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Strengthening of steel hollow pipe sections subjected to transverse loads using CFRP

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Abstract. Nowadays using Carbon Fiber Reinforced Polymer (CFRP) has been expanded in strengthening steel structures. Given that few studies have taken about strengthening of steel hollow pipe sections using CFRP, in present study, the effects of CFRP sheets using two layers as well as in combination with additional reinforcing strips has been assessment. Strengthening of five specimens was carried out in laboratory tests. As well as numerical simulation was performed for all specimens by Finite Element Method (FEM) using ABAQUS software and high correlation between the results of numerical models with experimental data indicate the power of FEM in this field. The results of both laboratory and simulated specimens showed that load-bearing capacity of circular cross-sections can be significantly increased using CFRP retrofitting technique. Also, application of additional CFRP reinforcing strips and layers caused more strength for the strengthened specimens.

Keywords: retrofitting; steel hollow pipe section; transverse load; CFRP

1. Introduction

The proper functioning of structural members is of particular importance in structural design. For various reasons, it is possible a structural member can’t be able to provide the structure need, these reasons are including design mistakes, poor implementation and overloading. In this case, the structural retrofitting appears necessary. Up to day, different methods are expressed to retrofit structural members. These methods, for steel structures, can be cited as the use of concrete jacket, adding web stiffener, adding steel sheets by welding, gluing or bolt it to members, and also the use of FRP strengthening sheets. Retrofitting using FRP materials is one of the novel methods of reinforcing. Nowadays, FRP materials are used for retrofitting and repairing structural members. Despite the relatively high costs, these materials have become a good choice in many reinforcing projects because of high stiffness and strength, corrosion resistance and the ease of transportation and installation. The use of these plates in the form of FRP cover, provide lateral confinement piece that increases strength and ductility of members. Several experimental models are available to predict the increase in load-bearing capacity of the structure reinforced with FRP. Comparing this model with experimental data shows a significant uncertainty associated with these models

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(Carolin 2003, Gablbraith and Barnes 1995, Gangarao *et al*. 2007, Narmashiri 2011).

Park and Choi (2013) showed that CFRP strengthening of concrete-filled steel tubes columns could improve the load-bearing capacity, significantly. Wang *et al*. (2015) showed that the flange damaged steel-concrete composite beams could be repaired using CFRP composites, appropriately. Park and Yoo (2015) presented that structural behaviors of steel structures in flexural and compressive loading improved using CFRP strengthening approach, significantly. Edalati *et al*. (2015) indicated that strengthening of steel plate shear walls using Glass Fiber Reinforced Polymer (GFRP) materials had also appropriate effects on the structural behaviors of shear walls.

Debonding of bonded CFRP plates from strengthened steel beams was investigated using a fracture criterion by Lenwari *et al*. (2002). Good agreement between the test results and the prediction method was found.

Narmashiri *et al*. (2010) researched on shear strengthening of the full-scale steel I-beams using CFRP strips. The results showed feasibility of web strengthening steel beams using these materials.

Zhao and Mahaidi (2009) investigated the web strengthening of light weight steel beams using CFRP subjected to the end load-bearing. They used three strengthening approaches: applying CFRP plates on the outer side, inner side, or both sides of the web. As the light steel sections had high web slenderness, they investigate the web crippling of the specimens. The CFRP strengthening improved the web-buckling capacity especially for those with large web depth-to-thickness ratio. Also, Zhao *et al*. (2006) investigated the end load-bearing capacity of the cold-formed rectangular hollow sections that were strengthened by using CFRP wraps. They found that by using CFRP wrap, the load capacity can improve appropriately.

To prevent external corrosion of steel pipes, external wrapping of damaged sections using fiber reinforced polymer (FRP) materials was investigated by Duell *et al*. (2008). It was found that the deficiency width around the circumference had little effect on the ultimate rupture pressure of the repaired vessel, but influenced the stress state in the underlying pipe substrate. Application of FRP wraps to strengthen buried steel pipelines under permanent ground deformations was investigated by Mokhtari and Alavi Nia (2015). According to results achieved on the research, application of FRP wraps to repair buried steel pipelines under permanent ground deformations was recommended.

