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Structural behaviors of notched steel beams strengthened using CFRP strips

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Abstract. This paper presents the findings of experimental and numerical investigations on failure analysis and structural behavior of notched steel I-beams reinforced by bonded Carbon Fiber Reinforced Polymer (CFRP) plates under static load. To find solutions for preventing or delaying the failures, understanding the CFRP failure modes is beneficial. One non-strengthened control beam and four specimens with different deficiencies (one side and two sides) on flexural flanges in both experimental test and simulation were studied. Two additional notched beams were investigated just numerically. In the experimental test, four-point bending method with static gradual loading was employed. To simulate the specimens, ABAQUS software in full three dimensional (3D) case and non-linear analysis method was applied. The results show that the CFRP failure modes in strengthening of deficient steel I-beams include end-debonding, below point load debonding, splitting and delamination. Strengthening schedule is important to the occurrences and sequences of CFRP failure modes. Additionally, application of CFRP plates in the deficiency region prevents crack propagation and brittle failure.

Keywords: Carbon Fiber Reinforced Polymer (CFRP); failure modes; deficiency; I-beam; steel; strengthening

1. Introduction

Several steel structures all over the world have corrosion problem due to environmental exposure (Rahgozar *et al.* 2010) and need to be strengthened. A noticeable amount of interest has recently been given to take advantage of Fiber Reinforced Polymer (FRP) materials to strengthen existing structures because of its low weight, and high tensile strength. FRP is routinely used for strengthening concrete structures. Recently, application of FRP for strengthening steel structures is more attracted by researchers (Gholami *et al.* 2016). Installing CFRP strips on the tensile flange is able to improve the beams' flexural behavior. Generally, the FRP materials are installed to the bottom (tensile) flange for flexural strengthening. Edberg *et al.* (1996) presented an experimental research in which five various configurations of Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) which were attached to the tensile flange of small scale steel wide flange beams using adhesive bonding. Furthermore, a similar investigation was conducted by Ammar (1996). The small scale steel beams in four-point bending were tested by Tavakkolizadeh and Saadatmanesh (2001). All these aforementioned studies demonstrated that it will be practical to strengthen flexural steel beams using CFRP plates. There are a substantial number of structures in the world. Because of aging and environmental factors such as corrosion, lack of appropriate maintenance, and fatigue, sensitive damage are created and consequently load bearing capacity decreases. In addition, many of these structures need upgrading to handle larger loads or need to be strengthened. Conventional repair and retrofit methods of steel sections generally use steel sheets by the help of bolting or welding to the structure. Considerable dead load increase to the structure and the need to heavy lifting equipment are addressed as some drawbacks of such methods. Moreover, welding is not a favorable solution as a result of fatigue problems and using bolted connections which enhance fatigue life are time-consuming and costly. Employing FRP materials has been addressed as a successful technique to fix the strength and stiffness of defected structure elements. FRP, as a structural material, enjoys great advantages restoring the lost capacity of damaged structures (Kim and Heffernan 2008, Van Den Eindel *et al.* 2003). Research on reinforcement of steel beams using adhesively bonded elastic strips was conducted by Sebastian and Luke (2007). It was found that at intentionally unbonded length of strip, buckling failure occurred initially and afterward at the edges of the buckle, incremental brittle separation was seen. Through-thickness variations of axial strain in the strips and local variations of interface quality might be affected by interface stresses. Some researches were conducted including the study on increasing fatigue life for both analytical and numerical investigations on small scale specimens (Colombi 2006a, Liu *et al.* 2009a, b, Nakamura *et al.* 2009) and full scale cases by Experimental tests (Dawood *et al.* 2007, Jones and Civjan 2003, Nozaka *et al.* 2005, Tavakkolizadeh and Saadatmanesh 2003). Experimental studies which were conducted by Wu *et al.* (2012), and Jiao *et al.* (2012) proved the effectiveness of using a CFRP-retrofit scheme to extend the fatigue life of defected steel girders. Hmidan *et al.* (2011), Kim and Harries (2012), Kim and Brunell (2011), on the other hand, studied the strategies of CFRP repair for steel beams with experienced notched damages. The bonded

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and un-bonded reinforcement systems were compared with those of Ghafoori *et al*. (2012). Beams undergoing the cracked section which were strengthened by the PBR system revealed a local strain concentration on the CFRP plate, while the PUR system enjoyed a uniform strain distribution along the CFRP strips.

