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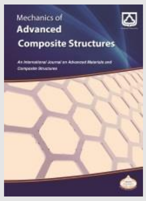


# Experimental and Numerical Study on the Strength of Repaired Steel Pipes with Composite Patches under Internal Pressure

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**K E Y W O R D S**

Repaired steel pipe;

Composite patch;

Hydrostatic test;

Experimental study;

Numerical simulation.

**A B S T R A C T**

Considering the old methods of maintenance and repair of oil and gas pipelines such as welding or replacing a part of the damaged pipeline which include high costs and spending a lot of time, the important usage of novel methods with lower costs such as the use of composite patches can be highlighted. In this research, the strength of steel cracked pipe with composite patches of glass fibers and epoxy/polyester resins has been studied experimentally. A crack with a length of 15 mm in the longitudinal axis of the pipe is considered. The specimen was subjected to internal pressure by a hydraulic pump to evaluate the strength of the glass/epoxy and glass/polyester composite patches considering the effects of fiber distributions, fiber angles, number of layers, and dimensions. Also, a comparison has been made between glass/polyester composites in two modes of complete curing and initial curing. Finally, the experimental test results were compared with the numerical simulations obtained by Abaqus software and the accuracy and precision of the study were verified. Some of the obtained results indicate that arrangement and number of layers have significant roles in the pressure-bearing capacity of composite patches. In this paper, for the first time, the effect of composite patches with different fiber orientations and the number of layers as well as curing effects are considered for the cracked pipe. The results show that the pressure-bearing capacity of composite patches rises with increasing the number of composite layers. Also, it can be seen that after complete curing of the glass-polyester composites, the pressure-bearing capacity rises about 3 times in 3- and 5-layer composites, and in 7-layer ones, it increases about 2 times.

## 1. Introduction

Pressurized pipes have always been exposed to damage during operation due to internal pressure, temperature change, and corrosion. Due to the high cost of repairing and maintaining oil and gas pipelines, the use of newer and less expensive methods such as utilizing composites can replace the old methods including welding or replacing the part of the damaged pipeline. One of the newer methods is the use of fiber-reinforced polymer-based composite patches. Various research works have been presented in the field of repairing damage to pipes and pressurized vessels [1-8]. For instance, Mattos et al. [4] analyzed corroded thin-walled metallic pipes reinforced with polymer-based composite repair systems. They propose a methodology to estimate the failure pressure of a reinforced pipeline with arbitrary geometry of the corroded region. The authors of ref. [5] studied the probability of monitoring the repair region of the pipeline with a permanently-attached array of piezoelectric sensors emitting ultrasonic-guided waves. Li and his colleagues [6] experimentally analyzed the external surface crack growth in the steel pipeline reinforced with a composite system repaired. Elhady et al. [7] investigated the failure examination of the cracked steel pipeline repaired by glass fiber

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reinforced polymer utilizing the 3-dimensional elastic-plastic finite element method. Zhang and his colleagues[8] studied the debonding failure investigation of corroded pipelines repaired with carbon fiber-reinforced polymers subjected to tension and bending moment.

Traditionally, the in-service defective pipelines were repaired with the external welding technique, the damaged part was cut off and new substitutions were used [1, 9]. Nowadays, welded leak boxes, full encirclement steel sleeves, and steel mechanical clamps are commonly utilized. Nevertheless, some concerns exist with those repair methods, such as high residual stresses, pipe wall melting, and hydrogen-assisted cracking [10, 11]. For tackling these defects, an alternative in-service repair technique, namely, composite repair systems can be used [12-14]. In these composite repair systems, the external defects (or cracks) of the pipe wall are filled with grouts, including epoxy resins, then coiled with composite layers using interlayer adhesive. The composite repair system provides different benefits. It needs lower maintenance costs and a shorter time. Moreover, the integrity of the pipeline is maintained during the repair process, therefore the pipelines can continue to operate without any leakage. Furthermore, the potential danger of explosion is omitted [15-17]. Some studies have been conducted based on experimental, analytical, and finite element techniques on the defective pipelines repaired with composite repair systems [18-21].

Many composite repair systems are based on the wrap repair technique. While the defect geometry has a notable effect on the remaining strength of defected pipeline [22], the complete wrap repair technique may be excessive for some small (or shallow) defects. Therefore, the application of patch repair could be practical. Furthermore, by utilizing a pre-cured composite patch, the time for repairing can be significantly reduced. Theisen and Keller [23] performed experimental tests and finite element simulation for the patch as well as wrap repairs on through-wall defects. Their results illustrated that the maximum strain of the patch was nearly higher than that of the wrap type. Ayaz and his colleagues [24], perused the composite patch restoration for a tiny through-wall hole. They concluded that the increment in overlap length may increase the failure strength. Sulu and Temiz [25] studied the internally pressurized composite (made of E glass fiber/epoxy) pipe system using various radii pipes via the finite element technique and experimental failure tests. Mehditabar and Rahimi [26] studied functionally graded (FG) pipes utilizing continuum damage mechanics parameters and exposed them to thermomechanical loadings. Ebrahimi-Mamaghani et al. [27] examined thermo-mechanical vibrations of FG pipes conveying fluid using Rayleigh beam theory and power-law distribution function. Yu et al. [28] analyzed the elastic-plastic investigation of thin-walled pipes. The mechanical feature of adhesively repaired pipes exposed to internal pressure was studied by Citil et al.[29]. In their paper, the cracked pipes were repaired using adhesive and galvanized steel patches. Savari[30] theoretically studied failure analysis of composite repaired pipes exposed to internal pressure. Also, Savari et al.[31] studied failure pressure examination of pipe repaired using composite sleeve exposed to thermal and mechanical loads. Sadrabadi and his colleagues[32] studied steel pipe repair with a composite sleeve experimentally and numerically. The examination of the tensile and flexural behavior of the nano clay wood-plastic composite was performed by Golmakani et al[33]. In another study, Golmakani and his colleagues[34] investigated wood flour size, aspect ratios, and injection molding temperature on the mechanical properties of wood flour/polyethylene composites. Omidi and his colleagues[35] perused the repair of circumferential through-wall cracked pipe utilizing a local composite patch.

