Proceedings of the Seventeenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 6, Paper 11.5
Civil-Comp Press, Edinburgh, United Kingdom, 2023
doi: 10.4203/ccc.6.11.5

A Design Reference for RHS Steel Beams Strengthened with FRP Subjected to Bending

E. ElKassas, A. Morsy and N. Khaled

**Construction and Building Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport (AASTMT)
Abu Kir, Alexandria**

Abstract

Rectangular hollow sections (RHS) are widely used in construction. Strengthening of RHS is a major concern due to design errors, environmental effects, and the need to withstand increased loads. Traditional methods for external strengthening using steel plates can be a successful solution, but it has many disadvantages such as, tough in shaping and heavy weight which requires large equipment for lifting. On the other hand, non-traditional method of strengthening structures using carbon fiber reinforced polymer (FRP) did not show any of these defects. Using FRP for strengthening beams became popular and a solution for the problems facing the steel structures, because of its high tensile strength. This paper gives a quick design reference to the designers about the best way to strengthen RHS. Designers needs to know, FRP type, length, thickness and position and corresponding increase in the load carrying capacity. Three types of FRP, (CFRP) carbon fiber reinforced polymer, (GFRP) glass fiber reinforced polymer and (AFRP) aramid fiber reinforced polymer. A finite element model using ABAQUS was done using a simple beam subjected to a mid-span concentrated load. This paper gives the designer engineers a quick reference about the best way to strengthen RHS beams.

Keywords: rectangular hollow sections, strengthening, bending, fiber reinforcement polymer, finite element analysis, ABAQUS

1 Introduction

The advanced composite material known as carbon fibre reinforced polymer (CFRP) has various benefits, including low relaxation, high strength, high corrosion resistance, and high fatigue resistance. Many researchers investigated strengthen of RHS using FRP. The effects of hollow steel beams strengthened by carbon fibre reinforced polymers (CFRP) used in transverse orientations were studied by Anwar Badawy Abu-SenaWael et al. [1]. The impacts of adding more layers of wrapping were studied. According to the type of bending moment used, specimens in a four-point bending test were divided into two groups. In the first group, bending moments were applied along the main axis, whereas in the second group, bending moments were applied along the minor axis. The results indicated that CFRP transversal wrapping systems can prevent strengthened steel beams from buckling. Furthermore, if more CFRP wrapping layers are added, the improvements become much greater in comparison to strengthen beams using a single layer of CFRP. Hanan Hussien Eltobgy et al. [2] examined the behaviour of hollow steel beams reinforced with composite laminates made of unidirectional carbon fibres that were positioned in both longitudinal and transverse directions. The four-point loading test involved two groups of six rectangular hollow sectional specimens (RHS) were developed. Two different positions were used to analyse each group of three samples (Mx and My). A reference beam and two specimens that had been longitudinally and transversally reinforced with CFRP laminates were included in each group. The results revealed that when compared to strengthened beams with transversal laminates, longitudinal laminated beams showed a greater improvement.

Salah [3] examined how cracked RHS steel beams respond to CFRP plate using 3D Finite element models using ABAQUS. Various parameters were considered, including the thickness, the length, and the kind of employed adherent material. In comparison to using adhesive materials with varied properties, the results showed that using adhesive materials with low elastic stiffness and high tensile strength resulted in higher strengthened beam load resistance. An investigation into circular hollow section (CHS) beams strengthened with sheets of carbon fibre reinforced polymer was conducted by Kabir et al. [4] utilising experimental and numerical software. Under four-point bending tests, several orientations of the CFRP layer were used to bond the circular hollow steel beams. Several factors have been studied, including the impact of, section types, bond length, adhesive layer thickness, adhesive types, and CFRP tensile modulus. The results showed that there was a considerable increase for all strengthened beams in plastic and elastic stiffness at higher loads compared to unstrengthen beams. Chen et al. [5] investigated rectangular hollow section (RHS) steel beams' flexural behaviour containing an initial crack that was externally strengthened using carbon fiber reinforced polymer (CFRP) plates. In a test where three points are loaded until failure, eight specimens were tested. The yield loads and ultimate loads with or without repairing were investigated, along with the CFRP plate's strain distributions. The results observed that by repairing cracked beams, yield loads could be improved. However, the ultimate loads were also gradually increased.

