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ORIGINAL RESEARCH PAPER

Analysis of Fiber-Reinforced Polymer (FRP) Rehabilitation of Cracked Pressure Vessel Using Finite-Element Method (FEM)

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Abstract

Investigation of repaired crack in pressure vessels plays a critical role in the maintenance of cylindrical vessels which are under static loads. Pressurized vessels are critical elements in many industries that may be subjected to degradation and cracking due to working conditions. There are several methods to repair such reservoirs, including welding of damaged points, but this is not possible in some conditions, such as the presence of inflammable materials inside the reservoir. One of the most reliable ways to repair these types of vessels is using composite materials. In this research, crack created in the reservoir is repaired using carbon/epoxy composites. Results of this study confirm the association between the strength of vessels walls and thickness of composite materials. In this paper, the effect of different parameters such as thickness and radius of the reservoir, and composite thickness are investigated. The results show that increasing the thickness of the composite is effective, so by doubling the thickness of composite, stress intensity factor decreases by 13%. Moreover, the use of composites in thin wall tanks is much more effective than the case of a thick reservoir wall.

1. Introduction

Research and interest in management of the issue of repair and reinforcement of pressure vessels is of great importance to private companies, and researchers due to deterioration of existing systems and components, occurrence of catastrophic failures, and continued maintenance deferment because of limits on financial resources. This will improve the behaviour of the reservoir in practice as well as increase in the resistivity of the reservoirs against unexpected accidents. In general, repair and reinforce of existing tanks in order to withstand the increasing in design loads, improving the defects caused by erosion, increasing the reservoir ductility or other materials, using the proper materials and proper methods of operation are normally carried out. The use of steel plates in the form of external coatings, concrete or steel pillars, and external extrusion are available in a number of conventional methods [1].

One of the materials that has been used extensively in reinforcing and strengthening various reservoirs in recent years are composites of Fiber Reinforced Polymer (FRP). The use of FRP for building and strengthening construction has increased persistently. FRP materials offer multiple benefits contrasted with steel, including superior resistance against corrosion and fa-

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tigue, as well as having low coefficient of thermal expansion, as well as being lightweight. An additional advantage of FRP is in the endless ways in which polymers and fibers can be combined with a material to suit the specific needs of a structure [2].

A considerable amount of literature has been published on the repair and reinforcement of various structures using FRP composites. These studies indicate that the application of adhesives is an efficient way for repairing cracks in the fractured constructions by increasing the fatigue life of the damaged components. Composite materials play a very important role in engineering optimization [3]. Low weight and high strength of these materials as well as their high corrosion resistance have made FRP composites be widely used in various sciences and structures in order to repair and enhance their efficiency. The effect of geometric defects in the reservoirs is unavoidable due to the presence of valves and their inlets and outlets [4]. For this reason, high stress pressures in these areas may cause a stress concentration phenomenon that can cause local instability and buckling that can be increased by the use of composite materials to increase the local or universal load capacity of the reservoirs. Lukács et al. [5] investigated a numerical and laboratory study for the structural strength of the pipelines repaired by composite materials. Their composites consisted of carbon fiber and put their specimen under fatigue and explosion loading. Allah Bakhshi and Shariati [6] in a study have analyzed the buckling analysis of composite reservoirs under combined loading. In their research, they investigated the effect of loading conditions and crack size on the buckling behavior of composite reservoirs under different loading conditions such as axial loading, bending, internal pressure and external pressure. Their results indicated that reducing the axial load pressure and increasing the external pressure load on the buckling of all the devices is effective and increasing the pressure load and decreasing the external pressure on the buckling of the local motions was studied.

Ghaffari and Hosseini-Toudeshky [7] studied the effect of glass/epoxy composites on the rate of crack growth (in fatigue loading) in composite pipes. For this purpose, Ansys software was used to create a cylindrical load for internal pressure of the pipe. In their study, they investigated the effect of thickness on the growth rate of cracking.

