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Numerical Investigation for Selection the Optimal Flexural Strengthening Strategy of Reinforced Concrete Beams

Raad Abdulkhudhur [1], Murtadha Hardan Dawood [1], Hussein Al-Quraishi [1*]

[1] College of Civil Engineering, University of Technology, Baghdad, Iraq.

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Abstract

Reinforced concrete is the most widespread material that is used in structural applications. In structural systems, concrete beams can become damaged due to aging and increased design loads. Furthermore, for architectural purposes, specific dimensions may be imposed on concrete beams. For these reasons, it always needed to strengthen these beams. In this study, a numerical study was conducted to simulate the strengthening and improving of the flexural strength of reinforced concrete beams using three techniques: carbon fiber (CFRP sheets), steel plate, and external bars. The numerical analysis was verified with previous experimental studies. For the parametric study, the thickness, number of layers, and tensile strength were adopted for the CFRP strengthening technique. For the steel plates, the effect of changing the thickness and number of layers and yield stress was studied. Finally, for the additional external bars, different ratios of longitudinal reinforcement were investigated. After conducting numerical analysis of the studied models, the results showed a clear increase in the ultimate load and stiffness of the beams when strengthened with carbon fiber and steel plate, especially when increasing the tensile strength and yield strength, which was the most influential parameter, compared to a very limited effect of the number of layers due to the separation between the layers, especially for CFRP. However, both strategies showed brittle failure without clear ductility. Using additional external bars or increasing the ratio of longitudinal reinforcement was the most influential strengthening strategy in terms of increasing the beams' capacity for bending and ductility.

Keywords: Beam Strengthening; CFRP Sheets; Steel Plates; Additional External Bars.

1. Introduction

Concrete as a material due to its unique properties is widely used in construction of engineering structures. Research efforts and numerous studies have been focused on the actual behaviour of concrete and structural performance [1]. Concrete is poorly performing when subjected to tensile stresses and bending meanwhile, its considered a well resistance material when subjected to compressive stresses [2]. Usually, concrete structural elements, such as beams, need to be strengthened to resist flexural stresses resulting from increased service loads over time, structural aging, reinforcement corrosion, or design and construction errors, among other causes [3].

The flexural performance of concrete beams can be improved using different techniques or strategies using external bars, steel plates and CFRP sheets [4-6]. In the first technique, one or more layers of carbon fiber reinforced polymer (CFRP) sheets are added to the bottom fiber of the concrete beam to increase its flexural capacity. A practical experiment conducted by Duthinh & Starnes [7] compared an unstrengthened reinforced concrete beam with a beam strengthened using carbon fiber, concluding that the ultimate flexural strength of the strengthened beam increased by about 100% compared to the unstrengthened one. Furthermore, studies by Abdulkhudhur et al. [8] and Liu et al. [9] observed

* Corresponding author: hussein.a.alquraishi@uotechnology.edu.iq

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significant improvements in structural fatigue performance, extending the service life of the beam and leading to failure primarily through yielding of the reinforcing steel. These studies also reported a reduction in beam deflection of up to 80% [10, 11].

Another type of beam strengthening method involves the use of steel plates, which is a popular and effective approach for enhancing flexural strength. The steel plate is anchored to the tension zone of the beam using epoxy adhesive or anchor bolts [5]. Studies [12, 13] showed that adding a steel plate increased the flexural resistance of beams by 95% and 65%, respectively. Regarding the cracking moment and bearing capacity of the beams, improvements of 214% and 53% were recorded when using steel plates [14]. Another study focused on the failure behavior of beams strengthened with steel plates, observing a clear and gradual improvement in crack resistance and control [15], while the stiffness of beams with webs supported by steel plates improved by about 28% compared to those without support [16].

The third method of strengthening that is usually studied is strengthening with external bars. In this method, the area of the reinforcing steel of the beam is increased by adding external bars after construction, and then they are covered with concrete [17]. Many studies have addressed this method, such as Lee et al. [18]; they studied the addition of external bars to the beam and concluded that the ultimate flexural strength of the beam increased by 15% compared to the reference beam. Another study conducted by Lee et al. [19] and Roberts & Hajikazemi [20] recorded a 30% increase in the flexural strength and stiffness of the beam. Moreover, the quality of the concrete cover and its adhesion to the old concrete affect the structural performance of this strengthening technique [21, 22].

The previous studies deal with the above-mentioned techniques individually, each for a specific specimen and under different conditions of testing. This study provided a numerical analysis using ABAQUS/CAE 2019 through which the performance of the mentioned strengthening methods will be investigated in terms of improving the flexural strength of concrete beams in a purer form whose dimensions may be imposed for architectural purposes to know the engineering feasibility of each strengthening technique, and a comparison will be conducted between the three techniques in order to find the most appropriate and effective method under certain conditions.