This study provided experimental work and numerical simulations using finite element method for reinforced specimens with CFRP materials. Experimental specimens are include five steel beams with O-section. These specimens are modeled by ABAQUS finite element software. The aim of this research is investigation of load-bearing capacity, the maximum force in failure and corresponding deformations. Also, it express materials, devices and laboratory equipment, details of specimens, how to performing the experiments and methods of receiving information.

2. Experimental model

The used specimens were prepared in a steel mill and transported to the structure laboratory of Islamic Azad University of Zahedan. The mechanical properties of the used steel is according to Table 1.

Composite sheets used for shear strengthening of specimens are CFRP unidirectional fibers. Brand name of used CFRP is SikaWrap330C. The used adhesive is a two-part structural adhesive

Table 1 Mechanical properties of steel specimens

Modulus of Elasticity (GPa)	Yield Strength (MPa)	Ultimate Stress (MPa)	Ultimate strain (%)
187	385	589	11.8

Table 2 CFRP and adhesive specifications

CFRP (SikaWrap330C)	Thickness (mm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate strain (%)
	0.131	4300	238	1.8
Adhesive (Sikadur330)	Thickness (mm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Bending Modulus (MPa)
	0.35	30	4.5	3.8

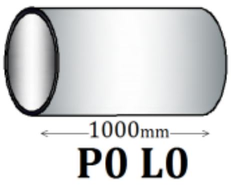
Table 3 Specification of the specimens

No.	Specimen name	Section	Strengthening system	Specifications
1	P0L0	O	Without Strengthening	Control specimens without any layer of CFRP
2	P1L0	O	CFRP	One CFRP layer around the specimen 400x500mm
3	P1L1	O	CFRP	One CFRP layer around the specimen and one CFRP Strip 400x100mm
4	P1L2	O	CFRP	One CFRP layer around the specimen and two CFRP Strips 400x100mm
5	P2L0	O	CFRP	two CFRP layer around the specimen 400x500mm

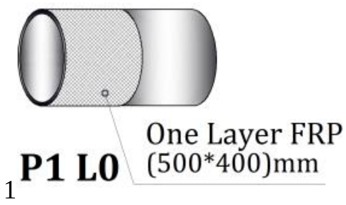
namely Sikadur330 that mixed with together with a ratio of one to four using mixer becomes gray color. A CFRP sheets with dimensions 400×500 mm is used for all of specimens. For some specimens strips with dimensions of 400×100 mm is used. The specimens will be described in more details. Impregnating a reinforcing fiber sheet is done using Sikadur330. Specifications of CFRP and adhesive is provided in Table 2.

Five steel specimens with circular hollow sections namely (P) with a length of 1000 mm are designed and built. Specimens cross-section is circular (O-shaped) with a diameter of 110 mm. Sandblasting machine have used for surface treatment of steel specimens. Sandblasting operation was performed in the shear zone at the end of all the specimens with a length of 500 mm. Then the surface of specimens and the CFRP were cleaned using thinner to completely remove impurities,. The wet installation method is used in order to connect the CFRP sheet to steel surfaces. For this, a proper resin layer was applied to the specimen shear zone. Then CFRP sheets was placed on a clean surface and smeared it with glue. At the end it has installed in the corresponding location on the specimen with a 40 mm of overlap. In the following fibers is saturated enough by the resin. The size and placement of CFRP sheets and strips is in this way that around sheets are considered with dimensions 400×500 mm and CFRP strips are 400×100 mm.

