

Research paper

Finite Element Analysis of Composite Natural Gas Storage Vessels

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Abstract

Keywords:

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Stress,
Displacement.

Composite pressure vessels (CPV) are used for large commercial and industrial applications such as softening, filtration and storage. In this study, the design of composite pressure vessels based on "unit load method" along with complete structural analysis and evaluation of additional parameters are performed using finite element commercial code ANSYS. "Unit load method" covers many of the weaknesses of traditional methods and carries out more detailed design using many factors that composite materials provide for designer. The FEM results are compared with experimental ones and a good agreement between them is noticed. By increasing the vessel pressure acceptable and appropriate behavior is observed in strain-pressure curves. As a result, the proposed method can be implemented with acceptable confidence and less cost for comprehensive design of composite pressure vessels.

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1. Introduction

Nowadays, composite materials are used in large volume in various engineering structures including spacecrafts, airplanes, automobiles, boats, sports' equipments, bridges and buildings. Widespread use of composite materials in industry is due to the good characteristics of its strength to density and hardness to density. The possibility of increase in these characteristics using the latest technology and various manufacturing methods has raised application range of these materials. Application of composite materials was generally begun only at aerospace industry in 1970s, but nowadays after only three decades, it is developed in most industries [1]. Properties such as high strength to weight, stiffness to weight ratios and excellent environmental properties such as resistance to corrosion, wear, fatigue at high temperatures are the main characteristics of composite materials.

One of the applications of composite materials is in pressure vessels. They can be used in missiles, aircraft, vessels carrying chemicals and fuels.

The use of compressed natural gas is rapidly increasing in the world. Therefore, there is an increasing national need for the production of CNG vessel is a complex, costly and time-consuming process, so that only a few developed industrial countries have been widely investing on the CNG vessel production. The production process of CNG vessel is too costly due to the need for accurate and sensitive machinery, expensive raw materials such as different kind of composite fibers, production technologies for initial forming to multi-layer composite walls and finally different tests done on the vessel such as quality control test in different stages of production including ultrasonic test, hardness test, volume control, the required quality control tests done on composite vessel such as controlling resin viscosity or fibers length, fibers drawing, damage tolerance tests, environmental tests, life cycle tests and many others [2].

Nunes et al. [3] investigated the production of large composite pressure vessels. They were made of thermoplastic liner, glass fiber and polymer resin. They showed that there is a good agreement between experimental results and elasto-plastic modeling for mechanical behavior of high density polyethylene liner under internal pressure. Koppert et al. [4] conducted experimental investigation along with finite element modeling on the composite pressure vessels made by dry filament winding method. They represented that the results of finite element model for vessels with one or two layers is consistent with experimental results but there are high errors for vessels with three or four layers. Chang [5] theoretically and experimentally analyzed failure of the first laminate of composite pressure vessels. He studied proximity of the theoretical and experimental analysis through fracture strength of the first laminate on the symmetrical laminate of composite pressure vessels using different materials with different number of layers under uniform internal pressure. The experimental results were compared with theoretical results based on the Hoffman, Hill, and Tsai-Wu maximum stress criteria which accurately predicted the pressure in which the failure of the first layer occurs. Zu et al. [6] conducted a study on filament winding system in order to manufacturing of toroidal composite vessels using non-geodesic pattern. They found that the simulation results are consistent with mathematical equations. By comparing the simulation results it was clear that in the non-geodesic paths against geodesic paths, fibers have higher strength and this is due to the small torsion angle. Koussios *et al.* [7] investigated the geodesic paths for optimal design of filament wound pressure vessels. They developed a computer aided filament winding system for the manufacturing of composite toroidal pressure vessels using non-geodesic pattern. It considers several factors, such as pattern optimization, the moving mathematics model of the winding machine and computer simulation for verifying the pattern, etc. The results illustrated that the non-geodesic pattern maximize strength of filaments, due

