Design and Analysis of Metal-Composite Vessel under Internal Pressure

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Abstract: This paper, firstly, investigates the behavior of a pressure vessel designed based on the netting analysis method. Then, the strain measurement result performed to examine the behavior of the vessel is presented. It has been observed that the reverse strain is occurred at the joint of the vessel cylindrical area and its head. To inspect the experimental data, the ABAQUS software (finite-element) was deployed. The simulation results turned out to be in good consistency with the experimental data. Later, to design the vessel, Von Mises and Tsai Wu criterion were used for liner and composite layers, respectively. The design results showed that the netting analysis method is not optimal and leads to increase in the cost and weight of the vessel. In addition, investigating the vessel behavior indicated that using softer liner results in more exploit of the composite properties which in turn, can bring better performance in special applications. The good consistency between the experimental and simulation results proved that the complexity involved in the design of pressure metal-composite vessels can be greatly reduced through employing finite-element simulation methods.

Keywords: Composite, Liner, Tsai wu, Vessel

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Research paper

1 INTRODUCTION

Pressure vessels are amongst the most usable structures in oil, petrochemicals, aerospace, automobile etc, and they can be categorized in four types based on design and manufacturing method. The first type is the metal vessel which has the problem of having too weight and needs to consume more energy for displacement. The second type of vessels is lighter. In these vessels, in addition to reducing the thickness of the cylindrical liner section, to reinforcement, filament winding is impregnated with resin which is lighter than the used metal liner. In the third type, the whole metal liner is wrapped in filament. The fourth type which is the lightest one is, in fact, the third type with the difference that its liner is not metal [1]. The role of the liner in the third and fourth types is to avoid leakage, but in the third type, a portion of the load is also shared by the liner. Hence, its design and usage are very important [2]. In designing of the composite vessels, one way to determine the number of composite layers is the netting method which is mainly used in primary design. In this method, it is assumed that the total load applied to the vessel from inner pressure is borne by the filament of the composite, and the role of the resin to strength is ignored [3]. The number of layers calculated by this method is more than the required one for bearing the applied load; therefore, design of the high-pressure composite vessels needs more accurate analysis. For analyzing composite vessels, classical limitation theory or elasticity theory is invoked [4]. The Classical Lamination Theory just calculates the stresses in the plane, and the stress from the thickness is not possible with this theory. In elasticity theory, we can calculate the stresses in 3D; therefore, the obtained results are more precise [5]. However, analysis approaches tend to be complicated as soon as the geometry of the vessel becomes a little complex, and a numerical approach should be used for this kind of vessels.

In recent years, there have been wide researches and studies in the field of metal composite vessels. Lifshitz and Dayan [6] conducted an experiment on a composite vessel with metal liner and compared the results with the Classical Lamination Theory, and the conclusion was superiority of the metal-composite to the metal vessel. Kabir [7] in his article, studied a composite vessel with metal liner while considering the load sharing by the metal liner. This article which uses netting analysis after obtaining the thicknesses and modelling with different vessel head geometries, presents the stresses results in a diagram. Mirzaee et al [8] investigated the third type of vessels with spherical head and compared their experimental results with numerical ones. Zia et al [9] analyzed a composite tube under inner pressure with 3D elasticity analysis and presented the stress and strain in a diagram. Ghen and pen [10] investigated the effect of elliptical head on liner of the third type of vessels. Gheshlaghi et al [11] performed the primary design of a composite vessel with the netting method and studied the effect of three types of head including spherical, geodesic with constant thickness and geodesic with variable thickness via the finite element method leading to the result that the vessel with head of variable thickness geodesic is better than the others. Mayoung [12] et al determined the thickness and optimized the shape of the third vessel via the finite element method. Vafaeesefat [13] also optimized a third type vessel via the finite element method. Ravuo et al [14] analysed a pressure vessel via layer classical theory and compared the results with those from the finite element method.

In this paper, a vessel with a monolithic (not welded) liner and specific dimensions is analysed. At first, using the netting analysis method, the number of the composite layers were determined. After that, the vessel was constructed and investigated, both experimentally and numerically. The investigation results were used to design an optimized vessel. Then, Von Mises and Tsai Wu criterions were employed to determine the liner thickness and the number of the composite layers, respectively. In the end, the specifications of the optimized vessel are extracted.

2 EXPERIMENTAL DETAILS

2.1. Manufacturing Vessel

The liner of metal-composite vessels is better to be manufactured monolithically and seamlessly so that it can be used for gas storing. There are various methods for manufacturing seamless liner including the one in which the bottom head and cylindrical body are made from a sheet and through the use of deep drawing technology, and the top head is shaped via the spinning method.

In another method, the liner is made from a seamless pipe. In fact, both sides of the pipe are closed via the spinning method. This is the approach that has been taken in our research. Figure 1 shows the manufactured aluminum liner.

