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Overcoming Strength-Lost in Deficient Steel I-Beams Using CFRP

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ABSTRACT

Time and environmental factors cause some problems such as rusting and decay for great constructs and buildings. Since these factors significantly contribute in reducing resistance, reducing load bearing capacity and defect created in structural components, it is required to take the necessary measures in order to improve the structure performance. This research studies the effect of CFRP strips on strengthening deficient steel beams by modeling seven beams through ABAQUS V6.11. It is worth noting that there was created a fixed, primary defect at the mid-span of tensile flange. The size and position of CFRP strips were different. The results indicated that application of CFRP could appropriately overcome the weakness occurred due to deficiency.

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INTRODUCTION

Since 1967, when a mandatory inspection and in situ control on bridges was conducted in the U.S.A, American Association of State Highway and Transportation Officials (AASHTO) and Federal Highways Administration (FHWA) have set a developed plan for 6-month inspection. As a result, it was found out that more than one third of all highway bridges in the United States are substantially below standard [1].

Klayber *et al* stated that more than 43% of bridges in the United States are made of steel. According to NBI report, metal bridges are classified as those kinds of bridges requiring improvement due to exhaustion and worn out, need of increasing service load, corrosion and lack of proper maintenance. Moreover, it is recommended to repair and strengthen the bridge preceding any movement. The costs of reconstruction and renovation, in most cases, are much less than replacement costs. Furthermore, repair and reconstruction normally take less time. Regarding the limited accessible resources to decrease the problems of steel bridges, it is evidently required to adopt new materials and economic methods [2].

In Mosses *et al* research, there are more than 120.000 steel bridges with welded details in the United States. More than 50,000 of which are older than 30 years old. According to the collected data, totally, the highway large bridge experiences more than 1.5 million truck cross per year. Considering the high traffic volume and the age of these bridges, this issue can reveal exhaustion limit from 2,000,000 cycles based on the project specification [3].

According to Klayber *et al*, prior to observing the crack of Yellow Mill Pond Bridge in Bridgeport resulted from exhaustion, it is impossible to name many steel bridges with cracked details. 11 years following the first crack seen in that bridge, the crack was seen in most coverage plates with end welding. [2] Fisher studied the problem and concluded that growing the crack resulted from exhaustion can be considerably occur after some high-stress cycles (when it exceeds the exhaustion limit) [4].

Lorenzo showed that CFRP plates with exhaustion sensitive characteristics in metal component can lead to increased resistance and longer exhaustion. The paramount mechanical and exhaustion properties of carbon fiber-armored fiber polymers can introduce them as the best option of repairing and strengthening of bridges' steel girders. CFRP plates guarantee one million cycles of exhaustion loading and the stress range is equal to 1.5 times the ultimate strength [5].

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Sin, in South Florida University, studied the possibility of applying CFRP in repairing concrete-steel composite bridges. A complete beam with 6.1 m span and a W203×10.9 steel cross-sections was connected to a 711 and 115 mm slab. The CFRP plates used in this research had 3.65 m length, 150 mm width with two different 2 and 5 mm diameters. They found that using CFRP plates significantly increases the composite beam's final (ultimate) capacity [6].

Tavakkolizadeh and Saadatmanesh, in Arizona University, studied the effects of epoxy connections on CFRP laminates in the normal and damaged composite (steel-concrete) beam for strengthening and repairing. Six composite beams of W355×13.6 steel section and the concrete slab of 910 mm width and 75 mm diameter were investigated. The research findings showed that CFRP plates can cause significant increasing of normal composite beam's ultimate load carrying capacity, returning the ultimate load bearing capacity and hardening of the damaged composite beam [7].

FRP sheets/strips are also effective in the strengthening of steel structural elements to extend their fatigue lifetime and reduce crack propagation [8-10] if galvanic corrosion is prevented and sufficient bond is provided [11, 12].

Kim and Harries, developed a three-dimensional (3D) non-linear finite element model for predicting the fatigue strength of notched steel beams using ANSYS software. The steel section was modelled using 3-D structural solid elements (SOLID45); and a linear stress-strain relationship was developed for the CFRP. A non-linear interface element (COMBIN39) with two nodes was applied for modelling the behavior of the steel-CFRP interface. For the element whose initial relative distance is zero, a bilinear bond-slip relationship was created for them. The strain life approach is mainly relevant to a member representing significant plasticity induced by hysteretic loads [13].