2. Materials and Methods

As stated above, the performance of structures in reinforced concrete beam was studied using three strengthening techniques. The material modeling for each component is described as follows:

- ***Concrete:*** It was modeled using the Concrete Damaged Plasticity (CDP) model, which is suitable for analyzing concrete under various stress conditions—both compressive and tensile. This model effectively represents the nonlinear behavior of concrete and accounts for cracking under both tension and compression [23–25].
- ***Carbon Fiber Reinforced Polymer (CFRP):*** The Lamina/Orthotropic Elastic Model was used to represent CFRP, as these fibers are typically oriented in a single direction and do not experience significant deformation before failure. Therefore, they can be accurately represented as a linear elastic material [26].
- ***Epoxy:*** the adhesive material was modelled using cohesive zone model which allow a gradual separation between concrete surface and CFP layer [27].
- ***Steel Plate:*** The Elastic–Plastic (Isotropic) model was applied for the steel plate, since steel behaves elastically up to its yield point and then enters the plastic stage beyond it. Steel is also considered an isotropic material, meaning its properties are uniform in all directions [28].
- ***External Bars:*** For beams strengthened with external bars, the bars were modeled using the same Elastic–Plastic (Isotropic) model, for the same reasons described above [28].

2.1. Geometrical Modeling

The geometry of the FE model of the reinforced concrete beam, illustrated in Figure 1, was represented using 3D isometric elements with 16 nodes. Each node had three translational degrees of freedom (X, Y, and Z). Regarding meshing, a hexahedral element with a size of 1 × 2 × 2 mm was used, while a finer mesh was applied in the loading regions (supports and applied load areas) [29]. The Newton–Raphson iterative nonlinear solver was used with a load step of 0.05 kN.

3. Numerical Analysis

ABAQUS/CAE 2019 software was used to simulate numerically the behaviour of concrete beams strengthened with external bars, steel plates and CFRP sheets. The finite element (FE) model was constructed based on the same dimensions and material properties used in previously published experimental studies. Initially, the present numerical model was validated by comparing its results with previous experimental studies for each strengthening method separately, to verify the accuracy of the geometrical and material modelling and the assumptions adopted during its development. The comparison between the experimental results and finite element included the load–deflection behaviour and the ultimate load capacity.

The parametric study was carried out after the accuracy of the adopted finite element model was confirmed. The tensile strength, thickness, and number of layers for CFRP and steel plate were studied. Also, rebar ratio was studied for external bar strengthened method. The present FE analysis considered the ultimate load capacity and load-deflection curve.

3.1. Strengthening with CFRP

The experimental load-deflection curve published by Balamuralikrishnan & Jeyasehar [30] was used to verify the FE model adopted in the present study using ABAQUS program. This study investigated conventional reinforced concrete (RC) beams strengthened with CFRP sheets under a four-point loading setup. The material properties, geometrical dimensions, and loading conditions from the experimental study were replicated in the simulation process. Figure 1 shows the strengthened of RC beam using CFRP sheet.

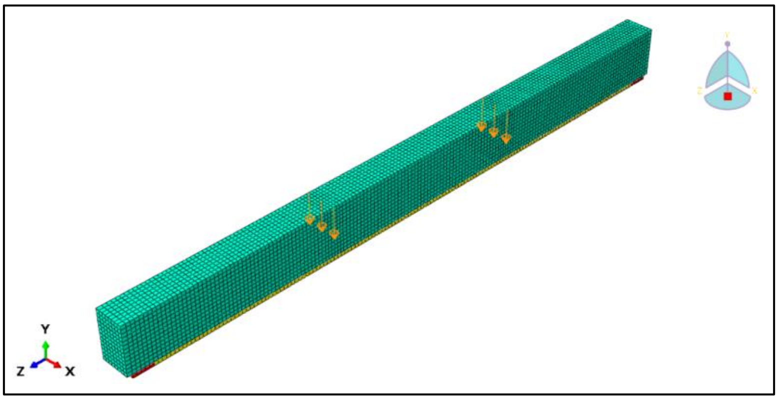


Figure 1. geometry of RC beam strengthened with CFRP

Whereas; Figure 2 shows the comparison between the results obtained from the experimental study and those obtained using the F.E. method.

