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Structural Behavior of Steel Bolted Connections having Different Types of Corrosion Damage

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ABSTRACT

Today, the use of steel structural systems is increasing rapidly due to its features such as high strength, fast manufacturing and ductility. Despite to the superlative properties of steel material, there are also some disadvantages like the formation of corrosion. Corrosion damage in steel structural systems, especially in the connection regions, is of great importance. A major damage to the structural members or fasteners in the connection regions can cause serious harms to the structure. In this study, the structural behavior of 6 mm thick bolted joint plates having different corrosion damages which were made of S235 grade steel was investigated experimentally under the effect of axial tensile force. For the bolted connection test specimens three types of corrosion formation methods including accelerated corrosion only on the bolt, accelerated corrosion on both the plate and the bolt, and artificial corrosion damage only on the bolt were applied. The amount of corrosion was formed as uniform or artificial corrosion with a loss of material of 10% by mass. Structural behavior differences, changes in bearing capacity and ductility of bolted connected test specimens were investigated and the most ductile behavior were obtained in test specimens with corrosion on both plate and bolt.

Farklı Tipte Korozyon Hasarlı Çelik Bulonlu Birleşimlerin Yapısal Davranışı

ÖZ

Günümüzde yüksek dayanım, hızlı imalat ve süneklik gibi özelliklerinden dolayı çelik taşıyıcı sistemlerinin kullanımı hızla artmaktadır. Çelik malzemenin üstün özelliklerinin yanında korozyon oluşumu gibi bazı dezavantajları da bulunmaktadır. Çelik taşıyıcı sistemlerde özellikle birleşim bölgelerinde meydana gelen korozyon hasarı büyük öneme sahiptir. Birleşim bölgelerindeki yapısal elemanlarda veya birleşim araçlarında oluşacak büyük bir hasar yapının büyük ölçüde zarar görmesine sebep olabilmektedir. Bu çalışmada, S235 kalitesinde çelikten imal edilmiş 6 mm kalınlığındaki bulonlu birleşimli levhalarda farklı korozyon hasarları oluşması durumunda eksenel çekme kuvveti etkisi altındaki yapısal davranış deneysel olarak incelenmiştir. Bulonlu birleşimli deney numuneleri için sadece bulonda hızlandırılmış korozyon, hem levhada hem bulonda hızlandırılmış korozyon ve sadece bulonda yapay korozyon hasarı olmak üzere 3 farklı tipte korozyon oluşturulmuştur. Korozyon miktarı kütlece %10 malzeme kaybı olacak şekilde üniform veya yapay korozyon olarak oluşturulmuştur. Bulonlu birleşimli levha deney numunelerinde farklı tipte korozyon hasarları için gözlenen yapısal davranış farklılıkları, taşıma kapasitesindeki ve süneklikteki değişimler incelenmiş ve en sünek davranış hem levhada hem bulonda korozyon olan deney numunelerinde elde edilmiştir.

Anahtar Kelimeler: Çelik, bulonlu birleşim, korozyon, çekme dayanımı, süneklik

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1. Introduction

The use of steel structural systems is becoming more common today due to its high strength, fast manufacturing, ductility, energy consumption capacity, etc. Structures such as steel bridges, port and parking lots are directly exposed to external environmental conditions. Corrosion may occur within the steel structural elements due to exposure to different corrosive environmental conditions such as humidity, temperature difference, soil effect, acid rain, etc. [1]. Corrosion is the physical and chemical deterioration of metals or metal alloys under environmental effects. With the formation of corrosion, mass loss emerges in the metal as a result of the physical and chemical reactions in the metal, and there is no behavioral difference proportional to the mass loss [2]. Research continues to study the changes in structural behavior that occur as a result of corrosion damage in steel structural system elements and connections. Wu et al. (2017) examined the ultimate load bearing capacity of beams in their experimental study for different corrosion zones and different corrosion thickness parameters in steel beams composed of I sections [3]. Saad-Eldeen et al. (2014) examined the behavior of box-section steel beams damaged by corrosion under vertical load experimentally and using finite element analysis [4]. Ahn et al. (2017) carried out an experimental study under artificial corrosion on high-strength bolted joint specimens that transfer loads by friction force [5]. Zhao et al. (2020) investigated pitting corrosion in Q345 steel. They concluded that there is no relationship between mass loss and strength [6]. Zhang et al. (2021) examined the effect of the interaction between corrosion and high temperature on the mechanical properties of Q355 structural steel [7]. Jiang et al. (2022) examined preload loss of high-strength bolts in friction joints considering the effects of corrosion damage and fatigue loading. [8].

