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Finite Element Analyses of Stresses Developed in Oil Separator Composite Tank Used in Screw Type Compressor Systems

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Abstract
Pressure vessels are geometrically cylindrical, spherical or conical work equipment used for the storage and transportation of pressurized fluid. In the case of design and/or manufacturing deficiency, or for the case of improper applications of such vessels due to working conditions, the damages that may occur can cause serious harm to the environment and employees. The aim of this study is to estimate the performance of a typical oil separator pressure vessel used in screw compressor systems, exposed to high pressure and temperature, using finite element method. Here, the aim is to estimate performance of this tank after modifications in design and to compare the results with that of pressure vessel designed using conventional materials. The inner liner of the separator tank is metal material and the other layers are wrapped with three different composite materials, including carbon fiber/epoxy, glass fiber/epoxy and kevlar fiber/epoxy, at different angles, and then were exposed to high pressures in the environment of finite element simulation software. As a result of the study, stress and deformation values were examined and the most suitable material and orientation angle for the composite pressure vessel were decided. According to the results, it was observed that the lowest first-ply equivalent stress value was obtained in glass fiber/epoxy coated separator tanks at 11.25 bar pressure and 45 degree winding angle. In addition, it was observed that the lowest total deformation value was obtained in kevlar fiber/epoxy coated separator tanks at 11.25 bar pressure and 45 degree winding angle.

1. Introduction

Pressure vessels inherit potential hazards that may affect human health and safety. For this reason, a careful and detailed analysis should be made in the pressure vessel design, all loads that may affect the system should be accurately determined and included in the calculations. Pressure vessels are generally produced using metal alloys. However, the need for more durable and lighter containers is increasing day by day. Manufacturers have started to produce cylindrical composite pressure vessels with fiber winding of thanks as a developing technology in production of high-pressure vessels. It has been demonstrated experimentally that the production of composite pressure vessels is not efficient for large pressure vessels.

Therefore, evaluation of the performance of such vessels using numerical methods such as finite element analyses are of high importance before initiating the production process in terms of both time and cost of production. There are some studies on this subject in the literature as summarized below.

Bozkurt [1] used the finite element approach to analyze maximum strains and stresses with filament and centrifugal winding methods. When designing the composite pressure vessel, glass fiber/epoxy, carbon fiber/epoxy and kevlar