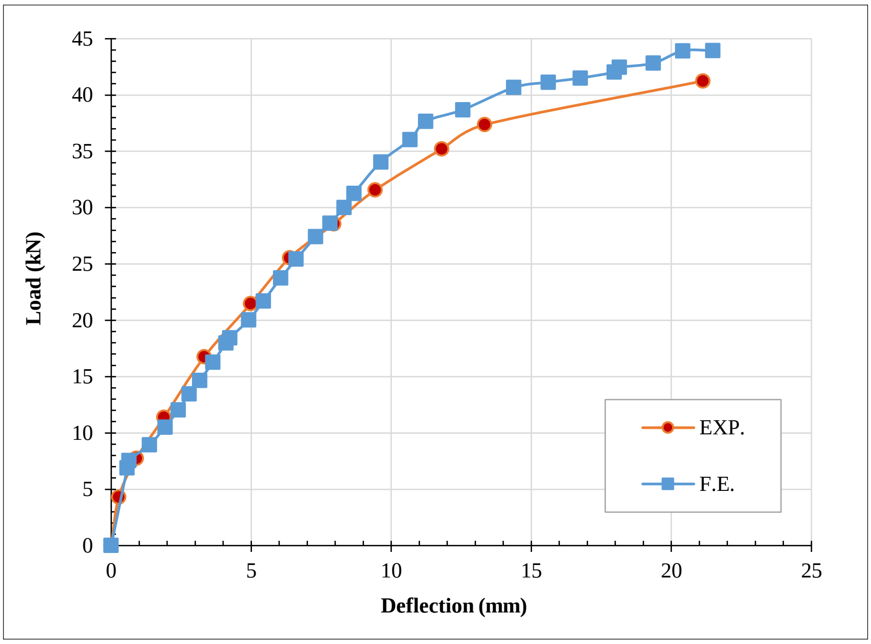


Figure 2. Load-deflection curves for experimental and numerical of RC beam strengthened by CFRP sheets

Figure 2 shows that the ultimate load obtained from the experimental study was 49.5 kN, compared to 52 kN recorded from the numerical model, with an approximate deviation ratio of 5%, indicating an excellent agreement between the two approaches. Additionally, both methods exhibited a similar flexural behavior.

After completing the verification process, several parametric studies were conducted to investigate the influence of various factors on the behavior of the reinforced concrete beam. The parametric study for CFRP strengthening considered the effects of sheet thickness, number of layers, and tensile strength. Following the simulations, the obtained results are presented in Figure 3.

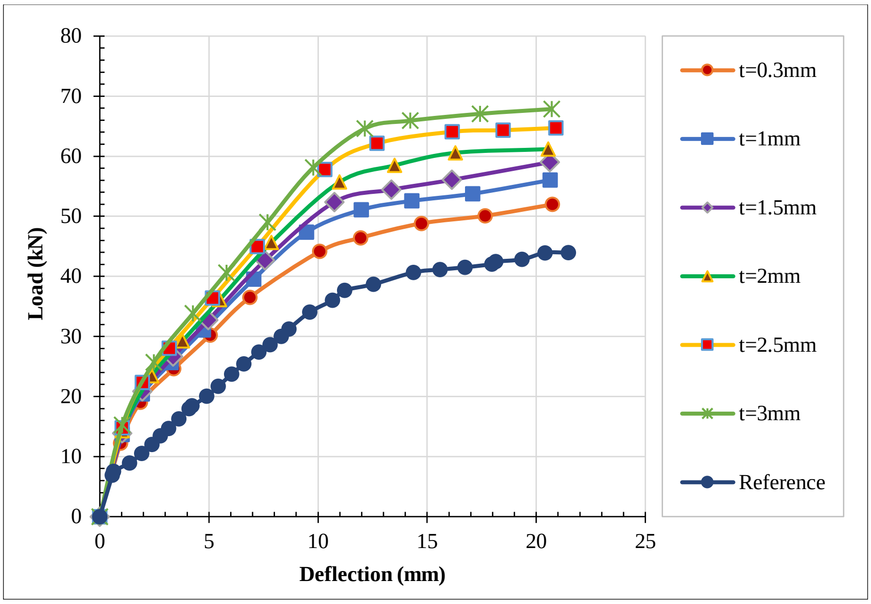


Figure 3. Load-deflection curves for strengthened RC beam with different thickness of CFRP sheets

