Numerical Analysis Of Crack Growth In A Multi-layer Composite Tank Under Thermal And Mechanical Loading

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Composite tanks are modern structures that are increasingly used in various industries due to their advantages, such as high specific strength, lightness, and corrosion resistance. Therefore, it seems necessary to investigate their mechanical behavior. Based on this, in the present research, crack growth in multi-layer composite cylindrical tanks under combined compressive and thermal loading is investigated using the extended finite element method. After validating using the results available in the literature, the effect of the number of composite layers and the arrangement of the layers on the crack growth of these tanks are investigated. Also, the results of composite and steel tanks with the same boundary conditions are compared. The results indicate that the composite tank behaves better against the internal pressure of the tank, and less stress is created at the same pressure with the value of 281.1 MPa instead of 292.2 MPa for the steel tank. Also, the composite tank tolerates 0.2 mm deformation instead of 0.25 for steel. In addition, it can be seen that composite tanks, while having low weight, have less crack growth compared to steel tanks.

Keywords: Composite tank, Crack growth, Extended finite element method, Thermal loading.

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1. Introduction

Composites have been mostly used in the past to build secondary structures. However, today, due to the increased awareness of how these materials can be formed and the increased competition in global markets for making light parts in many high-tech engineering applications, composites can be the chosen material in many sensitive and important structures [1–3]. Compared to metals, the special advantages of composites, such as high strength and stiffness-to-weight Ratio, fatigue resistance, corrosion resistance, and especially higher impact properties, have drawn attention for using them in many structural components of cars, planes, and ships [4–6]. Meanwhile, tanks and pipes under pressure are among the equipment that has special and significant use in the oil, gas, petrochemical, and most of the main industries, such as power plants and transportation. The industry uses these tanks as compressed air holders, water storage sources, boilers, gas storage, pressure chambers, reactor tanks, etc. [7–9].

The creation of cracks in different structures based on the application of different mechanical and thermal forces is one of the basic problems in all kinds of structures [10–12], which reveals the necessity of crack growth analysis in cylindrical tanks and many industrial structures [13–16]. As an example, Rezaei et al. [17] in a research state that the CNG gas tank made of carbon-epoxy composite with non-metallic lining is about 60% lighter compared to the aluminum tank with similar geometry, dimensions, and working conditions. Alizadeh et al. [18] numerically and experimentally investigated composite vessels reinforced with peripheral rings under external pressure. The results of their study show that the need for composite pressure tanks, especially tanks that can withstand higher pressure and at the same time have suitable weight, is felt more and more every day. These pressure tank simulations show that the composite failure behavior is acceptable.

Naraki and Ghabezi [19] analyzed thick-walled composite tanks under the effect of internal pressure and temperature. In their study, first, the equations of fluctuating stresses and strains were calculated using theoretical methods. Then, the temperature changes in the tank wall caused by the application of internal cyclic temperature were calculated using finite difference methods. Abedi et al. [20] numerically and experimentally investigated the dimensional characterization of glass/epoxy composite plate with an edge crack under cooling/heating cycles. Chou et al. [21] investigated the strength of tanks made of unidirectional carbon fibers. They found that their strength depends on the loading rate and its effect on the viscoelastic behavior of the matrix in the composites. Nebe et al. [22] numerically and experimentally studied the failure of the first layer of the pressure tank using different materials with different numbers of layers under non-uniform internal pressure. Zu et al. [23] investigated the effect of various damages on fatigue resistance in composite pressure tanks. Dadashi and Rahimi [24] experimentally and numerically investigated the onset and growth of damage in composite glass fibers/polyester cylinders twisted with a twist angle of ± 75 degrees under lateral loading between parallel rigid plates. The experimental observations, including the level of failure caused by loading and the cause of various damage mechanisms occurrence, were discussed and investigated. Comparing the results of experimental tests with the results of numerical simulation showed a good agreement. Therefore, the performed modeling could properly predict the behavior of the composite cylinder under the studied loading conditions. Alimirzaei et al. [25] studied the failure of composite pipes by the fiber twisting process. Their results showed that the highest percentage of failure is caused by matrix cracking, fiber failure, and fiber separation from the matrix. In their study, Ju et al. [26] examined the failure of cryogenic composite tanks using a non-isothermal classical laminate and plate approach. Their findings showed that the composite exhibited transverse thermo-mechanical resistance at 1500 kPa. Ruggieri and Hippert Jr [27] conducted a numerical investigation on the crack front region and the effects of crack-tip constraint in conventional fracture specimens with transverse delamination cracks. They identified important features of 3-D crack front fields in fracture specimens and concluded that these features directly influenced the toughness of isotropic materials. In a study by Lin et al. [28], a method for progressive failure analysis was proposed to investigate the failure modes of 35 MPa Type III composite pressure vessels during hydraulic burst tests. Rahul et al. [29] conducted a comprehensive review on the performance analysis of composite overwrapped pressure vessels. Their paper provides a detailed overview of various studies that evaluated the performance of these vessels under different design and environmental factors, including geometry factors, design factors, defects (such as notches and cracks), loading conditions, and performance parameters. Chang et al. [30] proposed a new analysis that quantitatively explains recent experimental observations of a transition from unstable to slow, stable through-thickness crack growth in cross-ply laminates. In a recent study, Rekbi et al. [31] investigated the crack growth behavior in filament winding composites under mode-I loading tests. They utilized double cantilever beam specimens cut from real pipes according to the ASTM D5528 standard for this purpose.