In this study, for bolted joint plate specimens made of S235 steel, 10% accelerated uniform corrosion by mass was formed on bolt and plate, 10% accelerated uniform corrosion by mass was formed only on the bolt and 10% artificial corrosion by mass was formed only on the bolt, and these were tested under the effect of axial tensile force. As a result, the bearing capacity and behavior differences in bolted connections with different corrosion damage were examined.

2. Experımental Study

In practice, it is generally observed that corrosion damage in steel structural members occurs in web-to-flange joint areas, weld seams or bolted connection regions of the bearing elements. Steel construction systems can be protected against corrosion with paint or various coatings, however environmental factors can also cause corrosion damage on steel elements by eroding the coatings [9]. In this study, the effect of corrosion damage on bearing capacity and structural behavior formed on all elements in the joint area and on only bolts in bolted joint plate test specimens under the influence of axial tensile force was examined. Types of corrosion and corrosion zones on the connections are shown in Table 1. Since corrosion causes mass loss in metals, corrosion damage is formed in 2 different types in this study. In the first type application, the elements were exposed to accelerated corrosion in NaCl solution as shown in Figure 1.

Table 1. Types of corrosion and corrosion zones on the connections

Specimen	Corrosion zone
SB-1 SB-2	Non-corroded (reference specimens)
SB1-c SB2-c	Accelerated corrosion in bolt and joint area
SB1-bc SB2-bc	Accelerated corrosion only on bolts
SB1-ac SB2-ac	Artificial corrosion only on bolts

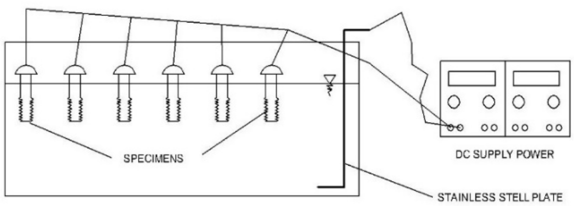

Figure 1. Schematic view of accelerated corrosion test setup

The accelerated corrosion formation test setup and the appearance of the bolts after they are placed in the solution are shown in Figure 2. In the second type of application, considering that corrosion causes mass loss in metals, artificial corrosion application was performed by mechanically reducing the bolt cross-section as shown in Figure 3. Corrosion damage on the bolts was applied so as to have 10% loss in mass.

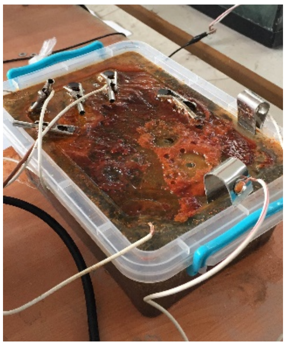

Figure 2. Appearance of bolts in solution

Figure 3. Artificial corrosion application

In the accelerated corrosion test setup, the specimens were immersed in a solution containing 3.5% NaCl. In the experimental setup, stainless steel plate was used as the cathode region and specimens were used as the anode region. With a current of 1 Ampere supplied from the DC power source, electron flow occurred from the test specimens to the stainless steel plate. In the areas of the specimens in contact with the solution, a loss in mass occurred over time. Accelerated corrosion can be applied by keeping the current or voltage fixed [10]. In this experimental study, the current was kept fixed in accelerated corrosion application. In addition, the time period in which the mass losses are to occur in the specimens calculated using the Faraday's equation (Equation 1) in ASM Handbook (1992) was determined [11].

$$A = \frac{I.t.A_W}{n.F} \quad (1)$$

Where, M: mass of dissolved metal, I: current (A), t: time (second), Aw: atomic unit weight of iron, n: atomic valence of iron (since the rust formed is often Fe(OH)2 n is taken as 2 or 3), F: Faraday constant (96500 coulombs)

In the artificial corrosion application, after calculating the amount of weight to be corroded, the bolt masses were reduced by 10% (in the amount of 2 grams) with the help of a grinding machine so that the surfaces of the cut parts in the threaded shank part of the bolts were to be flat (Figure 4).