Fig. 1 Aluminium Liner.

After manufacturing the liner, to evaluate the production quality and absence of leakage, the liner was tested with water pressure of about 40 bar. This test was performed in the lab while considering the safety issues.

2.2. Properties of Liner Alloy

The result of emission spectroscopy shows the ingredient of the alloy to be aluminum 6063, and also the results of two microscopic structure test and toughness metering test approved this alloy. Determining the standard accuracy of these results is based on performing the strength test which was carried out and showed agreement with the obtained results. In this standard, the sizes of the sample that should be cut are specified according to the tube radius. Figure 2 illustrates the sample provided in accordance with the standard.

Fig. 2 Pipes after cutting samples.

After preparing the samples of strength test, the test was performed (“Fig. 3”). Here, it is avoided to explain the test and its results in detail, and it just should be mentioned that the results of the strength test verified the results of the emission spectroscopy, macro toughness-metering and microscopy structure tests with an acceptable tolerance which all show the alloy is aluminium 6063.

Fig. 3 Samples in stretch test.

2.3. Composite Properties

The used composite is made from carbon fiber, and the reason behind this selection was the availability of this fiber, in addition to more resistance over glass fiber. Furthermore, the resin is epoxy 5052, and the properties of the used carbon epoxy are listed in the “Table 1” .

The studied vessel (“Fig. 4”) is made from four hoop windings and four layers of helical winding. While respecting the safety considerations, the vessel was tested within a steel chamber under 300 bar which is 1.5 times as the standard operating pressure which is 200. The test was passed without any proof of leakage, steady reshaping or destruction.

Table 1 Aluminum and Carbon/Epoxy composite specification

Values	Al
69	E(GPa)
0.33	υ
208	$\sigma_y(GPa)$
Values	Carbon/Epoxy
154.1	$E_1(GPa)$
10.3	$E_2(GPa)$
4.123	$G_{13}(GPa), G_{12}(GPa)$
3.311	$G_{23}(GPa)$
0.28	$\upsilon_{12}, \upsilon_{13}$
0.49	υ_{23}
2500	$X_T(MPa)$
1250	$X_C(MPa)$
60	$Y_T(MPa)$
186	$Y_C(MPa)$
85	$S(MPa)$

Fig. 4 Metal-Composite Pressure Vessel.

3 FINITE ELEMENT ANALYSIS

3.1. Introduction

Stress analysis in metal-composite vessels as a shell structure is one of the complicated problems in mechanical engineering. With development of the numerical and finite-element methods and also dramatic progress of the computer science, the role of the analytical methods to solve this kind of problem has been gradually reduced. In the recent years, researchers around the world have mainly considered the finite-element approach to describe the behavior of this kind of vessels. One of the most known software in the field of finite-element analysis of physical events is Abaqus.

3.2. Modeling Liner

In this research, the element of axisymmetric CAX4R is used for the liner section which one of the most important features of this element is more speed and accuracy in the calculation of the meshes. After simulation of the vessel under the pressure of 40 bar, the value of axial and hoop strain was extracted which are shown in “Figs. 5 and 6” , respectively.

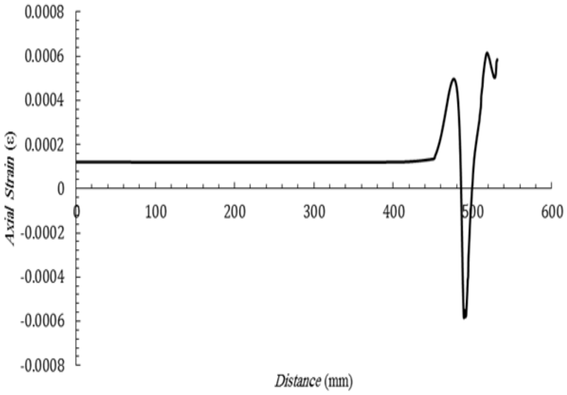

Fig. 5 Axial Strain along the Length of the Vessel.

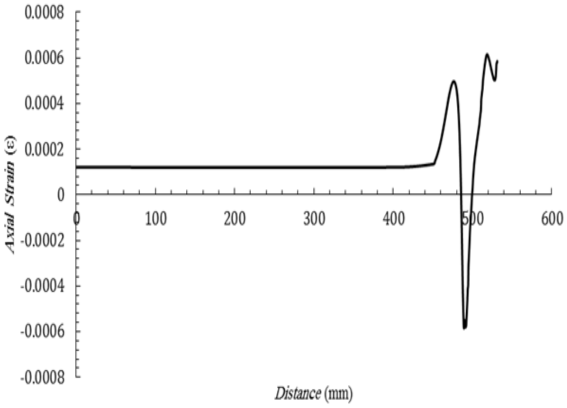

Fig. 6 Hoop Strain along the Length of the Vessel.