Today, with the advancement of technology, the techniques of storing fluids in pressure tanks have made significant progress, and engineers can design and analyze tanks under high pressure with high safety. However, reviewing the previous investigations indicated that there is a lack of adequate studies in the field of utilizing composite materials in pressure tanks, and the evaluations are in the early stages. Therefore, in this research, an attempt has been made to simulate the composite pressure tank and compare it with the steel tank to show the reliability of composite materials in related applications.

2. Finite element simulation

The specifications considered for the tank according to the standard dimensions of these tanks are from the reference [32]. According to Fig. 1, the considered length for the cylindrical part of the tank is 1200 mm, and the arc radius at the end of both sides of the tank is considered 150 mm. According to the mentioned reference, the thickness of the plate is 4.782 mm. Table 1 presents the extracted values for the T300 composite. Fig. 2 demonstrates layering, taking into account the overall thickness of the shell, which is 0.005172 m according to the standard thickness of the tanks. All the layers are made of composite T300 and the laminated composite configuration with 7 layers is $(0, \pm 45, 45, \mp 45, 0, 90)$. According to Fig. 2, the core of the tank is selected from alloy steel and the mechanical properties of A516 steel are presented in Table 2 [33].

In order to correctly conduct the simulations, one of the most important steps is the correct definition of boundary conditions. A pressure of 10 MPa is applied to the inner

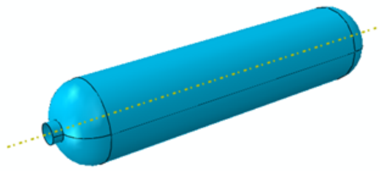


Fig. 1. The model designed in ABAQUS software.

Table 1. Mechanical properties of T300 composite.

Property	Unit	Value
Tensile Strength	MPa	1860
Compressive Strength	MPa	1470
90° Tensile Strength	MPa	76
In-Plane Shear Strength	MPa	98
90° Compressive Strength	MPa	85
Longitudinal Young's modulus, E_1	GPa	135
Transverse Young's modulus, E_2	GPa	8
Poisson's Ratio, υ_{12}	-	0.27
Shear Modulus, G_{12}	MPa	3800
Shear Modulus, G_{13}	MPa	7170
Shear Modulus, G_{23}	MPa	7170

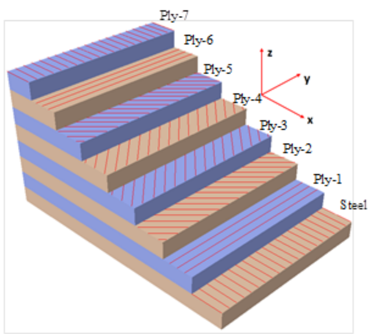


Fig. 2. A schematic of the layup as defined by the "Composite Layup" feature in Abaqus.

