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Effect of Length of Composite on CFRP Strengthened Steel Beam-Column Joints under Cyclic Load

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ABSTRACT

Steel members used in construction are highly durable but not invulnerable to deterioration. Once a steel structure has deteriorated, it may need to be reinforced to avoid replacing it altogether. Fiber-reinforced polymers such as CFRP (Carbon Fiber Reinforced Polymer) have drawn much attention in recent years across various research fields as a reinforcement material. This is due to many advantages such as their light weight, high strength-to-weight ratio, resistance to corrosion and high flexural strength. Numerous numerical and experimental studies have been conducted in the past for static load. In this paper, the numerical analysis of CFRP bonded along with bare steel beam-column joint has been carried out under cyclic loading for parametric conditions. The length of CFRP sheets is the parameter that is taken into account during this analysis. Three reinforced joints with varying length of CFRP reinforcement and one bare beam joint is used to compare the effects of various lengths of CFRP. The hysteresis curve, cumulative energy dissipation of the steel joint, as well as the stress distribution of the CFRP specimen were analysed. It is observed that increasing the length of CFRP reinforcement can improve the load carrying capacity of the beam.

Keywords: Steel, CFRP, Beam-Column Joint, Cyclic Load, Ansys

1. Introduction

Structural steel members are ubiquitous in modern construction. Most structural steel members are used in contemporary construction such as residential buildings, commercial buildings, railroad locomotives, and the marine industry. They are often preferred over concrete structures due to their relative lower weight, higher flexibility and higher load capacity. Steel I-beams can, however, be damaged by corrosion, fatigue, high-intensity load, a gradual loss in strength over time, and other factors. Once a steel structure is damaged, it might need to be reinforced or repaired because replacing it all might be too expensive. Typically, traditional metal joining, bolting, welding, and riveting methods are used for repairs or reinforcement. The classical methods may lose their applicability over time due to higher body-to-weight ratio than their strength, higher time-consumption and higher expense. Higher weight may lead to creep in the structure. FRP-based epoxy-bonded reinforcement or repairing methods have replaced these traditional methods because of their higher strength, durability and corrosion resistance. From the fibre-reinforced polymer, CFRP gained much attraction because the strength of CFRP is up to 10 times that of mild steel. And CFRP is also 3.5 times stronger than GFRP [1]. Because of these advantages, FRP composites have been used as reinforcement in concrete, bridge decks, modular structures, formwork, and external reinforcement for strengthening and seismic upgrades in new construction and rehabilitation of structures [2]. Seismic retrofitting is necessary for structures that are at risk of being damaged during an earthquake. Many beams and structures designed with pre-seismic codes or only for gravity and wind loads can be severely damaged due to catastrophic earthquakes. These members can easily be strengthened with CFRP sheets bonded with epoxy resin. Using epoxy bonded CFRP sheets saves intensive labor, detailing, change to dimensions, additional protection from corrosion and additional attachments associated with other strengthening methods [3].

In recent years, many kinds of research had been carried out in the CFRP bonded reinforcement field. FRP-reinforced steel I-beams under static loads have been studied extensively. Elkhabeery et al. investigated the effect of using CFRP sheets to flexural strengthen steel I-beams by reinforcing them at the tension flange experimentally and numerically [1]. They carried out a parametric study carried out a parametric study carried out a parametric study carried out a parametric study and it was found that the CFRP bonded specimen had better flexural characteristics than the ones without strengthening. Al-Salloum et al. investigated the effect of using CFRP sheets to repair and reinforce damaged RC beams built by following pre-seismic code [3]. Narmashiri and Jumaat did another numerical analysis comparing 2D and 3D simulation of reinforced steel I-beams using CFRP composites [4]. Both static linear and non-linear analyses were conducted, and the results found that non-linear 3D analysis had the best results compared to experimental values. Al-Mawed et al. conducted a numerical investigation of a rigid beam-column connection subjected to cyclic load [5]. The effect of the slenderness ratio of a steel I-section on a CFRP strengthened Islam and Hasib [6] investigated beam. Takhirov and Popov investigated the seismic capabilities of bolted steel beam-column connections using numerical analysis [6]. Shokouhian and Shi studied the effect of the slenderness of steel I-section beams on flexural strength [7]. Kypriadis et al. studied the effect of using CFRP patches to reinforce steel structures against bending [8].