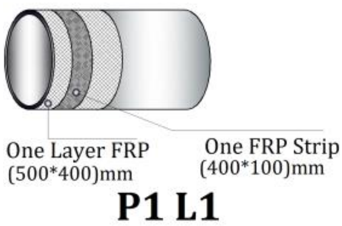
Five steel specimens are made with a length of 1000 mm which are located in five groups. Table 3 shows the classification of the specimens. P0 L0 of 110 mm and a thickness of 3 mm specimen was with a circle cross-section which was used as a control specimen and no preparation work has been done to improve on it. Comments on other examples are given in Table 3. The



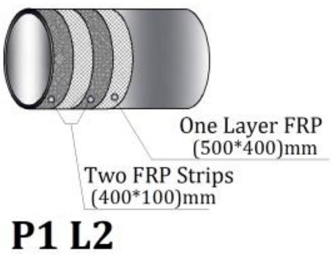
(a) Specimen P0L0



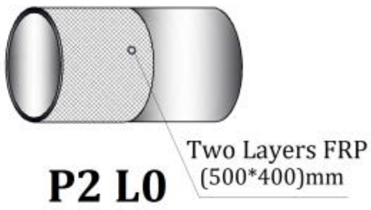
(b) Specimen P1L0



(c) Specimen P1L1



(d) Specimen P1L2



(e) Specimen P2L0

Fig. 1 Schematic of the specimens

(a) Hydraulic jack

(b) LVDT

(c) Force gauge

Fig. 2 Test equipment

overall shape of the specimens showed in Figs. 1(a) to 1(e).

In this experiment, specimens strengthened with CFRP are under uniforms static load. Testing devices including hydraulic jack system, force gauge, Linear Variable Differential Transformer (LVDT) and a device for data registering. The hydraulic jacks are used to load application on the specimens. A perfect view of the testing device has been shown in Figs. 2(a) to 2(c). Data including the force and displacement at the end of specimen are transferred to the device by force gauge and LVDT respectively. Load application accessories are including Pressure control systems, oil tanks, pumps and hydraulic jacks. Force gauge and LVDT are electrically transducers that convert the force of jack and the displacement into voltage or electric current. Changes in voltage or electric current transmitted to the channels of data recording devices. Then the amount of force and displacement will be displayed as a number by applying different calibration factors for each channel. In the following each of the five models were put under static tests and the results including the force applied and displacement expressed. Then the impact of the use of FRP on the load-bearing capacity of specimens will be compared with no strengthening.

3. Numerical modeling

The large number of tests to evaluate the parameters for the behavior of steel specimens will be costly and time consuming. Therefore simulation using Finite Element Method (FEM) can provide a suitable model for this experiment in real scale that does not have limitations of the laboratory tests. It will provide useful results if it run properly. FEM is a numerical method and instructions which can be used in various engineering problems in different scenarios such as stable, transient, linear and nonlinear. Sustainability, transient, linear and nonlinear issues in the field of stress, heat transfer, fluid flow and electromagnetic can be analyzed by finite element method. Also ABAQUS software is the most powerful and at the same time is the most widely used software that have the ability of two-dimensional and three-dimensional modeling with very high accuracy.

In the present study 6-11-1 version of ABAQUS software is used to perform numerical simulation of experimental tests. The same described laboratory tests are modelled and analyzed. All the elements including steel pipes, adhesives, and CFRP wraps are modelled using three-dimensional (3D) elements. Steel pipes and adhesive's materials are considered Isotropic, and CFRP wraps are modelled as Orthographic materials. Interaction of the surfaces are defined using tie option. Different mesh sizes are chosen, and the best size is chosen achieving the closest numerical result to the experimental ones. Deformation are applied gradually, at the top of the pipes using a steel plate, to achieve the related forces and displacements. Also, all analyses are in nonlinear static method. Geometry of the specimens without strengthening and strengthened using one CFRP layer, one layer+ one CFRP strip, one layer+ two CFRP strips, and two CFRP layers are shown in Fig. 3.

4. Results and discussions

4.1 Load- bearing capacity and deformation

The specimen deformation under load application under the jack will be provided. Load-displacement curve is presented in this section and will be compared with results of numerical models.

Deformation of specimens with circular cross-section with and without strengthening with listed patterns before and after loading and also in finite element model are provided in Figs. 4(a) to 4(s).