Figure 4. Accelerated and artificial corrosion of the bolts

A total of 8 test specimens were produced, two each the corrosion-free reference specimens and the test specimens with artificial and accelerated corrosion applied. The thickness of bolted joint plates made of S235 steel is 6 mm. Reference (corrosion-free), accelerated corroded and artificially corroded bolt specimens are shown in Figure 4. Grade 8.8 M12 bolts were used in bolted connections.

Corrosion-free reference bolted plate specimens are named as SB1 and SB2, the specimens with accelerated corrosion applied on the bolt and plate are named as SB1-c and SB2-c. The specimens with accelerated corrosion applied only on the bolts are named as SB1-bc and SB2-bc. The specimens with artificial corrosion applied only on the bolts are named as SB1-ac and SB2-ac. Details of test specimens with bolted connections are shown in Figure 5 [12].

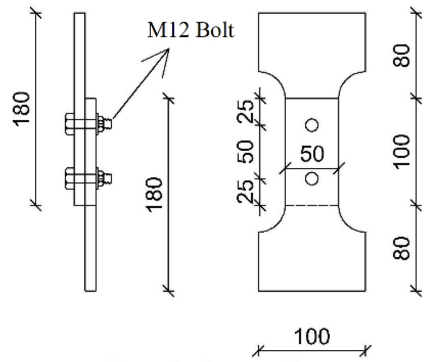

Figure 5. Test specimen details with bolted joint

Test specimens with corrosion damage were subjected to axial tensile test using a testing device with 110 kN capacity (Figure 6). For the axial tensile test, the constant speed applied to the jaws of the testing device was set as 2 mm/min.

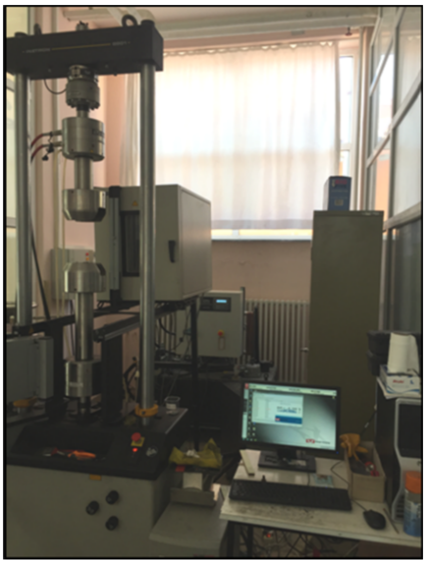
Figure 6. Axial tensile test device

The tensile stress-strain diagrams obtained from the axial tensile tests for the corrosion-free reference test specimens are given in Figure 7. The tensile stress-strain diagrams obtained for the test specimens with accelerated corrosion on the bolt and plate are given in Figure 8. The tensile stress-strain diagrams obtained for the test specimens with accelerated corrosion on the bolt are given in Figure 9. The tensile stress-strain diagrams obtained for the test specimens with artificial corrosion on the bolt are given in Figure 10.

The pre-test and post-test appearances of the bolted joint test specimens are shown in Figure 11. The comparison of the stress values for all test specimens is given in Table 2 whereas the comparison of the unit elongation values is given in Table 3. In addition, the regions where fracture occurred in the samples as a result of the axial tensile test are shown in Table 4.