to smaller winding angle. Vasiliev *et al.* [8] studied the filament wound composite pressure vessels that have commercial applications. Su *et al.* [9] used the nonlinear finite element method to calculate the stresses and the bursting pressure of filament wound solid-rocket motor cases which are a kind of composite pressure vessel. The effects of material performance and geometrical nonlinearity on the relative loading capacity of the dome were studied. Kim *et al.* [10] presented an optimal design method of filament wound structures under internal pressure. They used the semi-geodesic path algorithm to calculate possible winding patterns taking into account the windability and slippage between the fiber and the mandrel surface. In addition, they performed a finite element analyses using commercial code, ABAQUS, to predict the behavior of filament wound structures. Huang *et al.* [11] studied explosion of Zylon/Epoxy composite pressure vessel. They showed that the bursting pressure (maximal radial stress) is a monotonically increasing function of the ratio of the shell thickness to inner radius of the Zylon/epoxy shell. Therefore, the required thickness of Zylon/epoxy shell for the internal reinforcement in a magnet coil can be estimated directly from the plot. But and Haq [12] investigated two design methods to generate dome profiles for similar dome openings namely Netting Analysis and Optimal Design method. The optimal dome contour was studied in ANSYS with a trial design. Onder *et al.* [13] studied burst pressure of filament wound composite pressure vessels under alternating pure internal pressure. The study dealt with the influences of temperature and winding angle on filament wound composite pressure vessels. Finite element method and experimental approaches were employed to verify the optimum winding angles. The hydrothermal and other mechanical properties were measured on E-glass-epoxy composite flat layers. Some analytical and experimental solutions were compared with the finite element solutions, in which commercial software ANSYS 10.0 was utilized; close results were obtained between analytical and experimental solutions for some orientations.

Due to various constraints that exist in testing of composite pressure vessels, finite element analysis (FEA) can be considered as a suitable method for analysis of CPV. This paper touches upon finite element analysis of a vehicle composite CNG pressure vessel using commercial code ANSYS. Complete structural analysis is performed and effect of some parameters such as fiber angle is investigated. The proposed method can be implemented with acceptable safety and low cost for comprehensive design of CPVs.

2. Unit load method

A new method called unit load method is used in design of composite pressure vessels [14]. The old design method was based on allowable stress which by having ultimate tensile strength and dividing it to safety factor, the design allowable stress was obtained. This method was successfully applied for metallic vessels and it was also attempted to use it for glass fiber composite vessels, but, desired results did not acquired. In

addition, all codes based on the design allowable stress consider two basic assumptions: a) The material is isotropic; b) properties are uniform along the material thickness. None of these two conditions are completely true for composite materials with glass fibers. Therefore, the unit load method is applied for designing of composite pressure vessels.

2.1 Safety factor

The design factor k is obtained through Eq. (1) as,

$$K = 3K_1K_2K_3K_4K_5 \quad (1)$$

The coefficient “3” is constant and is chosen as initiation factor for designing in order to confidence of reduction of materials strength due to long time loads. K_1 to K_5 factors are chosen based on the manufacturing methods and performance conditions. The design factor K varies between 6 and 40 and its common range is 8 to 15. The limited allowed unit load is given in Eq. (2) as,

$$u_L = \frac{u}{K} \quad (2)$$

Where, u denotes the ultimate tensile strength and is obtained from Table 1.

The value of maximum allowable strain is 10% of the strain of pure resin fracture ($0.1 \epsilon_R$) or 0.2% of it and usually the lower one is selected. The reason for studying the allowed unit load in terms of strain is the significant differences in stress-strain curves of metals and composites with glass fibers. The allowed unit load is calculated based on strain limit and is obtained through product of unit modulus in allowed strain (Eq. (3)).

$$u_s = X_z \epsilon \quad (3)$$

Table 1: Properties of reinforced laminate layers

Type of fiber	Unit ultimate tensile strength	Unit modulus
	N/mm (Per Kg/m ² glass)	N/mm (Per Kg/m ² glass)
Chopped strand mat	200	12700
Woven roving	300	16200
Unidirectional filament (fiber direction)	500	28000