Ghafoori, *et al*, proposed an analytical method using the experimental test data (the external bending moment, the length of the crack and the corresponding strain imposed on the CFRP strip under the cracked segment). They used ABAQUS software (version 6.8) to analyze the FE model of the steel beams to validate the results. The method was developed to assess the sufficient level of the CFRP prestressing to arrest the fatigue crack growth [14].

There are different methods in order to strengthening, which CFRP strengthening as the best those is proposed. Fibre-reinforced polymer possesses outstanding advantages as a structural material, including high strength, anticorrosion properties, high durability and is able to restore the lost capacity of damaged structures. In addition, CFRP causes reduction of cost and repairing time considerably.

This research studies the effect of binding CFRP plates on the steel beam structural behavior and recovering the deficient beam's hardening and load bearing capacity. Different sizes of CFRP plates are used in simulation to obtain the suitable length. The studies in this research were conducted given the crack's fixed length and width during loading; in addition, the impacts of crack extension are disregarded. Eventually this paper has provided a new method for strengthening of deficient beams.

Materials and Specimens:

The effect of CFRP plates on improving exhaustion strengthening and increasing load carrying capacity in steel beams were studied through simulating a normal and deficient beam with no strengthening as well as 5 strengthened defected-beams. In order to make a defected component, a slot of 20×10 mm^2 was created at the center of each side of tensile steel beam flange and CFRP plates were placed on the cut area. Sizes and material properties of steel beam section IPE are presented in Table 1. Figures 1 and 2, also, illustrate loading, the place and dimension of the created defect.

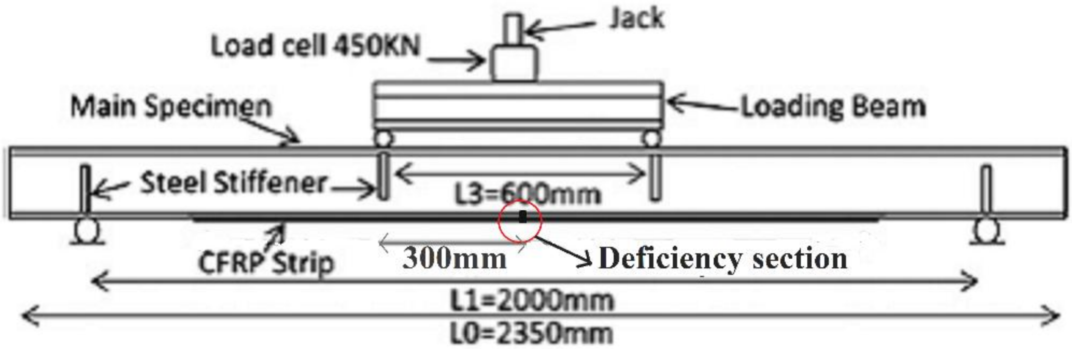

Fig. 1: Steel beams dimensions and location of deficiency.

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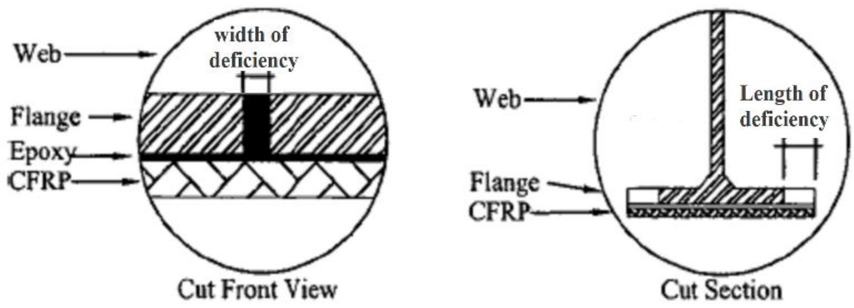

Fig. 2: Schematic of deficiencies in bottom flange.

Table 1: Dimensions and material properties of steel I-section.

