Finite Element Analysis of Locally Post-Tensioned Steel Beams using CFRP Bars

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Abstract – *This study analytically investigates the behaviour of steel beam locally prestressed using CFRP bars. Five finite element models were prepared using ANSYS 16.1 software. The beams were analysed under three-point bending and compared their performance with conventional beam in terms of load carrying capacity and stiffness. Four beam models were prestressed using CFRP bars at different level of prestress and one beam model is used as conventional beam for comparison. Results showed that locally prestressed CFRP bars significantly improved the ultimate load carrying capacity of steel beam at different level of prestress.*

Key Words: Local post-tensioning, External post-tensioning, CFRP bars, Jacking distance, ANSYS.

1. INTRODUCTION

Prestressed steel structures have many advantages over steel, reinforced cement concrete and prestressed concrete structures. The term "prestressed steel" means application of a pre-determined concentric or eccentric force to a steel member so that the state of stress in the member resulting from this force and from any other anticipated external loading will be restricted to certain specified limit. This is done by inducing opposite stresses in a structure before it is put to its actual use by application of external forces. These forces are controlled in magnitude and direction to counter act the developed stresses in beam due to working loads. It is very difficult to establish a bond between the prestressing tendon and a steel beam. Hence external post-tensioning technique is adopted for prestressing of steel beams [1].

External post-tensioning is an effective method for strengthening of existing steel structures as well as for the construction of new structures. This technique involves welding end anchorages and using conventional high-strength post-tensioning cables. This type of strengthening improved the flexural capacity of steel I beam to 30%-40% and creates a stiffer steel beam when the proper amount of prestressing force is applied and when detail techniques are appropriately combined [2]. In steel concrete composite beams, externally post-tensioned tendons improved the flexural behaviour under static loading by increasing the beam capacity and reducing the tensile strain in the bottom flange of the steel beam [3]. However, this technique requires special technologies and equipment, which are relatively expensive and may not be available in all cases or simply cannot be used in particular cases such as in strengthening and reconstruction.

As a simplification to the external post-tensioning technique, applying prestressing in a localized region within a steel beam can be used for strengthening existing steel bridges and repairing severely damaged steel I-beams, and this will reduce the cost of post-tensioning This kind of local post tensioning increases the stiffness and the load carrying capacity of the steel structural member through adding reinforcing steel bars to a segment of the beam. In local post-tensioning the prestress is achieved by elevating the steel bars from the soffit of the steel beam by using a manual screw jack that generates a tensile force in the steel bars. Thus, local post-tensioning is simple and low-cost alternative to modern high-tech post-tensioning techniques because it uses conventional reinforcing bars and a manual screw jack instead of tendons and hydraulic jacks, to apply post-tensioning to the new or existing structure [4, 5]. In external prestressing, corrosion of exposed prestressing bars or tendon is a major issue. Fiber reinforced polymers (FRP) are a promising alternative to high strength steel bars and tendons for prestressing. Many studies showed that externally post-tensioned tendons enhance the load carrying capacity, high stiffness and high energy absorption than steel [6, 7]. From all FRPs, CFRP tendons and bars show very similar mechanical properties to steel tendons, and thus, present a promising alternative to steel for use in prestressing applications.

This paper presents an analysis of steel beam prestressed using CFRP bars incorporating local post-tensioning technique in ANSYS software. The main objective of this study is to investigate the behaviour of steel beam prestressed using CFRP bars at different level of prestress. Compare the behaviour at different level of prestress in terms of load carrying capacity and rigidity of beam. Results are compared with those of conventional beam to study the effectiveness of local post-tensioning for strengthening purposes.

2. LITERATURE REVIEW

Sunkyu Park et al. (2010) studied the flexural behavior and strengthening effect of bridges using a steel I-beam that had been externally prestressed with unbonded tendons. Eleven steel beams were fabricated and tested in terms of the tendon type, the amount of tendon or prestressing force, the installation of a deviator, and the embedment of a draped tendon. The results showed that the externally prestressing method creates a stiffer steel beam when the proper amount of prestressing force was applied and when detail techniques were appropriately combined.