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They found that the CFRP patches can increase the load-carrying capabilities of steel structures and that increasing the length and thickness of CFRP can improve its performance. Dogaheh et al. studied the effects of using prestressed CFRP laminates to reinforce steel structures [9]. It was found that the reduction in interfacial stresses was limited, and step prestressing was found to be the most effective method. Al-Ridha et al. studied the effect of strengthening steel I-beams using CFRP of varying lengths [10]. It was found that the percentage of increase in ultimate load was increased for increasing CFRP length. Wang et al. studied the seismic behavior of steel beam end plate connections numerically using ABAQUS [11]. Three different connection methods were considered for the analysis to study their behavior in a seismic zone. It was found that to choose the appropriate connection methods in high seismic zones, hysteretic behaviors, failure modes, and seismic ductility should all be considered. Sumner and Murrey experimentally investigated the effect of the design of extended steel end-plate moment connections under cyclic loading [12]. It was found that extended end plate moment connections which was stronger than the connecting beam are suitable for use in seismic force resisting moment frames. Agag et al. experimentally studied different reinforcement techniques for openings in RC beams [13]. They found that CFRP sheet reinforcements placed near the opening at the shear zone had the best performance. Wang established a cohesive zone model to study the behaviour crack induced debonding of FRP-plated concrete beams [14]. A bi-linear cohesive bond-slip model was used, which showed good agreement with experimental results. Jahangir and Esfahani numerically investigated the effect of the bond-slip mechanism in externally bonded CFRP composites [15]. A numerical model has been developed to provide an understanding of slip and strain profiles in FRCM composites.

It can be seen that very little numerical research has been done on cyclic loading imposed on steel structures. In recent years, frequent earthquakes may influence a researcher to study the structure's seismic loading test and their reinforcement. But there is very little research concerning cyclic loading of CFRP bonded steel beams. To mitigate this lacking, this present study has been proposed. In this present study, epoxy-bonded CFRP reinforced steel beam-column joints under cyclic loading were analyzed numerically and the effect of effects of various lengths of CFRP on reinforced beam-column connection were observed.

2.0 Materials and Methodology

2.1 Materials

Table 1 Mechanical properties of Steel [5]

Yield Strength (MPa)	Poisson's Ratio	Young's Modulus (MPa)	Tangent Modulus (MPa)
200000	0.3	355	6700

Table 2 Mechanical properties of CFRP [16]

Young's modulus in X direction (MPa)	310000
Young's modulus in Y direction (MPa)	11200
Young's modulus in Z direction (MPa)	11200
Poisson's Ratio XY	0.0058
Poisson's Ratio YZ	0.3
Poisson's Ratio XZ	0.0058
Shear Modulus XY (MPa)	26500
Shear Modulus YZ (MPa)	3700
Shear Modulus XZ (MPa)	26500
Tensile strength (MPa)	3100

Table 3 Mechanical properties of Epoxy Adhesive [1, 19]

Young's Modulus (MPa)	11200
Poisson's Ratio	0.3
Tensile Yield Strength (MPa)	29
Maximum normal traction (MPa)	25
Normal displacement jump at the completion of debonding (mm)	0.005
Maximum tangential traction (MPa)	16
Tangential displacement jump at the completion of debonding (mm)	0.21
The ratio of displacement at maximum traction to displacement at debonding	0.5
Non-dimensional weighting parameter	0.1

In this study, a steel beam-column joint was strengthened using CFRP to investigate the performance of strengthening under cyclic load. Table 1 shows the material properties of steel. The bilinear kinematic model was used to define the plasticity properties of steel. The CFRP was installed on the steel I-beams using epoxy adhesive. Table 2 and Table 3 shows the properties of CFRP and the mechanical properties of the epoxy adhesive respectively. The ‘Bilinear for Interface Delamination' model for the cohesive zone was employed for the epoxy to simulate the adhesive properly and properly simulate the adhesive propertiessimulate the adhesive properties.

2.2 Finite Element Model

Finite element analysis was carried out using the general-purpose software package Ansys 2020 R1. A 3D FE model was established, which consisted of a beam and

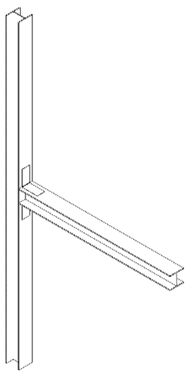


Fig. 1 Isometric view of the reinforced beam-column connection.

column joint, adhesive and CFRP. All the parts were modeled using higher-order 3D 20 nodes solid elements, SOLID186. Surface-to-surface contact was defined using the CONTA173 contact elements. The geometry chosen for the steel beam-column joint is shown in Fig. 1. A column of length 4m and a beam of length 2m were modeled for the analysis. The beam-column joint was modeled at the mid-section of the beam. The thickness of the epoxy adhesive and the CFRP used was 1 mm each.