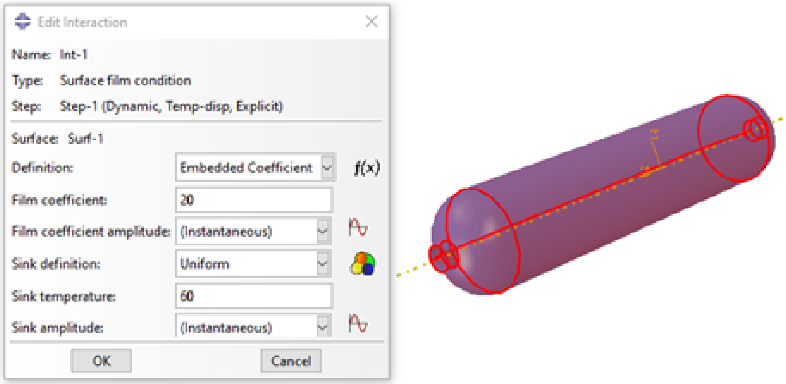
Table 2. Mechanical properties of A516 steel.

Material	Yield stress	Tensile strength	Young modulus
Steel A516	408MPa	580MPa	210GPa

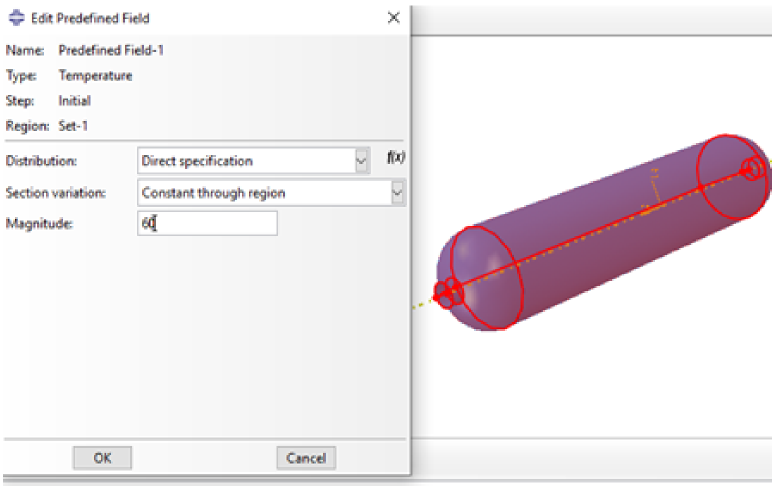
walls of the tank. On the other hand, to apply thermal loading, the thermal properties of the material must be entered first, which is done in the material properties step. In the next step, it is necessary to use the temperature-displacement coupled analysis. As shown in Fig. 3, the preload caused by 60 degrees Celsius is entered in the loading part. In the numerical simulation using ABAQUS 2021, a Windows 10 PC with a 64-bit operating system, 8 CPUs, 32 GB of RAM, and an Intel Core™ i7-11700 processor was utilized. The metal part of the vessel was meshed using eight-node linear brick elements with reduced integration (C3DR8). On the other hand, the composite sections were meshed with eight-node quadrilateral continuum shell elements (SC8R). Before conducting detailed analyses, a mesh convergence study was performed. The Finite Element Model (FEM) employed in this study comprised 25,182 elements and 34,208 nodes, which aided in reducing the CPU time of the conventional computer used. In the finite element analysis, the temperature was applied to the system as an initial condition. This means that during the analysis using the temperature-displacement couple analysis, the temperature remained constant throughout the entire system. Additionally, an external force was applied to the system in the form of pressure with a specific value.

3. Crack modeling by extended finite element method

One of the methods that can be combined with the extended finite element method (XFEM) to model crack growth is the Linear Elastic Fracture Mechanism (LEFM), which is suitable for modeling cracks in brittle parts [34]. In this method, the displacement term of the crack tip is not considered. The strain energy release rate is calculated using the Virtual Crack Closure Technique (VCCT) at the crack tip, and when the strain energy release rate of the element nodes is higher than the crack tip release energy value, the nodes are separated from each other, and a crack is created in the element. Crack growth modeling by the combination of XFEM and LEFM is also used to investigate the fatigue of parts and crack growth due to cyclic loads. In the displacement method, it is impossible to define different values for the failure behavior under normal or shear stresses, and only the displacement value after the failure initiation should be defined. In the energy method, different behavior and strengths can be defined in terms of normal and shear stress in different directions to simulate the failure behavior of the element. Investigating the creation and growth of cracks is one of the basic issues in the design of components and estimating their strength and lifetime. In ABAQUS, XFEM can be used to calculate stress intensity factors and analyze crack propagation. In this research, the XFEM is used to investigate the crack growth



(a)



(b)

Fig. 3. Applying thermal loading and preheating.

