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Tensile Behavior of Damaged-steel Plate Strengthened by One-sided CFRP Patch in Acidic Environment

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Abstract

Today the adhesively bonded joint of FRP/steel for repair and strengthening are being widely used. In this case, investigating the effect of various mechanical loading, as well as harsh environmental conditions on this joint, is very important. In this paper, the strength of the damaged-steel plate reinforced with CFRP patches under acidic environment is investigated experimentally. The damage is considered in the shape of a central hole with two narrow central notches on two sides of the hole. In order to simulate more realistic conditions, the bonding of the patch to the steel plate is considered one-sidedly. To evaluate the amount of strengthening, the specimens are subjected to the simple tensile test at room temperature. The results of dry patched-specimens compared to non-patched specimens show significant reinforcement with at least 40% increase in load-carrying capacity and at least 50% increase in displacement. The comparison between the patched-specimens immersed for 8 weeks in concentrated sulfuric acid and the dry patched-specimens show no significant effect on the load-carrying capacity. However, the tests of standard CFRP specimens in a similar immersion environment show a reduction in modulus of elasticity and tensile strength compared to the dry CFRP ones.

1. Introduction

The usual method of repairing and strengthening large tanks for storage of chemical materials and petroleum derivatives or towers used in refinery chemical processes is to employ steel patches that are jointed to the damaged area by welding methods. These methods are not quite suitable for various reasons, such as increasing the weight of the tank or tower and the technical problems of connecting the patch to the damaged area. Moreover, the heat from welding operations can cause some residual stresses and distortion in the bonding plates. Furthermore, it can be highly hazardous in environments with flammable and explosive chemical materials. Hence, cold repair methods can be a good alternative [1]. For this purpose, the bonding of FRP materials to the metal surface by using adhesive can be a useful solution [2-7].

Despite the many benefits of FRP materials, they weaken resistance to humidity, high temperatures, seawater, acidic, and alkaline environments. Hitherto, a large number of research have been carried out on FRP materials considering various types of resins, reinforcing fibers, and environmental conditions [8-15]. More recently, a comprehensive study was conducted by Liu et al. [16], which showed more than 1900 tests were reported and discussed in this field by researchers. Although the studying the effects of acidic environments

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is very time consuming, accelerating methods such as immersion in high concentrations acid can investigate these effects of environments in a shorter time [13, 17-19]. Several studies have been conducted to investigate the effects of acidic environments on FRP materials.

Despite the different capabilities of FRP materials for reinforcement of plates or steel structures, the adhesive bonding area is weak point of the joint. Some technical tips should be considered to perform proper bonding, such as preparations on adherends, the procedure of curing, and choosing the right adhesive. In addition to the strength of the FRP bond to steel, the durability of the bond in working conditions which is also a very important and extensive research has been performed in this field [9, 11, 12, 15, 18, 20].

In most studies, the bonding between the metal and composite has been considered as a single-lap or double-lap joint. The use of plate specimens with the special shape of damage (central hole with narrow notches), which seems to be more suitable for simulating real conditions [3, 14], has been less observed in the previous studies. In the Wang study [14] in 2018, this shape of damage on the steel plate with two-sided bonding of carbon patch (prepared with epoxy resin) and exposed to similar sea environmental conditions was investigated.

The aim of the present study is to investigate the amount of reinforcement of damaged steel plates by using Carbon Fiber Reinforced Polymer (CFRP) patches. Moreover, the effect of acidic environments on the reduction of reinforcement after a long time is considered. For this purpose, the strength of damaged-steel specimens repaired by patches of CFRP composite was investigated under a simple tensile test at room temperature. Specimens were made from steel plates and the shape of the damage was considered as central hole with two narrow notches on two sides of the hole. Owing to the importance and application of one-sided reinforcement in some structures such as tanks or pipes, these types of bonding are considered here. Some patched-specimens and CFRP standard specimens were immersed in concentrated sulfuric acid to evaluate the effects of harsh environments. After eight weeks, these specimens were subjected to a simple tensile test. The obtained results were compared with the results of dry environment specimens (control specimens consist of patched-specimens and CFRP standard specimens).

2. Materials and Tests

2.1. Materials

To perform the desired tests, ASTM A516 Grade 70 carbon steel plate, with application in the refinery industries and production of tanks, was used. The uni-directional Youchang fibers (Fibertech. Co., Korea) were used to produce FRP composite plates. The Deraken 411, epoxy vinyl ester bisphenol-A resin (Ashland Co., USA) was used for preparation of composite plates. This resin is resistant to acid and includes 143MPa tensile strength, 12GPa tensile modulus. Using the above-mentioned fibers and resins, the required CFRP plates (included 5- layers) were made in a hand-layup process to prepare the standard specimens and composite patches. The mechanical properties of steel and composite are explained in sec 3.1.1. Moreover, Camattini spa thermosetting resin was used as an adhesive type of adhesively bonded between steel plate and FRP. Some properties of this adhesive are tensile strength of 50-56MPa and elongation at break of 5.5-8 percent [21].