The dimensions of the specimen are shown in Fig. 2. Both the bottom and top end of the column were fixed. An axial load of 140 KN was imposed on the top surface of the column. A periodic displacement boundary condition was applied to one end of the beam to act as a cyclic load. The lateral loading condition was applied to simulate the effects of seismic activity. An interfacial delamination model was also applied to the resin epoxy specimen to simulate the cohesive zone characteristics.

An amplitude function was defined to apply the cyclic load. The maximum displacement according to the amplitude function was 5 cm from the neutral position in the Y direction. The amplitude function of the applied displacement can be seen in Fig. 3.

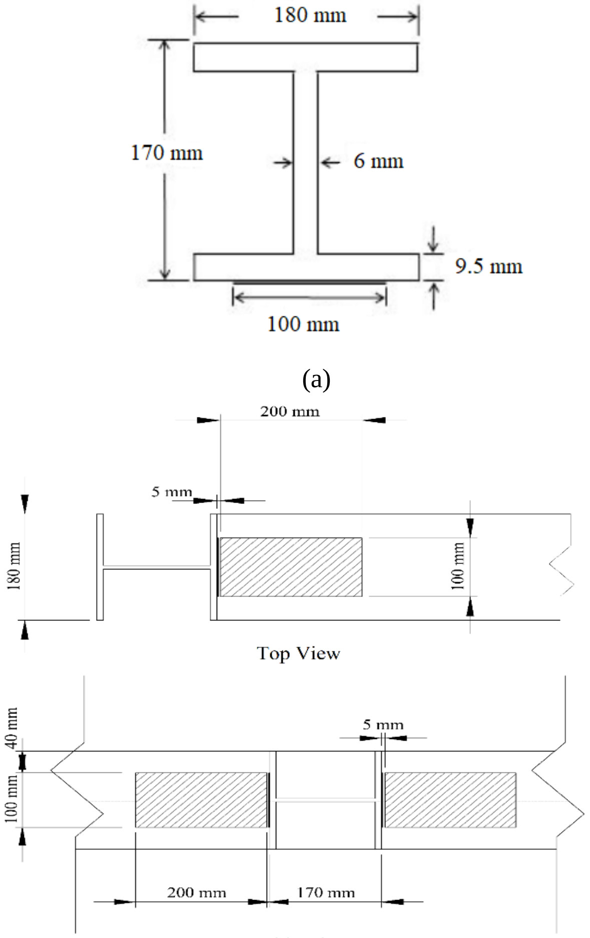


Fig 2 (a) Dimensions of the Steel I-section (b) Dimensions of the specimen.

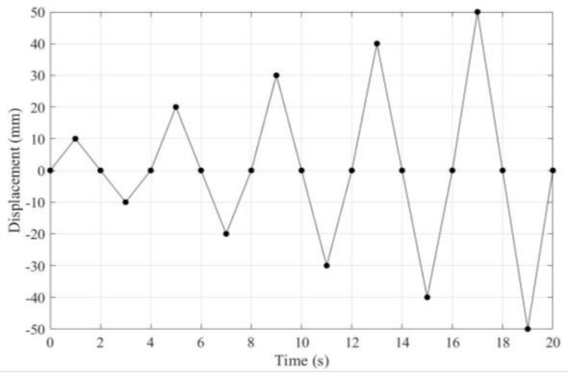


Fig. 3 Time history of cyclic load.

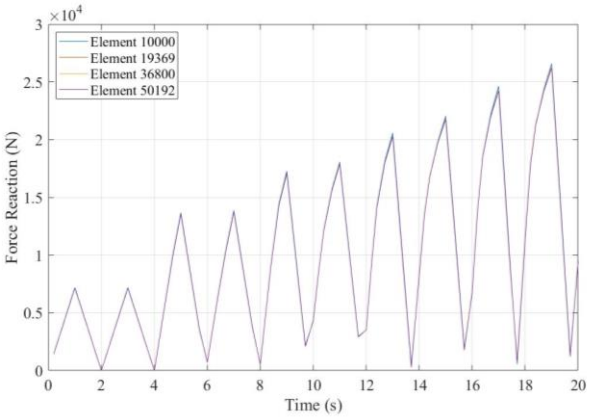


Fig. 4 Time-dependent force reaction plot for various element count.