Hosseini-Toudeshky and Fadaei [8] used the elastic-plastic finite element analysis method to investigate the effect of the longitudinal defects (along the length of the pipe) placed inside the tube during pressure stage that causes the pipe to be destroyed. In this study, they investigated the effect of composite length and thickness. Their results showed that at a certain thickness of composite and internal pressure cause destruction for repaired vessels and the flawless tube could be the same. To determine the effects of mechanical and geometrical properties of the patch on the Stress Intensity Factor (SIF) at crack tip, Shavalipour and Karimi [9] investigated the effect of different crack length, composite fiber angle, crack length and fiber angles in two-layer composite patch and different reservoir radius. Meriem-Benziane et al. [10] examined the repair of gas pipelines using carbon-epoxy composites, and, assuming a longitudinal cracking (I-failure mode), the effect of the number of composite layers (one layer and two layers) was investigated. To do this, finite element method was used and also to determine the stress intensity at the tip of the crack.

In previous studies on rehabilitation of cracked pipes rarely the problem of damaged tankers was studied, in this work the effect of two important parameters on crack growth of damaged tankers is investigated. Two investigated parameters that were studied in this work are the effect of reservoir thickness and the effect of the number of composite layers (single layer and double layer in I-failure mode)

2. Geomaterial and Material Model

In order to ensure the accuracy of the numerical modeling and results, first the model in Meriem-Benziane et al. [10] was built and the results were compared with each other. The geometry of the model that is assumed in Meriem-Benziane et al. [10] is shown in Fig. 1. This model has 1-meter length, a radius of 147mm and a thickness of 17.5mm. In the reference [10], the effect of parameters of crack length and internal pressure on crack tip parameters has been investigated.

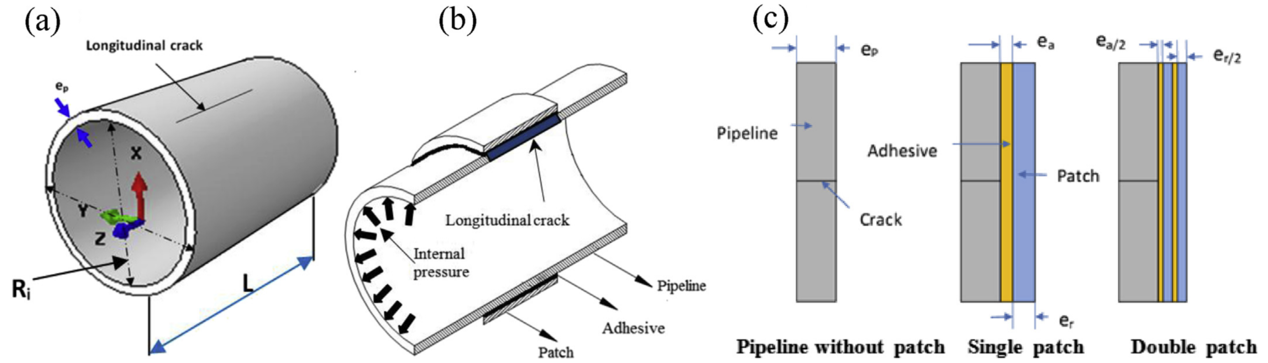

Fig. 1. a) Pipeline with longitudinal crack, b) Geometrical model, and c) Different shapes of the repaired structure (pipeline, adhesive, and patch).

Table 1
Mechanical properties of carbon/epoxy composite materials [11].

Mechanical properties	E_{11}(GPa)	E_{22}(GPa)	E_{33}(GPa)	E_{12}(GPa)	E_{13}(GPa)	E_{23}(GPa)	ν_{12}	ν_{13}	ν_{23}
Value	135	10	10	5	5	5	0.3	0.3	0.3

To compare the results obtained in Abaqus software and the results presented in Meriem-Benziane et al. [10], the following case is considered: small damage (crack) in the body of pipe with the length of 50mm is created and the internal pressure is 30MPa, the process of making the model in Abaqus software starts with the construction of pipe geometry. A 3D model was used to construct a model, such as Meriem-Benziane et al. [10]. Crack was formed in the middle of the tube (Fig. 2).

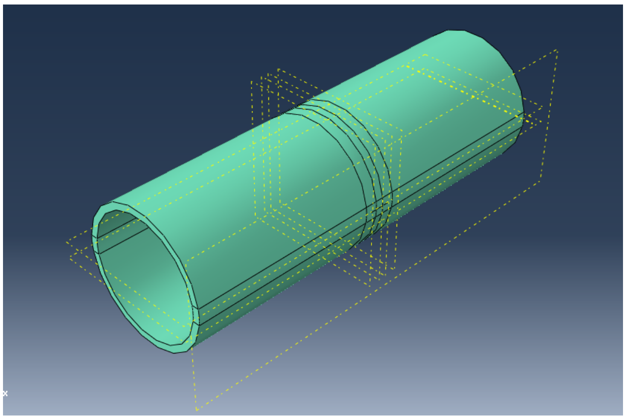

Fig. 2. Creating a tank model geometry and cracks on it.