In addition, When the initial crack depth increased, the impact of the repair became noticeable.

Elchalakani [6] examined the outcomes of tests conducted on two series of model box girders that had been strengthened and repaired using CFRP under quasi-static three-point bending with substantial deformation. Twelve rectangular hollow section (RHS) beams that came from the manufacturer were strengthened in the first group using CFRP sheets that have been externally wrapped. The rehabilitation of forty-one intentionally deteriorated RHS beams using externally wrapped sheets or bonded plates was the focus of the second group. The type of section, the slenderness of the section and members, along with the type and quantity of CFRP sheets were the main factors studied. The results demonstrated that by adhering CFRP, the steel box girder's combined flexural and bearing strength can be improved considerably. Jimmy Haedir and Xiao-Ling Zhao [7] proposed a design approach for assessing the bending resistance of CFRP-strengthened steel CHS tubular beams. Various parameters were considered which are changing amounts of CFRP, the hoop fiber's elastic modulus, and steel yield strength. The results showed that the tube's local flexural stiffness and strength are ultimately increased due to the longitudinal CFRP's excitation, which reduced the influence of local buckling in the tube wall. Jimmy Haedir et al. [8] evaluated the effects of the amount of CFRP reinforcement, fibre arrangement, fibre and adhesive volume fractions, and material non-linearity in a theoretical examination of the non-linear behaviour of circular hollow steel beams joined with thin carbon FRP sheets. Moreover, the cross-sectional response of CFRP-reinforced steel tubular beams to moment curvature was studied. The results indicated that the strengthened CHS may exhibit enhanced stiffness due to a higher fiber volume fraction.

Haedir et al. [9] discussed the experimental investigation using CFRP sheets to strengthen CHS beams in pure bending. Eighteen experiments produced a comprehensive set of results for the rotation, bending moment, and strain at top and bottom fibres for hollow and composite cross-sections of CHS beams. The results of the experiments revealed that the strength of composite beams is significantly influenced by the amount of fibre reinforcement and the direction of the fibre skin. Xiao-Ling Zhao et al. [10] focused on the improved web-crippling behaviour of rectangular hollow sections (RHS) strengthened by carbon fibre reinforced polymer. Many strengthening methods were employed, including applying CFRP plates inside or outside the RHS and wrapping CFRP sheeting outside the RHS.The results showed that the web crippling capacity was shown to be greatly increased by CFRP strengthening, particularly for those with large web depth-to-thickness ratios.

Regardless of the efforts performed by the researches described above to investigate the RHS steel beams strengthened with FRP sheets. When strengthening steel beams using FRP sheets, a number of variables, including the FRP sheets' position, thickness, length, and type of FRP sheets could be examined. Most of these research projects concentrated on one of these characteristics. Thus, these factors must be analyzed simultaneously to obtain the optimal method for strengthening. Moreover, the majority of these studies focused on strengthening steel beams with

CFRP sheets, disregarding the other FRP types. Hence, there is a need for more research on the behavior of most FRP types. Consequently, there is a need for extensive research into strengthening RHS steel beams using various FRP types. Therefore, the present study addresses these literature gaps and to give a guide to the structural designer for the percentages of improvement in the strengthened beams' capacity to withstand additional loads. Thirty-one steel beams were examined using the ABAQUS modeling program. Additionally, the load-deflection relations of these beams were studied. The FEM results were compared with the experimentation performed by Tao Chen et al. [5] in order to validate the model. Section 2 provides details of creating computational FE models, material behavior, and FE model verification. The outcomes of the parametric investigation are discussed in section 3 of the paper. Section 4 provides a brief discussion of the findings, conclusions, and proposed work.