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fiber/epoxy materials with winding angles of [30°/-30°], [45/-45°], [60°/-60°] and [75 °/-75°] were used. After examining Von-Mises stresses and total deformations, the author reported that the optimum values of maximum stresses and strains occur in pressure vessels designed with glass fiber/epoxy composite material with an orientation angle of 60°/-60°. Yaylagan [2] investigated the optimal layer angle orientation at different temperatures and maximum burst pressure for the first layer damage of antisymmetrical layered, thin-walled, internally plastic-lined composite pressure tubes by using the finite element method and experimentally. The author found that the most suitable winding angle was about 55º for helical angle coiled composite pipes under internal pressure. Pehlivan [3] worked on the modeling composite pressure vessels produced with fiber winding techniques at different loads. After validation of analytical model using experimental results, the author evaluated the optimum winding angles at which the maximum compressive strength of pressure vessels were obtainable. Sinha and Pandit [4] conducted a study on the cylindrical part of a four-layer carbon fiber reinforced polymer (CFRP) composite pressure vessel. The pressure vessel was designed and modeled using the finite element software ANSYS. They estimated burst pressures for various fiber orientations using Tsai-Wu criteria. The results showed that the optimum fiber orientation angle for the composite pressure vessel subjected to high internal pressures was ±45°. Zhang et al. [5] obtained an analytical solution based on the theory of thermo-elasticity to determine the stress distribution of a multilayer composite pressure vessel subjected to internal fluid pressure and thermal loading. The results showed that the proposed process can be used in the initial stages of multi-layer composite pressure vessel design involving fluid pressure and thermal load. In addition, there are other studies in the literature that were focused on the design and analysis of conventional pressure vessels. Sancaklı [6] has introduced the basic design rules of pressure vessels according to ASME Chapter 8 Part 1, ASME Chapter 8 Part 2, EN 13445 and AD 2000 codes. Accordingly, certain design conditions and geometries resulted in the minimum wall thickness for the vessels of different configurations of the head, including elliptical, torispheric and hemispherical. Thus, these codes benefited the engineers and designers with developing the pressure vessels of desired features, while the cost of production is minimized. Mestan [7] applied hydrostatic pressure tests to pressure vessels under the influence of internal pressure. The author employed the theoretical approach of a cylindrical pressure vessel subjected to axially symmetrical loading, calculated the Von Mises stresses from the SOLIDWORKS program and compared the displacements and stresses obtained as a result of stress analysis. Usta [8] investigated the resistance of welded joints in thick-walled pressure vessels under the hydrostatic pressures determined according to the TS 377 standard. The author examined the welded areas of the heating boiler, steam boiler and air tank according to the TS 17020 standard. The thick-walled pressure vessels under the examination were tested for their suitability for dynamic working conditions, sweating, and leakage or crack formation in the vessel. Tjelta [9] studied the advantages and disadvantages of different methods used in the design of pressure vessels. The author disclosed the details of tools used in pressure vessel analysis and the calculation for the relevant standard. Raparla and Seshaiah [10] examined the advantages of multilayer high pressure vessels over single layer high pressure vessels according to ASME VIII-1 standard. The theoretically calculated results of the stresses in the pressure vessels were compared with the results obtained from the ANSYS program. It has been determined that the cost of the multi-layer container is about 26% less than the single layer vessel, plus the variation of strain along the thickness is less, and it is more durable under high temperatures and pressures. Ahmet et al. [11] calculated Von-Mises stresses, tangential stresses and deformations in pressure vessels with different geometries subjected to thermal and static loads using the finite element method (ANSYS) for optimization. The results revealed that the tangential stresses increase with a decrease in the pressure vessel thickness. Wadkar et al. [12] designed various pressure vessels with different head types according to ASME VIII-1 and calculated equivalent stresses both analytically and numerically. The author reported that the smallest equivalent stresses were observed in the cylindrical container with a hemispherical head. Kolekar and Jewargi [13] analyzed 8 bar pressure and 24-liter pressure vessels designed according to ASME VIII-1 in five different head types (hemispherical, flanged, elliptical, flat and conical) based on finite element analyses using ANSYS program. The results showed that the least stresses were developed in the vessels with hemispherical head. Khan [14] investigated the variations in the loadings applied to the pressure vessel support legs through changing the geometric parameters. It was aimed to introduce the most appropriate values for the ratio of the support distance to the pressure vessel length and the ratio of the pressure vessel length to the vessel radius. The author reported that the minimum stresses developed at the ratios of 0.25 for the former and the less than 16 for the latter.

In this study, the oil separator tank used in a typical commercial screw compressor system, produced by the SARMAK Co. according to ISO 1217 standard, have been analyzed based on finite element method for three different operating pressures. These thanks were composed of a metallic vessel that have been warped with different composite materials, including carbon fiber/epoxy, glass fiber/epoxy and kevlar fiber/epoxy, at different angles. The aim was to introduce the most appropriate composite material and winding angle of fibers around the metallic vessel that would result in the least stress and deformation of the composite pressure vessel under internal pressure.

2. Material and Method

In this study, the following cases were handled separately, and first-ply equivalent stress values and total deformation values were investigated for three different internal pressures 11.25, 15 and 19.5 bar and a maximum temperature of 110 °C using the finite element method.

Case 1: 0.5 mm structure steel covered with 3.5 mm E-glass.

Case 2: 0.5 mm structure steel covered with 3.5 mm E-kevlar.

Case 3: 0.5 mm structure steel covered with 3.5 mm E-carbon.

As in 3 cases, carbon, glass and kevlar fibers/epoxies composites were used as reinforcement material. According to the literature, the most accepted methods of fabrication of such composite pressure vessels are filament winding and centrifugal winding technique [2]. Therefore, to be able to obtain reliable results from finite element analyses of these vessels, the accurate properties of density, Young's modulus, Poisson's ratio, tensile and shear modulus of composite structures should be assigned to the model developed in FEM software. The mechanical and thermal properties of carbon, glass and kevlar fibers/epoxies and structural steel are given in Tables 1 and 2, respectively.