3.3 Mesh Dependency Test

To obtain independent mesh for analysis, different mesh element amounts were compared as shown in Fig. 4. In this case, the time-dependent force reaction was compared for different elements. It can be seen that for different elements, the change in the force reaction was very little. The analysis became independent of mesh elements at 19369 mesh elements. It was found that meshing the model with an element size of 12 x 6 x 12 for the Beam and column joint, Epoxy adhesive, and the CFRP respectfully yielded the best results. Thus, this mesh element configuration was chosen for further analysis

3. Validation

In this study, the numerical analysis was performed using the finite element program "ANSYS 2020 R1." The finite element model was equipped to validate the model, and material properties were taken in accordance with the literature. Two pieces of literature were validated, corresponding to different aspects of the numerical analysis process.

A load vs. deflection plot was compared with literature by Narmashiri and Jumaat [4]. A bare beam under a four-point bending load was chosen for the comparison as seen in Fig. 5. Fig. 6 depicts the present study maintains a good agreement with the literature. A

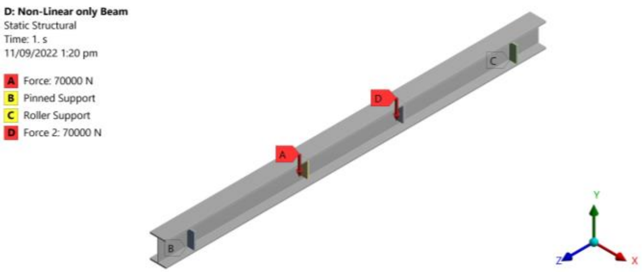


Fig. 5 I-beam equipped with four-point bending test.

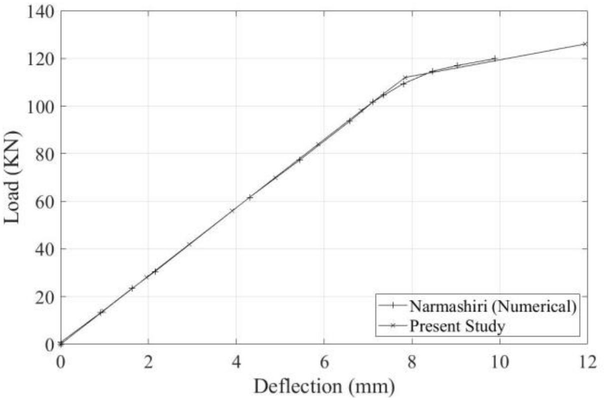


Fig. 6 Load-deflection curve for literature and present study.

slight deviation can be noticed at the yield point. The deviation was about 2% near the yield point, which was considered negligible. A beam-column joint under seismic load was considered again for validation. The geometry can be seen in Fig. 7. The time-dependent moment reaction of the beam without strengthening was compared with finite element analysis results as shown in Fig. 8. It can be seen that the present study maintains a good agreement with the reference beam from the literature [5]. The maximum deviation between the two datasets was found to be 27% and the minimum deviation was found to be 0%. The deviation may be due to differences in the cyclic loading history used in the present study and the literature.

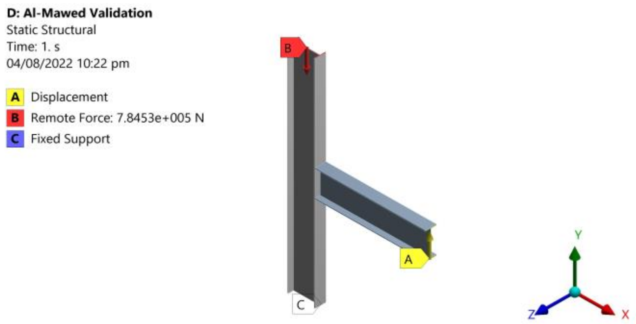


Fig. 7 Beam-column joint equipped with seismic load.