2 Model Development

2.1 Overview

This study consists of thirty-one steel beams, one of them was an unstrengthen control beam, while the other thirty steel beams were strengthened using different types, length, thickness, position of FRP sheets. The structure system and loading condition are as shown in Figure 1. The beam's cross-section is RHS 100 x 50 x 6 mm; the total length is 700 mm, including a clear span of 600 mm with 50 mm overhanging on both sides. The study compares strengthened beams to control beam (unstrengthen beam) in order to find the percentage of load increase in the elastic region. For each type of FRP, three groups were investigated. G1 stands for group1 with varying lengths of FRP sheets that are 400 mm ,500 mm 600 mm and 700 mm. G2 stands for group 2 of FRP sheets with differing thickness which are 1.2 mm ,1.3 mm and 1.4 mm. Lastly, G3 stands for group 3 and describes the attached position of FRP sheets. Load deflection curves were determined for each group using point of maximum deflection in the bottom fiber at middle of the RHS beam.

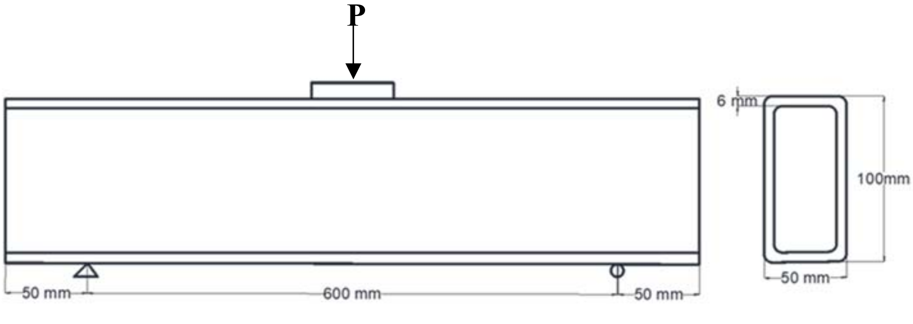


Figure 1: Details of RHS steel beam: (a) Longitudinal section and (b)cross-section.

2.2 Meshing and Simulation of Loading Boundary Conditions

ABAQUS was used to simulate the RHS steel beams .3D solid C3D8R elements have been used to represent RHS steel beam. The 4-node thin rectangular shell element (S4R), which has a minimal thickness in comparison to its other two dimensions (length and breadth), was used to depict the CFRP sheets. An 8-node cohesion component was used to represent the epoxy adhering layer (COHD8). In the following section, the details of identifying steel and FRP materials are covered. A static loading condition was assessed. Ties were used to simulate the connection involving the CFRP sheets and RHS steel beams. As illustrated in Figure 2, loading point (reference point) was placed at the top of plate, and at a node towards the bottom of the beam, the deflection was measured. For more accurate results, use a 20 mm fine mesh size with 0.1 to 1 increments.

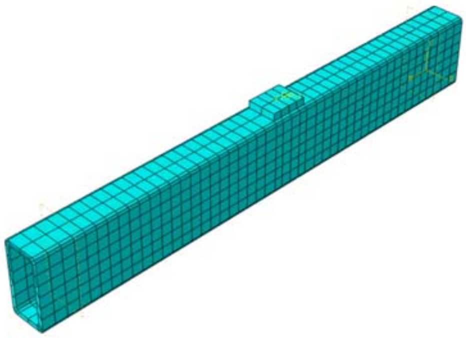


Figure 2: Finite Element 3D model.

2.3 Materials Characteristics

2.3.1 RHS Steel beam

For the finite element modeling, steel was considered to be an identical material that is linearly elastic, perfectly plastic, and behaves the same in tension and compression. The elastic modulus, the poisson's ratio, tensile strength and the yield stress were 187 GPA ,0.3 ,368 MPA and 298 MPA respectively. The stress strain curve for steel is shown in Figure3.