Steel I-section – mild steel IPE-160								
Steel I-section dimensions (mm)				E-modulus	Stress (N/mm^2)		Strain	
Width	High	Flange thick	Web thick	(N/mm^2) Mean value	Yielding (F_y)	Ultimate (F_u)	Yielding (ε_y) %	Ultimate (ε_u) %
82	160	7.4	5.0	210,000	250	370	0.12	13.5

CFRP:

CFRP plates have high tensile strength which causes improving the structural behavior of the deficient beam. In this research, a type of CFRP plate with medium elasticity module and the same thickness is used. The properties are provided in Table 2. The plate width, thickness and length were set 82mm; 1.2mm; 300, 400, 700, 1000 and 1500 mm, respectively.

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	1.2	300,400, 700, 1000,1500	160,000	2800	%1.70

Adhesive:

The adhesive used for bonding CFRP plates to steel beam must be sufficiently resistant in order to be able to transfer the surface stresses. The properties and dimensions of the selected adhesive are shown in Table 3.

Table 3: Adhesive dimensions and material properties.

Adhesive									
Dimensions (mm)			Compressive strength (N/mm^2)		Tensile strength (N/mm^2)		Shear strength (N/mm^2)	Bond strength (N/mm^2)	
Width	Thickness	Length	E-modulus	Strength (7 days)	E-modulus	Strength (7 days)	Strength (7 days)	Mean value	Min. value
82	1.0	Var.	9600	70-95	11,200	22.7	31.7	20	>15

Specimens:

Specimens' specifications and their ultimate load carrying capacity are represented in Table 4. Steel beams' sizes are fixed; whereas, CFRP size is different for each beam. S_1 is the non-strengthened normal beam applying for control. S_2 is the non-strengthened deficient beam; and, S_3, S_4, S_5, S_6 and S_7 are the strengthened deficient beams. The length of the applied CFRP is equal to 1500 mm, 1000mm, 700mm, 400mm and 300mm, respectively.

Table 4: Sample beams load carrying capacity.

No.	Specimen No	CFRP length (mm)	Load carrying capacity (kN)	Percentage of increasing or decreasing capacity
1	S_1	None	125	-
2	S_2	None	108	-%14
3	S_3	1500	159	+%27
4	S_4	1000	157	+%25
5	S_5	700	136	+%8
6	S_6	400	125	-
7	S_7	300	124	-%1

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Software analysis and simulation:

The simulation was done through using ABAQUS V6.11 software in which steel beam, stiffener plates, CFRP plates and adhesive were modeled in three dimensions and solid form with TET, Quadratic (10 nodes) elements. The break status was obtained through using nonlinear static analysis. The materials' linear and nonlinear properties were applied.

The software validity was tested by comparing two sample beams of Narmashiri *et al*. [15] The simulated sample was carefully validated by in vitro samples (F1 and F4) of the current research (Figures 3 and 4).