Ayman El-Zohairy et al. (2019) explained the static and fatigue tests on four steel–concrete composite specimens to evaluate the effect of externally post-tensioned tendons on the ultimate strength and fatigue behavior of composite beams. The static test results indicated that the external PT force improved the flexural behavior of the strengthened specimen by increasing the beam capacity and reducing the tensile strain in the bottom flange of the steel beam. The external PT improved the overall performance of the composite beam under fatigue by decreasing the strains in the shear connector, in the concrete flange, and in the steel beam at all stages of loading. The results demonstrated that external PT significantly decreased the stresses in the internal reinforcement at all stages of loading and hence extended the fatigue life of the strengthened beams.

Assaad Taoum et al. (2015) presented an experimental study incorporating the local prestress method to strengthen and upgrade steel I-beams. This paper investigated the behaviour of steel beams upgraded using locally pre-stressed reinforcing steel bars. From the experiments they concluded that the application of local pre-stressed reinforcing bars in conjunction with a stiffener to prevent buckling could add up to 60% of the load carrying capacity of the steel I-beams.

In their another work, presented an experimental study on the use of the local prestress method to strengthen steel beams damaged by severe fatigue cracks. The aim of the study was to investigate the behaviour of locally prestressed steel beams in three-point-bending and to examine the effect of the prestress levels on the rigidity and the load carrying capacity of the damaged steel beams. Results were compared with those of beams strengthened by other methods. Results showed that the level of prestress controlled the beams' stiffness, while restoration of their ultimate load-carrying capacity was governed by the bar size. Significantly higher repaired capacities were achieved by this method than by other published methods used for the strengthening of steel beams.

3. MODELLING

In this paper five were modelled and analysed in ANSYS software to determine the ultimate load carrying capacity and corresponding maximum deflection in beam under three-point bending. Out of five beam models, four models are prestressed beam and the remaining one is modelled as a conventional beam in which no prestress is applied. The steel I-beam is modelled using a 3-D twenty-node solid element SOLID186 with three degrees of freedom at each node. PRETS179 is used to define the 3D pretensioned section (external unbonded CFRP bar) within the meshed structure. CONTA174 is used in contact regions.

The steel beams used in this study were ISMB300 of span 3 m. Key geometric properties are an overall depth of 300 mm, a flange width of 140 mm, flange thickness of 12.4 mm and web thickness of 7.5 mm. A stiffener is provided at mid span to avoid buckling. Three -point bending test is adopted for loading in ANSYS to study the behaviour of the beams. A load plate is provided at the midspan to apply loading and the beam is simply supported at two ends using two support plates at each end. CFRP bars of nominal diameter 10 mm and with nominal area 71 mm^2 are used for local prestressing. Length of CFRP bar used for prestressing is 2.6 m. Two numbers of bars were used to prestress the beam and different models were modelled by varying the level of prestress as 30%, 50%, 80% and 90% respectively. The material properties of steel beam and CFRP bar are given in Table 1.

Table -1: Material properties of steel beam and CFRP bar

PROPERTIES	STEEL BEAM	CFRP BAR
Elastic modulus (GPa)	200	124
Yield strength (MPa)	350	-
Tensile strength (MPa)	-	2172
Poisson's ratio	0.3	0.3

Details of model used in this study are given in Table 2.