In “Fig. 5” , the hoop strain is seen on the external surface of the cylinder. According to the figure, the maximum of the hoop strain of the cylinder is at the joint of the head and body while minimum occurs at the head section and near the head-cylinder joint.

According to “Fig. 6” , which the axial strain is shown, the maximum of the axial strain is at the head section while the minimum occurs at a small section right to the head-cylinder joint.

3.3. Modeling Metal-Composite Vessel

To model the metal-composite vessel, two different materials are used in manufacturing of the vessel. The liner is made of aluminum and its composite is made of carbon-epoxy. Considering the fact that the modeling of the vessel in software and applying the real geometrical conditions need more precision, at first, the variations of the thickness (Equation (1)) and angle (Equation (2)) were calculated (based on the geodesic winding route “Fig. 7”) separately which are shown in “Figs. 8 and 9” , respectively.

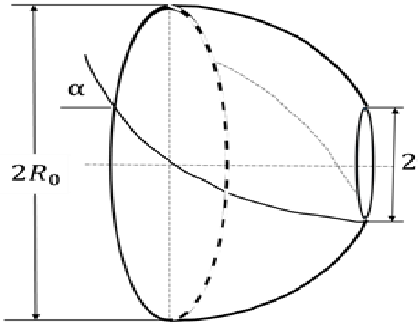

Fig. 7 Geodosic Path.

$$\alpha = \arcsin\left(\frac{r}{R}\right) \tag{1}$$

$$t = \frac{R_0}{R}\,\frac{\cos\alpha_0}{\cos\alpha}\,t_0 \tag{2}$$

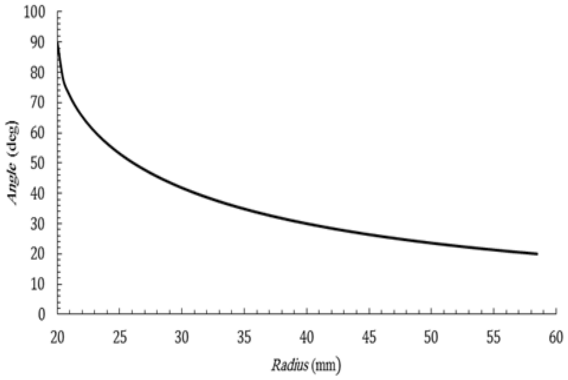

Fig. 8 Angular variation versus radial Distance.

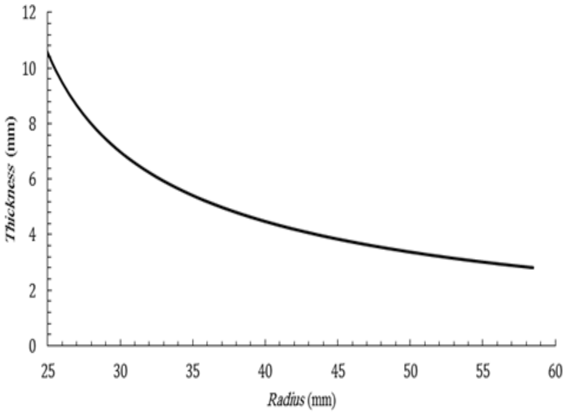

Fig. 9 Thickness variation Versus Radial Distance.

Since the thickness and angle of the composite are different at each section of the vessel, the modeling becomes complicated. To address this issue, the head area was divided to 74 sectors and then, the related thickness and angle were assigned to each sector.

After loading under the pressure of 150 bar, the calculation was processed with a computer which has an 8-core CPU and 8 GB of Ram. To investigate the behaviour of the vessel, its strain diagrams were extracted. In “Fig. 10” , the hoop strain is shown. According to this diagram, the value of the hoop strain is the maximum at the cylindrical section and near to the head-cylinder junction, and the minimum occurs at the head and near to the junction. Figure 11 shows the axial strain on the body of the vessel. As you can see, the maximum of the axial strain is at the head section which has been observed in the solution of the liner either, and the minimum occurs at the head and near to the junction.

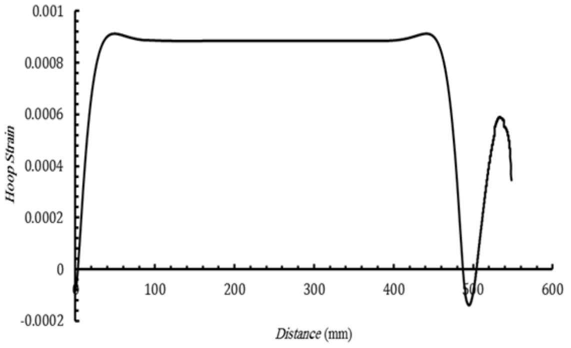

Fig. 10 Hoop Strain of Metal-Composite Pressure Vessel with Finite Element.