Knowing CFRP failure modes in flexural strengthened steel beams is useful for overcoming or retarding these failures. Al-Emrani and Kliger (2006) tested various kinds of fracture modes by examining composite elements with different mixture of CFRP-laminates and adhesives. They examined the effect of various material parameters on the behavior and strength of bonded steel–CFRP elements. Colombi (2006b) presented the delamination failure of steel beams flexural strengthened by externally-bonded FRP. He took advantage of the simplified fracture mechanics -based approach to study the edge delamination of the reinforcement strips. Narmashiri *et al*. (2012) studied the failure analysis and structural behavior of the CFRP flexural strengthened steel I-beams, CFRP failure modes including below point load splitting (BS), below point load debonding (BD), end delamination (EDL), and end debonding (ED). Due to splitting in lateral deformation, the CFRP strips are not able to carry the load in full-capacity state. Premature end-debonding happens through taking advantage of shorter CFRP strips as well as application of longer CFRP plates which have more resistant against end-debonding (ED). Below point load-splitting (BS) will be overcome through rising the thickness of CFRP strips. Nevertheless, applying too thick CFRP plate resulted in premature debonding. Sebastian and Zhang (2013) studied FRP strengthening along the positive and negative moment zones with variation between beams of the layout and amount of FRP. They bonded steel plate stiffeners to the beams' webs and flanges instead of welding. Using bonded steel stiffeners postponed local buckling of the beams considerably. In curtailment regions, the interfacial normal stresses were moderate relevant to the shear stresses. Narmashiri *et al*. (2010) reported applications of CFRP strips for shear strengthening of steel I-beams. The main aim of this research included the studying the need for CFRP application on one side or both sides of beam web as well as using different levels of CFRP on the web. The results presented that using CFRP plates on the webs can rise ultimate load up to 51%. Moreover, using less CFRP in shear zone for I-beams with equal load carrying capacity was one of the most significant achievements of this study. Recently, an investigation on damaged steel short tubular columns strengthened by CFRP carried out by Ghaemdoust *et al*. (2016). Horizontal and vertical deficiencies have been created on the short steel columns. Conclusions were drawn on structural performance of the columns. Results indicated that using CFRP materials increased load carrying capacity and delayed local buckling. Also, it was found that more layers of CFRP showed better performance.

From the past researches, it realized that using CFRP as a strengthening material for steel beams considerably improved the strength and stiffness of the steel beams. The major conducted investigations include fatigue life under cyclic loading by initial minor damage. The aim of this study is to assess the achievability of strengthening of deficient steel beams subjected to flexural loading by unidirectional CFRP strips. In order to observe the failure modes of CFRP under damage propagation, notches within 30×30 mm^2 on flexural flanges were applied. This paper examines the structural behaviors of strengthened notched steel I-beams and failure modes of CFRP strips. Both numerical simulation by using ABAQUS software and experimental tests were employed.

2. Materials and methods

In order to study the CFRP failure modes and structural behaviors of deficient steel I-beams, one non-strengthened control beam (non-defected beam) and four notched beams