Figures 3 to 5 show a significant improvement in the flexural capacity and ultimate load of beams when strengthen with CFRP. All strengthen beams showed an increasing in ultimate load compared to reference one, especially when the thickness, number of layers, and tensile strength were increased. The maximum enhancement in flexural capacity up to 34% when using a 3 mm thick sheet, this is due to the CFRP adds an additional resisting moment to the beam resulting from the product of the concentrated tensile force in the center of the CFRP and its arm (its distance to the compressive force of the concrete). While, the ultimate load increased by 18, 24, and 28% when strengthened with one, two and three layers, respectively, this increment achieved by increasing the internal moment of the beam due to of increasing its depth with CFRP layers. Also, increasing the tensile strength of CFRP improved beam capacity to a maximum extent when the tensile strength increased to 4000 MPa, where the improvement reached 24%, this attributed to increasing the internal tension force of beam. The figures also showed that all beams exhibited linear behavior during the initial loading stages. As the load increased, the behavior transitioned to a nonlinear phase. However, the reference beam exhibited a transition to nonlinear behavior at lower load levels. The curves of the strengthened beams demonstrated a greater ability to continue resisting loads during the plastic phase, reflecting the contribution of the CFRP in improving the structural efficiency of the beams. Despite this, the curves clearly show that the ultimate load is almost always associated with failure moment, with no post-peak behavior appearing. This is attributed to the absence of ductility in the beams and the likelihood that the failure is brittle.

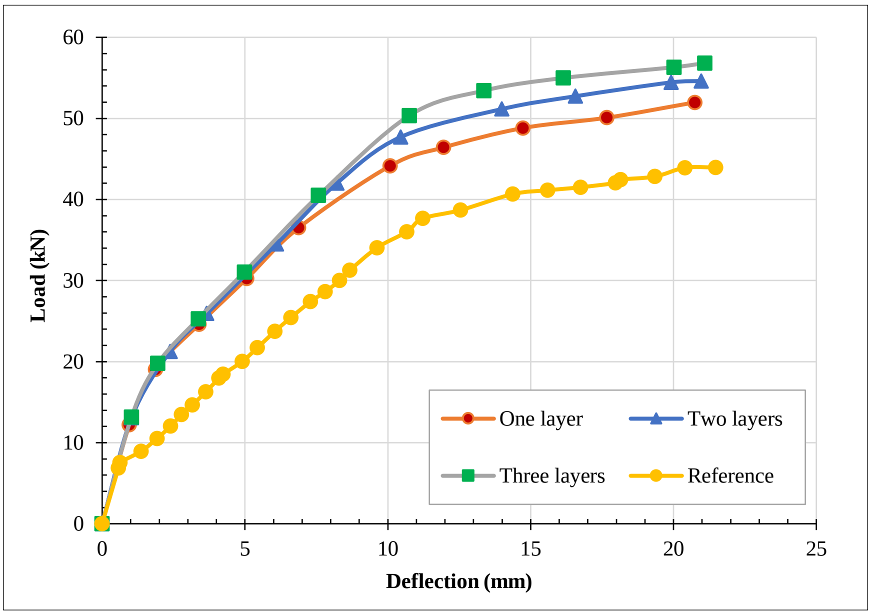


Figure 4. Load-deflection curves for strengthened RC beam with different number of layers of CFRP sheets