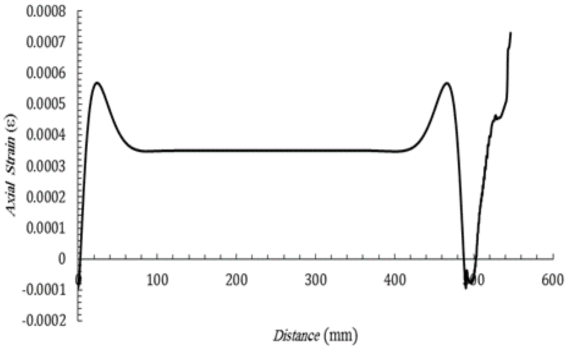

Fig. 11 Axial strain of Metal-Composite Pressure Vessel with Finite Element.

4 EXPERIMENTAL INVESTIGATION

To investigate many properties of materials and parts, it is needed to take experimental approach. By using analytical and numerical methods, one can calculate the strain and transformation of a part. Based on ISO11439, before mass production takes place, a sample should be prepared to perform some experiment on it.

4.1. Liner

To study the finite-element results, the liner is experimented with electrical strain gauge. The liner is loaded under the pressure of 40 bar. Figure 12 shows the vessel after installing the electrical strain gauge.

Fig. 12 Liner Vessel After Strain Gauge Installation.

4.2. Metal-Composite Vessel

The experiment has been done under the pressure of 150 bar using electrical strain gauge to investigate the behavior of the metal-composite vessel. Figure 13 shows the vessel after installing the strain gauge.

Fig. 13 Vessel after Filament Winding.

5 COMPARISON OF THE EXPERIMENTAL AND NUMERICAL RESULTS

One of the most known and precise approaches to study the behavior of structures is invoking the experimental methods. On the other hand, this method has the disadvantage of being too expensive. To overcome this issue, the numerical methods can be employed, but it must be checked that the chosen method meets the required accuracy. In this section, the results obtained from experiment and analysis are compared.

5.1. Liner

At first, the comparison of the liner strain results is performed. The hoop and axial strain are shown in “Figs. 14 and 15” , respectively. In these diagrams, the solid line represents the experimental value, and the dotted line represents the finite-element results.

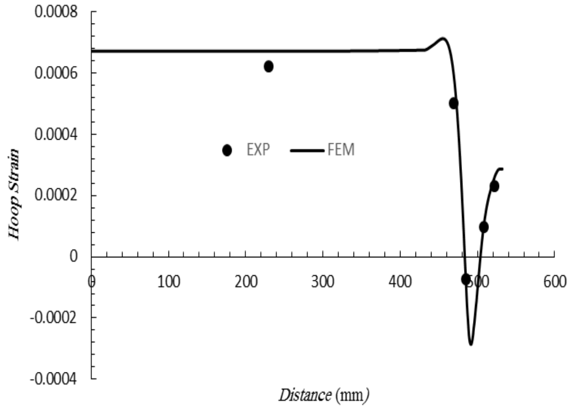

Fig. 14 Comparison between Experimental and Finite Element Hoop Strain in Liner.

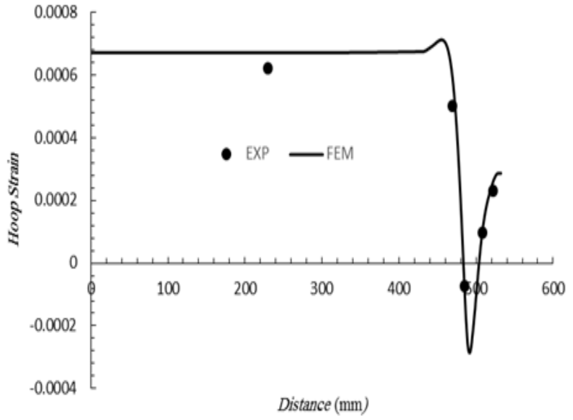

Fig. 15 Comparison between Experimental and Finite Element Axial Strain in Liner.

5.2. Metal-Composite Vessel

Figures 16 and 17 show the results of the experimental and numerical strain of the metal-composite vessel. Considering the figures, there are inconsistencies between two methods which will be discussed later.

As you can see in "Figs. 14 and 17" , the experimental and numerical results are in a good agreement proving that the finite-element method has been able to predict the behavior of the vessel properly so that it can be deployed to study the behavior of a vessel with this set of geometrical and material specifications. As can be seen in the figures, comparing the numerical and experimental methods, there are some errors which could be caused by individuals, measuring equipment, etc.

The trends of data extracted from the curves of both numerical and experimental methods are the same. The error is because of the manufacturing conditions of the liner and its specific geometry, there are differences between the numerical and experimental results. Figures 18 and 19 show the amount of the difference for the results respect to the experimental results for the liner.