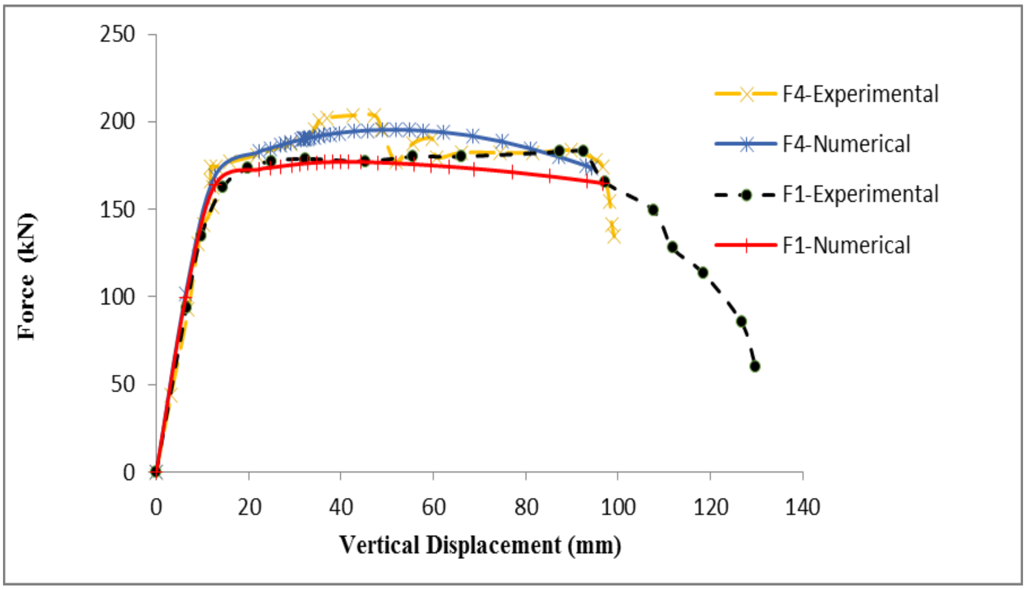
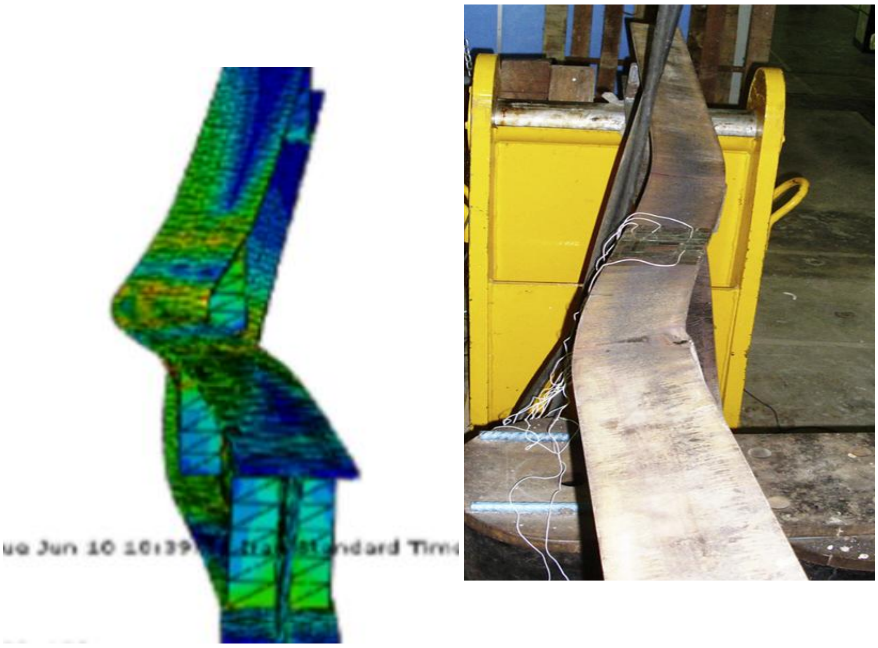


Fig. 3: Validation of vertical displacement at the mid-span (experimental and numerical).



(a) (b)

Fig. 4: Lateral-torsion-buckling (a) numerical (this research), (b) tested beam [15].

RESULTS AND DISCUSSIONS

One of the critical parameters in structures' strengthening is the load bearing capacity and stiffening of the strengthened structure's elements against non-strengthened structure. Regarding Table 4 and the force-displacement diagram in Figure 6, deficiency in the middle of tensile flange in non-strengthened sample beam (S_2) has caused decreasing 14% of load carrying capacity and increased deficiency. This increased deficiency of

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non-strengthened beam can be clearly seen in Figure 5. To strengthening, CFRP with 1500 mm length is initially used in which 27% increasing of load bearing capacity is seen. To achieve CFRP suitable length such that the defected beam performs like normal one, the applied length was reduced. The results are as follows.

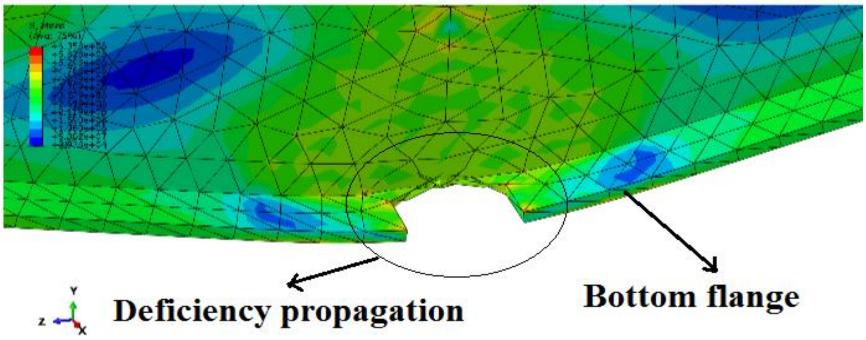

Fig. 5: Deficiency Propagation in tensile flange of non-strengthened beam.