2.2. Sample Preparation

It was necessary to make damaged-steel specimens to investigate the strengthening of the patched specimens. The damaged-specimens were made from steel plates with 250mm length, 30mm width, and 4mm thickness. The damage consisted of a 5mm diameter central hole and two narrow lateral notches with a length of 5mm and a width of 0.38mm. To make some proper comparisons, steel specimens with the dimensions mentioned above but without holes and narrow notches were also prepared as non-damaged specimens, Fig. 1. In order to strengthen each steel specimen, the CFRP patches were attached by adhesive to one side of the damaged area. For this purpose, 5 layers of CFRP patch with 120mm length and 30mm width (same width as the steel specimen) were prepared, as shown in Fig. 2. Moreover, to investigate the effect of composite material as one part of the patched-specimens, some specimens were made according to the standard ASTM D3039. These specimens, which consist of 250mm length, 25mm width, and 2mm thickness, were prepared for the simple tensile test, as shown in Fig. 3.

To prepare a better joint by the adhesive between the CFRP patches and the steel specimens, the surface of steel specimens were degreased by acetone and roughened by sandblasting based on standard ISO 17212, equivalent to SA2.5. The surface of composite patches was first degreased and cleaned by acetone and then roughed according to the FEPA standard by using sandpapers in the size of p120. Furthermore, the composite and steel plates were cleaned again by acetone before bonding. Then, the composite patch was pressed to the surface of the steel using spring clamps (Cleco type Fasteners) after bonding. Therefore, the adhesive was uniformly spread between the two surfaces. This procedure causes an increase in the strength of the adhesively bonded joints.

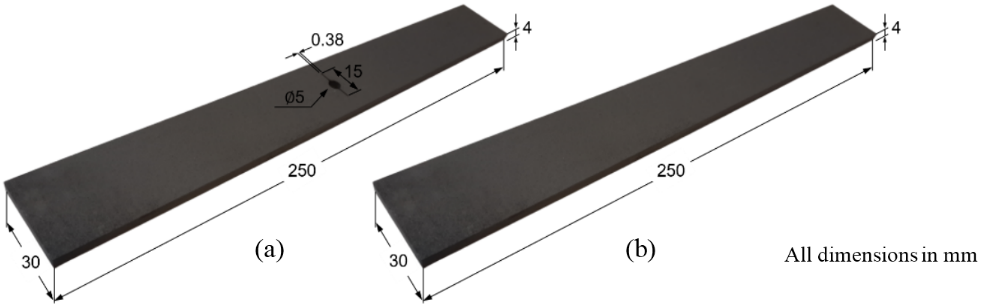

Fig. 1. The dimensions of the steel specimen, a) Damaged-specimen, b) Non-damaged specimen