In the specimen without reinforcing the most deformations are on sides of the pipe and a reduction in the height of specimen is obvious. In specimen with reinforcing good adhesion between CFRP and steel can be seen. The dominant failure mode of CFRP is rupture failure to strips on the sides of the specimen.

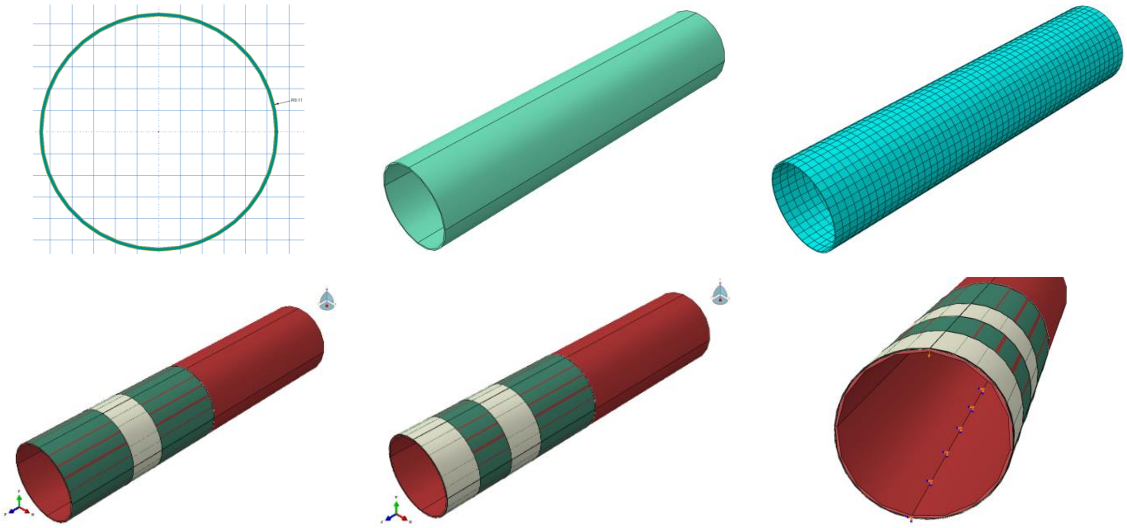
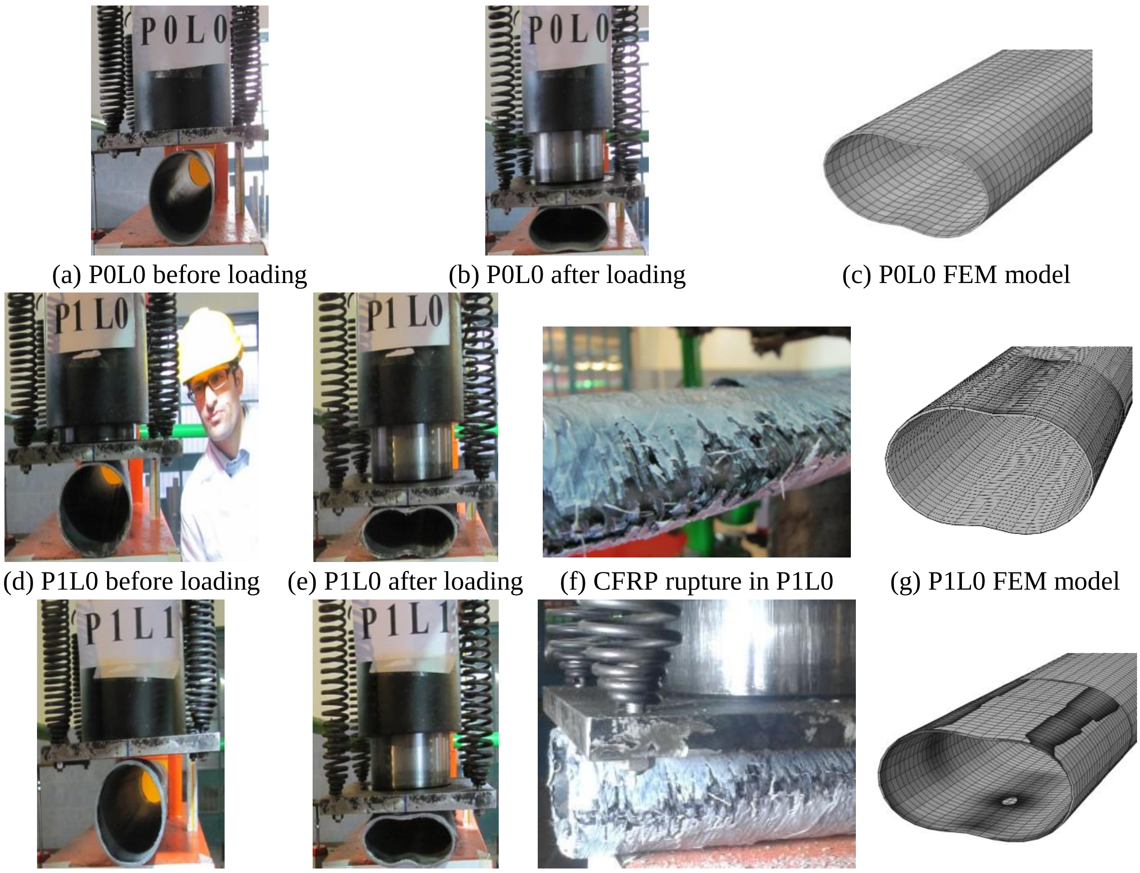