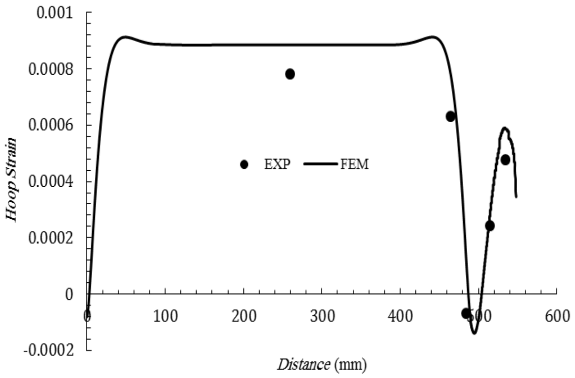

Fig. 16 Comparison between Experimental and Finite Element Hoop Strain in Metal Composite Vessel.

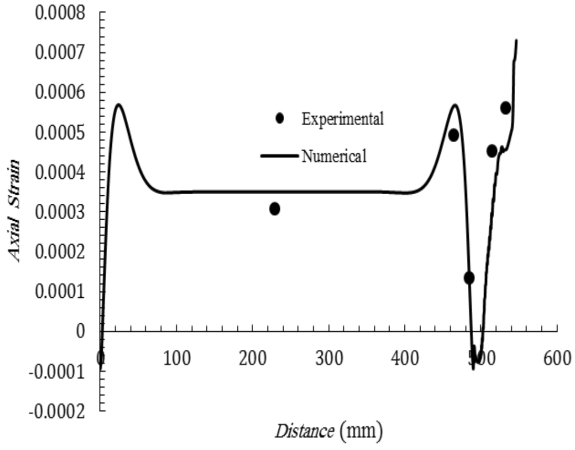

Fig. 17 Comparison between Experimental and Finite Element Axial Strain in Metal Composite Vessel.

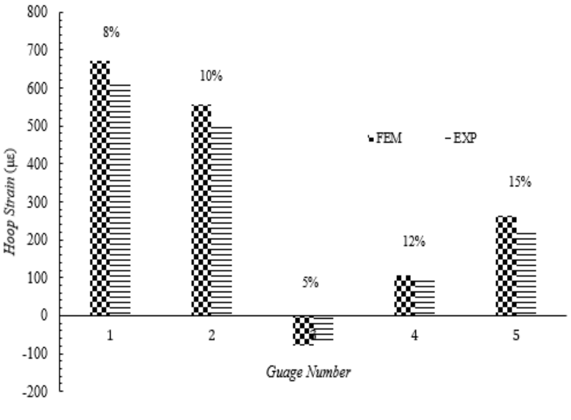

Fig. 18 Difference Percentage between Experimental and Finite Element Hoop Strain in Liner.

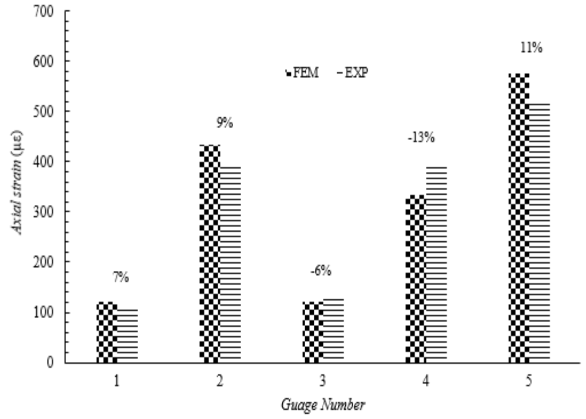

Fig. 19 Difference Percentage between Experimental and Finite Element Axial Strain in Liner.

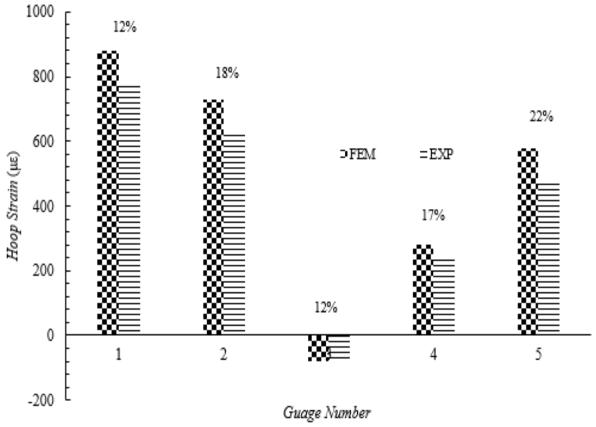

Fig. 20 Difference Percentage between Experimental and Finite Element Hoop Strain in Metal-Composite Vessel.