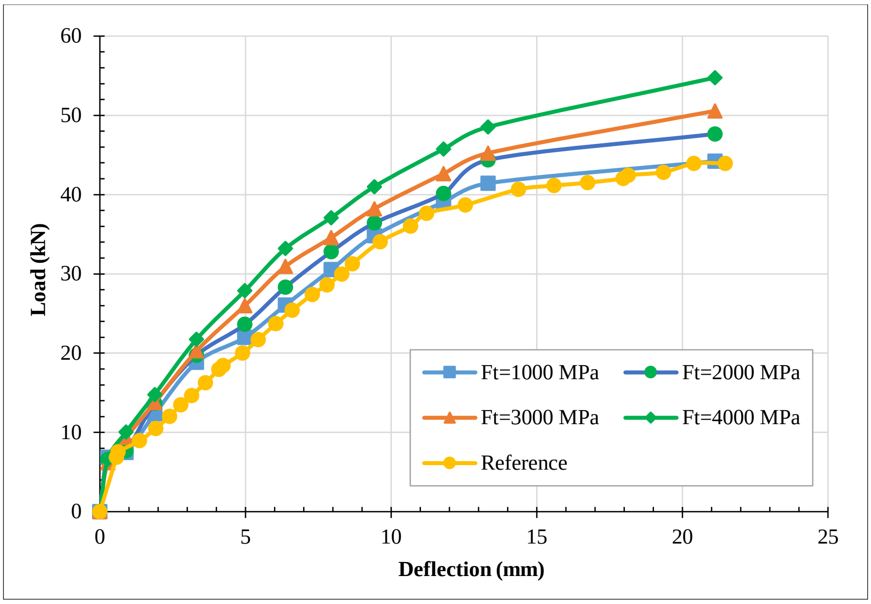
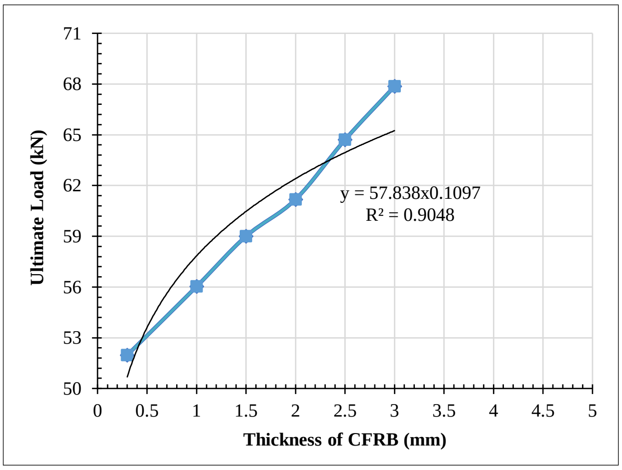
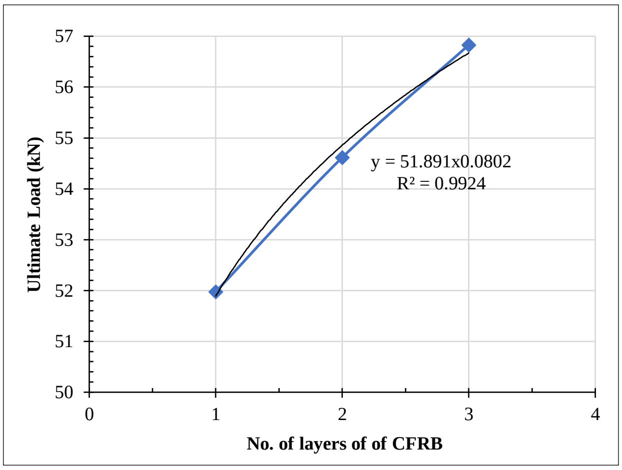


Figure 5. Load-deflection curves for strengthened RC beam with various tensile strength of CFRP sheets

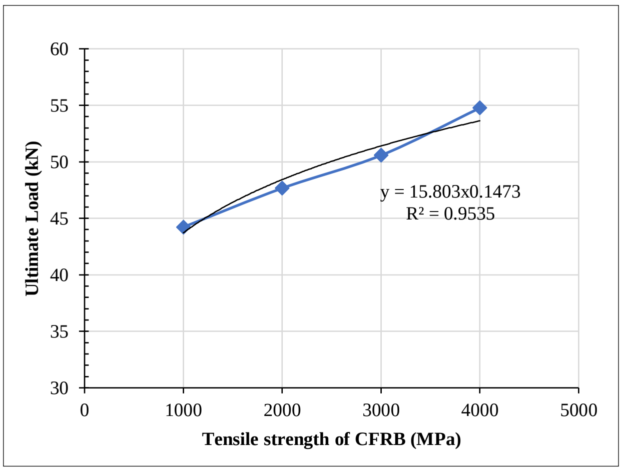
In order to investigate the most influential parameter in improving the flexural performance of the beam, an analysis of the influence function was conducted by plotting the ultimate load curve versus the studied variable. By knowing the power of the function for all parametric study, the most influential parameter in strengthening can be chosen. (see Figure 6).



(a) Influential function for thickness



(b) Influential function for No. of layers



(c) Influential function for tensile strength

Figure 6. Influential function for CFRB strengthening

After analyzing the functions in Figure 6, it was noted that the effect of increasing the number of CFRP layers is very limited, as the exponent of the function was less than 0.1. This limitation is attributed to the possible separation and debonding that may occur between the CFRP layers. In contrast, the tensile strength had the most significant influence on enhancing the flexural strength, where the function recorded a power value of 0.15, which was the highest among all the studied parameters.

3.2. Strengthening with Steel Plates

To verify the accuracy of the numerical model for steel plate strengthening, a comparison was conducted between the present finite element (FE) model and the experimental study published by Oh et al. [31], using the same material and geometrical properties. Figure 7 illustrates the FE model developed in this study.