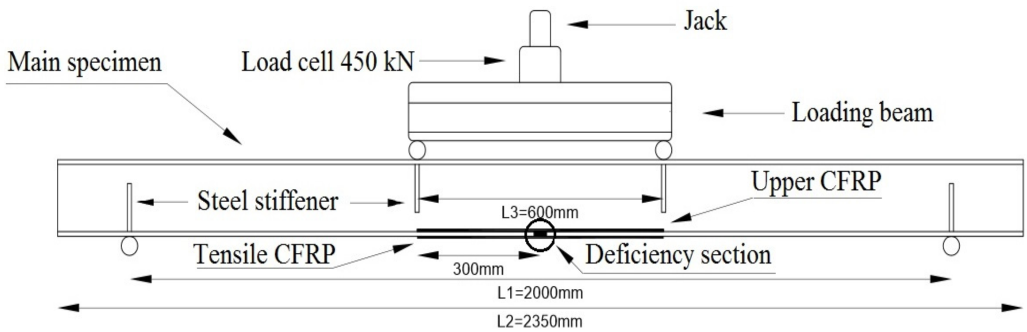


Fig. 1 Steel beams dimensions and location of deficiency region

Table 1 Dimensions and material properties of steel I-section

Steel I-section – mild steel IPE-160								
Steel I-section dimensions (mm)				E-modulus (N/mm^2) Mean value	Stress (N/mm^2)		Strain	
Width	High	Flange thick	Web thick		Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
82	160	7.4	5.0	200,000	307	412	0.12	15.2

Table 2 Dimensions and material properties of CFRP plates

Dimensions (mm)			Elasticity modulus (N/mm^2)	Tensile strength (N/mm^2)	Strain at break
Width	Thickness	Length			
82	1.4	400, 600, 800	210,000	2400	1.35%

Table 3 Dimensions and material properties of epoxy

Dimensions (mm)		Compressive strength (N/mm^2)		Tensile strength (N/mm^2)		Shear strength (N/mm^2)	Bond strength (N/mm^2)	
Width	Thick	E-Modulus	Strength (7 days)	E-Modulus	Strength (7 days)	Strength (7 days)	Mean value	Min. value
82	1.0	5485	80-110	11,520	22.7	31.7	20	>15

were selected and equal dimensions for deficiencies and CFRP strips were used in tension flange. Two addition specimens were investigated just using simulation method.

2.1 Materials

Steel beams

Table 1 lists the dimensions and material properties of the selected steel I-sections. Fig. 1 shows the dimension of the selected steel I-section and the test setup are also indicated.

CFRP

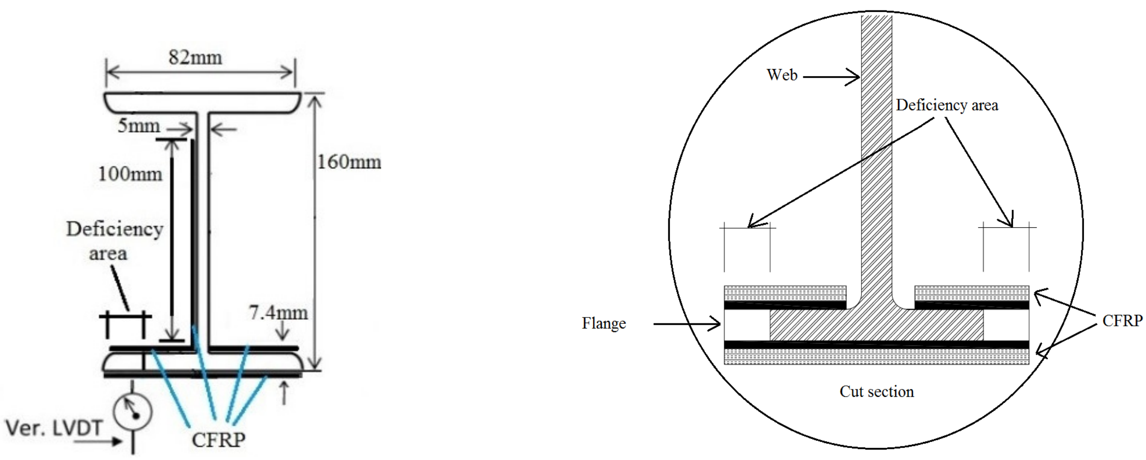
CFRP material has high tensile strength which is able to improve the structural behavior of structures. Generally, CFRP is produced in strip (plate) or a sheet (wrap) forms. In this paper, Sika® CarboDur® M1014, a unidirectional CFRP strips is only used. According to one directional behavior of CFRP strips, they are categorized in the orthotropic materials (Linghoff *et al*. 2009). Table 2 lists the material properties of CFRP strips. The lengths and thicknesses of CFRP plates are 400-600-800 mm and 1.4 mm, respectively. Table 2 lists the dimensions and material property of the CFRP strips.