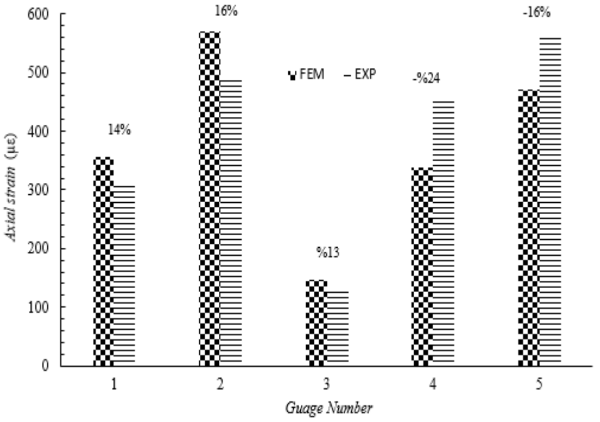

Fig. 21 Difference Percentage between Experimental and Finite Element Axial Strain in Metal-Composite Vessel.

In the analysis of the metal-composite vessel, the behavior has been predicted well by the numerical results although it has some differences with the experimental result which it can be acceptable considering the composite type and its manufacturing process. In addition, in winding the filament, the produced deviations from 20-degree angle are unavoidable. Figures 20 and 2″ show the numerical and experimental differences for the hoop and axial strain, respectively.

6 DESIGN OF METAL-COMPOSITE VESSEL

Nowadays, optimization is one of the most important aspects of all fields of engineering including mechanical engineering. On the other hand, high costs of providing the raw material and the high weight of the structures should be considered significantly. Under-pressure metal-composite vessels are mainly used as portable storage for oil, and they have many applications in industries such as automobile, aerospace, etc.

High number of studies that have been performed in this field shows that there are serious interests among the researchers to optimize this structure. These studies mainly investigate the behavior of the vessels in an analytical approach and pay less attention to the optimization problem. In the previous sections, it is shown that the finite-element software has a high accuracy in predicting the behavior of the vessel; therefore, in this section, the aim is to optimize the studied vessel with finite-element software.

As previously shown, the netting method is one of the metal-composite vessels design methods. Although this method can be a good hint for the primary design, it should be noted that in this method, the force-balance technique is used for the cylindrical part of the vessel to determine the number of the composite layers which its simplifying assumptions have the following weaknesses leading to considering the output design just as the primary design and not the final one.

1- In this method, the whole load is tolerated by the filament

2- The effect of the head and any connections that result in stress concentration is not considered in the calculations

3- The thickness along the radius direction is ignored and only the inner radius of the vessel is considered.

The abovementioned reasons are the most important ones to not trust this method and invoke other methods to achieve a safe and optimized design.

Determining the required material to manufacture the vessel for special operating conditions needs to investigate the bearable load by each making material. On the other hand, determination of the load which the vessel can bear requires the use of the destruction criteria. Considering the fact that the vessel is manufactured by a couple of materials, the used criteria for each one is different from the other.

One of the most common criteria for the isotropic material is the Von Mises criteria, which in this paper, is used for the liner part. To assess the destruction of the composite vessel, the Tsai-Wu, Tsai-Hill and Hashin are used. Since the Tsia-Wu is used in the most studies, it is also used to optimize the thickness and the number of the layers. In "Fig. 22" , the algorithm to design the vessel with try-and-error approach and by the use of the finite-element software is shown.

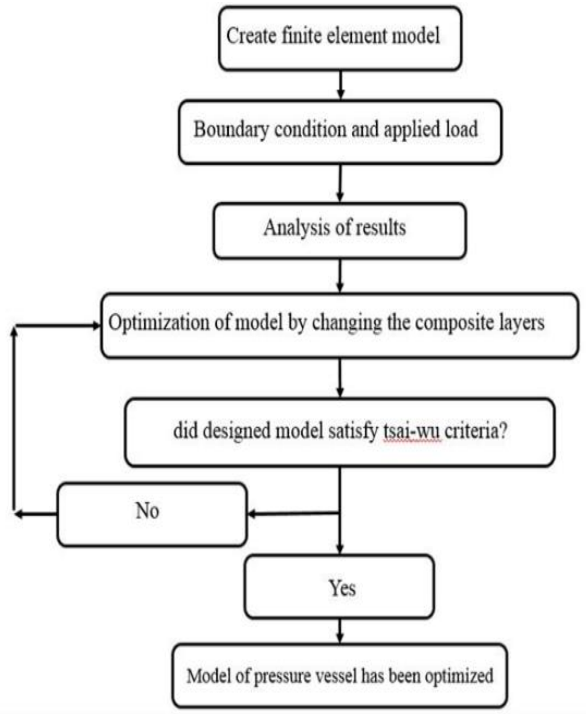

Fig. **22** Algorithm to Design the Optimized Vessel.