(as demonstrated in Fig. 4, a 4.5 mm crack is created in the tank).

4. Results and discussion

4.1. Validating the results

In the present research, the results of Ghiţă et al. [35] with a tank made of CrMo434 and placed at the pressure of 32.6 MPa and a temperature of 40 degrees Celsius are used to verify. C3D8R elements are used in this study. According to their results, the stress caused by the mentioned pressure and temperature was 510.67 MPa. In the present research, the total stress is 509.7 MPa (Fig. 5), which shows good agreement with their results.

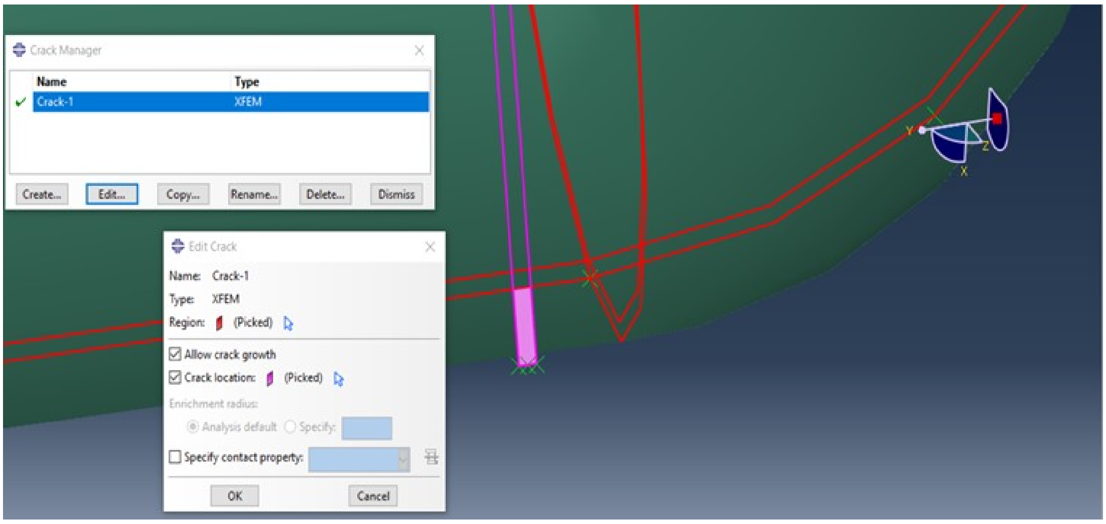


Fig. 4. Creating cracks by XFEM in ABAQUS.