Adhesive

The CFRP plates were bonded to the beams' flange and web using adhesive. The engineering epoxy (structural adhesive) must be strong enough to tolerate the high stress which is generated during loading. In order to achieve good bonding between steel beam and carbon fiber, Sikadur® 31 was utilized. Table 3 lists the specification and material properties of the chosen adhesive.

2.2 Beams properties

All types of steel I-beams enjoy similar dimensions. The specimens S1 is not strengthened and is not notched which is considered as the control beam. The beams S2 and S4 are notched in both sides at the middle of tensile flange. Cases S3, S5, S6, and S7 are defected at one side. The specimens S4 and S5 are strengthened by 600 mm length of CFRP strips and for beams S6 and S7 this amount is 400 and 800 mm, respectively. It is noteworthy that upper strips length for beams S4-S7 are 600 mm. In addition, the widths of CFRP strips for up and down are 35 mm and 82 mm, respectively as in Fig. 2. Deficiencies dimensions are the



(a) One-side notched strengthened beam (b) Two-side notched strengthened beam

Fig. 2 Schematic of notched strengthened steel beam

Fig. 3 Experimental test setup

same within 30×30 mm^2 for defected specimens.

2.3 Test setup

Total of five beams were examined experimentally including one non-strengthened and non-deficient beam (S1), two non-strengthened notched beams with one and two-side damages of S3, S2 respectively, beam S4 is two-side notched beam which is retrofitted using CFRP for up and bottom tensile beam flange, and beam S5 enjoys one-side damage strengthened by CFRP trips at web (damaged flange side), and up and bottom of flange as well. The experimental setup was designed based on the four-point bending test.

Fig. 3 shows the test setup of the specimens. In order to measure vertical deflection, Linear Variable Deformation Transducers (LVDTs) were employed in the blow bottom beams flanges. The load was applied through using a hydraulic jack that includes a load cell of 450 kN capacity. The load was transferred from the jack to the main specimen by loading beam. Two symmetrical point loads were applied in order to transfer the load's pressure to the main specimen and reactions were carried by two roller supports, so the loading state was four incremental bending point loads.

2.4 Numerical simulation

All mentioned specimens in Table 4 were investigated numerically. To model the specimens, the full 3D simulation was carried out using ABAQUS software. The CFRP plates, steel I-sections, steel stiffeners, and adhesive were simulated through 3D solid triangle elements (C3D10: A 10-node quadratic tetrahedron). Cohesive behavior was defined to interface surfaces between the steel I-beam, adhesive, and CFRP plates. As soon as the plastic strains exceeds the ultimate strain, debonding as a result of local bond stress effects and splitting occurred. In order to achieve the failures, non-linear static analysis was conducted. Linear and non-linear properties of materials were applied. The CFRP plate material properties were defined as linear and orthotropic, also adhesive and steel beams were defined as the materials with non-linear properties. Combination of the auto meshing and map meshing were used for meshing. In order to analyze crack propagation, the Extended Finite Element Method (XFEM), a numerical method, was employed based on the Finite Element Method (FEM). That is particularly designed for treating discontinuities.

3. Results and discussions

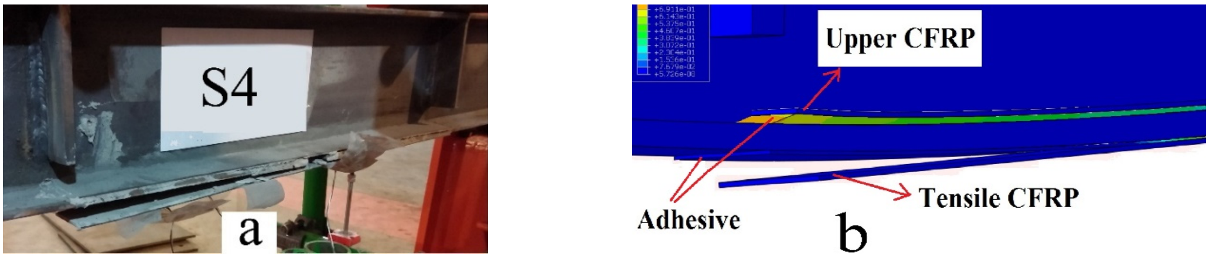
The results of numerical modelling and experimental studies are employed to investigate CFRP failure modes and structural behavior of deficient steel I-beams.