Table 1. Mechanical properties of Carbon Fiber/Epoxy [15]

Properties	Carbon Fiber/Epoxy	Glass Fiber/Epoxy	Kevlar Fiber/Epoxy
Density (kg/m^3)	1490	2000	1402
Young's Modulus (MPa) (x, y, z)	121000; 8600; 8600	45000; 10000; 10000	95710; 1.045E+5; 1.045E+5
Poisson's Ratio (xy, yz, xz)	0.27; 0.4; 0.27	0.3; 0.4; 0.3	0.34; 0.37; 0.34
Tensile (MPa) (x, y, z)	2231; 29; 29	1100; 35; 35	2231; 29; 29
Shear Modulus (MPa) (xy, yz, xz)	4700; 3100; 4100	80; 46.154; 80	25080; 25080; 25080

Table 2. Mechanical properties of Structural Steel.

Properties	Structural Steel
Density (kg/m^3)	7850
Young's Modulus (MPa)	1.98E+5
Poisson's Ratio	0.35
Tensile Yield Strength (MPa)	265
Shear Modulus (MPa)	73333

2.1. Geometry

The solid model of the separator tank used in the study was designed in the Autodesk Invertor package program according to 29/EU/2014 standards (Figure 1). Accordingly, the total height of the separator pressure vessel from the top flange to the leg support is 698 mm. The thickness of the dish ends and the cylindrical shell is 4 mm. The thickness of the flange is 24 mm. The inside radius of the separator pressure vessel is 342 mm. The reason for choosing the upper flange thickness to be larger than the thickness of the cylindrical shell is that the stresses on sharp surfaces are higher. Thus, a surface thickness that is more resistant to stresses is preferred in the upper flange with sharp corners.

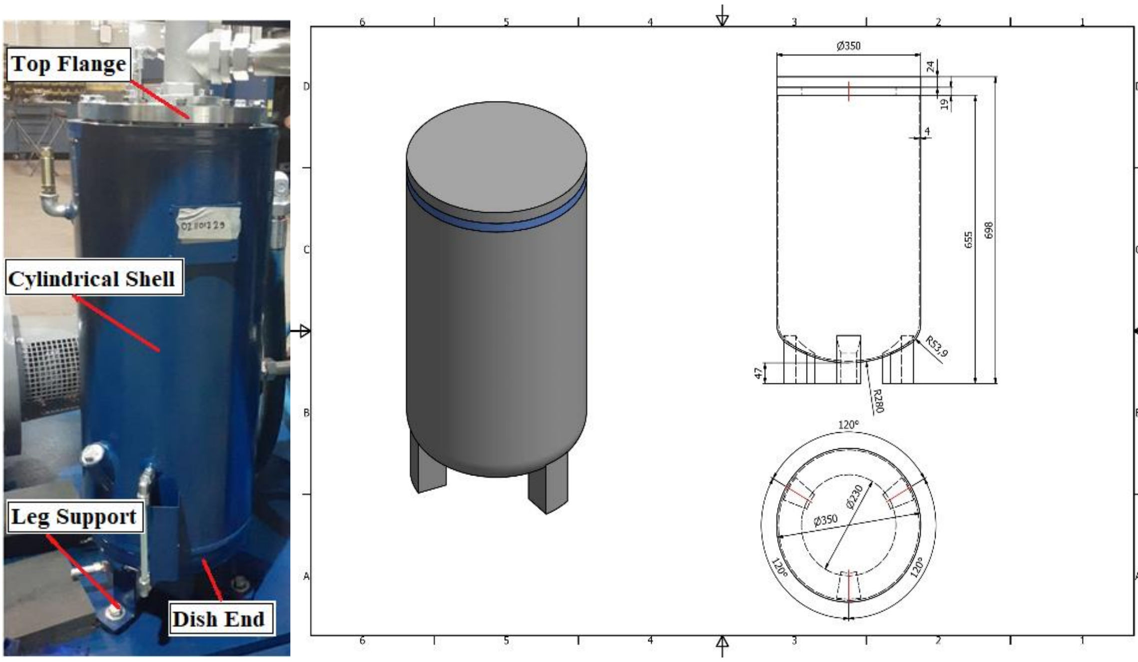

Figure 1. Figure of in-house developed oil separator pressure vessel components and technical details

2.2. Finite Element Analysis

The safety tests of pressure vessels are generally carried out at hydrostatic test pressures of about 1.5 times the operating pressure. The separator tank discussed in the study operates at three different operating pressures 7.5, 10 and 13 bar. Therefore, the boundary condition for 7.5, 10 and 13 bar internal pressures were applied as 11.25, 15 and 19.5 bar, respectively. Furthermore, the FEM analyses were carried out considering that the separator tank operates at a maximum temperature of 110 °C.

