Numerical Investigation of Fatigue Behaviors of Non-Patched and Patched Aluminum Pipes

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1. INTRODUCTION

The development of materials science has been a very important factor in the progress of technology in the process of history. For this reason, material science needs to be developed for the development of humanity. These two phenomena make up an inseparable whole. Developing materials science offers us solutions that are different, simple, practical, reliable and bring significant cost advantages for businesses when today's conditions are considered. These developments in material science provide cost advantages in the field of industry as well. Nowadays, instead of replacing damaged parts, it is generally preferred to carry out repairs to avoid time and money loss. In choosing repair methods, it is aimed to minimize time and cost. Particularly in tearing and cracking, patching method is preferred by using adhesive [1-6]. Therefore, there is no need for repair with mechanical connection forms such as screws, rivets, and welding. With this method, the destructive damages that may occur in the material can be prevented. In the literature, it is possible to find many studies on patching using adhesives. Some of these studies are presented below:

Lee et al. investigated the effect of different geometric shapes (rectangular, triangular, inverted triangular and parallelogram) on bonding strength [7]. In the study, consistent with the numerical results, they obtained the highest bonding strength in the inverted triangular patch. Gavgali et al. experimentally and numerically investigated the fatigue and static strengths of single-lap and three-step-lap joints, which were subjected to tensile and four-point bending tests [8]. In the study, they stated that the change in the geometry of the area where the bonding was made had a profound effect on both fatigue and fracture behavior of the joint. Sahin et al. investigated lifetimes of single-lap joints of five different adherend thicknesses obtained using AA2024-T3 aluminum alloy and DP460 structural adhesive under varying tensile fatigue loads [1]. In the study, they stated that the static tensile strength of the joints increased due to the increase in adhesion thickness. Karaman numerically investigated the behavior of double-sided lap joint of AA-5083 aluminum sheets with elliptical holes under bending load [9]. In the analysis, the bending damage loads of the samples were found. From the results, it was revealed that the patched samples carried a higher loads. Erkek experimentally investigated the effects of thermal aging on the buckling behavior of composite sheets repaired with a patch using adhesive from the outer part. In the study, it was observed that temperature and adhesive thickness variations affect the buckling load [10]. Ergün examined AA-5083 aluminum sheets with elliptical holes and glass fiber reinforced composite patches by joining them with DP-460 type adhesive. In the study, experimental and numerical results were found to be close to each other [11]. Adin et al. bonded
the composite material with AA-5083 aluminum material using DP-460 adhesive and examined the tensile strength. As a result of their studies, they stated that lap width and patch width are important [12]. Canbolat examined the repair of aluminum sheets by composite patches in case of damage. In the study, it was observed that damage loads and damage mechanisms converged experimentally and numerically [13]. Zarrinzadeh et al. investigated experimentally and numerically the effects of fatigue on crack growth in a cylindrical aluminum pipe with cracks. In the study, they stated that they approached the realistic behavior of the structure [14]. In another study, Zarrinzadeh et al. examined the fatigue life after patching on a cylindrical cracked aluminum pipe. Different from previous works, glass-epoxy composite material was used as patch material. In addition, they investigated the effect of patch length on fatigue life. As a result of the study, they found a directly proportional relationship between the increase in the number of layers and the fatigue life, and an inversely proportional relationship between the patch length and the fatigue life [15]. Liu et al. investigated the change in fatigue life as a result of patching the cylindrical cracked aluminum pipe with composite material. As a result of the study, they determined that there is a directly proportional relationship between the number of layers of the composite material and their fatigue life [16]. During the use of pipes, damages occur in the form of small cracks due to various internal and external effects [16-18]. In general, cutting out the damaged area and changing it with a new one causes loss of money and time. In this study, aluminum pipes with various cracks were repaired with patches made of glass-epoxy composite material. Later, the draft-pressure fatigue behavior of the patched pipes produced in this way was investigated by the finite element method. On the basis of the studies in the literature, the purpose of the research is to find the effect of the patch on the fatigue life of the structure. Studies in the literature investigate how fatigue life is affected after patching [19]. Although they used different parameters and materials, almost all of them obtained findings on the positive effects of the patch presence.

The tubular Al 6063 aluminum used in our study is a frequently preferred material in the industry. In case of damage of this material, its fatigue behavior was investigated after repair with a composite patch.

2. MATERIAL AND METHOD

In our study, numerical fatigue analyzes were performed using the Finite Element Method. Numerical analyzes were performed using the Ansys Workbench (15.0) finite element package program. In the analyzes, Al 6063 type aluminum pipe base material, [0/90], reinforced angle glass-epoxy patch and DP-460 industrial adhesive were used. In the analyzes, tensile-compression load was applied to the samples, and fatigue was achieved. Samples were modeled in three dimensions. The mechanical properties of Al 6063 type Aluminum pipe, [0/90], reinforced glass-epoxy composite material and DP-460 type industrial adhesive materials used in the analyzes are given in Table 1, Table 2 and Table 3 [11, 20].