Table -2: Description of models

BEAM DESIGNATION	PRESTRESSING BARS USED	LEVEL OF PRESTRESS
BC	-	-
BCF30	2 numbers of CFRP bars	30%
BCF50	2 numbers of CFRP bars	50%
BCF80	2 numbers of CFRP bars	80%
BCF90	2 numbers of CFRP bars	90%

The jacking distance and tensioning force required to prestress the beam is calculated using Eq(1) and Eq(2) developed by Assaad Taoum *et al.*[6]

$$f = l\sqrt{\frac{\sigma}{2E}}, \qquad (1)$$

Where

f Jacking distance

σ chosen value of prestressing

l length of reinforcement bar
E Young's modulus of steel

$$N = \sigma A. \quad (2)$$

Where, *N* is the tensioning force required to generate the prestress '*σ*' in prestressing bar having cross section area '*A*'. The CFRP bars are attached to the soffit of them (bottom flange). Bolt pretension tool is used in ANSYS to apply tensioning force in CFRP bars. The CFRP bars are provided in a single harped profile. The two ends of the bars were fixed on bottom flange at both ends. A deviator is fixed between bottom flange and CFRP bars to maintain the tendon profile. Table 3 shows the jacking distance and tensioning force required for each beam.

Table -3: Jacking distance and Tensioning force required for beam models

BEAM DESIGNATION	LEVEL OF PRESTRESS	JACKING DISTANCE mm	TENSIONING FORCE (For one bar) kN
BC	-		
BCF30	30%	133.3	46.2
BCF50	50%	172	76.9
BCF80	80%	217.6	123.4
BCF90	90%	230.8	138.8

After assigning the properties of material and sections used, loading is applied at the midspan to the meshed model for solving. Deflection controlled loading is applied in ANSYS. The ANSYS models BCF30, BCF50, BCF80 and BCF90 beams were shown in Fig 1 to Fig 5.

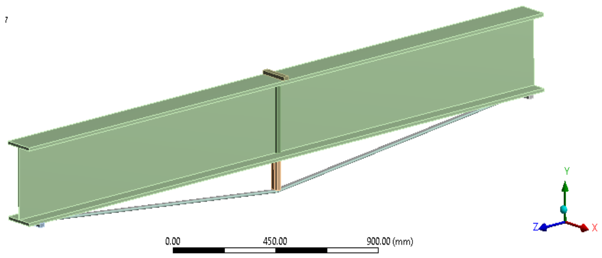

Fig -1: ANSYS model of BCF30 beam

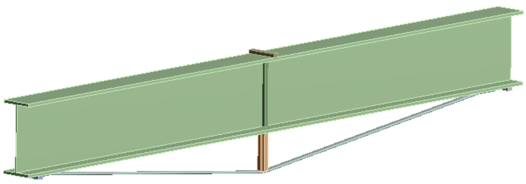

Fig -2: ANSYS model of BCF50 beam

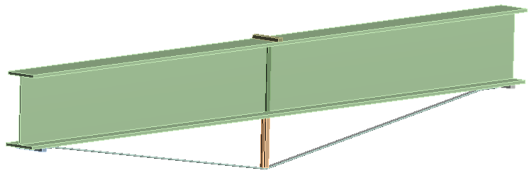

Fig -3: ANSYS model of BCF80 beam

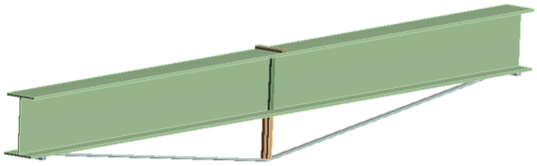

Fig -4: ANSYS model of BCF90 beam

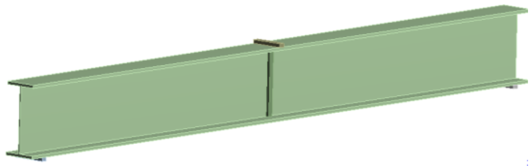

Fig -5: ANSYS model of BC beam

4. RESULTS AND DISCUSSION

The ultimate load carrying capacity of prestressed beams and conventional beams obtained after the analysis are given in Table 4.