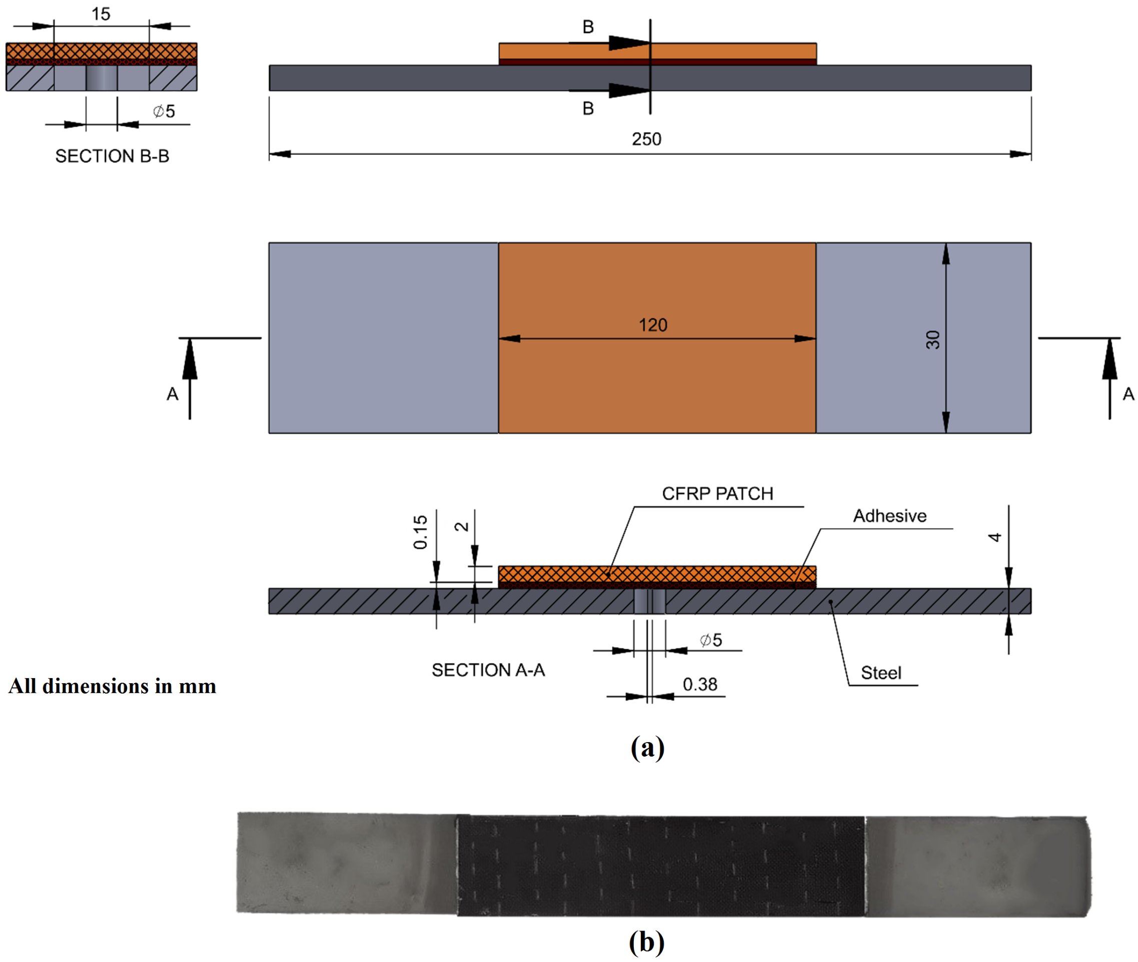

Fig. 2. CFRP steel patched-specimen, a) Schematic view, b) Real top view.

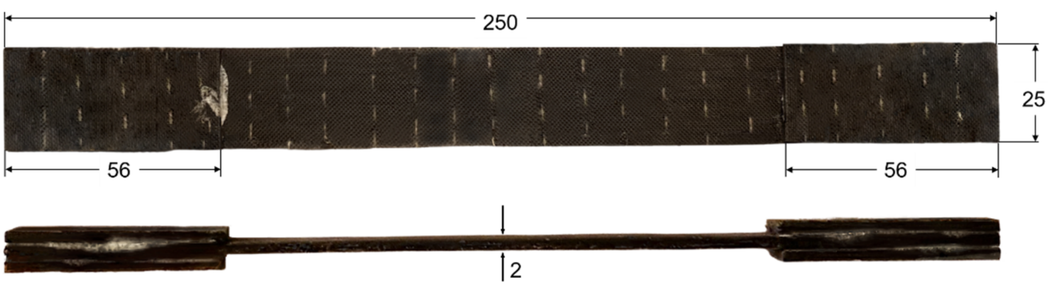

Fig. 3. Top and side view of standard composite specimen.

For the pre-curing of the specimens, they were kept at the room temperature for 20 hours and then post-curing was performed by placing them in the oven for 5 hours at a temperature of 70°C according to the datasheet. To protect the steel substrate from corrosion caused by acid, non-patched portions of the steel specimens were covered by a layer of resin.

2.3. Environmental Conditions of Specimens

Patched-specimens and standard CFRP specimens were kept in dry and concentrated sulfuric acid solution (80% by weight) environments. The results of the simple tensile test in the dry environment were considered as the basis of the comparison study. To accelerate the effects of acidic environmental conditions, the specimens were immersed in concentrated sulfuric acid for 8 weeks.

2.4. Tensile Tests

To make the tensile tests for all types of composite and steel specimens, 250 ton Zwick tensile test machine was used. The test speed for all specimens was considered as 2mm/min. The mechanical properties of all types of steel and standard CFRP specimens were obtained from the tensile tests. Except for the standard tests on the steel and CFRP specimens, other tensile tests were programmed as follows on 5 categories of specimens at the room temperature:

1. The non-damaged steel specimens (control specimens), Fig. 1.
2. The damaged-steel specimens (control specimens), Fig. 1.
3. The patched-specimens were kept in a dry environment (control specimens), Fig. 2.
4. The patched-specimens were immersed in concentrated sulfuric acid solution (80% by weight) for a period of 8 weeks at room temperature, Fig. 2.
5. The CFRP specimens were immersed in the concentrated sulfuric acid solution (80% by weight) for a period of 8 weeks at room temperature, Fig. 3.