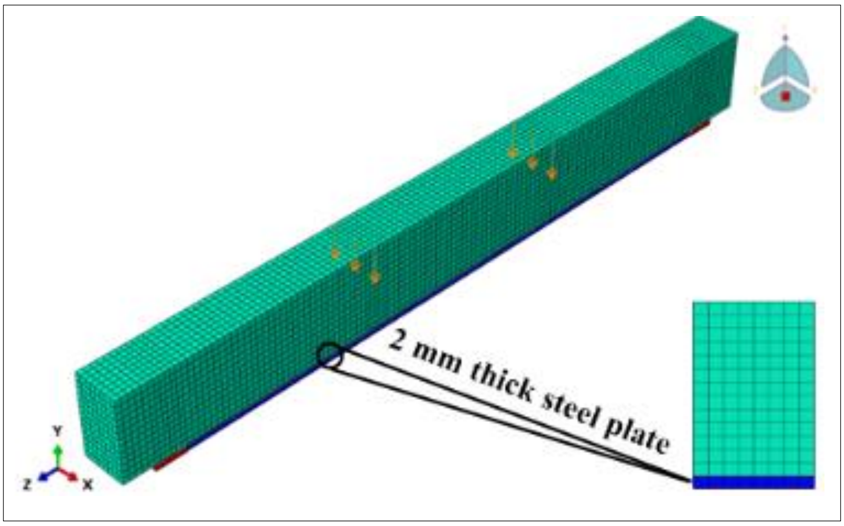


Figure 7. the steel plate strengthening geometry

Following the simulation, the results demonstrated an acceptable agreement between the experimental and numerical analyses, as the ultimate load obtained from the experimental study was 136 kN, compared to 144 kN from the numerical analysis, corresponding to a deviation of 5.8%. Figure 8 presents the comparison between the FE and experimental investigations.

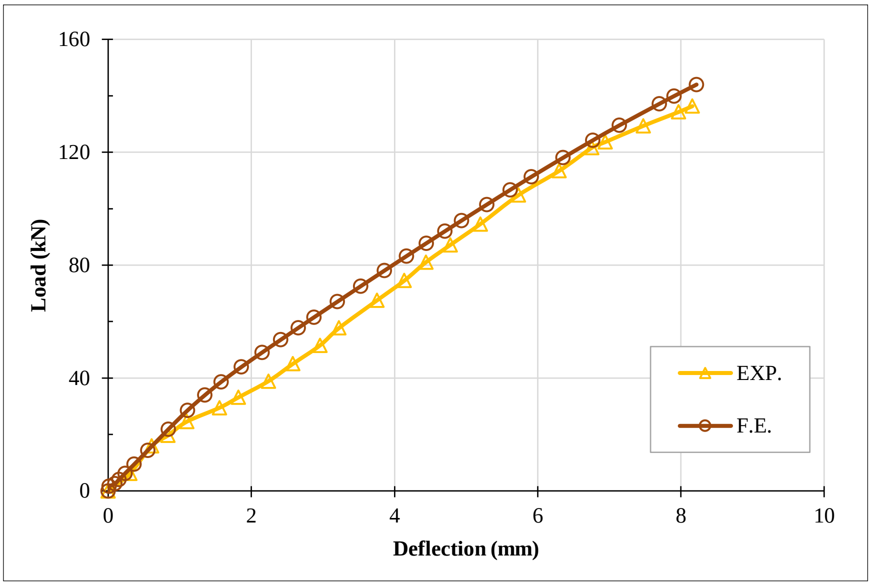


Figure 8. Load-deflection curves for experimental and numerical of RC beam strengthened by steel plates

For the parametric study of steel plate strengthening, the effects of plate thickness, number of layers, and plate yield strength were investigated. After performing the numerical analyses, the results were presented as load–deflection relationships, as shown in Figures 9 to 11.

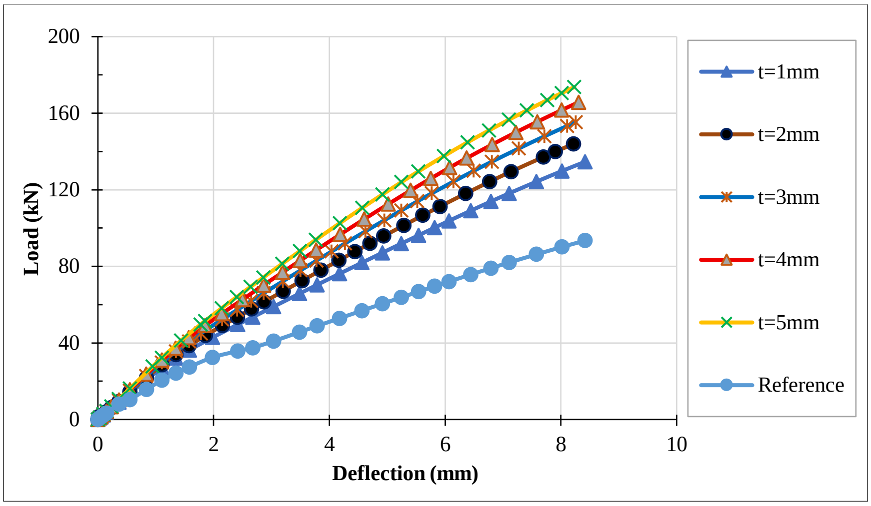


Figure 9. Load-deflection curves for strengthened RC beam with various thickness of steel plates