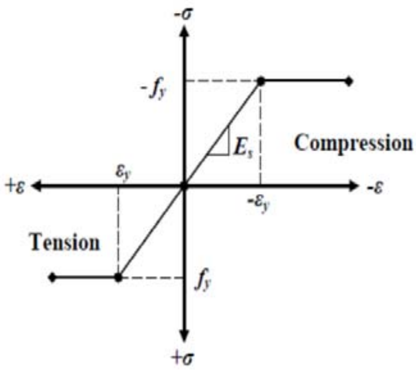


Figure 3: Linearly elastic-perfectly plastic stress-strain relationship of steel.

2.3.2 FRP sheets

Without any damage criteria, it was anticipated that the behavior of FRP sheets would be: isotropous linear elastic till failure [11,12]. FRP behavior was characterized as linear-elastic in the absence of any discernible yield point. Table 1 provides the ultimate strength, yield stress, and elastic modulus of steel and FRP. Figure 4 shows assumed stress strain curve for all types of FRP sheets. Where f_{frpu} is the ultimate tensile strength of the FRP (MPa), E_{frp} is the elastic modulus of the FRP (MPa) and ε_{frpu} is the ultimate strain of the FRP in tension.

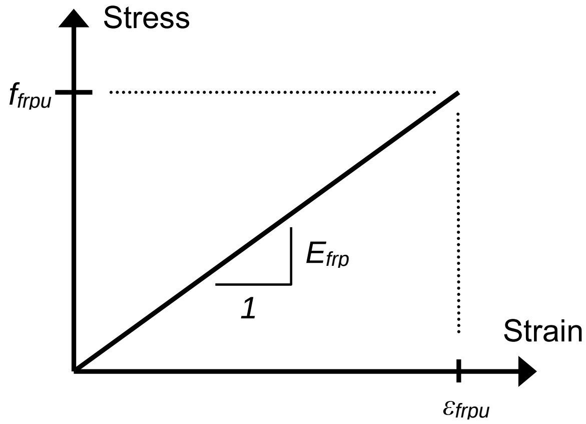


Figure 4: Assumed stress-strain behavior of FRP.

Material	Yield stress (N/mm^2)	Tensile Strength (N/mm^2)	Elastic Modulus (kN/mm^2)
CFRP	--	3089	191
GFRP	--	1500	40
AFRP	--	1900	100

Table 1: FRP and steel characteristics.

2.4 Verification of Finite Element model

To verify the finite element model of the RHS steel beam strengthened with CFRP, control beam from an experimental study done by Tao Chen et al. [5] has been compared with FEM analysis as shown in Table 2. By showing ratio of yield load (P_{FEM} /P_y) that are close to unity, the numerically computed yield load was closely validated with the experimental results.

Beam ID	Experimental yield load P_y (KN)	FEM yield load P_{FEM} (KN)	P_{FEM}/P_y
Control beam	63.2	66.4	1.05

Table 2**:** Comparison between the experimental yield load and FEM yield load.

3 Results

3.1 Effect of FRP sheet length

The effect of the strengthen of RHS using FRP sheets length in the bottom flange (position of maximum tension stresses due to bending) was examined for the three types of FRP including CFRP, AFRP, and GFRP. The examined lengths were approximate 50%, 70%, 85% and 100 % of span of beam. All FRP sheets thickness is 1.4 mm and the width is 40 mm. The applied load was incrementally increased and the deflection was determined at each load increment. Figure 5-a, b, c show load deflection curves for strengthen RHS using CFRP, AFRP and GFRP. Designers can use Figure 5-d to find the suitable FRP type and sheet length for a specified increased in applied load. As an example, if the increased of applied load is 45 %, the designer can use GFRP in the bottom flange with length of 50% and if the increase in loading is 60 %, he can use AFRP with 70 % of beam length.