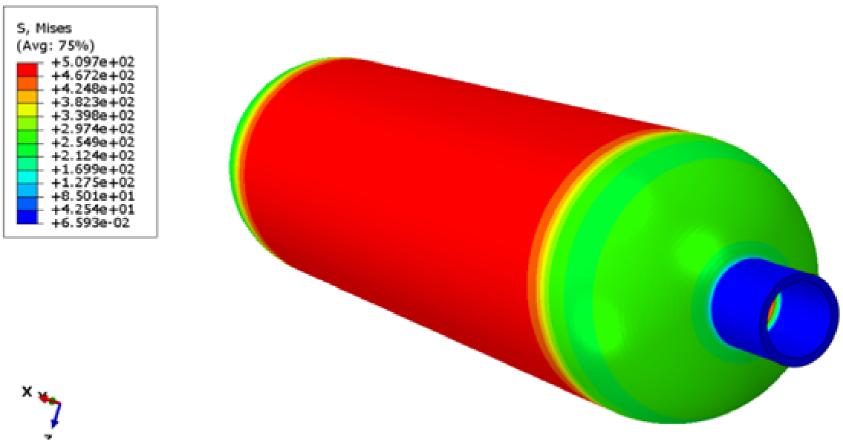


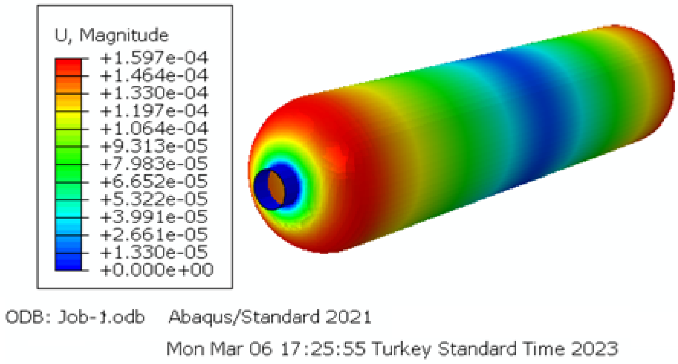
Fig. 5. Stress distribution in the validation sample.

4.2. Effect of parameters

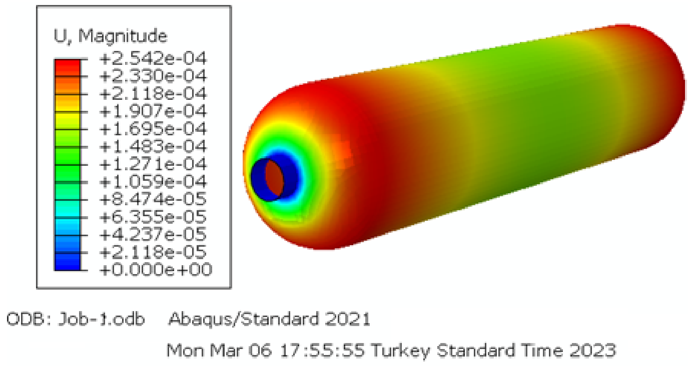
Fig. 6 demonstrates deformation in both tanks (steel and composite). The steel tank shows a deformation of 0.25 mm, while the composite tank shows a deformation of less than 0.2 mm. Also, as mentioned, the composite material shows better behavior. As can be seen for the steel material, there is more deformation in the center of the tank due to the internal pressure of the tank. Also, the deformation profile for the composite tank shows that the composite tank has higher resistance against the resulting loads.

As shown in Figs. 7 and 8, the maximum stress in the composite case is 281.1 MPa, while in the steel case, it is 292.2 MPa, which indicates that the stress level is higher for the steel case. Also, it is observed that the stress distribution in the composite tank is much more optimal, and the composite tank has smaller critical areas. The reason can be found in the different behaviors of steel and composite. Steel is isotropic, and if pressure is applied at one point, it cannot spread the applied pressure within itself. Therefore, the pressure is concentrated, and as a result, there will be more deformation [36].

On the other hand, the composite is layered, and when pressure is applied to the tank, it has the ability to spread the pressure within itself, and as a result, less deformation occurs in the tank. In addition, it can be observed that the stress on the tank wall has a direct relationship with the



(a)



(b)

Fig. 6. Deformation in the tanks: (a) composite material (right side) and (b) steel material (left side).

pressure and diameter. This means that as the pressure and diameter increase, the stress on the wall also increases.

Examining the deformations of metal and composite tanks shows better resistance of the composite tank against the internal loads resulting from the pressure inside the tank. The distribution of the XFEM circumferential damage ahead of the defect is illustrated in Fig. 9. According to the crack growth path shown in Fig. 9, it can be seen that for the composite tank, the crack starts at the pressure of 150 MPa and is horizontal and in line with the longitudinal axis of the tank. The results show that in these tanks and under high pressure, rupture occurs in the middle area of the tank. This is exactly consistent with experimental behavior [37]. This is the same location that the initiations of axial cracks were recognized on the high pressure. The initiation and partial growth of parallel cracks at the same section can be attributed to the ring loading nature of the deflagration pressure.

5. Conclusion

In the present research, after modeling the cylindrical steel and layered composite tanks in ABAQUS software and validating the results, the simulation results were studied.