Various numerical methods have been recently proposed for the fracture analysis of composites such as the differential quadrature [36] and Bezier methods [37] proved to have high stability and accuracy results.

Commonly, the composite patch repair technique is chiefly utilized for small-section through-wall defects. On the other hand, some defects may be a gradual deterioration procedure, and the pipe can be failed because of internal pressure (even in the case of the existing shallow defect on the pipe wall). From this literature review, it can be understood that increasing the strength and pressure-bearing capacity of pipes and reducing the repair process time is very important and necessary. Reducing the cost of repair is also very important and by meeting all these needs, a proper repair system can be achieved. Also, bonding composite patches with glue to the cracked pipe is a new, advanced, and economical reinforcement technology for repairing and strengthening damaged pipe. Although this method has many advantages, due to the brittleness of the adhesive, it may suddenly break and separate on the joint surface of the composite and the metal pipe before reaching the expected final capacity. For this reason, predicting the behavior of the adhesive is crucial.

According to the best knowledge of authors, there has been no published paper considering composite patches with different fiber orientations and the number of layers as well as curing effects for the cracked pipe. In the present paper, with the aim of achieving a suitable design for the restoration of pipes containing cracks with glass/epoxy and glass/polyester composite patches detailed experimental and numerical studies have been carried out considering the effect of patch dimension, fiber angles, and the number of layers. Also, the effect of curing and the roles of different fiber distributions have been investigated on the strength and capacity of composite patches (under internal pressure). Finally, comparing the experimental with numerical simulations obtained by Abaqus software show the accuracy and precision of the study.

## 2. Methodology

Materials used in the manufacture of composite patches (for the repair of pressure vessels) include 330g of unidirectional glass fibers type E of the product of Metyx company (of Turkey) with a relative density of 2.55 for the reinforcing section. Also, in the Matrix section, EPIKOTE epoxy resin 828 is selected with Hardener, a product of an American company, and polyester resin is applied with the catalyst and accelerator. In general, 36 samples were made, 18 of them are glass-epoxy and 18 samples are glass-polyester.

To select the dimensions and specifications of the pipe (including length, thickness, material, etc.), the ASME SEC VIII standard (standard for the construction of pressure vessels with a pressure less than 3000 psi) has been used. In order to investigate the behavior of the composite patch on the damaged pipe, a pipe according to ASME SEC VIII standard with a length ($L$) of 170mm with an outer diameter ($D_o$) of 90 mm, and a thickness ($t$) of 4 mm, was used to make the considered pipes. Also, a 15 mm long ($l$) crack in the direction of the longitudinal axis of the pipe is created by the laser.

Schematic of the cracked steel pipe and the components of the steel pipe (before and after assembly) are shown in Figure 1. It is noted that Tungsten Inert Gas (TIG) welding is used for making the specimens (Figure 1. C).

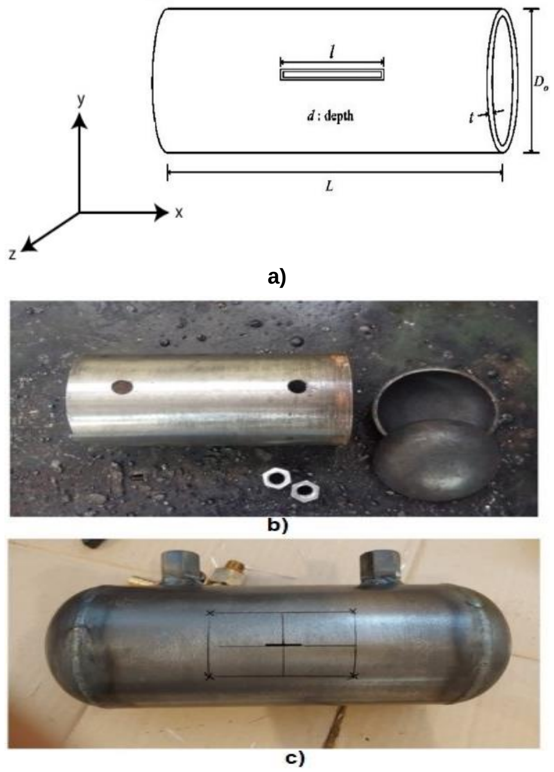



**Fig. 1.** Schematic of a) cracked steel pipe, b) steel pipe before, and c) after assembly

One of the most common methods of surface preparation (in order to achieve the necessary roughness) is the use of the sandblasting method. After removing imperfections and sanding the surface of the pipe with rough sanding (according to ASME PCC- 2 Standard), first, by wire brush, the desired surface was slightly roughened to better bond the adhesive to the surface of the steel pipe, and after removing dust, Acetone was used to clean the surface of the pipe from any dirt or grease.