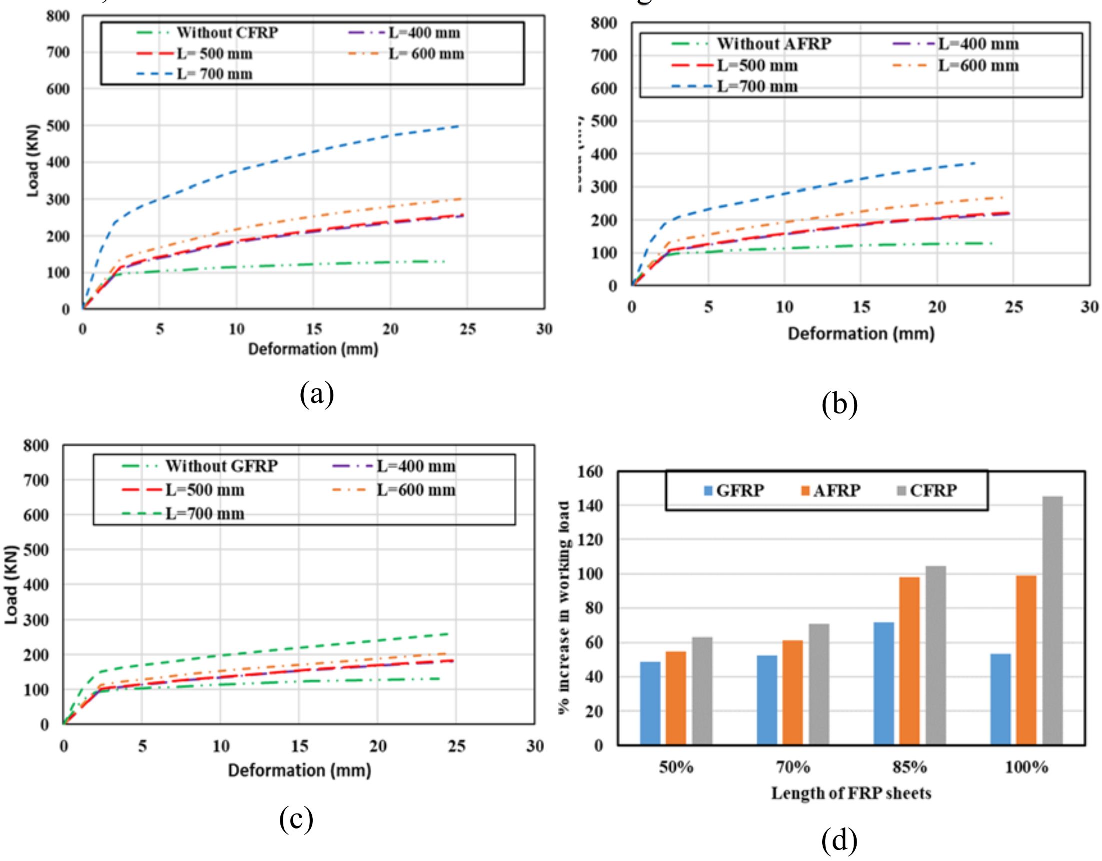


Figure 5: Load-Deflection curves for RHS beams with various length of sheets: (a) CFRP, (b) AFRP, (c) GFRP, (d) % increase in working load vs length of FRP sheets.

3.2 Effect of FRP thickness

The effect of the strengthen of RHS using FRP sheets thickness in the bottom flange (position of maximum tension stresses due to bending) was examined for the three types of FRP including CFRP, AFRP, and GFRP. The examined thicknesses are 1.2, 1.3 and 1.4 mm. The FRP sheet length is 100 % of span and the width is 40 mm. The applied load was incrementally increased and the deflection was determined at each load increment. Load deflection curves were determined in the elastic region. Figure 6-a, b, c show load deflection curves for strengthen RHS using CFRP, AFRP and GFRP sheets. Designers can use Figure 6-d to find the suitable FRP type and thickness for a specified increased in applied load. As an example, if the increased in load carrying capacity is 40 % the designer can strengthen using GFRP 1.2 mm thickness.