The properties of steel pipe that is used in this study include 207GPa for the modulus of elasticity and 0.3 for the Poisson's ratio. The composite materials are made of carbon/epoxy which properties are mentioned in the Table 1.

3. Modeling Using Finite Element (FEA)

In this article The FE analysis was done using ABAQUS to achieve the stress areas of the vessel as well as the stress intensity factor in opposition to the longitudinal crack tip. The contour integrated technique was used to determine the crack in addition to the fact that it was demanded as a parameter in the output to compute the stress intensity factor as well as J-integral at the crack tip. The FEM was utilized to be able to approach the cracked pipeline, the composite area, along with the adhesive while the pipeline ends were fixed (Ux, Uy and Uz ¼ = 0). As a consequence of the symmetry, just one-fourth of the pipeline was taken into consideration in the modeling. A twenty-node geometry was used to construct the model. The FE mesh for the longitudinal crack is shown in Fig. 1a and 1b.

The pipeline was meshed with three-dimensional hex-dominated quadratic elements. To be able to enhance the accuracy of the stress intensity factor values determined from the crack geometry, the symmetry (one-quarter) of the pipeline could be utilized which the simulation on crack area is carried out employing the 20-node brick components with high-level mesh improvement around the crack end. Fig. 2 demonstrates the mesh of the specimen along with the mesh enhancement in the crack end area. The variance of diverse fracture factors by rectifying the crack with single- as well as double-sided sections was evaluated.

4. Result and Discussion

In order to validate this study, the model was analyzed with the details described above with the help of Abaqus software and the results were obtained from the software output. Fig. 3 Shows the tensile contours around the crack. Since the tube and the loading are completely symmetrical, the pure mode I is expected and two symmetrical dumbbell shaped contour is formed in the upper and lower tip of the crack.

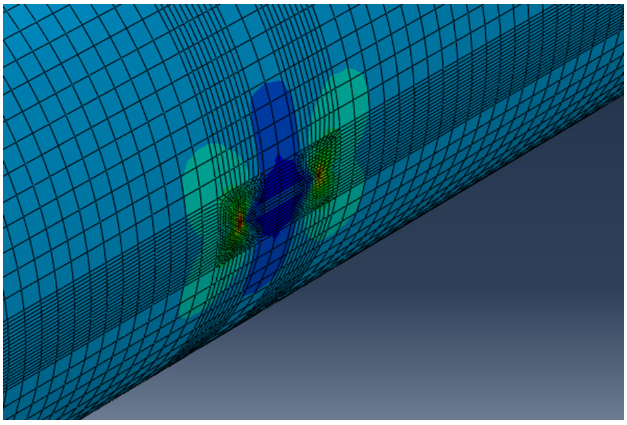

Fig. 3. Tension contours around the tip of the crack.

According to the results presented in the paper by Meriem-Benziane et al. [10], the value of the stress intensity factor of mode I is approximately 80MPa$\sqrt{m}$. And the results obtained from the software are 82.7MPa$\sqrt{m}$, which have a reasonable match with each other. Since the modeling method is validated, complete studies will be done on the model. For this purpose, consider the same previous model and connect two circular plate using the Tie command to the two ends of the pipe made in the previous step. In this way, the tank is ready for the future work (Fig. 4). To investigate the effect of composite patches on the reservoir, the following parameters are investigated:

1. Evaluation of the effect of reservoir thickness

2. Effect of the number of composite layers (single layer and double layer in mode I - failure)

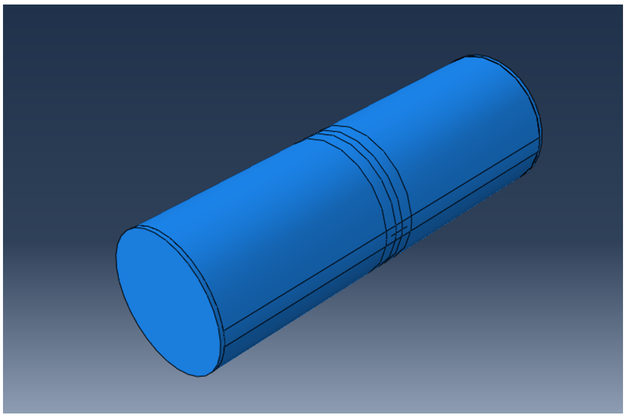

Fig. 4. The modeling of pressure vessel.