The manual layering method was used to make the composites. Multi-layers were considered as 3, 5, and 7 layers with different arrangements of 0/90/0, 0/120/0, and 0/150/0 and dimensions of 60 mm ×40mm. The resin and fibers were selected in the ratios of 60 to 40 of weight percentage, respectively, (due to the higher mechanical properties of the fibers compared to the resin). Also, the weight of fibers with the desired dimensions was measured by a digital scale with an accuracy of 0.01 g. Then, according to the weight obtained and the ratios of 60 to 40 (of the matrix to the reinforcement), the weights of the resin and hardener mixture were determined. After determining the material ratio, a thin layer of adhesive was applied to the surface of the pipe and then a layer of fibers and a layer of resin were used, respectively, to reach the desired number of layers or thickness.

The mixing ratio of resin and hardener in two-component epoxy (with the specifications of Table 1) is 2 to 1 (which means the amount of epoxy resin is as twice as the hardener), and three-part polyester resin includes 2% (weight percentage) of catalyst and 0.5% (weight percentage) of accelerators to the amount of polyester resin used.

**Table 1.** Epikote 828 epoxy resin specifications according to ASTM standard (2007)

| properties | Test method | Amount |
|---|---|---|
| Epoxy molar mass | - | 184-190 g |
| Viscosity (at 25°C) | ASTM D445 | 0-12.14 Pa.s |
| Density (at 25°C) | SMS 1347 | 1.16 kg/L |
| Flash point | ASTM D93 | 150°C > |
| Maximum elongation | % | 4 |

Also, specifications of polyester resin (according to ASTM standards) were assumed as viscosity (at 25°C) of 150 Pa.s, density (at 25°C) of 1.15 kg/L, and maximum elongation of 4%.

Composite patches are made by hand lay-up method, which is the simplest method and based on fiber cutting, the weighting of the desired resin, and taking into account the volume fraction of fibers and resin. The volume ratio of fibers to resin is 60 to 40, due to the higher mechanical properties of fibers compared to resins. In order to connect the composite patches to the surface of the steel pipe, after preparing the desired surface, the inside of the crack is filled with resin and after the resin has dried a little, a thin layer of glue is applied to the surface of the pipe and then we continue to arrange a layer of fiber and apply a layer of resin until the desired number of layers or thickness is reached. In this present method, the fiber sheets must be completely covered with resin, also for preventing bubbles between the composite layers, a roller and a wide adhesive tape (which was removed for 24 hours at room temperature before final curing) are used. Figure 2 shows a steel pipe repaired by composite patch using the hand lay-up method.

**Fig. 2.** Repair of cracked steel pipe using composite patches by the hand lay-up method

Glass/epoxy and glass/polyester were cured for about 12 and 6 hours at 70 ° C, respectively, to obtain the highest strength. The Schematic of repaired steel pipes can be seen in Figure 4.

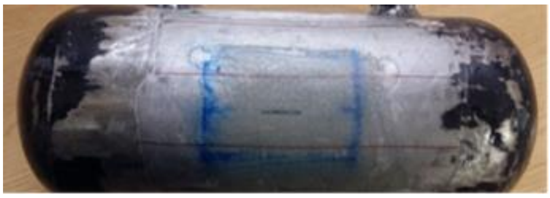


**Fig. 3.** Schematic of repaired steel pipes

One of the major techniques for finding the leakage pressure of pipes is hydrostatic testing, in which a manual hydraulic pump with a capacity of 150 bar pressure is used. In order to perform hydrostatic tests, in the first step, the pump storage and the considered pipe were filled with Behran HP46 hydraulic oil, and then the other parts, including the oil inlet hose and the calibrated pressure gauge, were installed on the pipe. The specifications of the hydraulic oil which is used in this paper, are presented in Table 2.

**Table 2.** Chemical characteristics of Baharan HP46 hydraulic oil

| Type of oil | Viscosity index | Flash point °C | Pour point°C | Density kg/m³ |
|---|---|---|---|---|
| Behran HP46 | 95 | 208 | -2 | 880 |

Before applying pressure, all parts were checked to prevent oil leakage. At this step, 36 samples were tested and to ensure the accuracy of the results, some samples were examined three times and their average results were recorded. In the Hydrostatic test, the pressure will continue to increase until the leakage occurs and the maximum allowable pressure should not be exceeded. As soon as the minimum leakage is observed, the test pressure is recorded and the test is terminated. Figure 4 describes how the hydrostatic test was performed in this study. Also, Figure. 5 shows the hydrostatic testing for the repaired steel pipe.