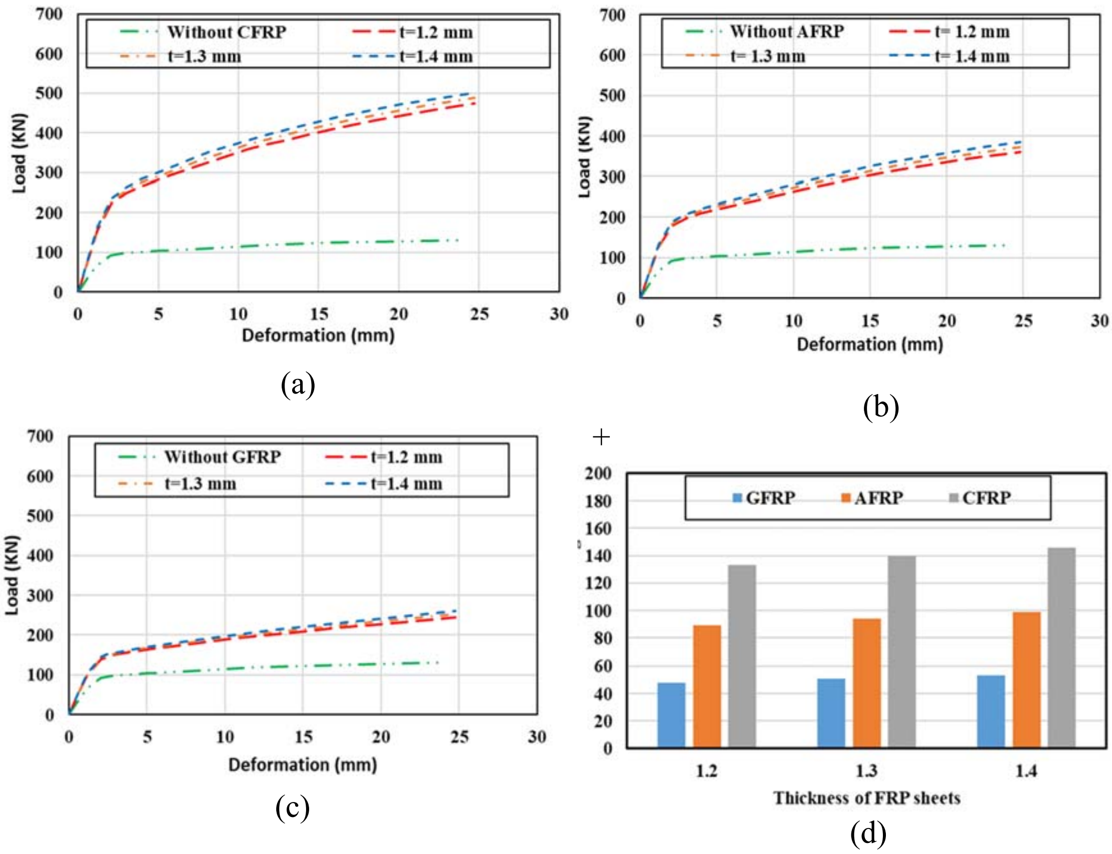
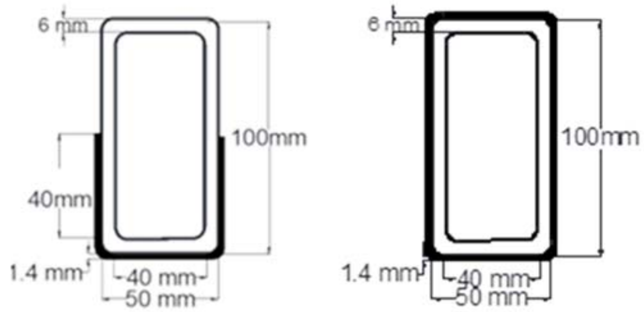


Figure 6: Load-Deflection curves for RHS beams with different thickness of FRP sheets: (a) CFRP, (b) AFRP, (c) GFRP, (d) % increase in working load vs thickness of FRP sheets.