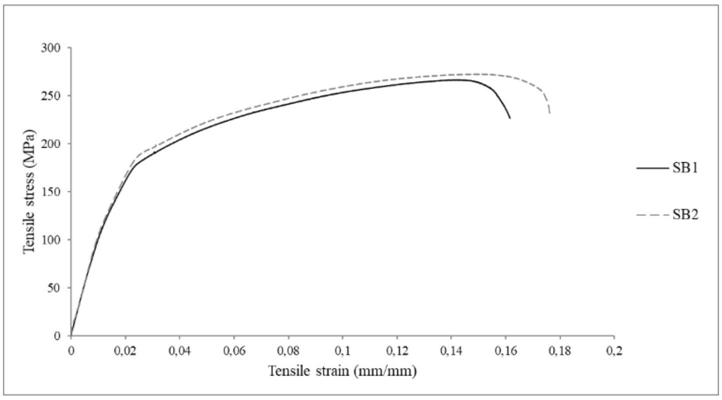

Figure 7. The tensile stress-strain diagrams for the reference test specimens

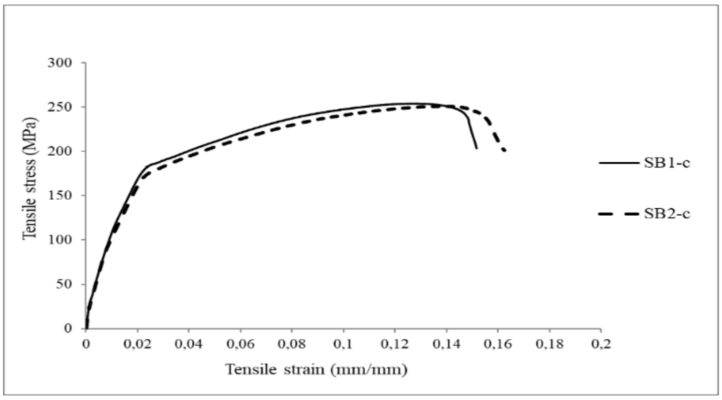

Figure 8. The tensile stress-strain diagrams for the test specimens with accelerated corrosion on the bolt and plate

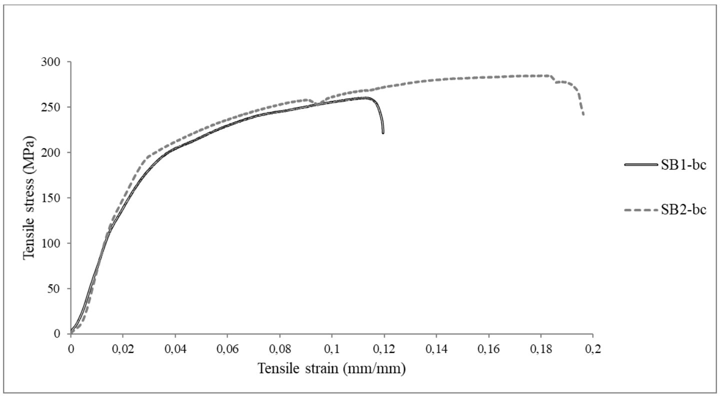

Figure 9. The tensile stress-strain diagrams for the test specimens with accelerated corrosion on the bolt

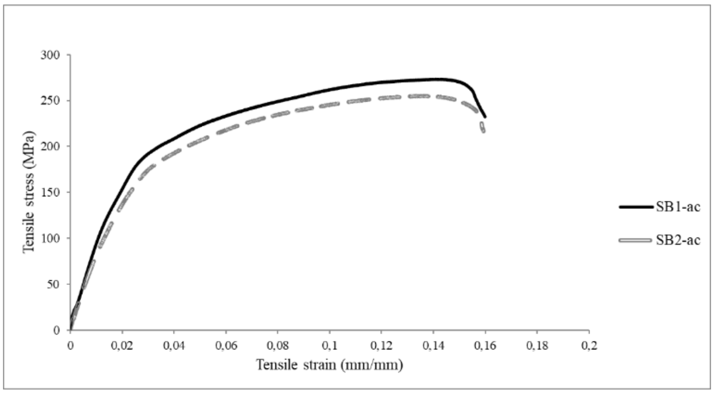

Figure 10. The tensile stress-strain diagrams for the test specimens with artificial corrosion on the bolt