Table 1 shows the summary of specifications of test specimens consist of non-damaged and damaged steel, the CFRP and patched specimens.

Table 1
Summary of specifications of test specimens.

Specimen name	Specimen	Patch material	Kind of experiment	Environment condition	Kind of adhesive	Immersion time (h)
S-T-1	Steel		Tension	Dry		
SHN-T-L-1 SHN-T-L-2 SHN-T-L-3 SHN-T-L-4 SHN-T-L-5 SHN-T-V-1 SHN-T-V-2	Steel		Tension	Dry		
SC-HN-T-3 SC-HN-T-5	Steel-composite	CERP	Tension	Dry	Camattini Spa AS90	
D1-CT-1(3) D1-CT-2(3) D1-CT-1(5)	Composite	CFRP	Tension	Dry		
D2-CT-1 D2-CT-2	Composite	CFRP	Tension	Dry		
SC.L.S.T-1 SC.L.S.T-2	Steel-composite	CERP	Lap Shear Test	Dry		
C-80-1-7-T-1 C-80-1-8-T-2	Composite	CERP	Tension	Acid (80%)		1100 1300
SC-80-1-8-T-1 SC-80-1-8-T-2	Steel-composite	CFRP	Tension	Acid (80%)	Camattini Spa AS90	1300

3. Results and Discussion

3.1. Test Results

3.1.1. Tensile Tests of Standard Specimens

The mechanical properties of ASTM A516 Grade 70 carbon steel plate were obtained from simple tension test according to the ASTM E8 standard. By using the standard tests, the ultimate tensile strength of 514MPa, the yield strength of 350MPa, and the modulus of elasticity of about 195GPa (according to ASTM E111 standard) were obtained.

Using the above-mentioned fibers and resins, the required CFRP plates (included 5- layers) were made in a hand-layup process to prepare the standard specimens and composite patches. According to the standard ASTM D3039, CFRP standard specimens were loaded in the parallel and perpendicular directions with respect to the fibers, and the tensile mechanical properties were obtained. Moreover, according to the standard ASTM D3518, in-plane shear modulus and shear strength were obtained. The average values are shown in Table 2. Moreover, the error bars for some mechanical properties of tensile loading in the direction of fibers are shown in Fig. 4. In addition, according to the standard EN 1465, the tensile lap-shear strength of the bond between steel and CFRP was obtained as 28MPa.

3.1.2. Tensile Test of Non-damaged and Damaged-steel Specimens (Control Specimens)

To investigate the effect of reinforcement on the strength of patched-specimens, it was necessary to compare the results of tensile tests on these specimens and the control ones (non-damaged or damaged-steel specimens). The tensile test results of control specimens are shown in the form of load-normalized displacement diagrams, as shown in Fig. 5. The normalized displacement is defined by the ratio of displacement to the initial length of specimen between two wedge grips of the tensile machine. In this figure, the results of the non-damaged specimen (S-T-1) are compared with those of the damaged specimens. Notably, damaged specimens were made by laser-cutting and wire-cutting manufacturing process, i.e. the specimens named with SHN-T-L-1, SHN-T-L-2, SHN-T-L-3 and SHN-T-L-5 were made by the laser-cutting and those expressed by SHN-T-V-1 and SHN-T-V-2 were produced by the wire-cutting process. The width of narrow notches produced by the laser and wire-cutting were about 0.38mm and 0.18mm, respectively. For the final production of the damaged steel specimens, the laser cutting process was preferred due to its manufacturing speed and cost-effectiveness compared to the wire-cutting process. Furthermore, the results show that the width of the notch does not affect the significant responses, as shown in Fig. 5a.

Table 2
Mechanical properties of CFRP composite.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	s_{11} (MPa)	s_{22} (MPa)	s_{12} (MPa)
72	3	3.89	0.27	775	6.2	35