The dimensions of the aluminum pipe used in the study are given in Fig. 1. All dimensions selected in the modeling of pipe samples were determined by considering the industrial uses of aluminum pipes. As seen in Fig. 1, the large diameter (D) of the aluminum pipe is 90 mm, the small diameter (d) is 86 mm, the length is 250 mm, and the pipe thickness is 2 mm. Cracked damaged pipes were examined in the analyzes [21]. The crack lengths in the pipes were taken as 1, 3, 5, 7 and 10 mm. The cracks occurred in the middle of the length of the pipe and perpendicular to the direction where the draft-compression loads were applied. Damaged pipe with a crack length of 10 mm is shown as an example in Fig. 1.

![Figure 1. Dimensions of damaged Al 6063 aluminum pipe.](https://dergipark.org.tr/en/pub/ejt)
length of the glass-epoxy patch material is 50 mm and its thickness is 0.4 mm.

Figure 2. [0/90]_2 reinforced angle glass-epoxy patch; a) front view b) isometric view (Unit: mm).

Analyzes were carried out in three parts as non-patched, quarter-circular and semi-circular patched. In the analyzes, the patches were positioned at the center of the pipe based on the center of the crack zone. Fiber orientation and reinforcement angles of the patches are given in Fig. 3.

Figure 3. Fiber orientation angles of glass-epoxy composite patches.

### 2.1. Fatigue analysis

In numerical analyzes, all three-dimensional models were made in the SolidWorks program according to the measurements given in Fig.1, and then finite element analyzes were made in the Ansys Workbench program [22]. Aluminum pipes are modeled as non-patched, quarter-circular and semi-circular composite patches. In addition, in case of three different patches for each crack length, a total of 15 different modelings was performed using the mechanical values given in Table 1, Table 2 and Table 3, and then numerical analyzes were carried out. In analysis, elasticity module, shear stress and poisson's ratio were introduced to the system respectively, and mesh operation was performed by selecting the mesh structure [23-28]. Then, fatigue analyzes of patched and non-patched pipes were carried out according to five different crack parameters. Fatigue analyzes were performed as tensile-compression [29-34]. When the analysis models were created, one side was accepted as a fixed support, as seen in Fig. 4, and 40.5 MPa, which is 45 percent of the yield strength of Al 6063 Aluminum pipe, was used. All analyzes were made in the case of quarter-circular and semi-circular composite patches with the same pipe sizes, five different crack lengths and two different geometric shapes. In addition, in order to measure the gain, analyzes were made in the non-patched form of the aluminum pipe and a total of 15 different analyzes were carried out. The mesh (mesh structure), which should be used in the finite element separation process, contains a special place that significantly increases the accuracy of the analysis results [35, 36]. Again, taking into account the studies in the literature, 0.25 mm for DP-460 and 1 size for Al 6063 and Glass - epoxy were selected. Other details of the mesh process are like this; three different face-sizing modules for three different materials were added to the Ansys Workbench feature tree section. After selecting individual element sizes and models, the Triangle Surface Mesher method was selected and the program was run.

| Pipe               | Crack length (mm) | Number of nodes | Number of elements |
|--------------------|-------------------|-----------------|--------------------|
| Non-patched        |                   |                 |                    |
| 1                  | 1.193.979         | 651.523         |                    |
| 3                  | 1.198.924         | 655.243         |                    |
| 5                  | 1.199.661         | 655.753         |                    |
| 7                  | 1.199.149         | 655.502         |                    |
| 10                 | 1.199.588         | 655.129         |                    |
| Quarter-circular patched |             |                 |                    |
| 1                  | 1.217.890         | 655.051         |                    |
| 3                  | 1.222.835         | 658.771         |                    |
| 5                  | 1.225.504         | 660.683         |                    |
| 7                  | 1.223.090         | 659.052         |                    |
| 10                 | 1.223.499         | 668.657         |                    |
| Semi-circular patched |                |                 |                    |
| 1                  | 1.235.435         | 657.583         |                    |
| 3                  | 1.240.380         | 661.303         |                    |
| 5                  | 1.241.117         | 661.813         |                    |
| 7                  | 1.240.605         | 661.562         |                    |
| 10                 | 1.241.044         | 661.189         |                    |

After the meshing process, data on the nodes and number of elements belonging to different samples divided into finite elements are given in Table 4.
3. FINDINGS AND DISCUSSION