5. Evaluation of the Effect of Reservoir Thickness

To examine the thickness parameter, first the different thicknesses of the reservoir were considered. Simulations of the tank with different thicknesses are shown in Fig. 5. The pressure applied to all these tanks was the same. In all these reservoirs, the outer diameter of the reservoir is the same and to change the thickness, the inner radius of the reservoir was variable. The reservoir in the middle of the Figure is chosen to be the reference vessel. To investigate the effect of reservoir thickness, first time analyses were done without using the composite patch and in the second simulation composite patch was attached to the reservoir.

In Figs. 6 and 7, the distribution of Von-Mises stress at the crack tip is shown for various thicknesses and in cases with and without composite patch. As shown, the stress at the crack tip in all cases with composite patches is less than the tubes without composite. In the case of reservoir without composite, the value of stress intensity factor is 109.5, 30.9, 14.5 and 8.1MPa, respectively. However, with using composite materials, the stress intensity factor will decrease to 28.4, 21, 12.5 and 7.6MPa in the same cases.

One interesting finding that can be obtained from the maximum stress values is that by increasing the thickness of reservoir the effect of the composite materials decreases. In other words, composite patches are more effective in thin-walled tanks. In Table 2, the values of the intensity factors for different cases are shown. The SIF values in this table confirm the above findings. As it was observed, the stress intensity factor for a thin wall with a composite patch was sharply reduced while it did not have much effect on the reservoir with a thicker wall.

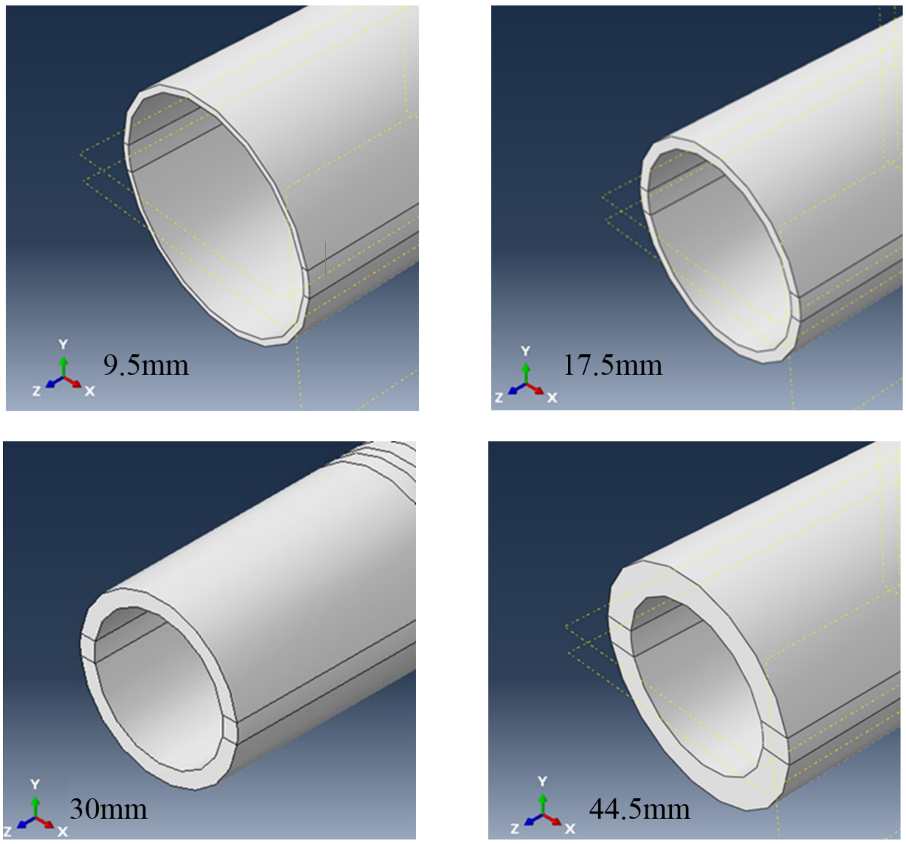

Fig. 5. Various models to examine the effect of vessels thickness.