Fig. 3 Numerical models



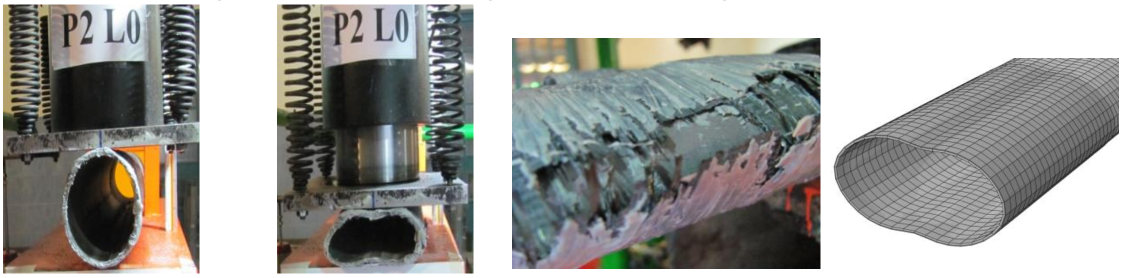
(a) P0L0 before loading (b) P0L0 after loading (c) P0L0 FEM model

(d) P1L0 before loading (e) P1L0 after loading (f) CFRP rupture in P1L0 (g) P1L0 FEM model

(h) P1L1 before loading (i) P1L1 after loading (j) CFRP rupture in P1L1 (k) P1L1 FEM model

Fig. 4 Experimental and numerical models

(l) P1L2 before loading (m) P1L2 after loading (n) CFRP debonding in P1L2 (o) P1L2 FEM model



(p) P2L0 before loading (q) P2L0 after loading (r) CFRP rupture in P2L0 (s) P2L0 FEM model