The design unit load u_z is determined for the all types of layers as:

a) If u_s for the all layers will be lower than u_L , the value of u_s will be the desired design unit load for all layers. It is evident that the design of layers when u_s is lower than u_L for all layers is limited to the strain.

b) If u_s for the all layers or some of them will be higher than u_L , the strain for all layers is obtained through Eq. (4),

$$\varepsilon_L = \frac{u_L}{X_z} \quad (4)$$

Considering that the composition of the layers forms the structure, the allowable strain ε_d is determined as the lowest value of ε_l . The design unit load for the all layers is obtained from Eq. (5),

$$u_z = X_z \varepsilon_d \quad (5)$$

The design unit loads for all types of layers are determined using the above two conditions. The design is performed based on obtained design unit load for each layer (Eq. (6)).

$$u_1 m_1 n_1 + u_2 m_2 n_2 + \dots + u_z m_z n_z \geq Q \quad (6)$$

In which, u_z is the design unit load for each layer of type z , m_z is fiber weight per unit area in a layer of type z , n_z is number of layers of type z and Q is the exerted maximum unit load. When the thickness is required, it is obtained from summation of thickness of the layers. The thickness of each layer is obtained through the amount of used glass in it as depicted in Figure 1.

3. Numerical method

The vessel is considered to be horizontal and the weight of the vessel and its contents are ignored. The mechanical properties of the vessel are given in Table 2. The properties of composite materials are a function of the used fibers and matrix strength. Materials which have high strengths have less toughness (such as glass or ceramics). So, they are not used in industry. The properties of E-glass/Epoxy composite are given in Table 3.