ANSYS finite element package was used to model the development of stresses and deformations in the high-pressure composite vessels under the aforementioned hydrostatic pressures. ACP (Pre) module was used to cover the design with composite, Static Structural module was used to determine the boundary conditions and ACP (Result) module was used to read the results. The layer thickness, material properties, total thickness and orientation angle of the pressure vessel were selected from the Stackups section (Figure 2).

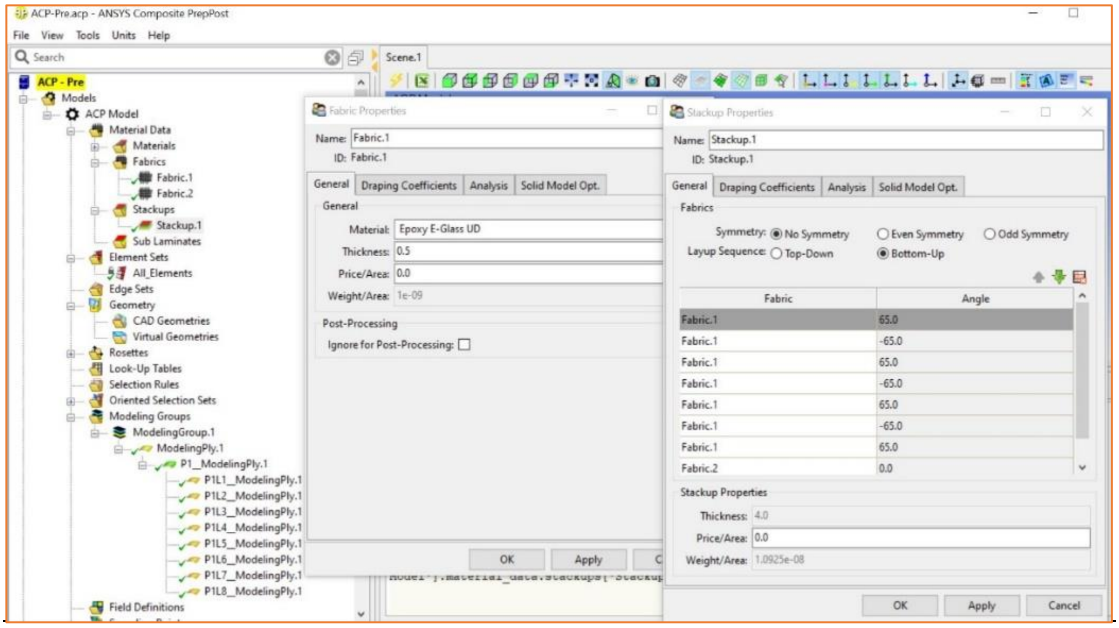

Figure 2. Display of material property, layer thickness, and orientation angles for epoxy E-glass

As shown in Figure 3, after defining the geometry conditions and element properties, the model was precisely meshed. To this end, the pressure vessel model is divided into very small areas called hexahedron elements of 0.5 mm thickness structural steel covered with 3.5 mm thickness composite material. For 0.5 mm structural steel, 262123 number of nodes and 77323 number of elements were assigned.

Figure 3. Meshed CAD Model

After the pressure and temperature values the boundary conditions were defined, the results of FEM in the form of equivalent stresses and total deformations of the model were obtained. A typical result of equivalent stresses distributed in the model of pressure vessel with the carbon fiber/epoxy as composite material and under the hydrostatic pressure of 19.5 bar is represented in Figure 4.