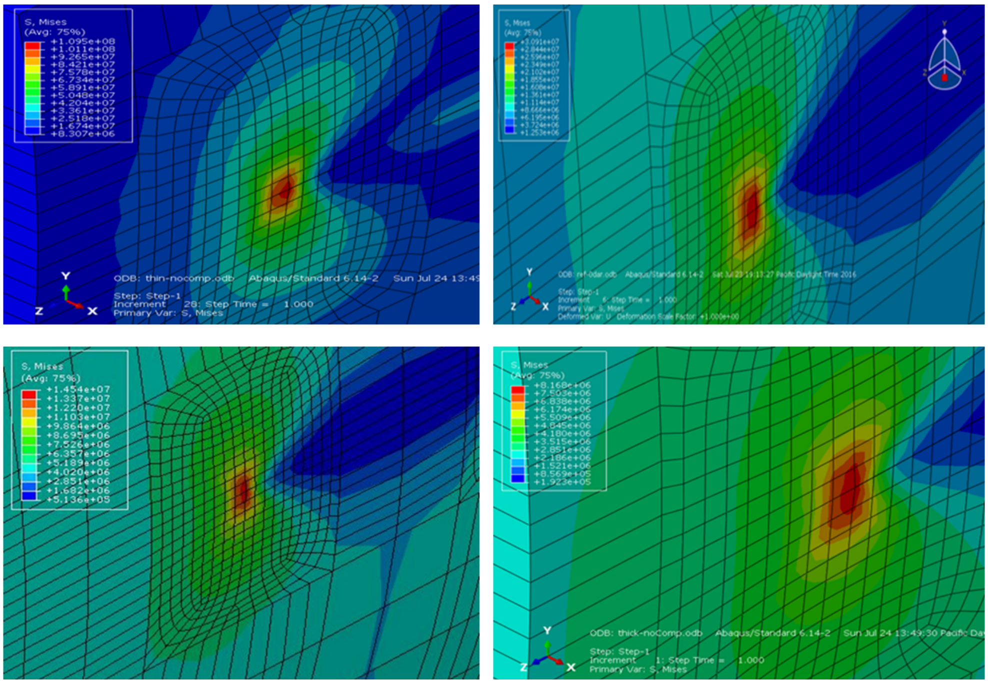

Fig. 6. Von-Mises stress contour around crack tip for different reservoir thicknesses (without composite patches).