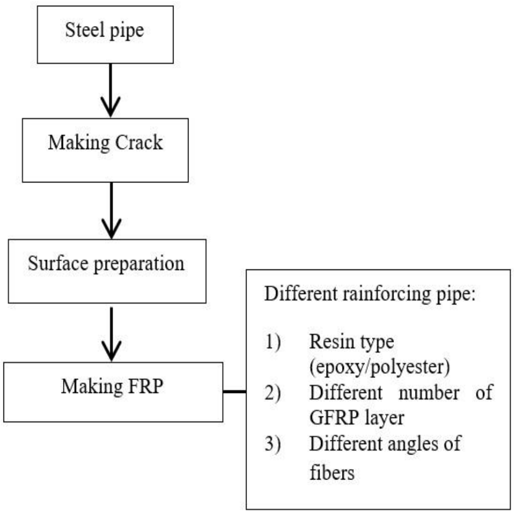



**Fig. 4.** Repair steps of cracked (or defected) pipe

**Fig. 5.** Hydrostatic testing for the repaired steel pipe

Leakage can be detected by pressure drop. In all tests, no complete rupture of connections or composite patches was observed and the leakage happened in the form of linear oil leakages, which can be seen in Figure 6.

**Fig. 6.** Composite patch leakage under internal pressure

## 3. Results and Discussion

Because performing experimental tests are very expensive, the use of finite element simulations can be applied as an alternative option, or in some cases, it can be utilized to verify the results of practical tests. The accuracy of the actual test in comparison with numerical simulation results are depended on the geometry, material behavior, boundary conditions, and loading. In this paper, the hydrostatic tests of the repaired pipes with composite patches were also numerically simulated by the Abaqus software [38]. The cracked steel pipe is designed in SolidWorks software and imported into Abaqus software from the import option. The composite patch is designed in a three-dimensional format and deformable shell type in the Abaqus part module. In the next step, in the property module, the elastic properties for each material are defined according to Table 3. In this study, the type of loading and boundary conditions are assumed as internal pressure and clamped-free boundary condition, respectively. Also, in the mesh module (of the Abaqus software [38]), the automatic sweep technique with a mesh size of 0.0022 is used for meshing the pipe. Moreover, the structure technique is used for the composite patch with a mesh size of 0.0015, and the mesh shape is set to Hex. Also, it should be noted, $D$ represents patch dimensions, $n$ is the number of layers and Θ is defined as an orientation angle.

In the repair process, the maximum stresses are transferred to the adhesive and consequently to the composite patch to reduce the stress at the crack tip. Therefore, the properties of the adhesive will have a great impact on the strength of the damaged pipe. As a result, the greater damage requires a lower pressure-bearing capacity of the pipe [39].

The properties of the adhesive are defined according to the elastic matrix of the cohesive material. In the non-coupled state, the adhesive is defined by only three components. In general, adhesive damage properties are usually defined based on the two theories of maximum nominal stress and quadratic traction.

These two criteria predict the onset of damage in adhesive elements, where the adhesive layers are separated by tension. Both theories evaluate the ratio of the stress between the amount of stress applied and the maximum amount of stress in all three directions. The relations of the theories are defined based on the following equations [38]:

Maximum nominal stress:

$$\text{MAX } \frac{\sigma n}{Nmax}\frac{\sigma t}{Tmax}\frac{\sigma s}{Smax} = 1 \quad (1)$$

Quadratic traction:

$$\text{MAX } \frac{\sigma n}{Nmax}\frac{\sigma t}{Tmax}\frac{\sigma s}{Smax} = 1 \quad (2)$$

It should be noted that parameters $\sigma s$, $\sigma n$, $\sigma t$ are the values of maximum tensile and shear stresses of the adhesive, and n, s, t are the directions of the stress components in the elastic range. In this section, the theory of quadratic traction is used which considers the simultaneous quadratic ratios between the nominal stress and the allowable stress in different directions, and the right-hand sides of equations 1 and 2 are equal to one, as a criterion for the onset of damage in the adhesive. Using the quadratic traction theory to predict the pressure-bearing capacity and the onset of failure and separation in the adhesive element, it can be concluded that the results of experiments with numerical simulation [38] are in good agreement (Table 4). As can be compared from Table 4, in the numerical simulation method, all tests showed less pressure-bearing capacity than the experimental tests. This can be persuaded by the fact that numerical results show only the beginning of the separation process and the beginning of the damage in the adhesive, but the experimental test considers the complete procedure. The results have an error of about 2% in the angle of 0/90/0, about 5% in the angle of 0/120/0, and the highest error of about 10% in the angle of 0/150/0.