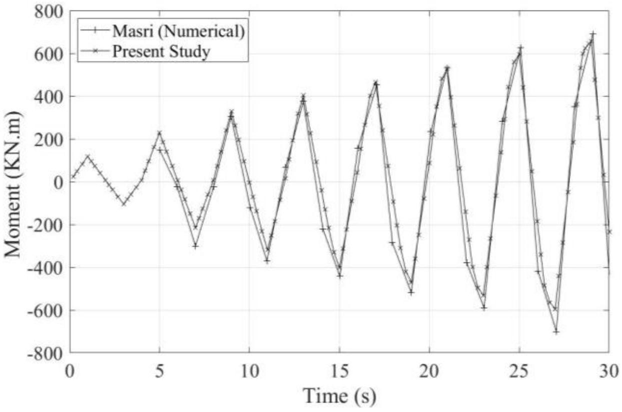


Fig. 8 Moment vs. time plot for literature and present study.

4.0 Result and Discussion

In this section, the results of the numerical analysis will be presented. The behavior of the beam-column joint such as deflection along with the length, cumulative energy dissipation and the stress distribution of the CFRP, have been analyzed through this numerical investigation. For the above behavior, three specimens CFRP-reinforced beam-column joints were considered. The configurations are distinguished through the CFRP length (200mm, 600mm and 1000mm). All other parameters were kept constant during the analysis. Fig. 9 shows the stress concentration in the joint region of the bare beam-column joint. It was found that the highest region of stress concentration was at the beam and the column. Thus, this was chosen as the region for CFRP reinforcement. The deflection curve of bare beam and the CFRP strengthened steel beam were compared as shown in Fig. 10. Here the change of deformation for different specimen can be neglected as a displacement boundary condition had been applied. However, an increase in force reaction denotes an increase in the specimen's load carrying capacity. It can be seen that the force reaction of the joint increases with the length of CFRP reinforcement, but the difference in force reaction of the four specimens is negligible. Fig. 11 shows the energy dissipation for varying lengths of CFRP. It can be seen that the energy dissipation is minimum for the bare beam.

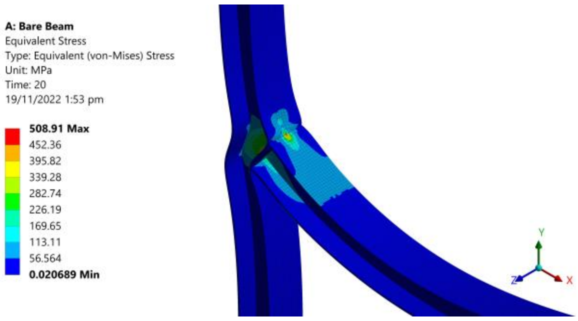


Fig. 9 Stress concentration at the beam-column interface.

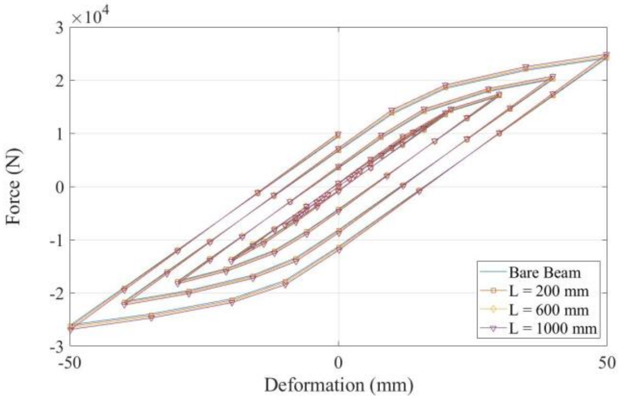


Fig. 10 Load-deflection curve of beam for varying length.

It increases along with increasing the length of CFRP, and the maximum energy is dissipated when the longest CFRP is used as a reinforcement. The stress distribution along the length of the CFRP had been observed in Fig. 12. The figure demonstrates that at the beam-column joint the stress is higher and stress distribution had reduced towards the free end. It had been found that the stress was reduced 4% when CFRP length increased from 200 mm to 600 mm. For the further increase of CFRP length from 600 mm to 1000 mm the stress was reduced by almost 9% as shown in Fig. 12. The stress distribution of the CFRP on the compressive flange of the beam can be observed in Fig. 13. It can be seen that the compressive stresses are concentrated closer to one end near the beam-column joint's region.