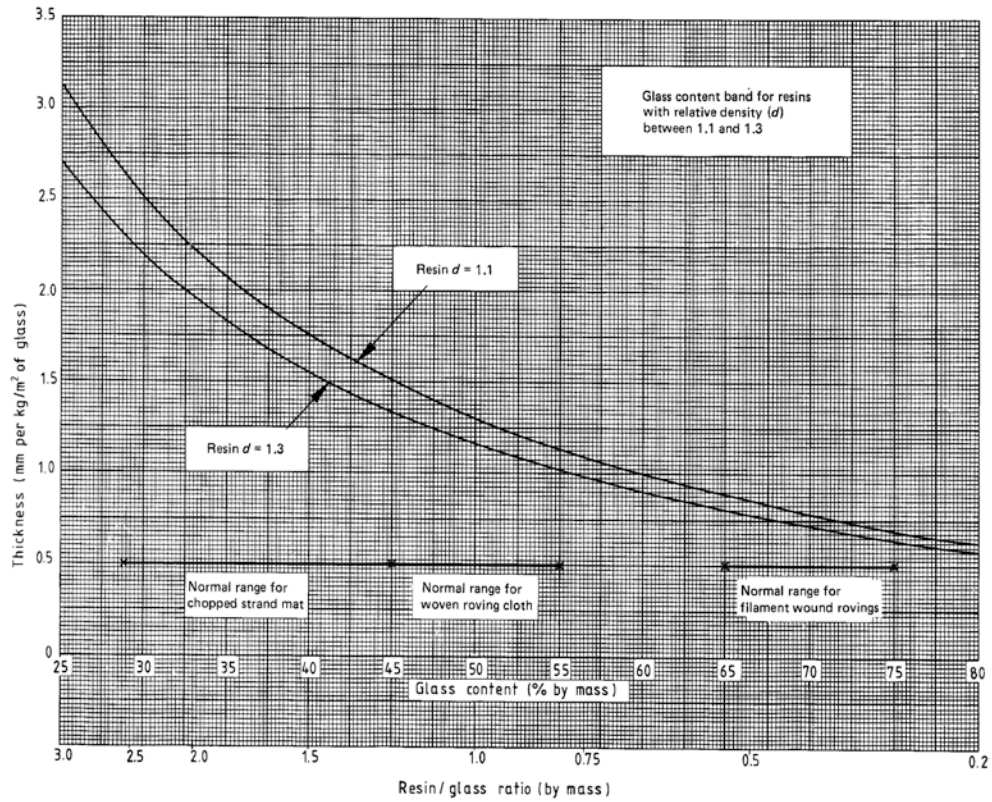


Fig. 1: Thickness versus fiber amount

Table 2: Specifications of the modeled vessel

Diameter	380 mm
length	880 mm
thickness	42.25 mm
Layers orientation	$\pm (54.7^\circ)_{40}$
Fiber volume percent	75%
Glass in the thickness	0.65 mm
Glass mass	$65 \frac{Kg}{m^2}$
Performance pressure	2.5 Mpa
Internal volume	80 Lit

Table 2: Mechanical properties of E-glass/Epoxy

E_l (GPa)	E_T (GPa)	G_1 (GPa)	G_T (GPa)	ν_L	ν_T
56.63	15.22	5.5	5.5	0.29	0.38

In the model analyzed in ANSYS, the composite vessel is under uniform pressure which is designed using unit load method and based on geometric dimensions of CNG vessel [15]. The vessel is fully modeled using the symmetry and to reduce the volume of computations octant of the vessel is modeled. The vessel is constrained in longitudinal and peripheral directions at transverse and longitudinal cuttings, respectively and the internal pressure is applied according to the perpendicular vector to the internal area of the vessel. The 3-D layered solid element is used to model the vessel as shown in Figure 2.

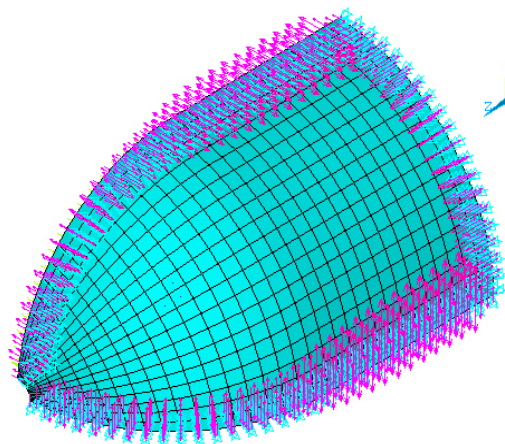


Fig. 2: The applied boundary conditions on the model

4. Results and discussion

The FEA results are compared with experimental ones obtained by Sakata [16]. The vessel is made of CFRP and is composed of 6 helical layers and 6 hoop layers. A schematic of it is illustrated in Figure 3. The strain diagram based on pressure for points 1&2 are obtained and compared to FEM and experimental results available in Ref. [16]. As can be seen in Figure 4, there is a good agreement

between experimental and numerical FEM results (The difference is less than 10%). Figure 5 shows the contours of radial, tangential stress and stress along the main axis of element.