After repair of aluminum pipes with different crack lengths Non-patched, quarter and semi-circular composite patched, the fatigue life is shown in Table 5 depending on the crack length. Here, N symbolizes the number of cycles.

| Crack length (mm) | Fatigue Life (N) Non-patched | Fatigue Life (N) Quarter-circular patched | Fatigue Life (N) Semi-circular patched |
|-------------------|------------------------------|------------------------------------------|----------------------------------------|
| 1                 | 11333                        | 15365                                    | 14746                                  |
| 3                 | 1704                         | 4872                                     | 4807                                    |
| 5                 | 1502                         | 6735                                     | 5333                                    |
| 7                 | 993                          | 4307                                     | 2543                                    |
| 10                | 521                          | 2944                                     | 2337                                    |

In the fatigue life calculation of the aluminum pipe made non-patched in Fig. 5a, it can be seen that the fatigue life decreased from 11333 cycles to 521 cycles during the progression of crack length from 1 mm to 10 mm. It was determined that this decrease is due to the crack length. In addition, it was observed from Fig. 5b and Fig. 5c that quarter and semi-circular composite patched aluminum pipes decreased their fatigue life due to the progress of the crack length. In the studies of Zarate and other researchers, the subject of research is the effect of the structure of the patch on the fatigue life [19]. However, it was seen from this study that the shape of the patch is also important.

Furthermore, it is seen from the comparison of all three cases in Fig. 6 that the fatigue life of the quarter-circular composite patch applied aluminum pipe has a better fatigue life than the semi-circular composite patch applied aluminum pipe. It is thought that the fatigue life increases of the patched specimens with 5 mm long cracks in Figure 5b and c are due to reaching the optimum point.
When Fig. 5b, c and Fig. 6 are examined, the effect of the patch on fatigue life can clearly be seen. Here, it was found that there is an inversely proportional relationship between the highest fatigue life and crack length. In other words, it was observed that the highest fatigue life was realized in samples with a crack length of 1 mm. When the fatigue life was examined according to the patch condition, the highest cycle number was obtained in the samples patched in quarter-circular form. The findings obtained about the fatigue life of different crack lengths as a result of patch repair and patch repair process seen in Fig. 6, formed by examining Table 5 with the cycle numbers, constitute the first step of the study. The second stage is on the efficiency of the repair process. In order to measure the efficiency, the differences between the fatigue life of the patched and non-patched samples are shown in Table 6 as % ratios. As seen in Table 6, it was determined that the fatigue life increases as a result of repairing the cracked pipe damage with a patch. Here, it was observed that the highest increase in life was in the quarter-circular patched pipe with 10 mm cracks and the increase rate was 565%.

### Table 6

| Crack length (mm) | Difference in fatigue life of non-patched and quarter-circular patched pipes (%) | Difference in fatigue life of non-patched and semi-circular patched pipes (%) |
|------------------|-----------------------------------------------|-----------------------------------------------|
| 1                | 136                                           | 130                                           |
| 3                | 286                                           | 282                                           |
| 5                | 448                                           | 355                                           |
| 7                | 434                                           | 256                                           |
| 10               | 565                                           | 449                                           |

As seen in Fig. 7, there is an inverse proportion between fatigue life and crack length. In this comparison, it was seen that the greatest contribution was achieved when the crack length was 10 mm. The reason for this contribution is that the patch coverage area varies. When all the results are examined, it is seen that there is a positive contribution of the patching process to the fatigue life. In addition, it was observed that the fatigue life of the quarter-circular patched pipes was higher than the semi-circular patched pipes.

### 4. CONCLUSION AND RECOMMENDATIONS

In this study, numerical damage analysis was carried out on non-patched or patched, assuming that 1, 3, 5, 7 and 10 mm long and 0.25 mm high cracks were formed in the center of Al 6063 type aluminum pipes. The patch material used in the study is [0/90]; reinforced angled glass-epoxy composite and the adhesive is DP-460. Ansys Workbench (15.0), which is a Finite Element Analysis program, was used in numerical analysis. The following conclusions were drawn from the data obtained on fatigue, stress and deformation.

As a result of patching the samples, it was observed that the fatigue lives increases. The most important point to be considered here is that the patch effect increases with the increase in the length of the crack. Increased fatigue life showed that it is possible to reuse the damaged pipe by patching. Considering the usage areas and costs of aluminum pipes, it is understood that it is more appropriate to patch them instead of replacing the damaged ones. For this reason, the use of pipes repaired with glass-epoxy composite patch will benefit both manufacturers and the national economy. In addition, if the cover area of the patch is patched with an area larger than the quarter-circular form, the patched pipe will have the highest fatigue strength.