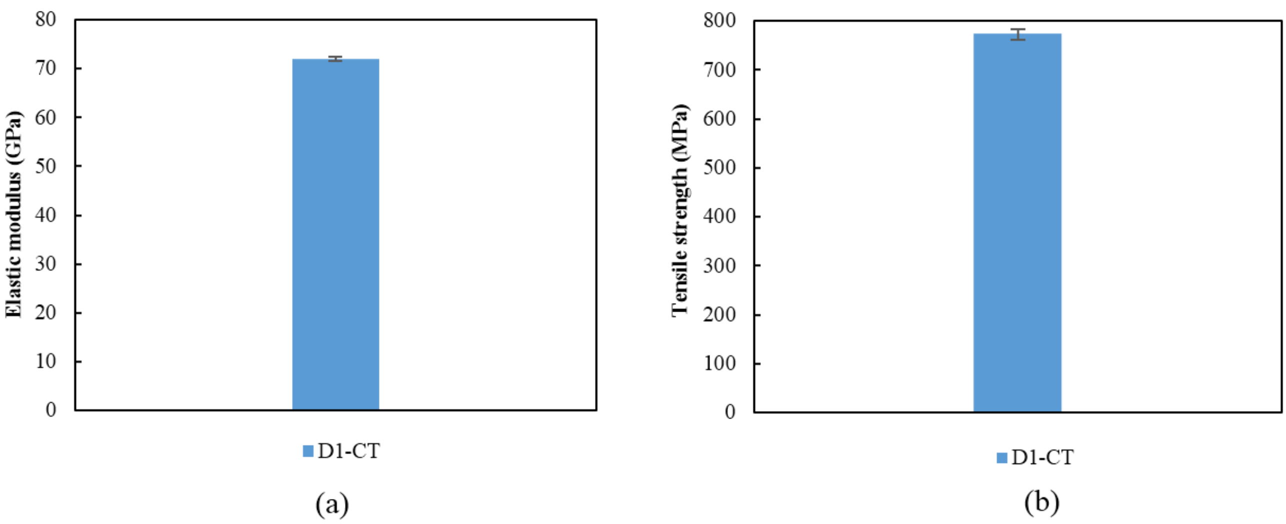

Fig. 4. The error bars for some mechanical properties of tensile loading in the direction of fibers, a) Elastic modulus, b) Tensile strength.

The load-carrying capacity of the damaged-specimens reached a maximum magnitude of about 32kN, which shows about 45 percent reduction in comparison to the corresponded value of the non-damaged specimens, Fig. 5b. Moreover, the maximum displacement of the damaged-specimens nearly reduces to one-fifteenth of the non-damaged ones. In the damaged-specimen diagrams, the first region at the beginning of the diagram is linear and a good conformity between the results of different damaged-specimens is observed. However, in the nonlinear portion of the diagram and after yielding, small difference between the results can be seen, as seen in Fig. 5a. The slopes of the curves in this region are less than those of the non-damaged ones. In the second region, yielding occurs and the load reaches to its maximum value, which is significantly less than that of the non-damaged ones. Then, with the occurrence of the necking phenomenon in the damaged region, the load-carrying capacity of the specimen reduces and finally rupture happens. Moreover, due to premature deterioration around the damaged area the displacement at the rupture point is also much smaller than that of the non-damaged ones.

3.1.3. Tensile Tests on the CFRP Specimens

To investigate the effect of CFRP patch on the strengthening of damaged-steel specimens, the tensile test on the CFRP standard specimens was necessary. Hence, the carbon composites specimens with standard dimensions were cut from the carbon plates so that the direction of fibers was along with the length of specimens, i.e. the direction of the load was parallel to the direction of fibers. All specimens were tested at room temperature and in the two conditions of the dry environment (room environment) and concentrated sulfuric acid solution. The tensile strength and elastic modulus for all specimens (D1-CT-1 (3), D1-CT-2 (3), and D1-CT-1 (5)) are close together and the average values are about 775MPa and 72GPa, respectively, as presented in Table 2.

Fig. 6 shows the stress-strain diagrams of dry CFRP specimens compared to those immersed in a sulfuric acid solution (80% by weight) for 7 and 8 weeks named by C-80-1-7-T-1 and C-80-1-8-T-1, respectively. The results of comparing the C-80-1-7-T-1 and C-80-1-8-T-1 with the dry specimens show a decrease of less than 8 and 11 percent in the tensile strength, respectively. For the elastic modulus, a reduction of about 13 percent is observed in both specimens. The results of the tests and also the appearance of the specimens after failure confirms the diffusion of acid into the inner layers of the composite. This can cause degradation of the composite components including matrix, fibers, as well as the fiber-matrix interface. However, the previous studies show that the acidic solutions have an anomalous effect on FRP materials [16], it seems considering the effect of immersion in the acidic solution on the tensile strength and elastic modulus of the CFRP specimens is essential.

3.1.4. Simple Tension of the Patched Specimens

The adhesive was selected from epoxy-based structural types (Camattini Spa AS90). The results of patched-specimens using this types of adhesives (SC-HN-T-4 and SC-HN-T-5) compared to the control-specimens are displayed in Fig. 7. The results show a 40 to 50 percent increase in the load-carrying capacity and more than 50 percent increase in displacement of the patched-specimens compared to the damaged ones. Using the patch, the stress distribution in the steel substrate becomes more uniform and no large stresses exist near the damage area and it is possible to increase the load carrying capacity and displacement of the damaged-steel specimen.

