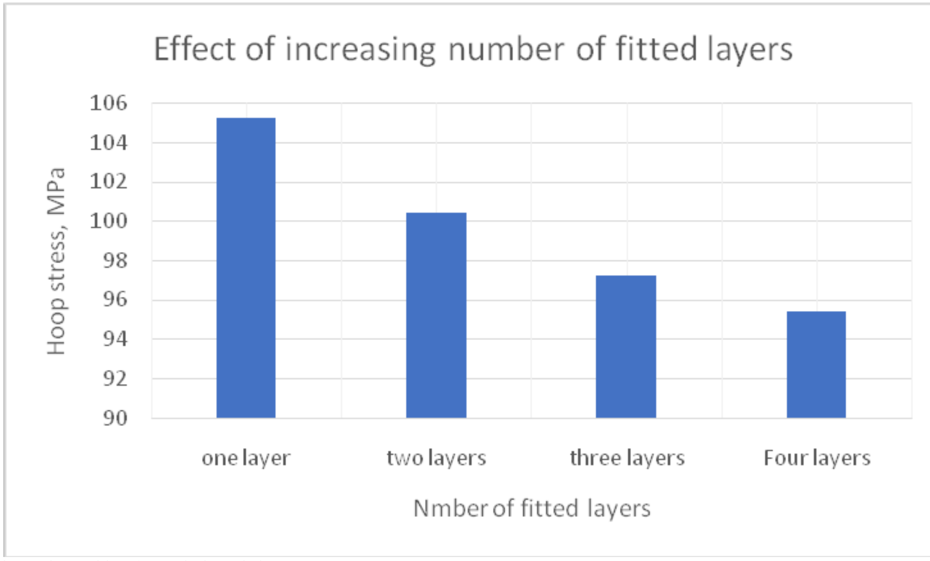

Fig. 7. Effect of number of laminated shrunk layers

C- Effect of thickness sequence of laminatedlayers around the inside liner of the vessel

The effect of arrangement sequence of laminated layers around the vessel'sinside liner have been manipulated here through interchangeably selection of the thickness of these layers around the inside layer. It was taken in four manners. The first manner was composed of 3 equal thickness-layers with thickness of one-third of the total wall thickness, for each layer. The other configurationswere composed of 3 layers arranged in three different methods. The first method was descending sequence of layer thickness as:0.56, 0.28 and 0.14 of the total thickness for t1, t2 and t3, respectively. The second method was ascending sequence of 0.14, 0.28 and 0.56of the total thickness. The third method was in a random sequence as 0.25, 0.5 and 0.25 of the total thickness. The results of these four configurations are shown in Fig. 8.

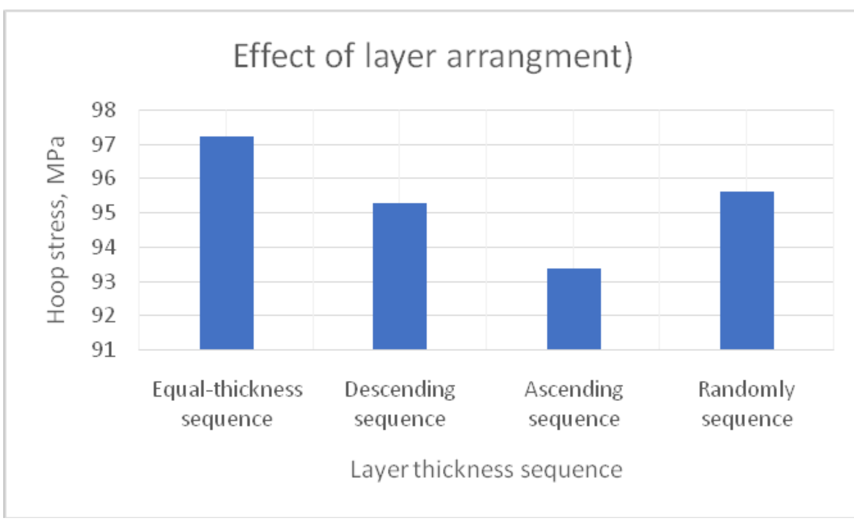

Fig. 8. Effect of thickness sequence of laminated layers

D- Effect of sequence of shrink fit between layers

In this section, the effect of sequence of changing the fits between the layers around the inside layerwas considered. It was taken in three cases: the first case is equal fit between all layers as 10 µm. The secondcase, the fit was selected in a decreasing manner (from inside to outside) as 30, 20 and 10 µm for δ1, δ2 and δ3, respectively. While, in the third case, it was used in an increasing manner as 10, 20 and 30 μm.The configuration of the layers' arrangement was taken basedon the best configuration obtained from the previous section (i.e. theascending sequence of layer thickness) as shown in Fig. 9.