Table -4: Ultimate load carrying capacity of beams

NAME OF BEAM	ULTIMATE LOAD (kN)	% INCREASE IN LOAD CARRYING CAPACITY
BC	341.11	
BCF30	440.75	29.2
BCF50	494.65	45.0
BCF80	499.44	46.4
BCF90	513.22	50.5

While comparing ultimate load carrying capacity, CFRP bars effectively improved the load carrying capacity of steel beam at all level of prestress. Maximum increase in ultimate load carrying capacity is obtained at 90% level of prestress, almost 50% increase in ultimate load compared to conventional beam. Minimum load carrying capacity is obtained at 30% level of prestress, 29% increase in load carrying capacity compared to conventional beam. So, in the case of CFRP bars the load carrying capacity is increased while increasing the amount of prestress.

Chart 1 shows the load deflection graph of beams prestressed using CFRP bars. At 30% and 50% level of prestress, the shape of load-deflection curve is similar to conventional beam. But at 80% and 90% the shape of curve is quite different from conventional beam; they follow a linear behaviour rather than yielding behaviour. This is due to the sudden failure of CFRP bars after reaching the ultimate load. In BCF90 beam ultimate load obtained is 513.22 kN and corresponding deflection is 16.54 mm after that sudden rupture of CFRP bar taken place and the beam model failed in ANSYS. BCF80 beam also performed similar to BCF90 beam. But in BCF30 and BCF50 models the maximum deflection corresponding to ultimate load is 71mm, so the beam model shows better yielding performance. Generally, CFRP bars and tendons are linear elastic to failure and do not exhibit yielding behaviour, they can be subject to brittle failure, and require special design consideration to avoid this. Allowable stresses in FRP tendons are typically limited to 40 to 65% of their ultimate strength due to stress-rupture limitations. Also, as per ACI committee 440 (2004), recommended maximum jacking stresses for CFRP tendon is 0.65 times of its ultimate tensile strength. Like CFRP tendons, CFRP bars in this study also perform similar ways in the applied loading and are readily apparent on the load-deflection graph of beams prestressed using CFRP bars.

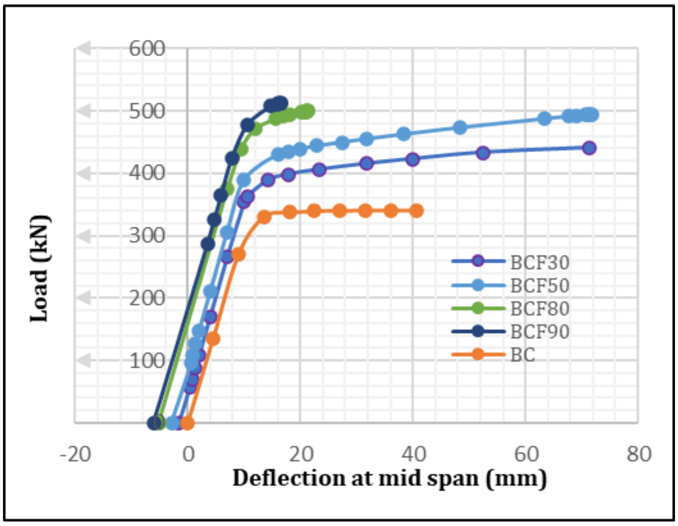

Chart -1: Load-deflection graph of beams prestressed using CFRP bars

The deflection of beams obtained from ANSYS are shown in Fig 6 to Fig 10.