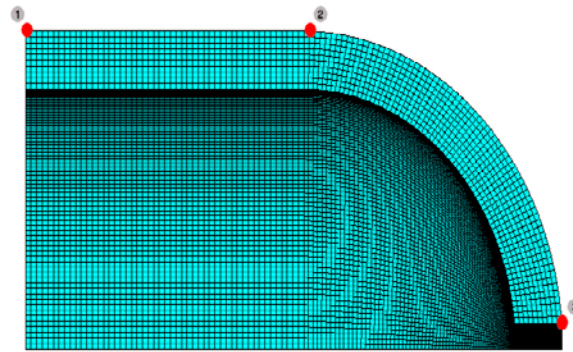


Fig. 3: Side view of the model

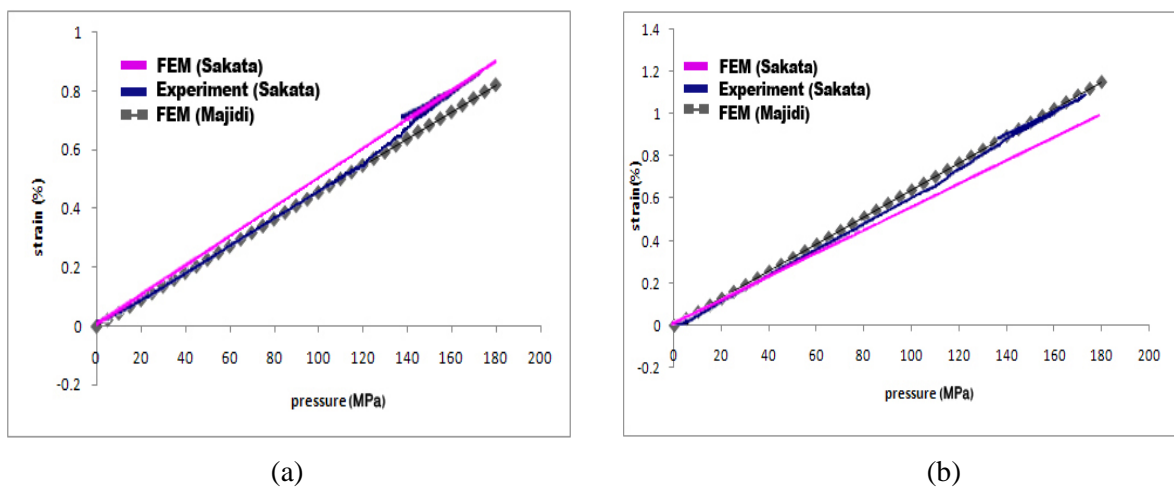
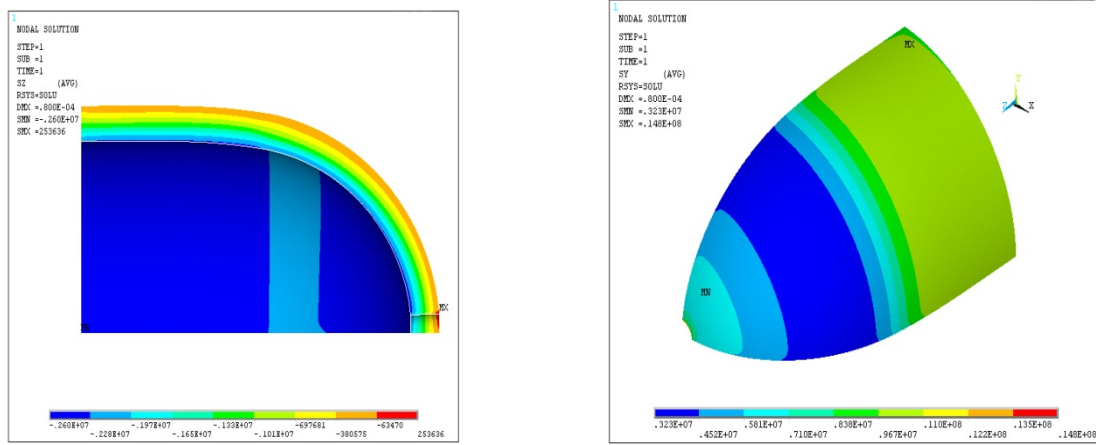
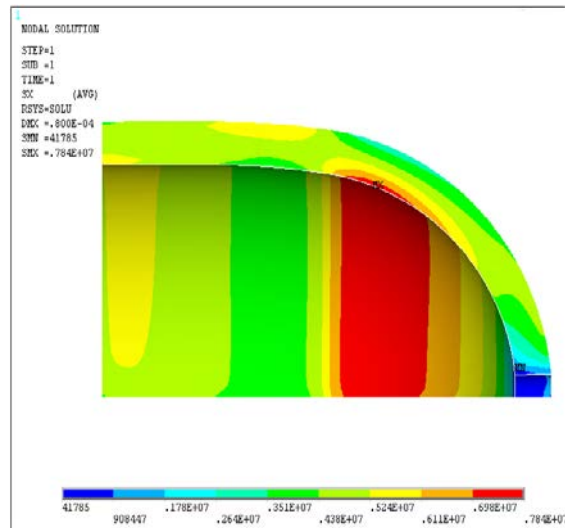