3.3 Effect of position of FRP sheets

The effect of the strengthen of RHS using FRP sheets position were investigated. According previous studies three positions of FRP were recommended. The first position in the bottom flange, the second position is U warped and the third is fully warped as shown in Figure 7. Three types of FRP including CFRP, AFRP, and GFRP were examined. The FRP length covers the whole span and thickness is 1.4 mm. The load deflection curves were determined in the elastic region. Figure 8-a, b, c show load deflection. Designers can use Figure 8-d to find the suitable FRP type position for a specified increased in applied load. As an example, if the load carrying capacity increased by 50 %, the designer can use GFRP in the bottom of the beam.



(a) (b)

Figure 7: Strengthening configurations; cross-sections:
(a) U-wrapped, (b) Full wrapped

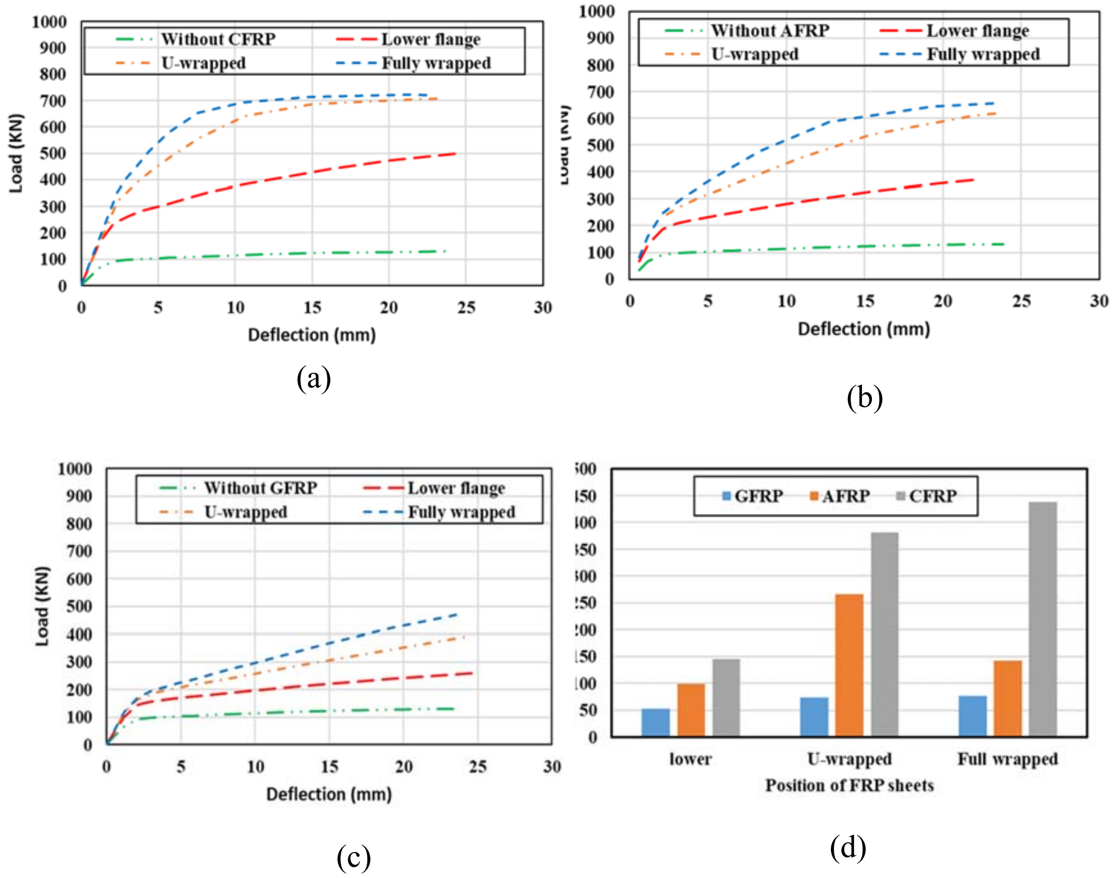


Figure 8: Load-Deflection curves for RHS beams with different positions of FRP sheets: (a) CFRP, (b) AFRP, (c) GFRP, (d) % increase in working load vs position of FRP sheets.