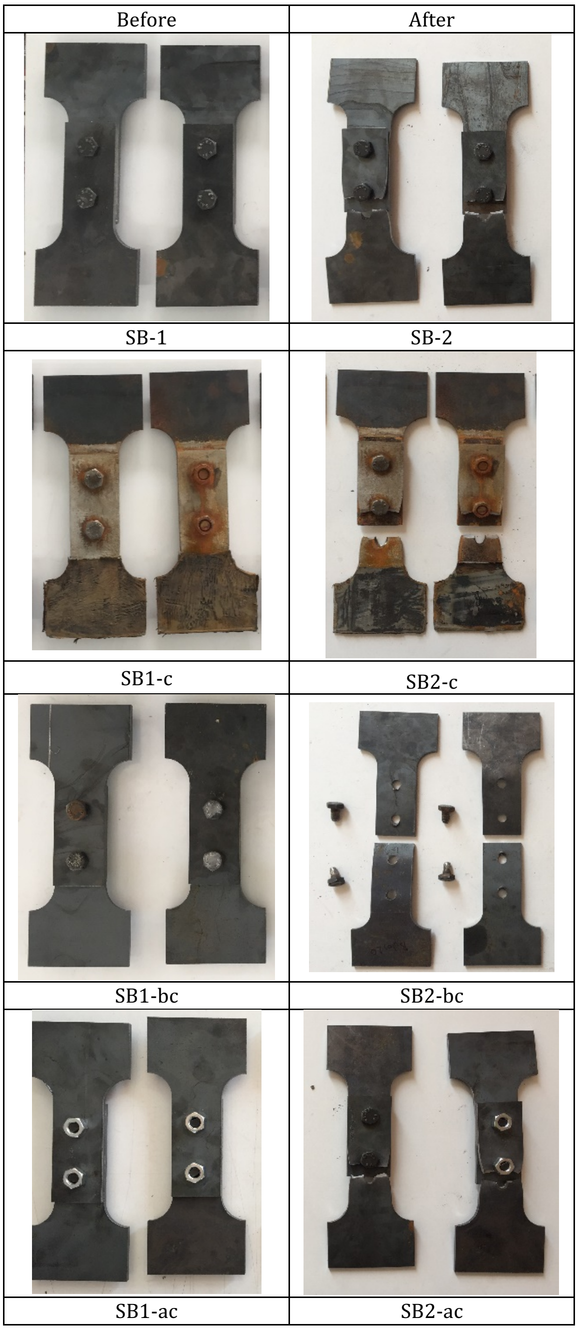

Figure 11. The pre-test and post-test appearances of test specimens

3. Comparison Of Test Results

When Table 2 is examined, it is seen that the greatest decrease in average yield stress and average maximum tensile stress is observed in the test specimens with accelerated corrosion applied on bolt and plate. In general, it is observed that there was a decrease in the average unit elongation values in the test specimens with corrosion applied compared to the reference corrosion-free specimens (Table 3).

Table 2. Comparison of average stresses

Specimen no	Yield stress F_y (MPa)	Average Yield Stress $F_{y,ave.}$ (MPa)	$F_{y,ave.}$/ $F_{y,ave.-ref.}$	Maximum Tensile Stress, F_m (MPa)	Average Maximum Tensile Stress $F_{m,ave.}$ (MPa)	$F_{m,ave.}$/ $F_{m,ave-ref.}$
SB-1 SB-2	189.51 177.84	183.68	1.00	272.59 266.48	269.54	1.00
SB1-c SB2-c	181.94 173.81	177.87	0.96	254.36 251.31	252.84	0.94
SB1-bc SB2-bc	193.01 199.18	196.10	1.07	260.59 285.01	272.80	1.01
SB1-ac SB2-ac	190.83 176.86	183.85	1.00	272.20 255.11	263.65	0.98

Table 3. Comparison of elongations

Specimen no	Yielding elongation ε_y (mm/mm)	Average Yielding elongation $\varepsilon_{y,ave.}$ (mm/mm)	Fracture elongation ε_u (mm/mm)	Average Fracture elongation $\varepsilon_{u,ave.}$ (mm/mm)	$\varepsilon_{u,ave.}$ / $\varepsilon_{u,ave.-ref.}$	Ductility ratio ε_u / ε_y
SB-1 SB-2	0.02570 0.02377	0.02474	0.16156 0.17616	0.16886	1.00	6.82
SB1-c SB2-c	0.02371 0.02351	0.02361	0.15122 0.16269	0.15696	0.93	6.64
SB1-bc SB2-bc	0.03386 0.03342	0.03364	0.11954 0.19620	0.15787	0.93	4.69
SB1-ac SB2-ac	0.02937 0.03105	0.03020	0.15989 0.15928	0.15959	0.95	5.28

Table 4. Type of corrosion and fracture zones on the connections

Specimen	Corrosion type	Fracture zone
SB-1	-	Net section region of plate
SB-2	-	Net section region of plate
SB1-c	Uniform	Net section region of plate
SB2-c	Uniform	Net section region of plate
SB1-bc	Uniform	Sliding of bolt thread
SB2-bc	Uniform	Sliding of bolt thread
SB1-ac	Artificial	Net section region of plate
SB2-ac	Artificial	Net section region of plate

As a result of the tensile test, in case of the specimens with 10% corrosion by mass only on the bolt (SB1-bc and SB2-bc), scraping occurred between the nut and bolt since it was not fully clamped with the nut due to the fact the threads on the bolt were reduced after corrosion. In the other specimens, the fracture occurred in the area of the loss (net area) of the plate, as shown in Table 4. In the specimens with corrosion only on bolt (SB1-bc and SB2-bc), the average yield unit elongation was found to be 36% higher than the reference specimen due to the reduction of the diameters of the bolts as a result of corrosion and the larger space between the bolt holes and the bolt compared to the other specimens.