Fig. 4: Strain-pressure curve: a) point 1; b) point 2

Layers of the vessel are under a suitable portion of the load regarding their location due to the relatively complete theoretical design and selection of optimum fiber angle and as moving forward toward the outer layers, the layers will be under lower uniform stress amount in a way that realize the stressful condition in a normal vessel. This point can be well understood through Figure 6 which depicts the reduction of stress level along the vessel thickness at three different points (Figure 3).

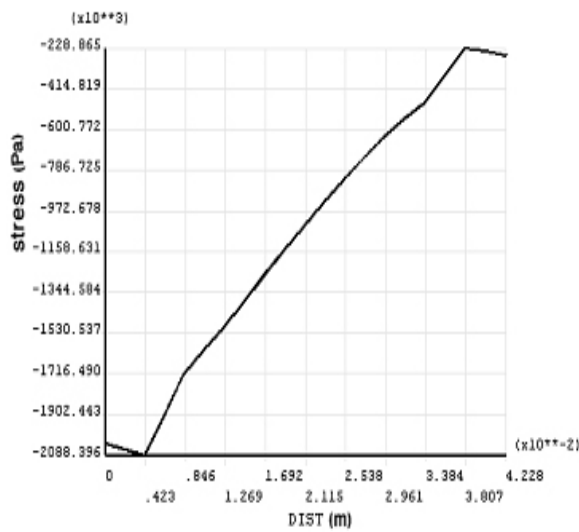


(a) (b)

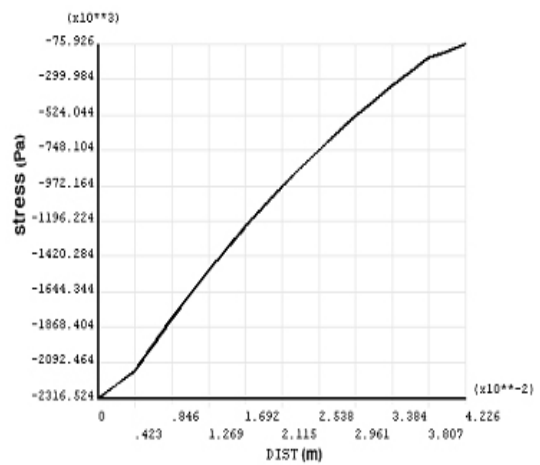


(c)

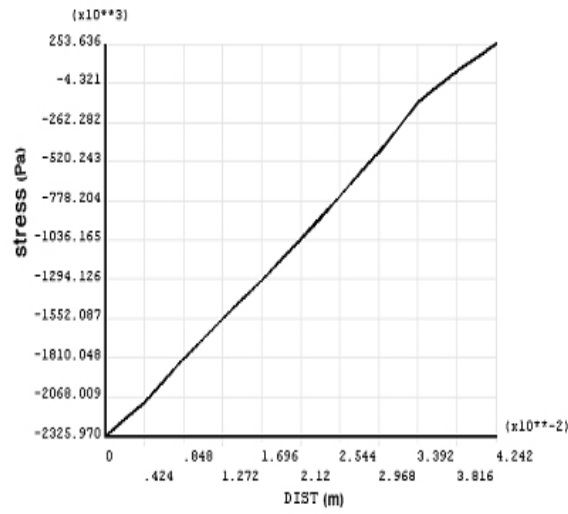
Fig. 5: Stress contour: a) radial direction; b) tangential direction; c) along the main axis element



(a)



(b)



(c)

Fig. 6: Stress level in radial direction along the vessel thickness: a) point 1; b) point 2; c) point 3

But in the case of tangential stresses as well as expected the head will be under lower stress levels and maximum stress occurs at a point on the cylinder and the in the middle of vessel. As shown in Figure 7, small irregularities observed in the middle of the curve are due to the geometric deformation of vessel in the intersection of the head to the cylinder.