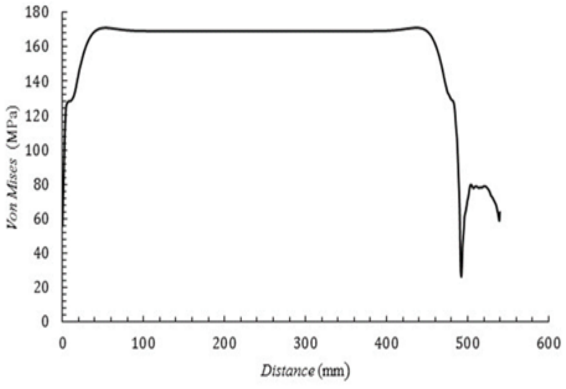

Fig. **23** Distribution of Equivalent Von-Mises Stress for The First Vessel.

Considering the above explanation, at first, the prototype vessel (experimental sample) is examined. For primary vessel, the internal pressure of 300 bar is applied, and then, the results of the Von Mizes and Tsai-Wu criteria have been extracted. Figure 23 shows the Van Mizes equivalent stress on the vessel profile. As the figure shows, the Von Mizes stress is less than the yield stress of the liner material, hence, the number of the layers can be reduced just before that. The Tsai-Wu criteria should be inspected to check if there is a layer that has been destructed or not?

Figure 24 shows the Tsai-Wu criteria. As you can see, it reaches maximum near the nozzle with a value of less than 1 proving that the composite has not been destructed.

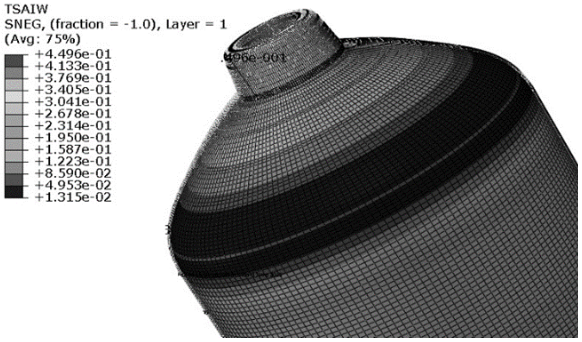

Fig. **24** Tsai wu Failure for The First Vessel.

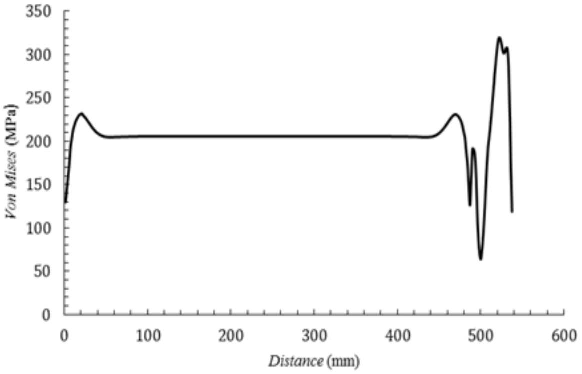

Fig. **25** Distribution of Equivalent Von-Mises Stress for The Second Vessel.

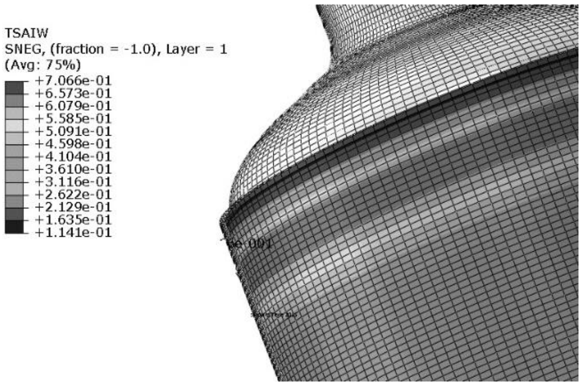

Fig. **26** Tsai wu Failure for The Second Vessel.

By examining the results of the criteria for this vessel, it can be concluded that the number of the layers and or the thickness of the composite can be decreased. After spirally reinforcing multiple models and making the vessel wall thicker at the head location, there is a possibility that applying additional reinforcement can be prevented by transforming the vessel to a type 2 vessel. To do this, the second vessel was reinforced at the cylindrical part with the radius of 3 mm, and after modeling, the loading was performed and analyzed which the results of the Von Mizes and Tsai-wu criteria are shown in "Figs. 25 and 26", respectively.

As "Fig. 25" shows, the head penetrated the plastic section meaning that the liner has been destructed. Figure 26 demonstrates the fact that the composite layers were not hurt. The second vessel shows that reinforcing just in the cylindrical section cannot be enough and reinforcing at the head is necessary. Several vessels with reinforcement at the head section and with different thicknesses were modeled and investigated, and the optimized vessel has been determined. This vessel has a circumferential thickness of 2mm and spiral thickness of 1.4mm. Figure 27 shows the distribution of the composite thickness on the head of the optimized vessel.