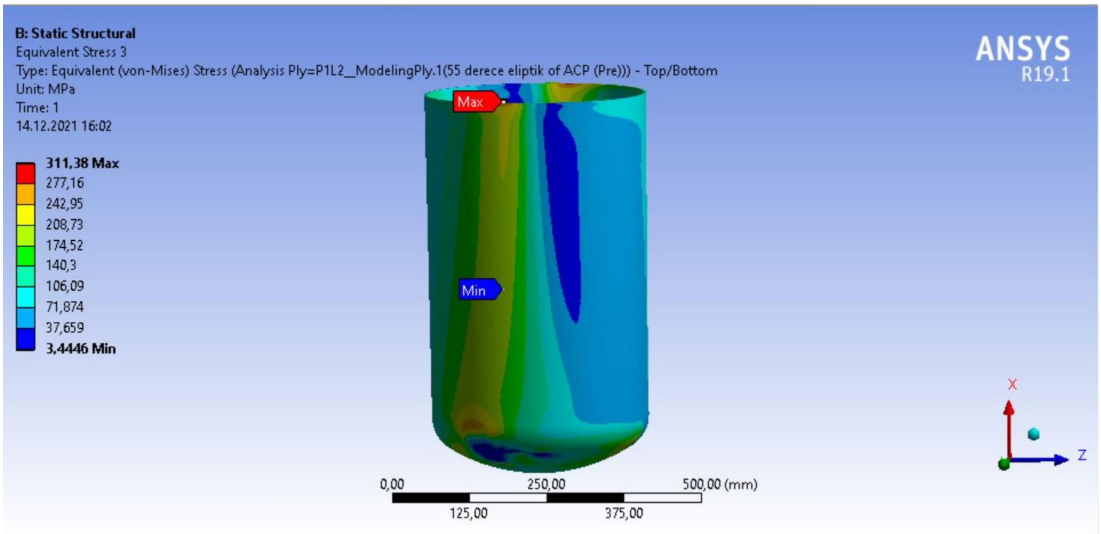

Figure 4. Typical result of equivalent stress distribution in the pressure vessel carbon fiber/epoxy composite material under the hydrostatic pressure of 19.5 bar

3. Results and Discussion

As explained in previous sections, in this study, a FEM was developed in the ANSYS environment in order to analyze the stress and total deformations developed in the composite pressure vessels. The model was composed of a metal body of separator tank that was covered with 7 layers of different composite materials, including glass fiber/epoxy, carbon fiber/epoxy and kevlar fiber/epoxy, each layer with a thickness of 0.5 mm. The material properties, wall thickness, number of layers, orientation angles and boundary conditions of the pressure vessel model were introduced to the model in the ANSYS environment. Analyses were performed at a constant internal temperature of 110 °C, using different winding angles (35°/-35°, 45°/-45°, 55°/-55° and 65°/-65°) and different internal pressure levels. The stresses and total deformations obtained as a result of the analysis were examined and the most suitable composite material and winding angle were decided for different pressures. The results of FEM analyses are represented and discussed as follows.

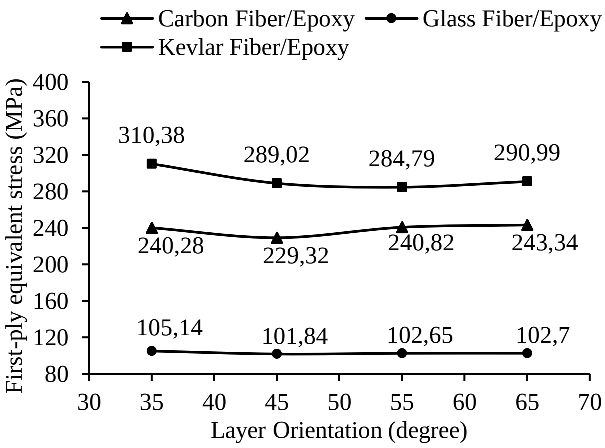

Figure 5. The graph of first-ply equivalent stress on the pressure vessel at hydrostatic pressure of 11.25 bar

Figures 5 to 7 represent the First-ply equivalent stresses (FPES) developed in different composite vessels versus the winding angle of the fibers of composites at hydrostatic pressures of 11.25, 15 and 19.5 bar, respectively. As shown in Fig. 5, the lowest FPES value is 101.84 MPa developed in the pressure vessel covered with glass fiber/epoxy with the orientation angle of 45°. In contrast, the highest FPES value under the 11.25 bar internal pressure was observed in the separator tank with kevlar fiber/epoxy composite material and a 35° layer orientation.

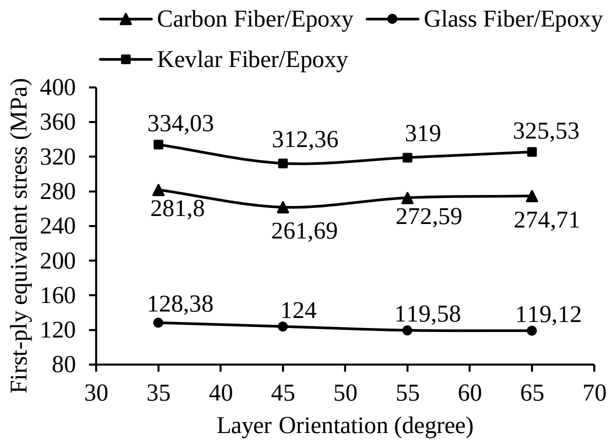

Figure 6. The graph of first-ply equivalent stress on the pressure vessel at hydrostatic pressure of 15 bar