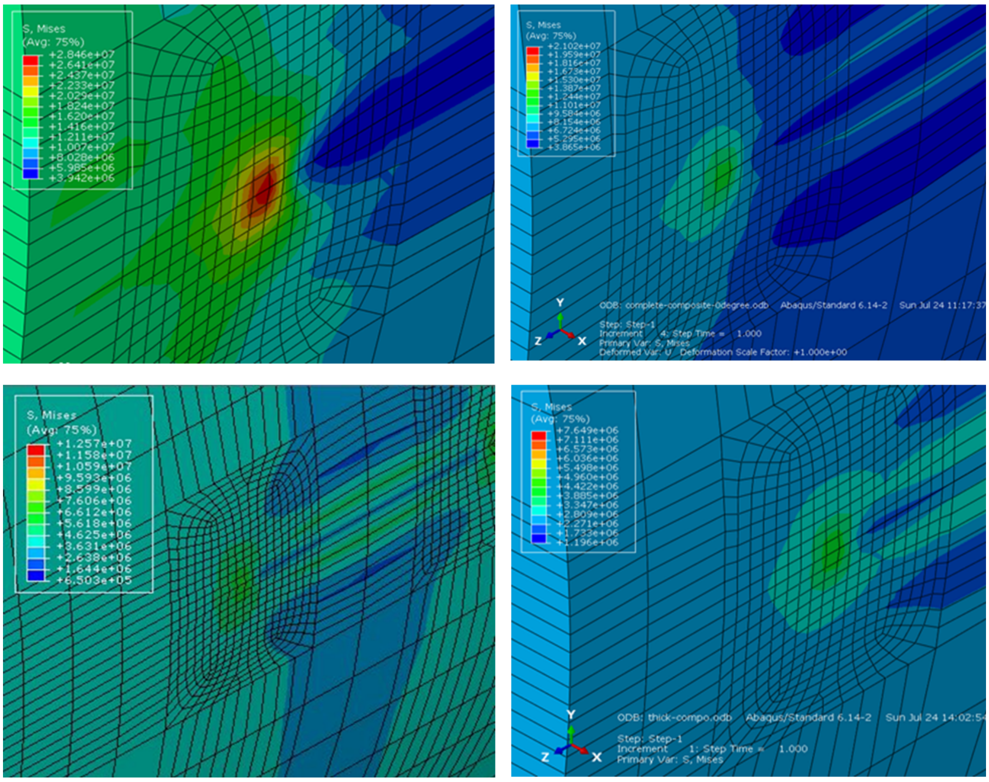

Fig. 7. Von-Mises stress contour around crack tip for various reservoir thickness (composite).

Table 2
Stress intensity factor values (MPa$\sqrt{m}$) for different wall thickness conditions.

	Thickness t=44.5mm	Thickness t=30mm	Thickness t=17.5mm	Thickness t=9.5mm
Without composite patch	0.84	1.38	2.77	9.7
With composite patch	0.79	1.217	1.92	2.58

Table 3
Stress intensity factor values (MPa$\sqrt{m}$) for composite thickness

	Thick composite layer $h = 15.5$mm	Thin composite layer $h = 7.75$mm
Without composite layer	2.77	2.77
With composite layer	1.92	2.2

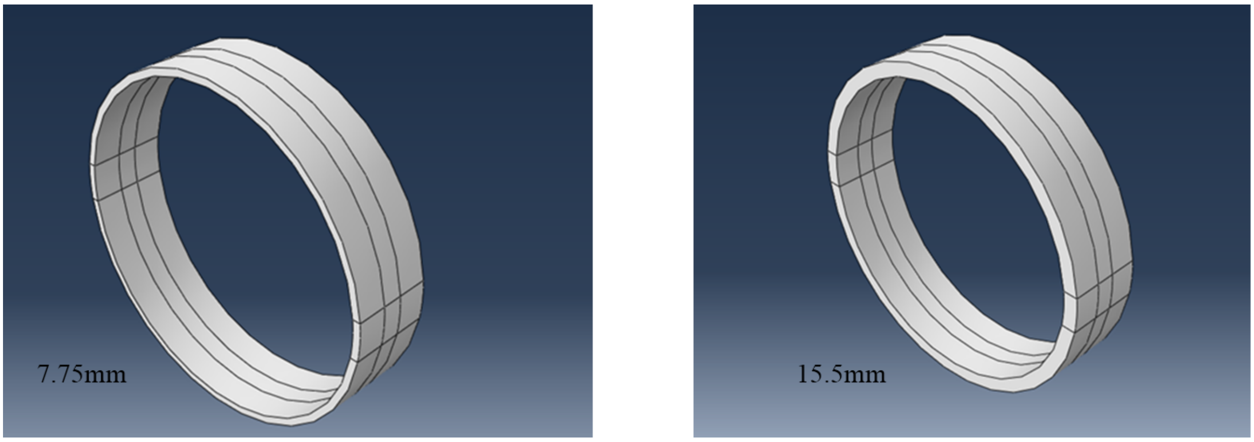

Fig. 8. Various composite thickness.

6. Effect of Composite Patch Thickness

In order to investigate the effect of composite patch thickness on the stress intensity factor value, 15.5mm and 7.75mm for thickness were considered. Fig. 8 shows the composite layers that were used in this paper. Furthermore, the thickness of the vessel is 17.5mm. The results presented in Fig. 9a relate to a reservoir with a composite patch thickness of 7.75mm. Comparison of the results presented in Figs. 9a to 9c shows that the change in the thickness of the patches does not affect the results of stress, strain and displacement in the entire reservoir. In this case, the maximum Von-mises stress was 129MPa for both states and the maximum displacement was about 0.005mm.

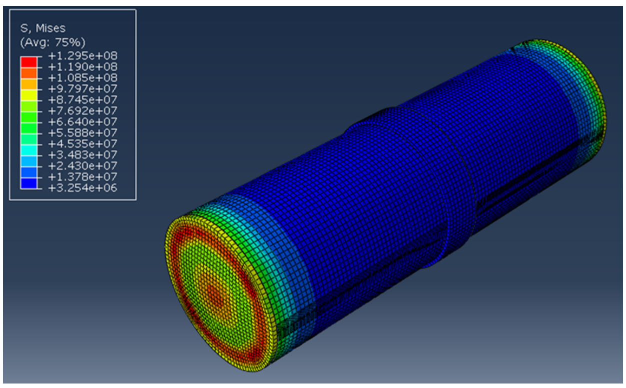

Fig. 9a. Von-Mises stress in modified composite layer (7.75Mm).