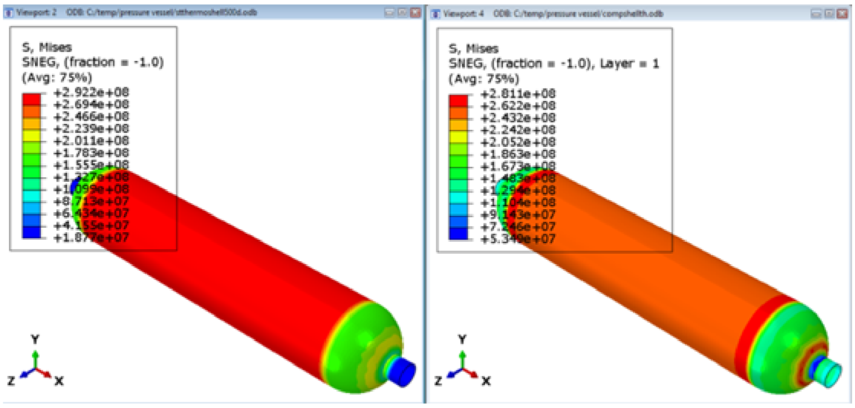


Fig. 7. Stress distribution in the tanks: composite material (right side) and steel material (left side) for the temperature load of $40^{o}C$ and the pressure load of 150 MPa.

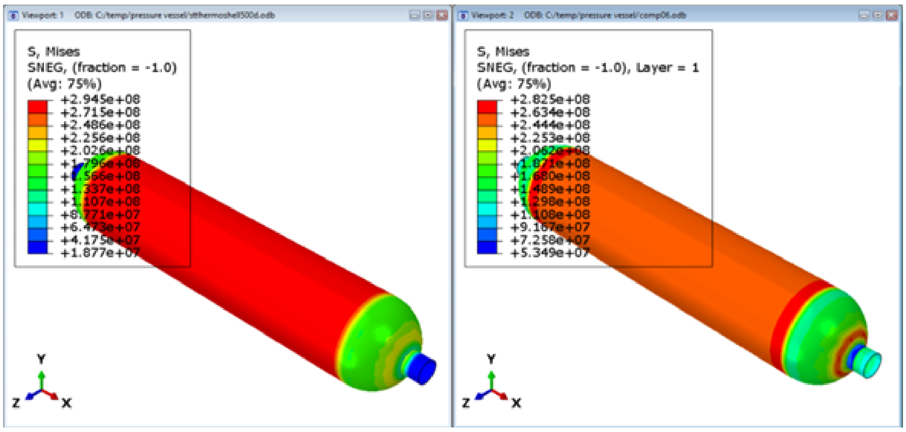


Fig. 8. Stress created in the composite (right) and steel (left) tanks for the temperature load of $60^{o}C$ and the pressure load of 150 MPa.

The results showed that the deformation of the metal tank is about 0.25 mm, while the deformation of the composite tank is less than 0.2 mm. Also, the steel tank sustained more deformation compared to the composite tank, with a maximum stress of 292.2 MPa instead of 281.1 MPa for the composite tank, which depicted that the stress level was higher in the steel tank. Moreover, the composite tank could tolerate more pressure due to the layer. Also, the composite pressure tank demonstrated better resistance against the deformations caused by the pressure inside the tank compared to steel material. According to the mentioned results, it can be derived that the proper composite materials can be a reliable alternative to steel material in pressure tanks. It is expected that with more studies on composite structures, more applications can occur in other fields of study.

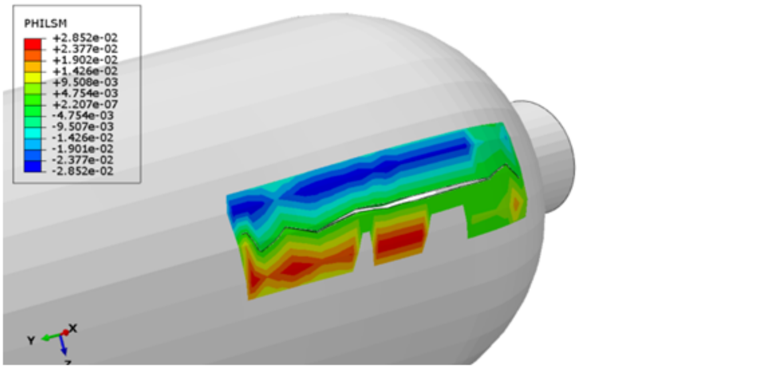


Fig. 9. Crack propagation in the composite tank at the pressure of 150 MPa.

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