Fig. 4 Continued

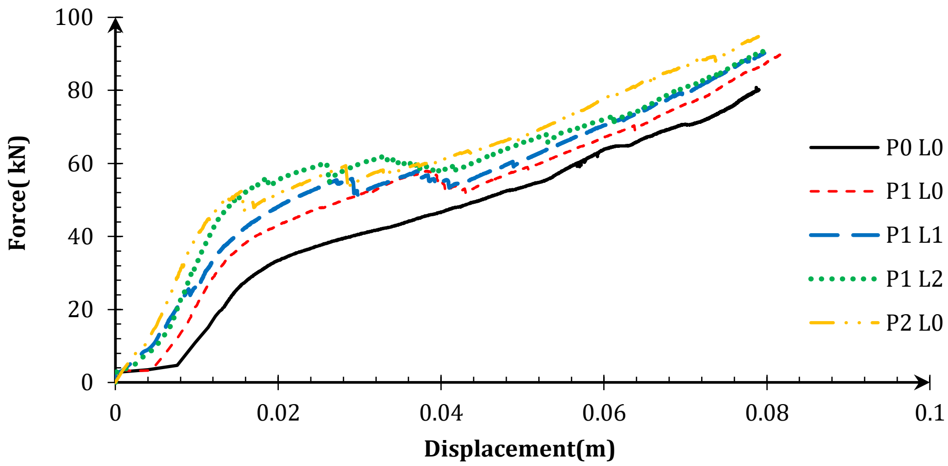


Fig. 5 Force-displacement graph in laboratory test

The results of the tested specimens including force-displacement graph which represents the load-bearing capacity of specimens are provided in Fig. 5. Force-displacement graph showing 95.71 kN of load-bearing capacity for specimen P2L0 according to the Fig. 5. This increased the amount of 15.6 kN or 19.47 percent. This model have more increasing in load-bearing capacity comparing to the other retrofitted models. The load-bearing capacity of P2L0 was 5.7 kN more than P1L0. It has 7.12 percent increase comparing to P1L0. Also there is 6.87 and 5.49 percent increase in comparison with P1L1 and P1L2 respectively. Ultimate load-bearing capacity and its increase in the laboratory test are presented in Table 4. It can be seen that

Table 4 Load-bearing capacity, the rate of increment in the specimens, and failure modes

Model	Load-Bearing Capacity					Sequence of Failure Modes (Experimental)*
	Experimental		Numerical		Difference Between Numerical and Experimental Result (%)	
	Ultimate Load-Bearing Capacity (kN)	Increase Ratio of Load Bearing Capacity (%)	Ultimate Load-Bearing Capacity (kN)	Increase Ratio of Load-Bearing Capacity (%)		
P0L0	80.1	-	80.03	-	0.08	DH, SI, YS, PH, FS
P1L0	90	12.35	90.09	12.57	0.10	DH, SI, YS, DBL, PH, RP, FS
P1L1	90.2	12.60	90.22	12.73	0.02	DH, SI, YS, DBS, DBL, PH, RP, FS
P1L2	91.3	13.98	91.4	14.20	0.10	DH, SI, YS, DBS, DBL, PH, RP, FS
P2L0	95.7	19.47	95.9	19.83	0.20	DH, SI, YS, DBL, PH, RP, FS

*decreasing the height (DH), increasing the stress and strain on steel pipe (stress and strain intensity/ SI), yielding of steel (YS), debonding CFRP strip (DBS), debonding CFRP layer at the corners (DBL), creating plastic hinges at corners (PH), CFRP rupture (RP), and failure of steel (FS).

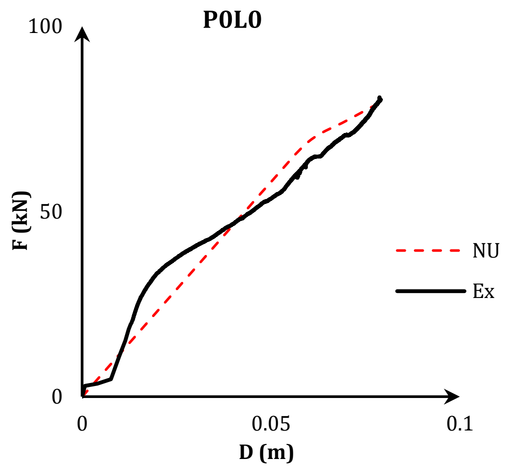


Fig. 6 Force-displacement graphs in numerical and experimental for P0L0

the specimens with two layers of strengthening sheet has the highest rate of increase in load-bearing capacity.