3.1 Steel failure modes

Since the specimens were not laterally constrained,

Table 4 Specifications, load bearing capacities, and deficient dimension of the beams

No.	Specimen	CFRP length (mm)		Deficiencies dimensions (mm^2)	Load bearing capacity (at elastic zone)			
					Experimental		Numerical	
		Tensile CFRP	Upper CFRP		Load (kN)	Increase/decrease (%)	Load (kN)	Increase/decrease (%)
1	S1	N/A	N/A	N/A	108.7	N/A	104.6	N/A
2	S2	N/A	N/A	Two-Side: 30×30	78	-28.24	83	-20.65
3	S3	N/A	N/A	One-Side: 30×30	91	-16.28	87	-16.82
4	S4	600	600	Two-Side: 30×30	104.3	-4.04	101	-3.44
5	S5	600	600	One-Side: 30×30	112.4	+3.4	109	+4.2
6	S6	400	600	One-Side: 30×30	N/A	N/A	107	+2.29
7	S7	800	600	One-Side: 30×30	N/A	N/A	117	+11.85



(a) Experimental test (b) Numerical study

Fig. 4 CFRP end-debonding

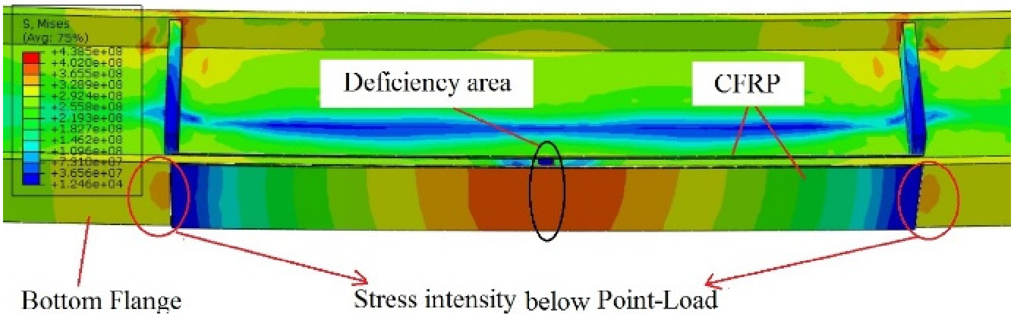


Fig. 5 Stress intensity below point load

Fig. 6 CFRP splitting occurred for case S4

when the concentrated loads were applied to steel beams, all specimens without CFRP show lateral buckling failure namely Lateral Torsional Buckling (LTB). Vertical deflection initially occurred, then by exceeding elastic zone, beams started to lateral buckling. Following, for the specimens with notch while deficiency extended, crack created and propagated. Eventually, the final failure for all specimens was lateral buckling.

3.2 CFRP failure modes

Generally speaking, CFRP flexural strengthened steel beams contain four failure modes: Laminate rupture at the mid-span, debonding failure because of shear strain intensity at the end and below point load, splitting, and delamination. In this study, S4 and S5 were strengthened using CFRP which are notched within 30×30 mm^2 at tensile flange mid-span. CFRP strengthening by 600 mm strips length for both up and bottom to cover this large damage section was appropriately applied. In the case of S4 with two-side deficiencies, end-debonding phenomenon took place Fig. 4 because of high stress and strain intensity at CFRP tips. Before yielding, the ends of CFRP reinforcement used to be more critical, but, high stress below point-load (Fig. 5) led to rising adhesive stress