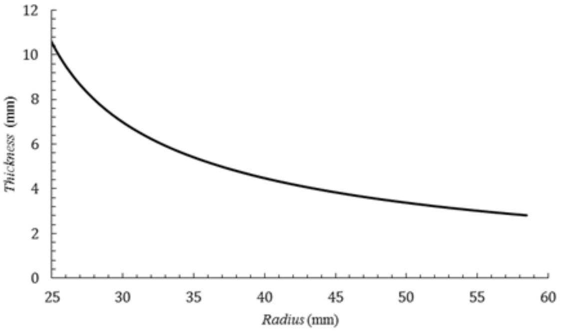

Fig. 27 Distribution of the Composite Thickness over the Head of the Optimized Vessel

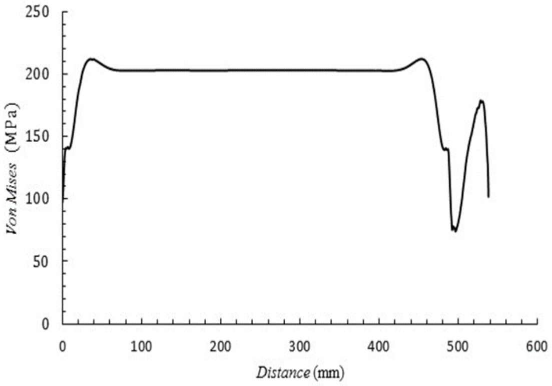

Fig. 28 Distribution of Equivalent Von-Mises Stress for The Optimized Vessel

Figures 28 and 29 show the results of the Von Mises stress and Tsai-Wu criteria, respectively. As you can see in "Fig. 28", the Van Mises stress at the cylindrical section and nearby the intersection of the head has boundary value, and it is near to the yield stress of the liner material. Figure 29 shows the value of the Tsai-Wu criteria at the point that the Von Mises stress has the maximum value indicating that the next point with maximum value of the Tsai Wu criteria is near to the nozzle. The value difference between these two points is minor. Repeatedly, in this vessel, the Tsai-Wu value is less than 1 implying that the number of the layers can be reduced, but since the value of the Van Mises stress would become higher than the yield stress of the liner, the optimization procedure is not continued.

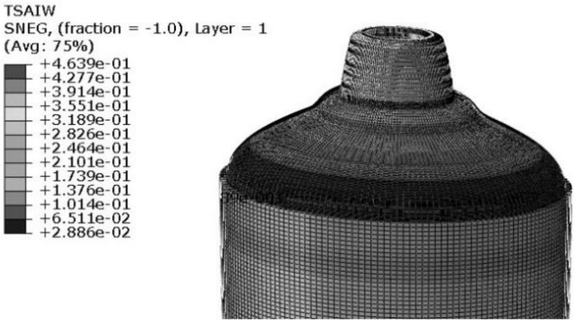

Fig. 29 Tsai wu failure for the Optimized Vessel.

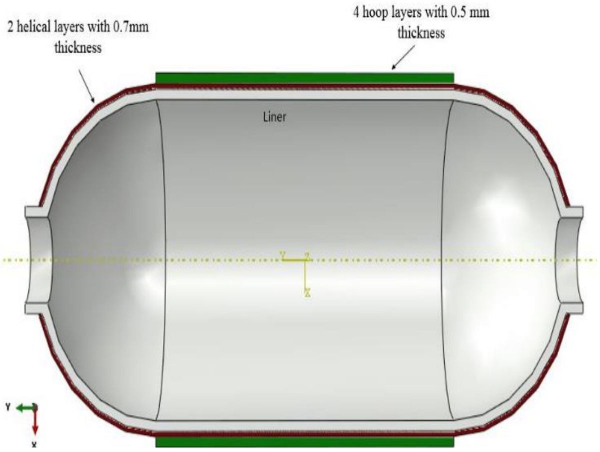

Fig. 30 Schematic of the Optimized Vessel.

7 CONCLUSION

In this research, at first, the numerical and experimental results of a vessel with specific dimensions have been studied which can be produced inside country, and then the vessel was optimized by the use of numerical methods. The first composite vessel was made by four composite layers with circumferential thickness of 0.75mm and four spiral layers. Applying the destruction criteria proved that the number of the spiral layers is more than what was needed. The vessel was optimized by using the Von Mises and Tsai-Wu. The optimized vessel has four composite layers with the thickness of 0.5mm and two spiral layers with the thickness of 0.7mm. The weight of the vessel is 3506 grams which is almost 1 kg lighter than the first vessel with the weight of 4521 grams. The decrease in weight regarding the production and transportation costs can be considerable in mass production. Figure 30 shows a schematic of the optimized vessel.

7.1. Some of the Results

1- The examined vessel, due to the variation of the stress at the location of the connection between the head and cylindrical body, has reversible stress in a small area causing fatigue in the low loading cycles.
2- Considering the results of the destruction criteria, wall being thick should not make us ignore this section in design
3- Reinforcing the vessel at the cylindrical section cannot ensure a safe design
4- The softer the liner, the more taking advantage of the composite properties
5- Using the criteria control method, we can make the stress distribution uniform over the vessel

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