According to Fig. 6, the lowest level of FPES of 119.12 MPa under the internal pressure of 15 bar has been seen in the pressure vessel covered with glass fiber/epoxy at the orientation angle of 65°. In contrast, the highest FPES was observed on the separator tank with kevlar fiber/epoxy composite material and at 35° layer orientation. An important observation from the results of analyses was that the stresses decreased while the layer orientation for the glass fiber/epoxy composite material increased from 35° to 65°.

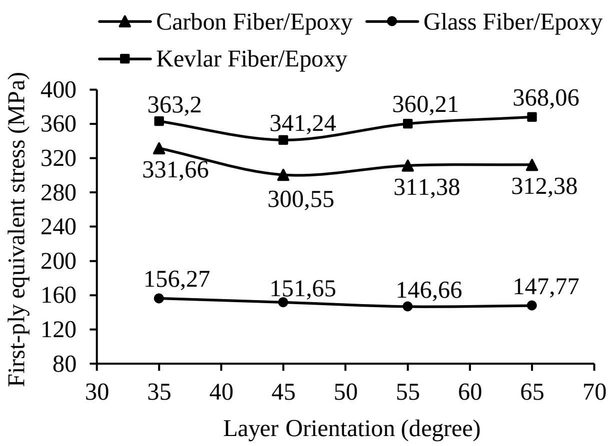

Figure 7. The graph of first-ply equivalent stress on the pressure vessel at hydrostatic pressure of 19.5 bar

Additionally, as shown in Fig. 7, the lowest FPES of about 146.66 MPa under the internal pressure of 19.5 was developed in the pressure vessel covered with glass fiber/epoxy at the orientation angle of 55°. In contrast, the highest FPES value was observed in the separator tank with kevlar fiber/epoxy composite material winded at orientation angle of 65°.

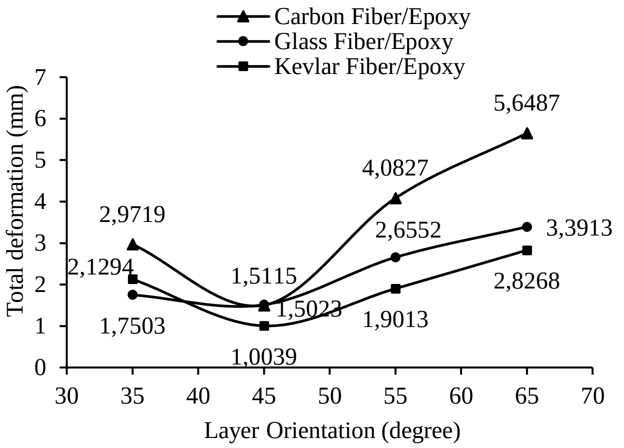

Figure 8. The graph of total deformations on pressure vessel at hydrostatic pressure of 11.25 bar

Furthermore, Figs. 8 to 10 represent the total deformation of different composite vessels versus the winding angle of the fibers of composites at hydrostatic pressures of 11.25, 15 and 19.5 bar, respectively. As shown in Fig. 8, under the internal pressure of 11.25 bar, the lowest total deformation value of about 1.0039 mm was obtained in the pressure vessel covered with kevlar fiber/epoxy with the orientation angle of 45°. In contrast, the highest total deformation value was observed on the separator tank covered with carbon fiber/epoxy composite at a winding angle of 65°. In general, under the internal pressure of 11.25 bar, the lowest levels of total deformation for all the composite vessels were observes at the composite later orientation of 45°.