In Fig. 6, the load-bearing capacity of P0L0 (as an example) versus displacement in the FEM simulation and experimental are shown. Also maximum load-bearing capacity and its differences with experimental model are presented in Table 4. According to Fig. 6 and Table 4, the differences between results in the lab and finite element method are very low and reflects the high accuracy of modeling in this field.

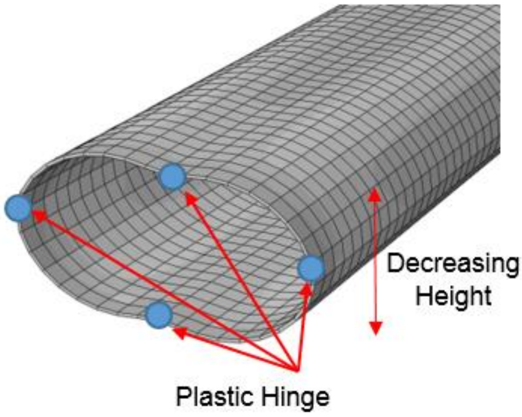


Fig. 7 Failure of non-strengthened specimen (P0L0)

4.2 Failure modes

Knowledge of failure modes is an impact point for engineers and designers because this knowledge helps to consider points for retarding or preventing failures. In this section, failure modes and the related reasons will be discussed. The failure modes of the specimens and their sequence are tabulated in Table 4.

For non-strengthened specimen (P0L0), as shown in Fig. 7, the sequences of failure modes are followed: decreasing the height (DH), increasing the stress and strain on steel pipe (stress and strain intensity/ SI), yielding of steel (YS), creating plastic hinges at corners (PH), and failure of steel (FS).

For the strengthened specimens using one layer CFRP (P1L0), the following failure were observed: decreasing the height (DH), increasing the stress and strain on steel pipe (stress and strain intensity/ SI), yielding of steel (YS), debonding CFRP layer at the corners (DBL), creating plastic hinges at corners (PH), CFRP rupture (RP), and failure of steel (FS).

For the strengthened specimens using one layer CFRP+ one/ two CFRP strips (P1L1 and P1L2), the following failures were subsequently observed: decreasing the height (DH), increasing the stress and strain on steel pipe (stress and strain intensity/ SI), yielding of steel (YS), debonding CFRP strip (DBS), debonding CFRP layer at the corners (DBL), creating plastic hinges at corners (PH), CFRP rupture (RP), and failure of steel (FS).

The failures were observed for the specimen strengthened using two CFRP layer (P2L0) include: decreasing the height (DH), increasing the stress and strain on steel pipe (stress and strain intensity/ SI), yielding of steel (YS), debonding CFRP layer at the corners (DBL), creating plastic hinges at corners (PH), CFRP rupture (RP), and failure of steel (FS).

According to abovementioned failures of the specimens, it can be concluded that application of CFRP caused more flexible failures. Also, using additional CFRP strips may retard debonding of the main layer. Additionally, applying more CFRP layer caused less stress intensity on steel following retard of steel yielding.

5. Conclusions

The results of this research exhibit the feasibility of using Carbon Fiber Reinforced Polymer (CFRP) for strengthening steel hollow pipe sections under transverse loads. A significant increase in the load-bearing capacity of steel pipe sections reinforced with CFRP is generally seen. Also, the results indicate that load-bearing capacity will be increased as the number of CFRP layers increases. For the investigated specimens, it was found that the use of a layer of CFRP has increased the load-bearing capacity equal to 12.35 percent compared to models without strengthening. This is 12.6% for the model strengthened with a layer of CFRP and an additional CFRP strip, 13.98% for the model reinforced with a layer CFRP and two additional CFRP strips, and 19.47% for the model strengthened using two layers CFRP. Additionally, it was found that application of CFRP caused more flexible failures. Using additional CFRP strips retard debonding of the main layer, and applying more CFRP layers caused less stress intensity on steel following retard of steel yielding. The results obtained from finite element model have been very consistent with laboratory results.

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