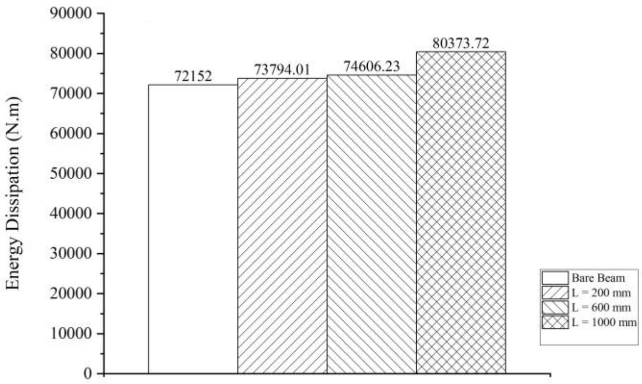


Fig. 11 Energy dissipation for varying length of CFRP.

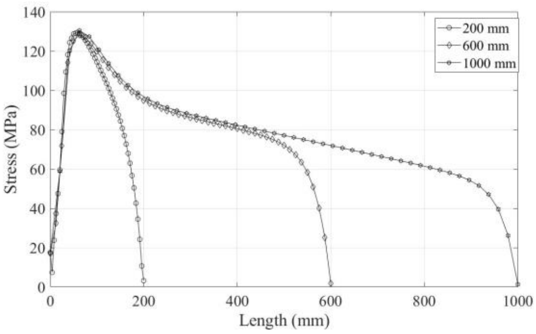
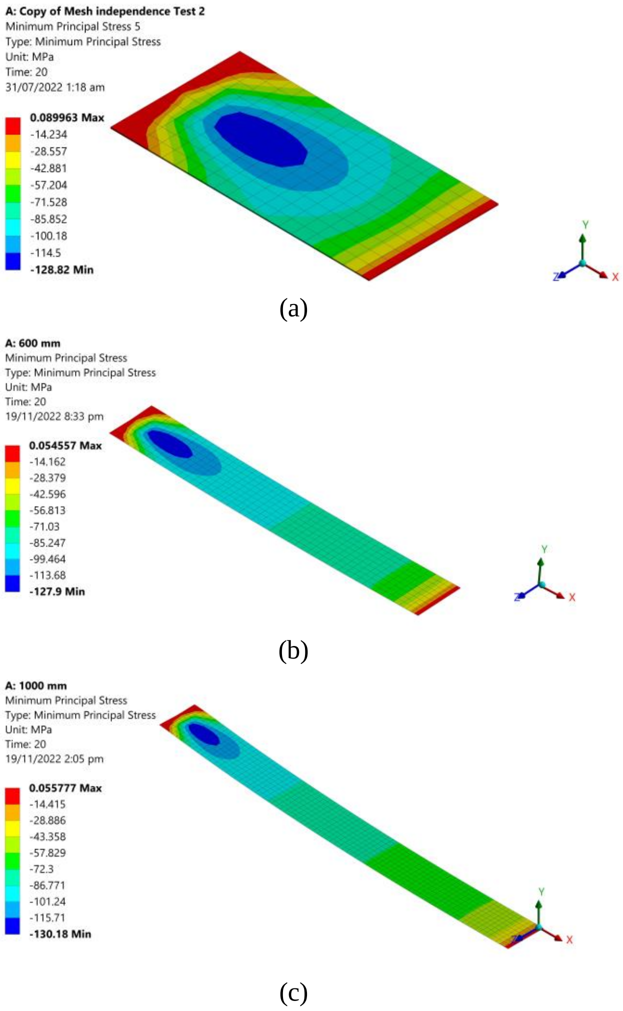


Fig. 12 Stress distribution curve of CFRP for varying length.



(a)

(b)

(c)

Fig. 13 Stress distribution of CFRP sheet placed at compressive flange of the beam.

5.0 Conclusion

In this paper, a three-dimensional finite element model analysis was carried out using "Ansys 2020 R1" to analyze the behavioral pattern of the Bare beam-column joint, as well as the CFRP strengthened steel beam. The major findings are as follows:

- The bare beam had been compared with three beams reinforced with varying lengths of CFRP reinforcement.
- The change in the load-deflection curve after reinforcement was found to be negligible.
- It was found that the amount of energy dissipated increased with the increase in the length of CFRP.

- The stress distribution of the CFRP specimen shows that the stress reduced along with increasing the length of CFRP.

Thus, it can be concluded that increasing the length of CFRP reinforcement when reinforcing a steel beam-column joint subjected to seismic load can improve the load-carrying capacity of the beam.

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