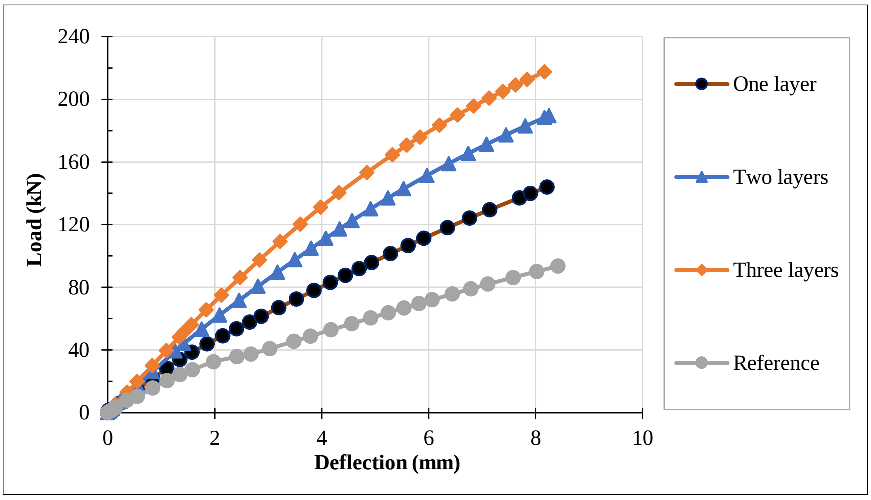


Figure 10. Load-deflection curves for strengthened RC beam with different number of layers of steel plates

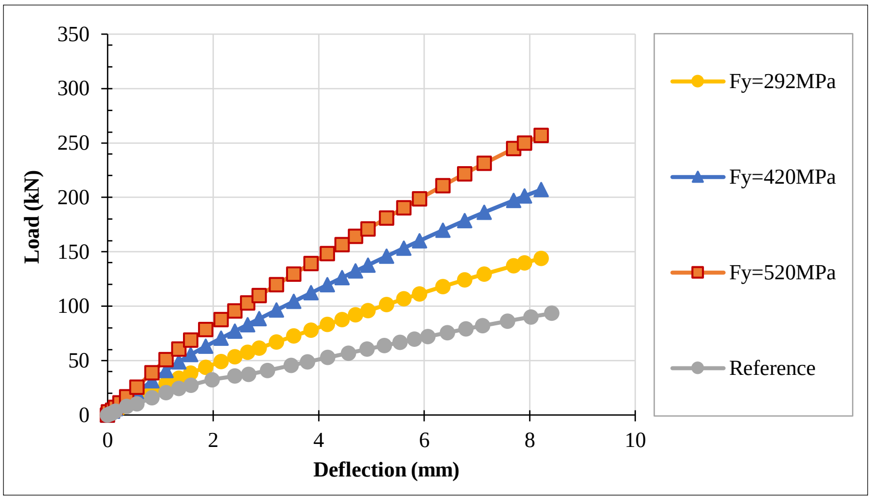
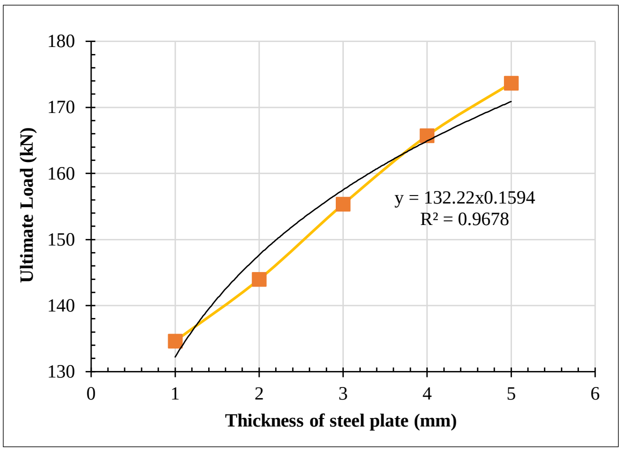
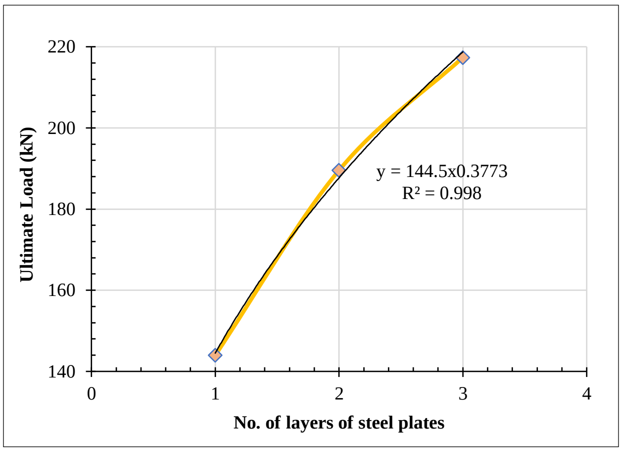