In the specimens with artificial corrosion on the bolt (SB1-ac and SB2-ac), the average yield unit elongation was obtained 22% higher. The reason for this is that the bolt was cut and the bolt moved in the direction of some tensile force inside the bolt hole. It was determined that the average yield unit elongation of the specimens with corrosion on both plate and bolt (SB1-c and SB2-c) was 5% lower than the reference sample. Compared to the corrosion-free specimens, the elongation at break decreased by 7% on average in the specimens with corrosion on both the plate and bolt and in the specimens with corrosion only on the bolt, and the elongation at break decreased by 5% on average in the specimens with artificial corrosion on the bolt.

As a result of the tensile tests, compared to the corrosion-free specimens, there was an average 1% increase in maximum tensile stresses in case of the specimens with corrosion on the bolt, an average of 6% decrease in the same in case of the specimens with corrosion on both the plate and bolt, and an average of 2% decrease in the same in case of the specimens with artificial corrosion on the bolt.

In addition, the tensile stress-strain diagrams obtained from the axial tensile tests for all test specimens are shown in Figure 12 comparatively. When the diagram in Figure 12 is examined, it is seen that there is not a big difference between the maximum tensile stresses and yield stresses. The difference between yield and rupture elongation is due to the larger gap between the bolt and the bolt hole as a result of corrosion formed on the bolt shank. In the specimens with corrosion on both the plate and bolt (SB1-c and SB2-c), the corrosion occurred only on the plate surface and the head and threaded part of the bolt, due to the absence of NaCl solution penetrating between the bolt hole and the bolt, and the yield and rupture elongation of the specimens were obtained close to the reference samples.

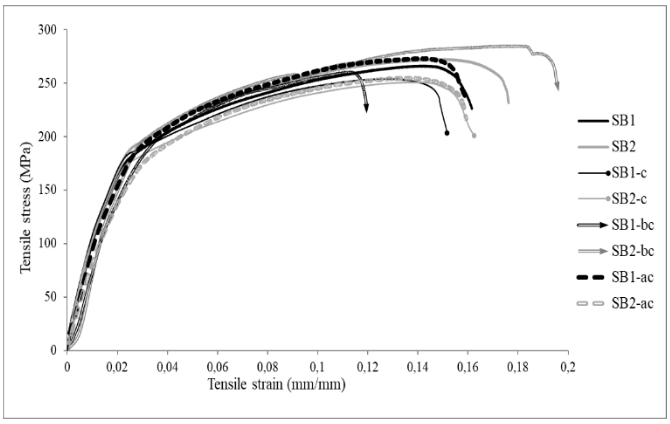

Figure 12. Comparison of the tensile stress-strain diagrams for all test secimens

4. Conclusion

Under the effect of environmental conditions, corrosion damage may occur within the body of steel structural members, and corrosion causes loss in metal mass. As the corrosion formation time increases, the mass loss in the material also increases, and the mechanical properties vary. Within the scope of this study, 10% corrosion damage by mass was formed on the bolted joint steel plate test specimens, and the test specimens were subjected to axial tensile test. As a result of the tests, it was observed that the bolt did not break for 10% corrosion amount on the plate joints, however scraping could occur due to the corrosion damage on the threads in the threaded part of the bolt. The test specimens with accelerated corrosion on the bolt and plate were the specimens whose strength decreased the most since the net area of the plate decreased as a result of corrosion. It was determined that the reduction in strength in the corroded specimens did not cause a decrease in proportion to the mass loss, due to the fact that corrosion creates chemical changes in the metal. As a result of corrosion, the rate of decrease in elongation at fracture of the elements is higher than the decrease in their strength. Therefore, for corroded specimens, the ductility rate of the elements decreased. The ductility ratio of the specimens exposed to artificial corrosion is higher than the other specimens.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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