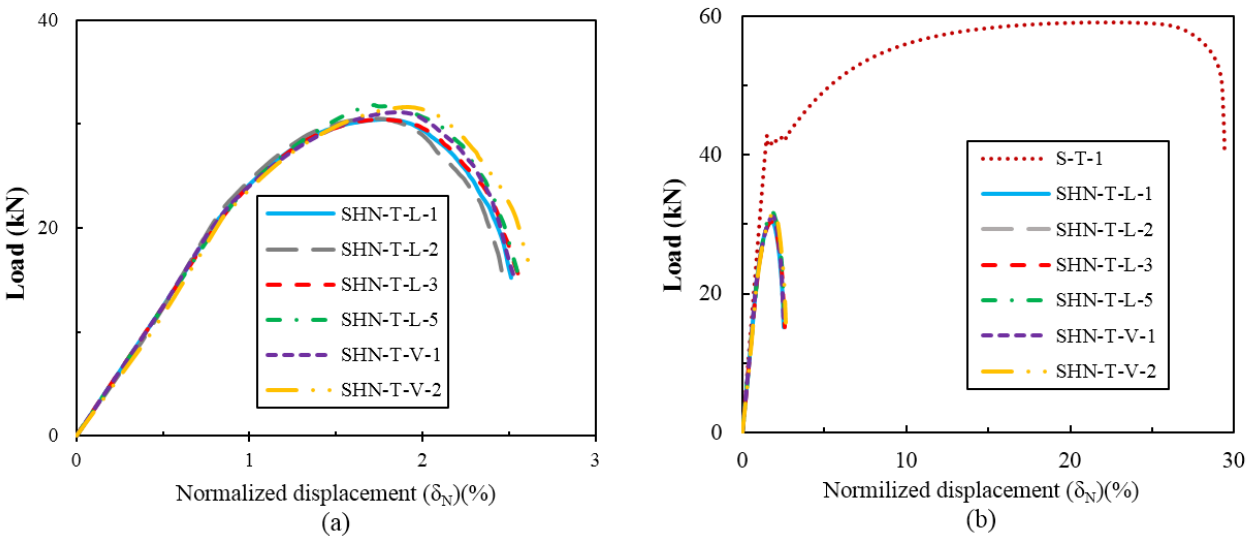

Fig. 5. The comparison of load-normalized displacement of control-specimens, a) Six damaged specimens, b) A non-damaged and six damaged-specimens.

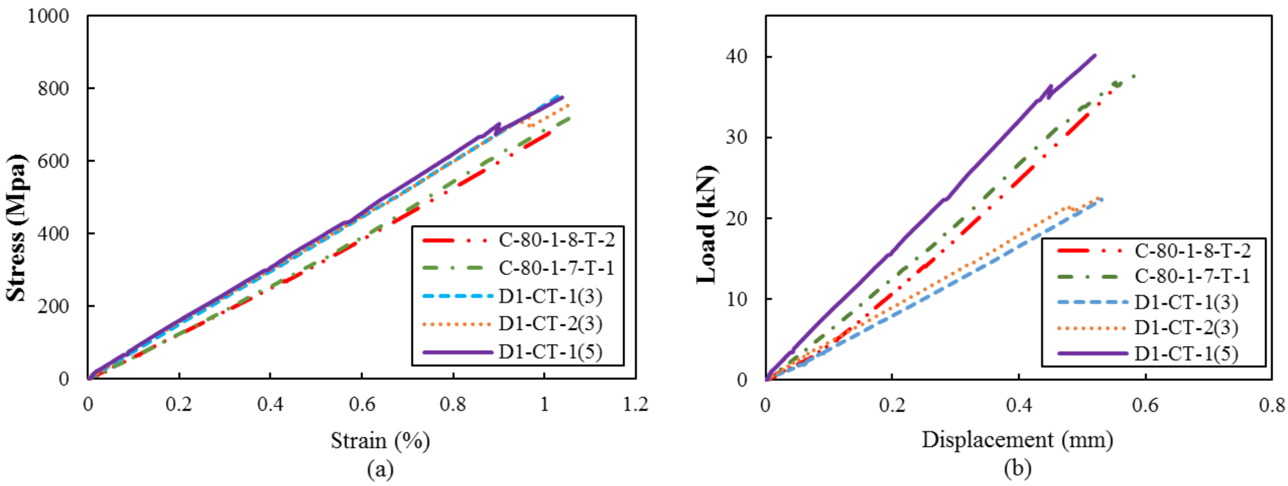

Fig. 6. Comparison between tensile tests of CFRP specimens (dry and immersed in acid sulfuric solution), a) Stress-strain diagrams, b) Force-displacement diagrams.