4 Conclusion

In this paper, a quick design reference for nontraditional strengthen of RHS using FRP was developed. Three FRP types CFRP, GFRP and AFRP were investigated as nontraditional strengthen method and materials. Factors affecting carrying capacity such as type, length, thickness and position were done. We can conclude the followings: generally non-traditional strengthen method using FRP is an optimal solution for RHS steel beams. Strengthen using FRP increased the load carrying capacity of RHS beams but to what extend?. This paper answers the question for the designer engineer, that is if he have a certain increased of load for RHS beam what are the suitable type of FRP, length, thickness, and position?. Designer can find answer of this question in Figures 5-d, 6-d and 8-d for RHS steel beams. Also, CFRP is capable of achieving a higher strengthened beams load carrying capability compared to the use of aramid and glass.

References

[1] A. B. Abu-Sena, H.H. Eltobgy, O.N. Abdelnabi, “Behaviour of Rectangular Hollow Steel Beams Strengthened with Multi-Layers of Transversal CFRP Wrapping”, International Journal of Scientific & Technology Research, 2021.

[2] H.H. Eltobgy, A. B.Abu-Sena, O.N. Abdelnabi, “Behaviour of Rectangular Hollow Steel Beams Strengthened with CFRP Sheets Applied in Longitudinal and Transversal Directions”, International Journal of Scientific & Technology Research ,2021.

[3] W.A.Salah,“Rehabilitation and Strengthening of Rectangular Hollow Section Steel Beams Using Carbon Fiber Reinforced Polymer”, IJSRSET ,2017.

[4] M.H.Kabir,S. Fawzia, T. H. T.Chan, J. C. P. H. Gamage, J. B. Bai,“Experimental and numerical investigation of the behaviour of CFRP strengthened CHS beams subjected to bending”,Elsevier,Engineering Structures,2016.

[5] T.Chen, M.Qi, X. L. Gu, Q. Q. Yu, , “Flexural Strength of Carbon Fiber Reinforced Polymer Repaired Cracked Rectangular Hollow Section Steel Beams”, Hindawi Publishing Corporation , International Journal of Polymer Science, 2015.

[6] M.Elchalakani , “CFRP strengthening and rehabilitation of degraded steel welded RHS beams under combined bending and bearing”, Elsevier, Thin-Walled Structures,2014.

[7] J.Haedir, X. L Zhao , “Design of CFRP-strengthened steel CHS tubular beams”, Elsevier, Journal of Constructional Steel Research, 2012.

[8] J.Haedir, X. L. Zhao, R. H. Grzebieta, M. R. Bambach, “Non-linear analysis to predict the momentcurvature response of CFRP-strengthened steel CHS tubular beams”, Elsevier, Thin-Walled Structures,2011.

[9] J.Haedir, M. R.Bambach, X. L.Zhao, X. L., R. H Grzebieta, “Strength of circular hollow sections (CHS) tubular beams externally reinforced by carbon FRP sheets in pure bending”, Elsevier, Thin-Walled Structures, 2009.

[10] X. L.Zhao, D. Fernando, R. Al-Mahaidi, “CFRP strengthened RHS subjected to transverse end bearing force”, Elsevier, Engineering Structures,2006.
[11] M.Kobraei, M.Z. Jumaat, P. Shafigh,” An Experimental Study on Shear Reinforcement in RC Beams Using CFRP-Bars”, Scientific Research and Essays ,2011.
[12] I.S.Abbood, S.A. Odaa, K.F.Hasan, M.A.Jasim , “Properties Evaluation of Fiber Reinforced Polymers and Their Constituent Materials Used in Structures—A Review”, Elsevier, Engineering Structures, Materials Today: Proceedings,2021.