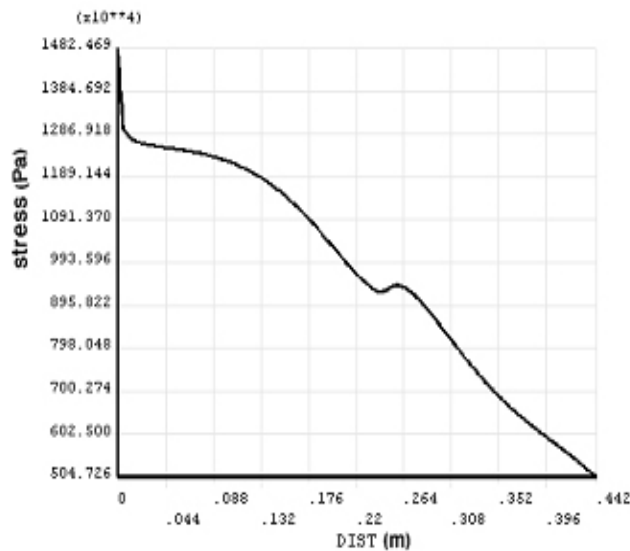


Fig. 7: Variation of first layer stress along the tangential direction based on distance from middle of vessel

According to Figure 8, it is obvious that as moving forward from the middle of vessel toward the head, the value of stress is reduced and in the intersection of the head to the cylinder stress is increased due to the geometric deformation of vessel.

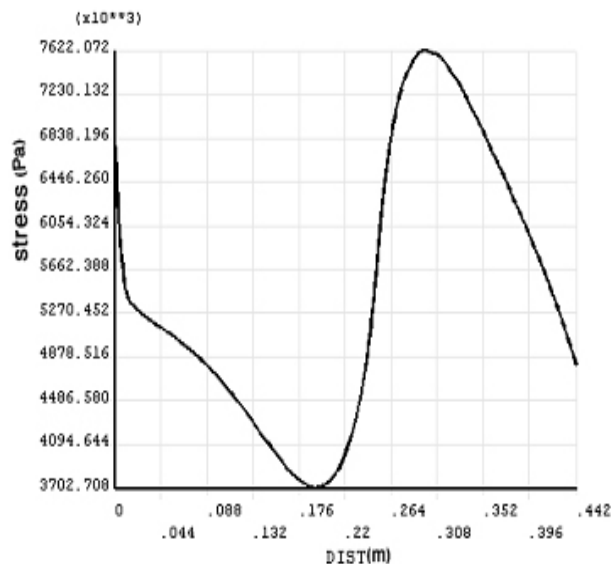


Fig. 8: Variation of first layer stress along the main axis of element based on distance from middle of vessel

5. Conclusions

In this paper, the FEA of CNG composite pressure vessels based on "unit load method" according to the BS4994 standard along with complete structural analysis and evaluation of additional parameters are conducted using ANSYS. The numerical simulations are performed on a real Vehicle CNG composite vessel. The following results are obtained:

- The vessel is modeled using unit load method under 2.5 Mpa internal pressure. By increasing the vessel pressure acceptable and appropriate behavior was observed in strain-pressure curves. This indicates high safety of this method in the design of composite pressure vessels.
- The effects of fiber angle in the vessel is undeniable and particularly if it is performed based on the theoretical model (unit load method), accurate and appropriate response is not received. Therefore, another method is needed for selection of the appropriate fiber angle regarding the geometry and loading of vessel.
- Layers of the vessel were under a suitable portion of the load regarding their location. This can be one of optimum cases that exist for different layers in load toleration on the vessel.

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