**Table 3.** Mechanical properties of pipe, composites, and resins according to ASTM standard tests [40]

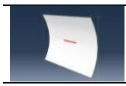
|  | Steel pipe | Glass-Epoxy | Glass-Polyester | Epoxy | Polyester |
|---|---|---|---|---|---|
| E1 **(GPa)** | 190 | 55 | 52.2 | 2.55 | 2.61 |
| E2, E3 (GPa) | - | 15 | 14.2 | - | - |
| υ12,υ13 | 0.33 | 0.33 | 0.217 | 0.33 | 0.38 |
| υ23 | - | 0.428 | 0.382 | - | - |
| G12, G13 (GPa) | - | 4.7 | 4.2 | - | - |
| G23 (GPa) | - | 3.28 | 2.9 | - | - |

**Table 4.** Comparison of experimental results and numerical simulation in glass-epoxy composite

| Number | Composite patch | Experimental pressures, PEXP (Bar) | Numerical pressures, PNUM (Bar) | PExp/PNum |
|---|---|---|---|---|
| 1 | 3ply[0/90/0] | 90 | 88.11 | 1.021 |
| 2 | 5ply[0/90/0] | 115 | 113.045 | 1.017 |
| 3 | 7ply[0/90/0] | 125 | 121.375 | 1.029 |
| 4 | 3ply[0/120/0] | 90 | 85.77 | 1.049 |
| 5 | ply[0/120/0] | 122 | 117.73 | 1.035 |
| 6 | 7ply[0/120/0] | 127 | 121.793 | 1.041 |
| 7 | 3ply[0/150/0] | 92 | 83.94 | 1.096 |
| 8 | 5ply[0/150/0] | 122 | 111.996 | 1.082 |
| 9 | 7ply[0/150/0] | 128 | 117.352 | 1.091 |

The simulation results with the stress contour for the pipe and the composite patch are shown separately. Figures 7 and 8 show the von Mises stress around the crack in the steel pipe and glass-epoxy composite patch, respectively. As can be seen, most of the stresses of the cracked pipe are around the damaged area and at the edges of the crack tip. Moreover, there are local stresses in the axial direction of the pipe, and the stresses are significantly reduced by moving away from the crack tips. In a pressurized cracked pipe reinforced by the composite patch, the highest stress concentration is located in the center of damage. Furthermore, the most stresses are seen in the peripheral axis which can be persuaded by the fact that the internal stress in the peripheral direction is about twice as much as the axial stress of the pipes under pressure. So, most leakages occur in this direction. As a result, increasing the dimensions of the patch in the axial direction cannot have much effect on the strength of the pipe.

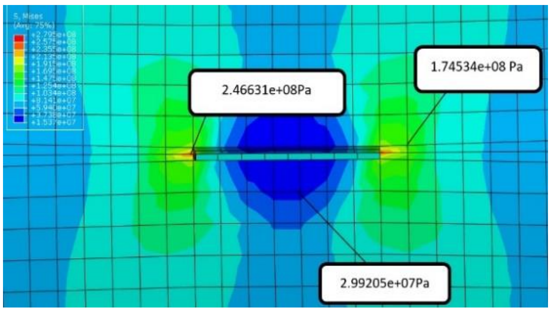



**Fig. 7.** Stress around the crack in the cracked steel pipe

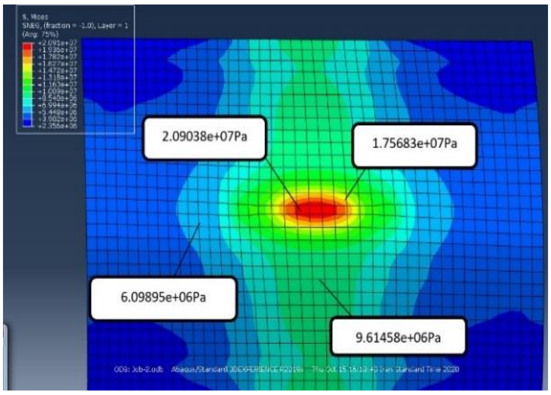



**Fig. 8.** Stress in the composite patch

Tables 5 and 6 show the comparison of the internal pressure-bearing capacity of glass/epoxy and glass/polyester composites with different parameters of fiber angle and the number of layers (n) for pipes with patch dimensions of 60mm×40mm and 80 mm×60mm, respectively. In this study, the crack is located in the axial direction of the pipe and as shown in the Tables, the angle of 0/120/0 has a higher pressure-bearing capacity than 0/90/0.

The results of angles of 0/150/0 with 0/120/0 do not differ significantly (in terms of increasing the pressure-bearing capacity) and show almost the same behavior against internal pressures. With increasing the number of layers, the difference in the amount of pressure-bearing capacity at different angles in glass/epoxy and glass/polyester composites has become more significant.

**Table 5.** Comparison of hydrostatic internal pressure test results for different fiber angles and numbers of layers for the patch dimension of 60 mm ×40mm

| Internal pressure, Bar<br>Patch dimensions: 60 mm ×40mm | | | | | | |
|---|---|---|---|---|---|---|
| | Glass-Epoxy | | | Glass-Polyester | | |
| *n* | [0/90/0] | [0/120/0] | [0/150/0] | [0/90/0] | [0/120/0] | [0/150/0] |
| 3 | 90 | 90 | 92 | 70 | 80 | 85 |
| 5 | 115 | 122 | 122 | 95 | 98 | 100 |
| 7 | 125 | 127 | 128 | 120 | 120 | 123 |

**Table 6.** Comparison of hydrostatic internal pressure test results for different fiber angles and numbers of layers for the patch dimension of 80 mm ×60mm

| Internal pressure, Bar<br>patch dimensions: 80 mm ×60mm | | | | | | |
|---|---|---|---|---|---|---|
| | Glass-Epoxy | | | Glass-Polyester | | |
| *n* | [0/90/0] | [0/120/0] | [0/150/0] | [0/90/0] | [0/120/0] | [0/150/0] |
| 3 | 90 | 120 | 122 | 85 | 90 | 92 |
| 5 | 120 | 125 | 126 | 97 | 105 | 107 |
| 7 | 125 | 128 | 128 | 120 | 122 | 125 |