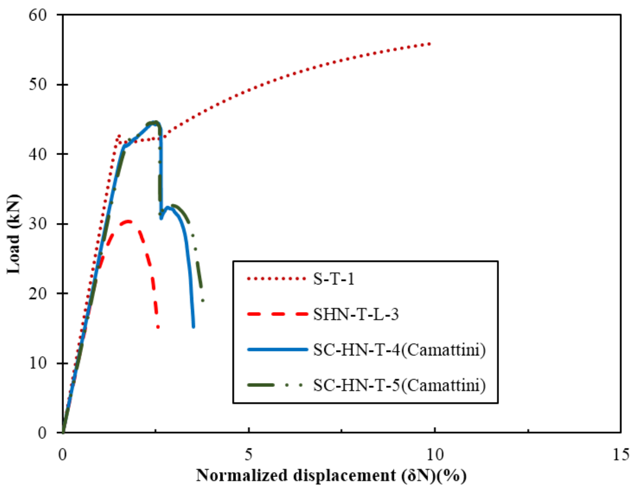

Fig. 7. The load-normalized displacement diagrams of the two types of patched-specimens (using two types of epoxy-based adhesives) compared to the control specimens.

The results of stress analysis using analytical and numerical methods indicate the existence of different components of stress, including interlaminar shear and normal stresses in the composite and interfacial shear and peeling stresses between adhesive and adherends [22, 23, 24]. Moreover, the results of these analyses indicate that the maximum values of these stresses occurred at the free edges of the joints. Furthermore, the axial tensile loading is applied to the steel substrate and the patch is one-sided, so the loading is eccentric and it causes some bending, as well [22]. However, despite the low patch thickness, the bending effect is not so significant. If it is assumed that the bending load in addition to tensile load supplied to the non-patched damaged specimens, the strength of these specimens will be less than the reported value under the effect of pure tensile load. In other words, in a more accurate comparison, the difference between the results of patched specimens (with bending load) and non-patched specimens (without bending load) is slightly greater.

In the study of the patched-specimens, it can be observed that the linear portion of the load-normalized displacement of two specimens is significantly developed compared to the damaged-ones, and the results are close to the non-damaged steel specimens. After the linear portion, the curve slope is suddenly reduced due to yielding in the steel substrate almost with the same behavior as non-damaged specimens, so that with the small changes in the load, the displacement significantly increases. Finally, with the failure of bonded joint, the behavior of the patched-specimens is similar to the damaged-specimens. Moreover, good conformity is observed by comparing the diagrams of the patched specimens.

Fig. 8 shows the effects of concentrated sulfuric acid solution (80% by weight) for 8 weeks at room temperature on the CFRP patched-specimens (SC-80-1-8-T-1 and SC-80-1-8-T-2) and displays tensile test results in comparison to the dry patched-specimen. The Camattini adhesive was used for all specimens. Despite the visible effect of acid on the composite patch, there is no significant influence on the strength of the specimens. Nevertheless, the results of the standard composite specimens immersed in the acidic environments for 8 weeks show a relatively significant reduction in the tensile strength and elastic modulus. The investigation of these specimens after the damage shows change the failure modes compared to the dry specimens. In the dry specimens, the main failure mode is the delamination of composite near the steel surface, and the rest failure mode is debonding of adhesively bonded joint or cohesive failure. For the specimens immersed in the acid, the failure indicates that the acid dissolved the resin matrix on the top layers of the composite patch and penetrates from top surface and free edges in to the inner layers along with changing the color of these layers and dissolving the steage fibers, Fig. 9. In this case, the weakening of the bond between the fibers and the matrix is probable which can cause the delamination in the layers close to the steel surface which have higher shear and peeling stresses especially in free edges [22]. The failure mode study of dry and acidic specimens shows the mostly and completely delamination, respectively. This is probably the main reason for no change in results of tensile strength for these types of specimens. However, it is expected that with more penetration of acid into the inner layers and saturation of the composite, the adhesively bonded joint is damaged and the failure mode tends towards debonding, which in turn will reduce the bond strength. It should be noted that the appearance of the specimens did not show any effect of acid on the steel substrate.

The results of some tensile properties of different specimens including non-damage, damaged, patched of dry environment, and patched specimen of the acidic environment are summarized in Table 3.