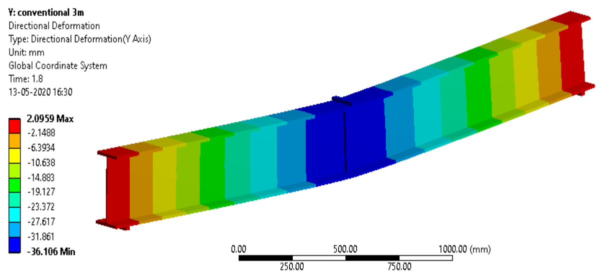

Fig -6: Deflection of conventional beam (BC)

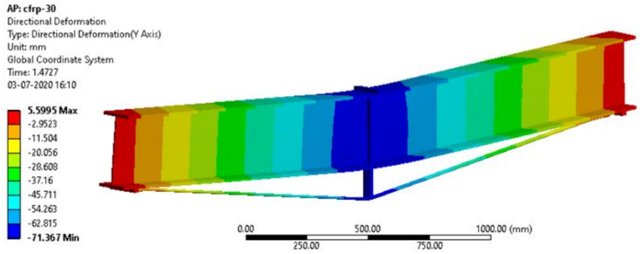

Fig -7: Deflection of BCF30 beam

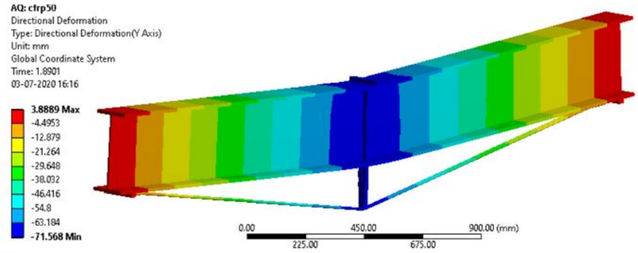

Fig -8: Deflection of BCF50 beam

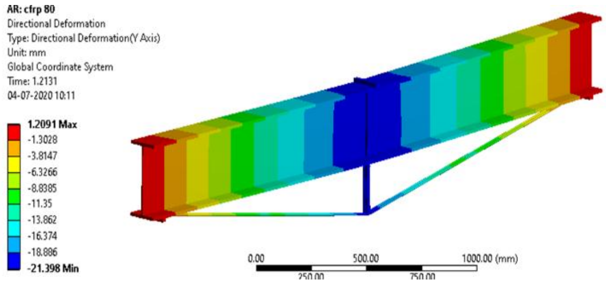

Fig -9: Deflection of BCF80 beam

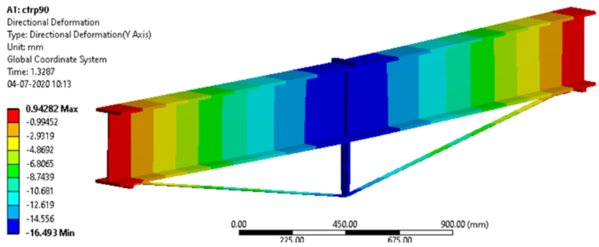

Fig -10: Deflection of BCF90 beam

The maximum deflection corresponding to ultimate load and initial stiffness of beams prestressed using CFRP bars are tabulated in Table 5. While comparing the initial stiffness of prestressed beams with conventional beam, significant increase is not observed from the results obtained. But the initial stiffness is slightly increased at 30% and 50% level of prestress.

Table -5: Maximum deflection and stiffness of beam

NAME OF BEAM	MAX.DEFLECTION (mm)	STIFFNESS (kN/mm)
BC	36.106	30.175
BCF30	71.37	31.66

BCF50	71.57	32.16
BCF80	21.4	30.81
BCF90	16.54	30.12

5. CONCLUSIONS

This paper presented a finite element analysis of prestressed steel beam using CFRP bars to understand the effectiveness of local post-tensioning using CFRP bars as a method of strengthening, upgradation and for new construction of steel beams.

The following conclusions were drawn based on the investigation.

- Instead of steel bars, CFRP bars can be used to increase the load carrying capacity of steel beams using local post-tensioning methods.
- Steel beams prestressed using CFRP bar shows 30-50% increase in load carrying capacity at different level of prestress.
- Load carrying capacity is increased while increasing the level of prestress, but the CFRP bars are failed earlier at 80% and 90% level of prestress.
- Compared to conventional beam, initial stiffness of steel beam is not significantly improved while prestressed using CFRP bars

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