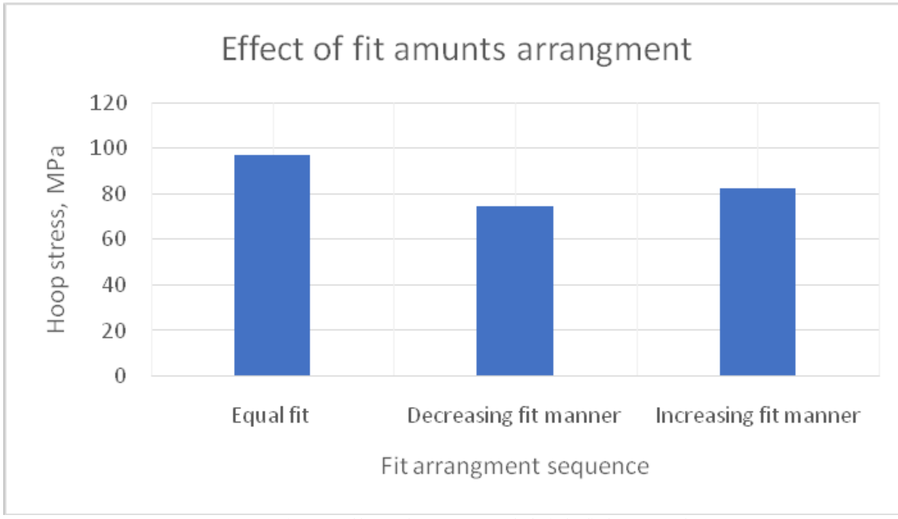

Fig. 9. Effect of sequence of shrink-fit between layers

IV. DISCUSSION OF RESULTS

Four factors have been analyzed in this study to see their effects on the design of laminated pressure vessels. The hoop stress induced in the inside liner wall was used as an indicationparameterto see the results of changing these factors. The four factors used were: 1- interference fit between layers, 2- number of layers forming the vessel wall, 3- layers thickness sequence arrangement around the vessel and4- interference fit sequence between layers. Figure 7 showed that increasing the inference fit between the fitted layers from 10 μm to 40 μm could reduce the hoop stress by a ratio of 14.4%. This means that increasing the interference fit amount between the layers can increase the pressure loading capacity of the vessel.

Figure 8showed that increasing the number of laminated layers from one layer tofour layers could decrease the induced stress by a percentage ratio of 15.4%, which means that increasing the number of shrink-fitted layers can increase the vessel pressure loading capacity of the vessel.

Figure 9 showed the influence of sequence configuration of the layers' thickness around the vessel liner. It was shown that using the ascending sequence layers-thickness could decrease the induced stress by an amount of 4% lower than the equal-layers thickness vessel. This means that the best configuration of the vessel building is using ascending sequence for layers' thickness from inside to outside direction of the vessel.

Figure 10 showed the effect of interference fits-sequence between the layers. It was shown that using descending sequence could reduce the hoop stress by an amount of 15.3% relative to the equal-fits sequence.

V. CONCLUSIONS

Throughout the results obtained from this study, the following conclusions could be withdrawn:

1- Many factors can affect the design analysis of laminated pressure vessels as: number of fitted layers, amount of interference fits between layers and the configurations of both the layers' thickness sequence and interference fit amount sequence.
2- Increasing the number of thin layers forming the vessel can reduce the induced stress in vessel wall and so increasing the pressure loading capacity of the vessel.
3- Increasing the shrink fit amount between layers can increase the vessel pressure capacity.
4- The best configuration for the layers' thickness sequence is the ascending sequence.
5- Whereas, the optimum sequence for changing the fits between layers is the descending sequence.

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