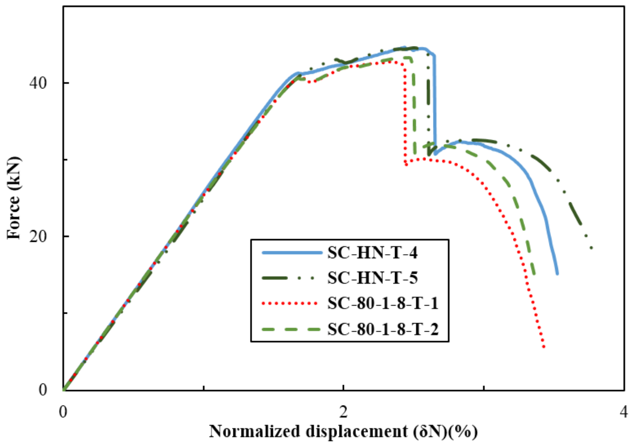

Fig. 8. Load-normalized displacement diagrams, comparison of immersed specimens in the sulfuric acid with the dry ones.

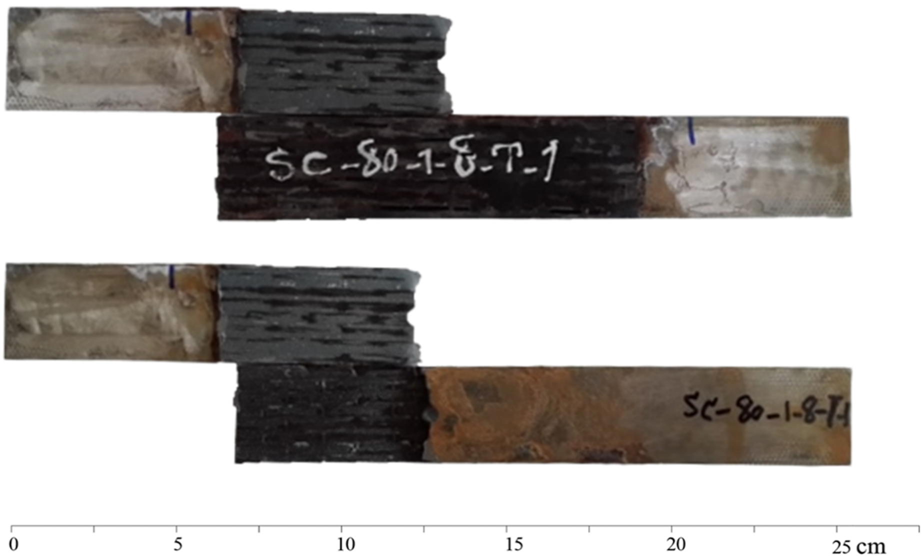

Fig. 9. The effect of acid on the specimen immersed for 8 weeks, a) On the upper surface of the CFRP patch, b) On the inner layer at the interface between CFRP and steel.

Table 3
Summery of some tensile properties of different specimens.

	S-T-1	SHN-T-L-3	SC-HN-T-4	SC-HN-T-5	SC-80-1-8-T-1	SC-80-1-8-T-1
Environment	Dry	Dry	Dry	Dry	Acidic	Acidic
Ultimate load (kN)	59.1	30.4	44.6	44.5	42.7	43.2
Max. Nor. Dis. (%)	29.4	2.6	3.5	3.8	3.4	3.7

4. Conclusions

In the present study, the strength of the damaged-steel specimens which were reinforced by the CFRP patch was investigated under a simple tensile test at room temperature. The damaged- specimen was included a steel plate with the damage in the shape of the central hole and two narrow notches on the sides of the hole. For producing the patched-specimens, the CFRP plate was adhesively joint-bonded to the one side of the damaged-specimens. To evaluate the effect of reinforcement on the strength of patched-specimens, a comparison was performed between the results of the damaged and patched-specimens under tensile load at room temperature. To examine the harsh environmental effects in shorter time, some patched-specimens and CFRP standard specimens were immersed in the accelerated environments consist of concentrated sulfuric acid for 8 weeks. The obtained results of simple tensile test were compared to the dry-specimens results consisting of the patched-specimens, and the CFRP standard specimens (the control specimens) under the same testing condition were also investigated. According to the above explanations, the following conclusions can be drawn:

- For the dry patched-specimens compared to the damaged ones, the load-carrying capacity and the displacement value increase above 40 and 50 percent, respectively.
- Studying the failure modes of the CFRP patched-specimens in dry environment indicates a combination of debonding of adhesively bonded joint and delamination of composite and cohesive failure.
- The results of carbon composite-specimens immersed in the concentrated sulfuric acid solution (80 percent by weight) for seven and eight weeks compared to the dry ones show a decrease of about 13 percent in the elastic modulus and 8 to 11 percent in the tensile strength of these specimens. The failure mode is delamination of composite near the steel surface.
- Despite the reduction in the mechanical properties of the immersed composites in the sulfuric acid environments, the results of the patched-specimens in these environments indicate no significant change in the ultimate load of these specimens.

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