High-pressure pipelines have a pressure of about 70 psi to 110 psi. As shown in Tables 5 and 6, glass/epoxy composites with 3 layers have reached a sufficient pressure capacity to be used in high-pressure pipelines. In glass/polyester composites, this strength is created in 5 and 7 layers. It can be concluded that in polymer-based composites the strength rises with increasing the thickness of the composites (especially in polyesters which have lower strength and mechanical properties than epoxies). Another point that can be concluded from the data of the Tables, is that in both types of composites, with increasing the number of layers, the strength has increased significantly. Also, as the number of composite layers increases, the difference in the strength of glass/epoxy and glass/polyester composites decreases, and the results are very close to each other. On the other hand, in the number of layers with less thickness, there is a significant difference between the two types of composites.

In composites, the dimensions of the patches should be the optimal size, because increasing the length of the composite patch does not always increase its bearing capacity and only increases the repair costs. In experiments performed on glass-epoxy composites, there was not much difference between 60 mm ×40mm, and 80mm×60mm dimensions, therefore 60 mm ×40mm can be considered as the suitable patch size, but in glass-polyester composites, with increasing dimensions, it is better to consider the dimensions of 80mm×60mm as the appropriate size because of observing about 1.5% increase in the pressure-bearing capacity. In general, increasing the patch thickness and decreasing the adhesive thickness increases the strength of the damaged pipes. However, increasing the thickness of the patch excessively with a large number of layers (or a dramatic decrease in the thickness of the adhesive layer) will lead to undesirable performance and untimely separation. As can be compared from the Tables, when glass/epoxy composite is used to repair the pipe, the strength of the pipe is increased more significantly.

The effect of complete curing on the strength and pressure-bearing capacity of glass-polyester composites under internal pressure is illustrated in Table 7. The results of complete curing on glass-polyester composites show that after the curing process, the pressure-bearing capacity and efficiency of the composites increase several times. For curing composite patches in pipelines where it is not possible to use a furnace, heat blankets made of elements and silicone layers are used.

Furthermore, it can be seen (in Table 7) that in 3- and 5-layer composites, the pressure-bearing capacity rises about 3 times and in 7-layer composites, it increases about 2 times after complete curing. Also, it can be seen that by increasing the dimensions of the composite patch, the pressure-bearing capacity has increased.

**Table 7.** Effect of complete curing on the strength and pressure-bearing capacity of glass-polyester composites under internal pressure

| | Internal pressure, Bar | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $D1$=60 mm ×40mm | | | | | | $D2$=80 mm ×60mm | | | | | |
| | θ[0/90/0] | | θ[0/120/0] | | θ[0/150/0] | | θ[0/90/0] | | θ[0/120/0] | | θ[0/150/0] | |
| $n$ | B.C | A.C | B.C | A.C | B.C | A.C | B.C | A.C | B.C | A.C | B.C | A.C |
| 3 | 20 | 70 | 25 | 80 | 28 | 85 | 30 | 85 | 40 | 90 | 45 | 92 |
| 5 | 25 | 95 | 30 | 98 | 33 | 100 | 50 | 97 | 55 | 105 | 55 | 107 |
| 7 | 55 | 120 | 58 | 120 | 60 | 123 | 57 | 120 | 60 | 122 | 65 | 125 |

## 4. Conclusions

The composite repair method is a newer and less expensive method than the old methods such as welding or replacing a part of the damaged pipeline. The purpose of this study is to investigate the strength of damaged steel pipes reinforced by glass/epoxy and glass/polyester composite patches considering the effect of patch dimension, fiber angles, number of layers, fiber distributions, and curing. Finally, the experimental test results were compared with the numerical simulations obtained by Abaqus software and the accuracy and precision of the study were verified. Some of the key results are as bellows:

- The pressure-bearing capacity rises with the increasing thickness of composite patches, especially in glass/polyester composites compared to glass/epoxy ones because of the lower strength and mechanical properties of polyester.
- As the number of composite layers increases, the difference in the pressure-bearing capacity of glass/epoxy and glass/polyester composites decreases, and the results are very close to each other. But in fewer layers (or less thickness), there is a significant difference between the two types of composite patches.
- The effect of fiber angles of glass/epoxy composite patches is more significant than glass/polyester types in the strength of damaged steel pipes.
- It can be seen that after complete curing of the glass-polyester composites, the pressure-bearing capacity rises about 3 times in 3- and 5-layer composites, and in 7-layer ones, it increases about 2 times.
- The glass-polyester composite reaches about 30-50% of its final strength in a short period of time before complete curing.
- Finally, the following subjects are recommended to researchers for future research:
- Investigating the impact of the dimensions of composite patches in repairing the damaged area using the finite element method.
- Examining damage geometry in tanks and pipes under internal pressure in terms of stress concentration using the finite element method.
- Investigating the effect of adhesive thickness in all types of adhesives on the strength of composite patches.
- nvestigating the effect of different reinforcements in resin compounds to increase the strength of composites in different industries.