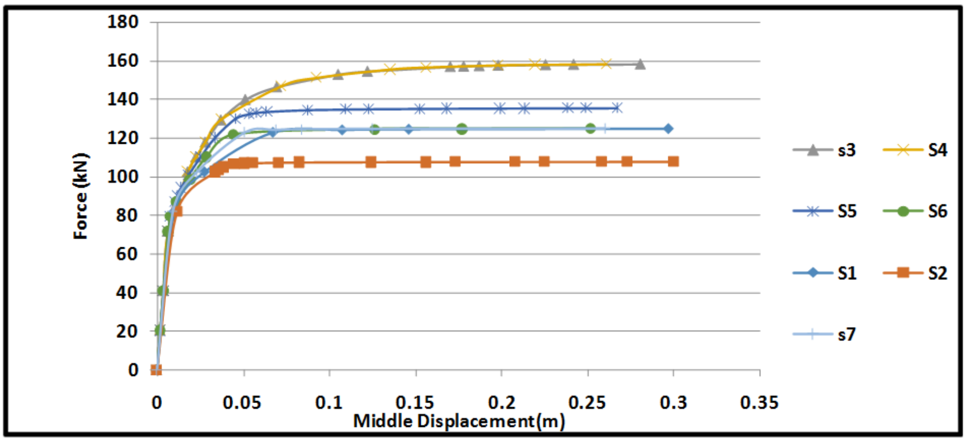

Fig. 6: Force- Displacement diagram for the middle of flange.

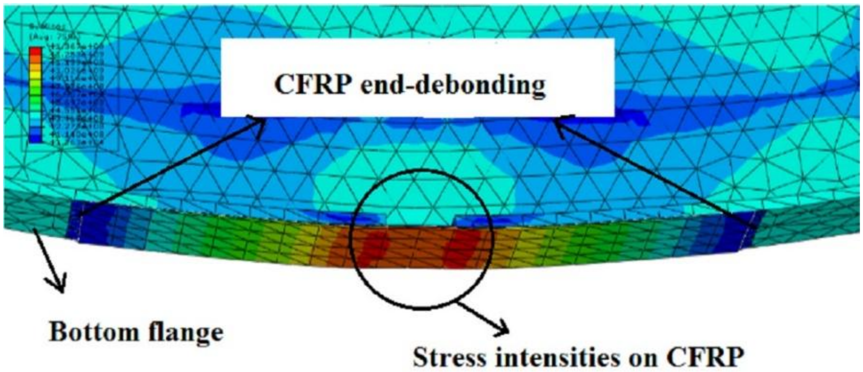

Fig. 7: End-debonding of CFRP at the tip of plate and stress intensity on CFRP at the deficiency area.

Load carrying capacity increased 25% for 1000 mm length, 8% for 700mm; and the best performance in terms of load bearing capacity and deformation similarity to normal beam was seen in the length 400 mm (Figure 6). It is worth noting that in 300 mm, 1% decrease was seen in load bearing capacity; regarding high deformations, 400 mm was selected as the most appropriate length. Using CFRP plates in the tensile flange area led to reduced stress and strain in the area of strengthened beam's deficiency which properly prevents defect extension (Figure 7). As it can be seen, CFRP plates can be applied as the best strengthening materials for deficient beams such that a length of 16% of the beam's length provides a beam with the loading capacity of a normal beam. According to short length and small thickness of CFRP plates, the elastic stiffening of the strengthened and non-strengthened beams is similar.

Beam's stiffness initiate decreasing followed by the first crack expansion in the flange, when the crack grows more than 10 mm; and preceding to arriving at the corner, such that the deficient beam's rupture take place in a short time. In non-strengthened beams, the rupture occurs before stiffening reduced to more than 10% [16].

Conclusion:

In this research, CFRP plates with various lengths and medium elasticity module were applied to increase steel beams' load carrying capacities with deficiency on the tensile flange at the mid-span. The results of force-displacement diagrams obtained from limited components method in the studied samples demonstrated that using these plates significantly influences on improving deficient beam's performance. So, the beam's flexural strength and load bearing capacity are completely recovered in the strengthened specimens. Moreover, using CFRP plates largely contributes in decreasing stress in the beam's deficiency area preventing defect extending. Since most bridges and constructs are metal encountering aging and deficiency over time; in addition, the costs of building new construct and replacing the component are high and time-consuming, using these materials significantly reduces the time and costs. Therefore, they are recommended as the best materials for repairing defected beams under loading.

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