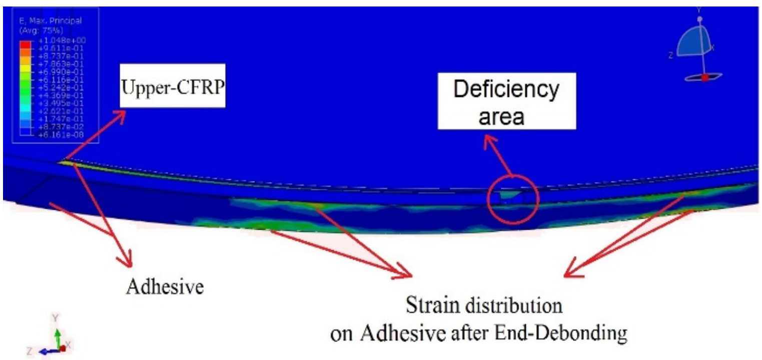


Fig. 7 Strain intensity (shear stress) on adhesive

intensity after yielding which caused below point load debonding. Also, shear stresses as a result of large lateral deformation caused CFRP splitting failure along strip initiated below the point loads and developed to whole length of CFRP strip as shown in Figs. 6 and 7.

S5 is defected by one-side notch (30×30 mm^2) which is strengthened by 600 mm CFRP strips on the up and bottom of tensile flange. An asymmetrical damage, one-side deficiency causes critical local buckling. In order to prevent local buckling, web strengthening (notched side) was utilized using 600×100 mm^2 length of CFRP. At the beginning of yielding, shear stress of web rose and CFRP splitting failure happened consequently. By appearing first cracks at web CFRP, tensile laminate starts to debond (End-debonding occurred). Splitting failure modes are as a result of CFRP weakness in the transverse direction and web deformation. Furthermore, distributed shear stresses on web cause CFRP delamination concurrent loading increase as in Fig. 8. The CFRP strips used in this research are unidirectional type, meaning that they have high longitudinal (axial) strength and low latitudinal (transverse) strength. Upper CFRP is under compressive stress along strip and shear stress in the vicinity of damage area; moreover, it is indicated debonding for upper CFRP tip Fig. 9.

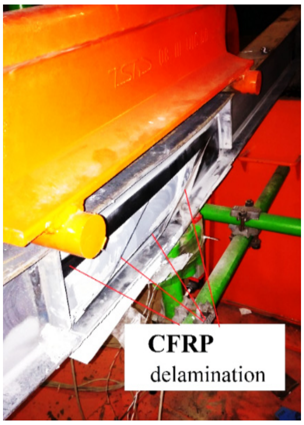


Fig. 8 CFRP delamination on web

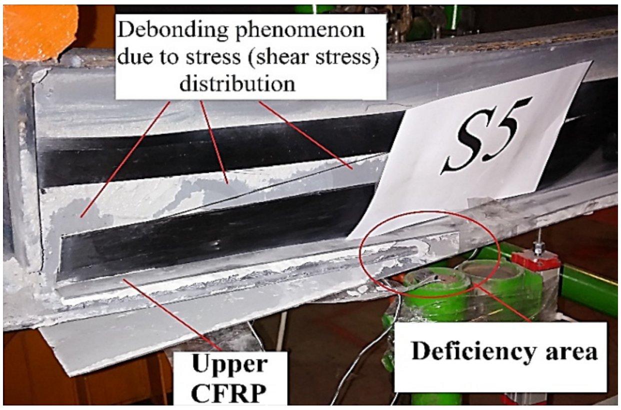


Fig. 9 Splitting failure mode for web CFRP

3.3 Structural behavior of deficient steel I-beams

According to Table 4, load carrying capacity and rigidity of non-strengthened and strengthened deficient steel beams were compared with that of control beam (S1). To study the above-mentioned structural parameters, ABAQUS modeling and experimental test were used. Fig. 10 shows the load-vertical deflection graphs at the mid-span for specimens S1, S2, S3, S4, and S5 obtained from experimental tests using an LVDT. S1 is non-strengthened and non-defected steel beam, which it underwent the108 kN -load bearing capacity.