## Nomenclature

| | |
|---|---|
| $E$ | Young's modulus |
| $v$ | Poisson's ratio |
| $G$ | Shear modulus |
| $D$ | Dimension of the patch |
| $D_o$ | Outer diameter of the pipe |
| $n$ | Number of layers |
| $P$ | Pressure (internal pressures) |
| $A.C$ | After Curing |
| $B.C$ | Before Curing |
| $L$ | Length of the pipe |
| $l$ | Length of the crack |
| $\theta$ | Fibers angle orientation |

## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

## Appendix A

After designing the tank elements and the composite patch, in the assembly module, the tank and the composite patch for each specimen were placed in the correct position relative to each other which can be seen in Figure A.1. It should be noted that in this paper for the simulation using Abaqus, linear static analysis has been used.

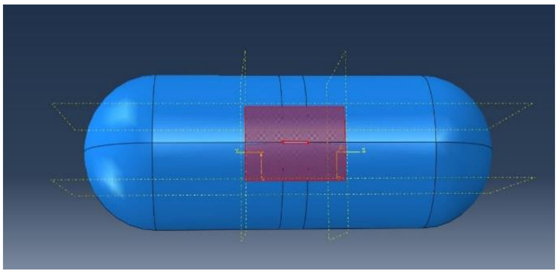


**Fig. A1.** Placing the composite patch in the correct position to repair the crack

In the next step, in the module step, the analytical needs and the process of doing the work are defined, in this section, the type is considered static, and in the interaction module, the surface-to-surface contact is chosen and shown in Figure A2.

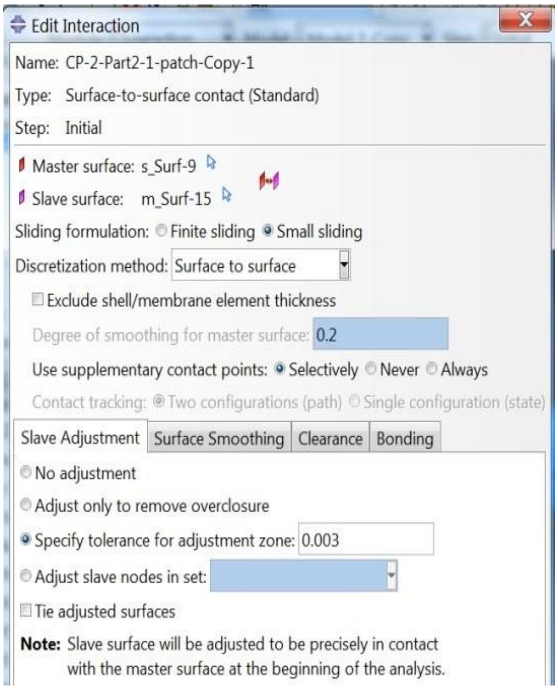



**Fig. A2.** Interaction module settings for a composite restored tank design

Next, from the contact property option, the adhesive contact properties are defined (figure A.3).

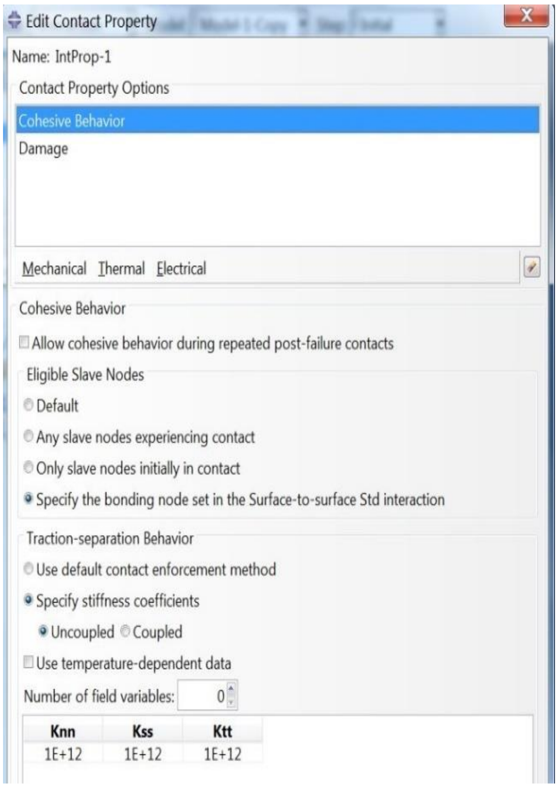



**Fig. A3.** Defining the adhesive and damage properties

In the load module, we specify the type of force and boundary conditions (figures A.4 and A.5).