As shown in Fig. 7, the maximum Von-mises stress at the tip of crack is about 21MPa when used with a thick composite patch. While in Fig. 9d, the maximum stress is about 24MPa. This suggests that with a 50 percent reduction in thickness, stress in the crack tip increased around 3MPa. Meanwhile, the stress intensity factor is 2.2MPa$\sqrt{m}$ when using a thin composite patch, while according to Table 2, this value is equal with 1.92MPa$\sqrt{m}$ for the modified reservoir with a composite layer. The results are presented in Table 3.

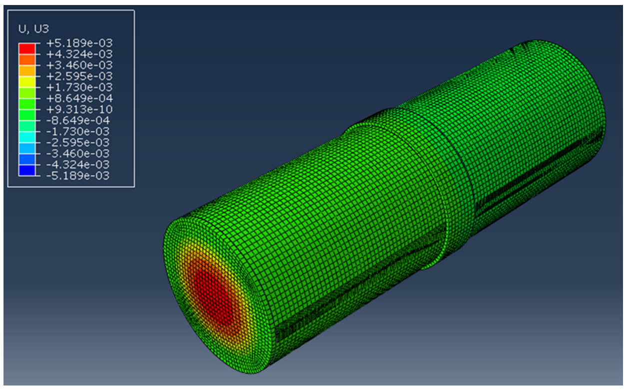

Fig. 9b. Strain in modified composite layer (7.75Mm).

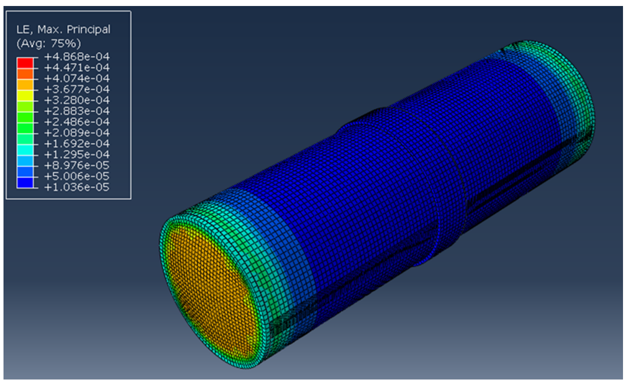

Fig. 9c. Strain in modified composite layer (7.75Mm).

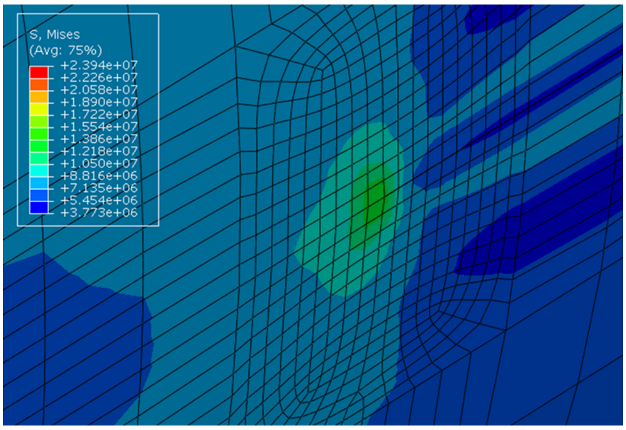

Fig. 9d. Von-Mises stress in modified composite layer (7.75mm).

7. Conclusions

In this study, pressure vessels with crack were investigated in parametric way. Two important parameters that were never investigated in previous paper were studied in this work. There are various approaches to repair these reservoirs, and one of the easiest, most cost-effective and safest methods is to use fiber reinforce polymers. One of the parameters that is very important in failure mechanics is the stress intensity factor. The greater the value of this factor causes the greater possibility in the risk of crack growth. Therefore, it is attempted to reduce the coefficient at the tip of the cracks using composite materials. Accordingly, the following results were obtained:

1. Studies have shown that increasing the thickness of the reservoir decreases the effectiveness of the composite patch. In other words, the composite patch has a greater effect on the walls which are thinner.

2. Double increase of composite patch thickness caused a 13% decrease in stress intensity factor.

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