The two-side notched damage within 30×30 mm^2 for case S2 resulted in a considerable load- carrying reduction at elastic phase by 78 kN. By rising loading in the plastic region after yielding, damage section expanded and initiated crack propagation on the flexural flange as shown in Figs. 11 and 12. Also, a brittle fracture of web occurred at 95 mm vertical deflection abruptly (it is shown on another side of beam web) Fig. 13. S4 is strengthened two-side defected beam using CFRP which increased flange stiffness and strength at elastic region. Load bearing capacity reached to

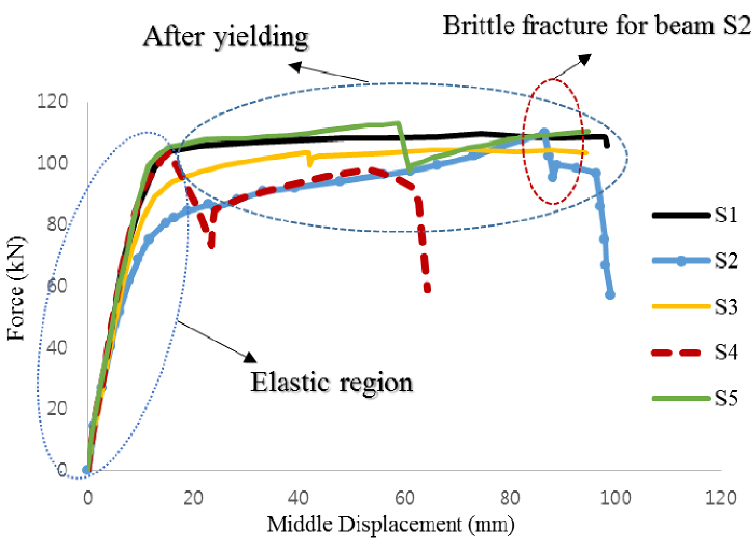
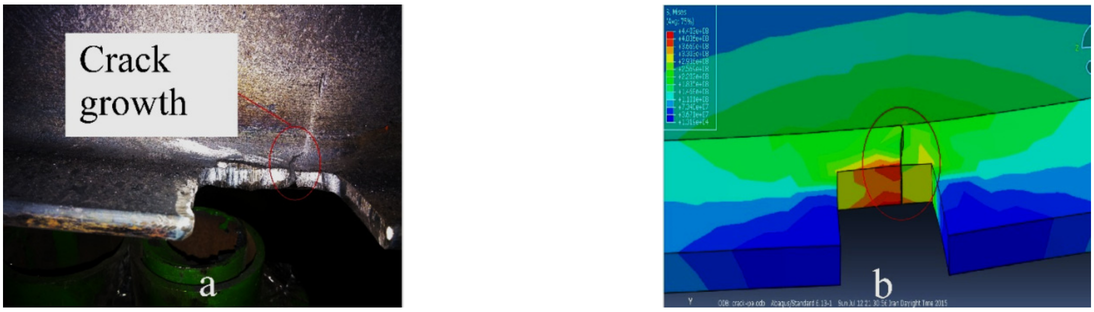


Fig. 10 Vertical deflection at the mid-span (experiments)



(a) Experimental test (b) Numerical modeling

Fig. 11 Increasing damage and crack propagation

(a) Experimental test (b) Numerical modeling

Fig. 12 Crack propagation on tensile flange

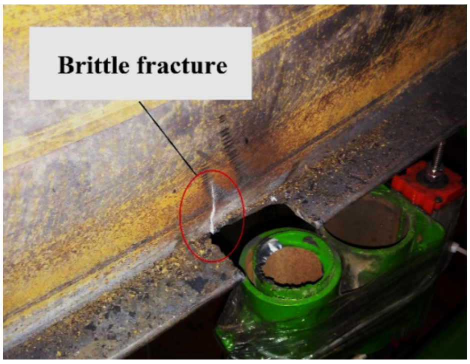


Fig. 13 Brittle fracture on the web

104 kN by 33% enhancement compared to case S2. After yielding, due to the extent of the damage, CFRP strips debonded during efficiently prevented brittle fracture occurrence. In addition, after CFRP debonding, a substantial ultimate load reduction happened at the beginning of plastic zone as in Fig. 10. One-side deficiency, beam S3 underwent ultimate load by 91 kN which showed declined load bearing up to 16% at elastic zone. In this case crack was not observed, even though local buckling was critical Figs. 14 and 15. In terms of specimen S5, it is notched by one-side deficiency and strengthened. Using CFRP improved beam structural functionality and flange stiffness; also, load carrying capacity reached to top of 112 kN that demonstrated a negligible rise compare to control beam. Concerning beam S6, it was built up by 400 mm tensile CFRP that recovered ultimate load decrease and showed lesser local buckling in comparison with beam S3. Increase