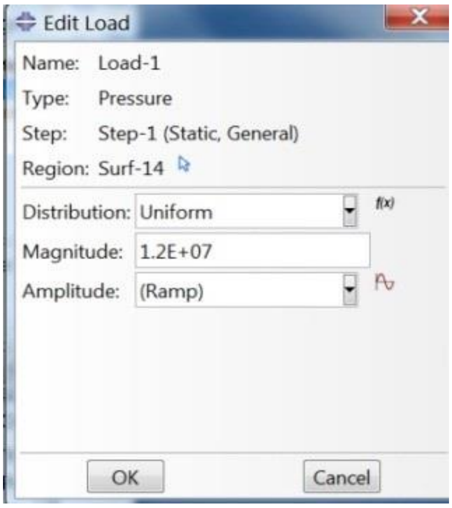



**Fig. A4.** Applying internal pressure to the steel tank

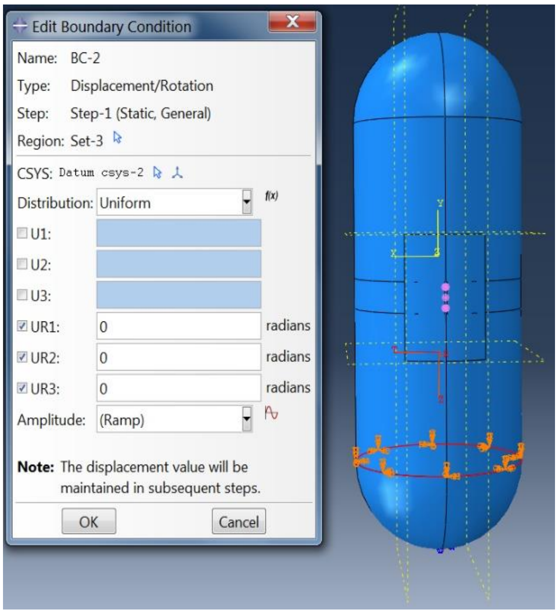



**Fig. A5.** Applying the boundary conditions

In the mesh module, the automatic sweep technique is used for meshing the tank in mesh size 0.0022 and the structure technique is used for the composite patch in mesh size 0.0015 and the mesh shape is set to Hex (Figure A.6).

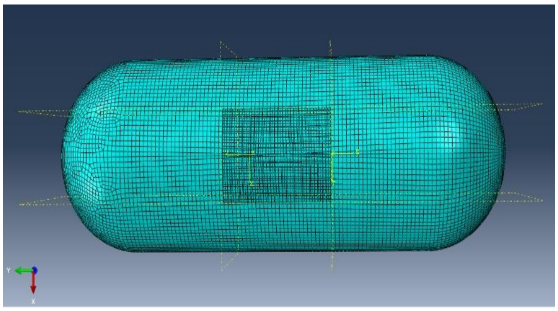


**Fig. A6.** Tank with a composite patch in mesh module

In the next step, in the job module, the simulated internal pressure test process was performed. Figure A7 Shows output selection using quadratic traction theory. Also, Figures. A8 and A9 show repaired tank model and prediction of adhesive element fracture based on quadratic traction theory using Abaqus software.

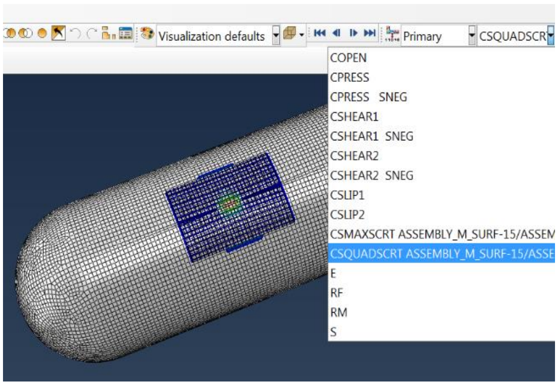



**Fig. A7.** Output selection based on quadratic traction theory

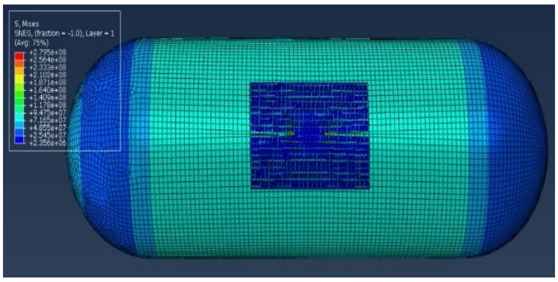


**Fig. A8.** Repaired tank model

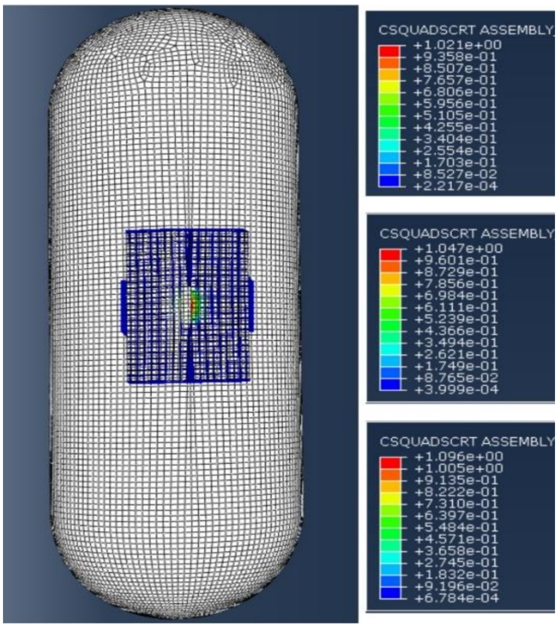



**Fig. A9.** Prediction of adhesive element fracture according to quadratic traction theory

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