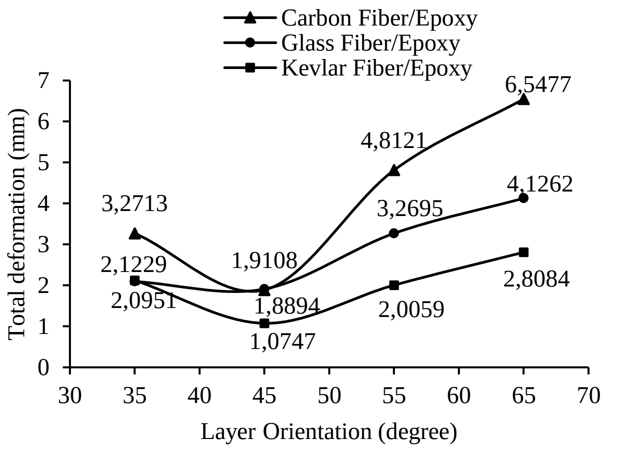

Figure 9. The graph of total deformations on pressure vessel at hydrostatic pressure of 15 bar

Under the internal pressure of 15 bar, as shown in Fig. 9, the lowest level of total deformation of 1.0747 mm was obtained for the pressure vessel covered with kevlar fiber/epoxy winded at orientation angle of 45°. In contrast, the highest total deformation occurred in the separator tank with carbon fiber/epoxy composite at orientation angle of 65°. Similar to the behavior of composite pressure vessels under the internal pressure of 11.25 bar, the lowest level of total deformation under the internal pressure of 15 bar, regardless of the type of composite material, was observed at layer orientation of 45°.

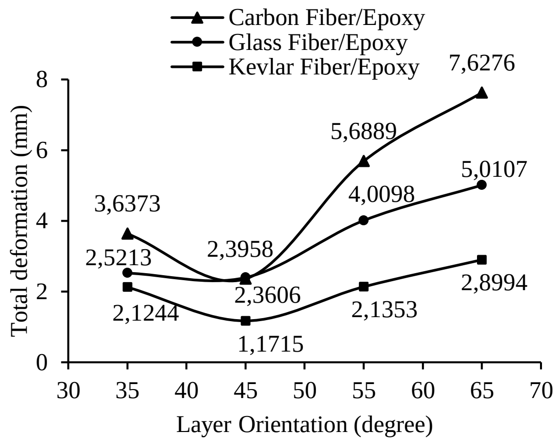

Figure 10. The graph of total deformations on pressure vessel at hydrostatic pressure of 19.5 bar.

Additionally, as shown in Fig. 10, the lowest level of total deformation of about 1.1715 mm under the internal pressure of 19.5 bar was has been obtained for the pressure vessel covered with kevlar fiber/epoxy composite at an orientation angle of 45°. Similar to previous cases, the highest total deformation value under the internal pressure of 19.5 bar was observed in the separator tank with carbon fiber/epoxy composite material winded at layer orientation of 65°.

4. Conclusion

In this study, the analyses of high pressure composites separator tanks, the base layer of which is 0.5 mm structural steel and the other layers are covered with three different types of composite materials, were conducted using finite element method under three different levels of internal pressure. It has been observed that the results of first-ply equivalent stress (FPES) and total deformation vary according to the types of composite material and orientation angle of the layers. Analyses were made using three different types of composite materials, namely carbon, glass, and kevlar fiber/epoxy, at four different winding angles of 35°/-35°, 45°/-45°, 55°/-55°, and 65°/-65°, and three different internal pressures of 11.25, 15 and 19.5 bar. In summary, it was seen that the lowest FPES values of about 101.84, 119.12, and 146.66 MPa under the internal pressure of 11.25, 15 and 19.5 bar were obtained in the separator tanks coated with glass fiber/epoxy with a winding angle of 45°/-45°, 65°/-65° and 55°/-55°, respectively. Furthermore, the lowest total deformation levels of about 1.0039, 1.0747 and 1.1715 under the internal pressure of 11.25, 15 and 19.5 bar, respectively, were observed in the separator tank coated with kevlar fiber/epoxy at a winding angle of 45°/-45°. According to the results, the lowest stress value was observed in glass fiber/epoxy coated separator tanks at 11.25 bar pressure and 45 degree winding angle. In addition, the lowest total deformation value was obtained in the kevlar fiber/epoxy coated separator tanks at the same pressure and winding angle. In addition, it is the type of material that is suitable for composite pressure vessels that will operate at 15 and 19.5 bar pressures, due to the low stresses obtained in glass fiber / epoxy material. However, the winding angles should be 65°/-65° for 15 bar and 55°/-55° for 19.5 bar.

Contributions of the Authors

VG: methodology, software, validation, formal analysis, investigation, writing—original draft, writing - review & editing, visualization CB: conceptualization, methodology, validation formal analysis, writing—original draft, writing—review and editing, visualization, supervision, project administration. MS: conceptualization, software, validation, writing-review and editing.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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