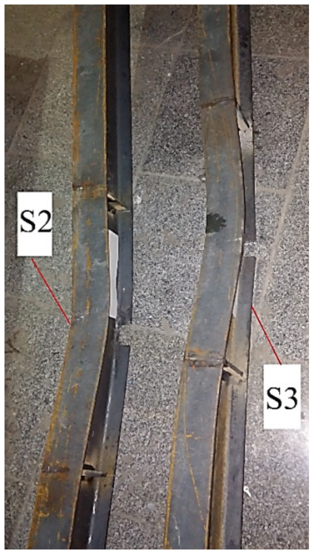


Fig. 14 Local buckling of experimental test

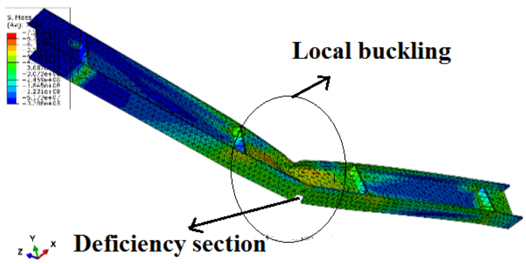


Fig. 15 Local buckling for non-strengthened beam which has one-side deficiency

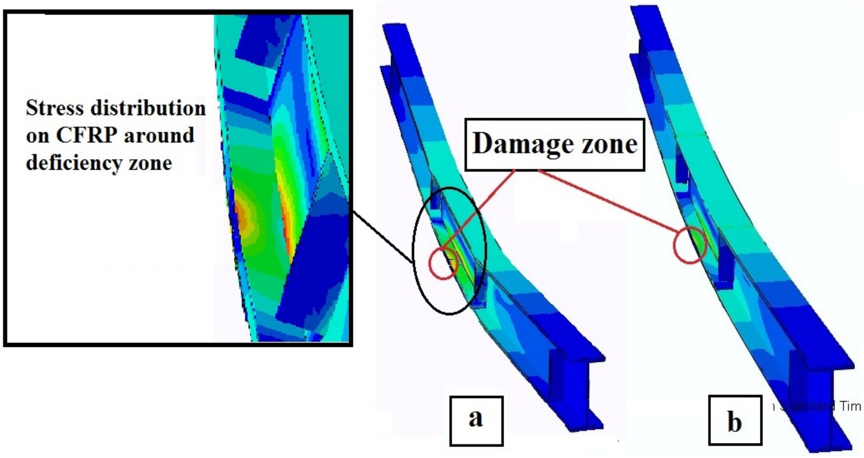


Fig. 16 Local buckling, (a) S6 (tensile CFRP 400 mm); (b) S7 (tensile CFRP 800 mm)

of tensile CFRP length in case S7 by 800 mm which is effective in stiffness development lead to delay local buckling more than beam S6 as in Fig. 16. It is essential to highlight the fact that specimen S6 can compensate strength-lost, beam S5 with 600 mm flexural CFRP was chosen in this paper due to critical condition for the reason that both ends of strip are directly under load points which resulted in premature end-debonding.

4. Conclusions

In this paper, CFRP failure modes and structural behavior of defected steel beams under static gradual loading were studied. In order to study aforementioned parameters, seven steel I-beams through experimental and numerical study were examined. Notched damage on the tensile flange caused a considerable reduction on load bearing capacity and rigidity. The specimens with two-side deficiencies showed less load carrying capacity in comparison by beams having one-side deficiency. When beams came to plastic zone, crack was created in the deficiency location and a brittle fracture occurred. The CFRP plates were proposed to fill the lack of strength-lost. Stress and strain intensity at the plates' tips and around damaged area caused debonding and splitting failures. The specimen strengthened by using CFRP strips which were settled under and upper deficiency in tensile flange and on the web adjacent to deficiency caused prevention in local buckling appropriately. Due to weakness of CFRP strips in the transverse direction, web deformation and distributed shear stresses on the web resulted in splitting and delamination of web's CFRP failures respectively.

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