Figure 11. Load-deflection curves for strengthened RC beam with different yield strength of steel plates

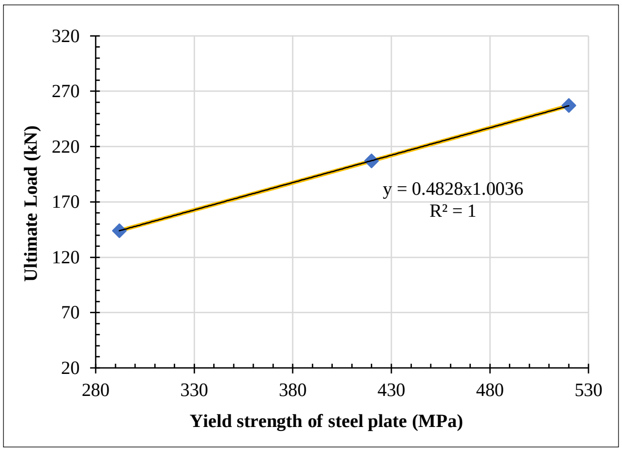
By changing the strengthening strategy to steel plate, flexural strength of beam was increased by 86% when the plate thickness was increased to 5 mm, and by 132% when strengthened with three layers. The maximum improvement, however, was recorded at 175% when using a steel plate with a yield stress of 520 MPa. These increments are attributed to the development of the internal moment within the beam, as the steel plate provides an additional internal moment generated by the cross-sectional area of the plate, multiplied by its yield stress, and by the lever arm between the tensile force in the plate and the compressive force in the concrete. To identify the parameter with the dominant effect on steel plate strengthening, a relationship was established between each parameter and its ultimate load, as illustrated in Figure 12.



(a) Influential function for thickness



(b) Influential function for No. of layers



(c) Influential function for yield strength

Figure 12. Influential function for steel plate strengthening

The results indicated that the yield strength is the most influential parameter in enhancing the beam's capacity when strengthened with a steel plate, as the power of the equation was approximately 1.00, compared to 0.16 and 0.38 for the thickness and number of layers, respectively.

3.3. Strengthening with Additional External Bar

Regarding the beam model strengthened by adding external rebar, or in other words, by increasing the reinforcement ratio, Figure 13 shows the geometry of this strengthening technique.

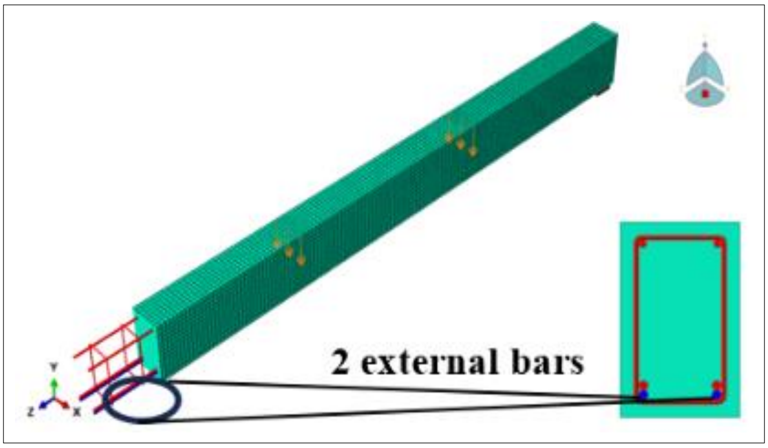


Figure 13. geometry of RC beam strengthened with external bars

The results revealed a considerable level of agreement with the load-deflection curve behavior, and the deviation was not more than 6.5% in contrast to the empirical study [30] (Figure 14).

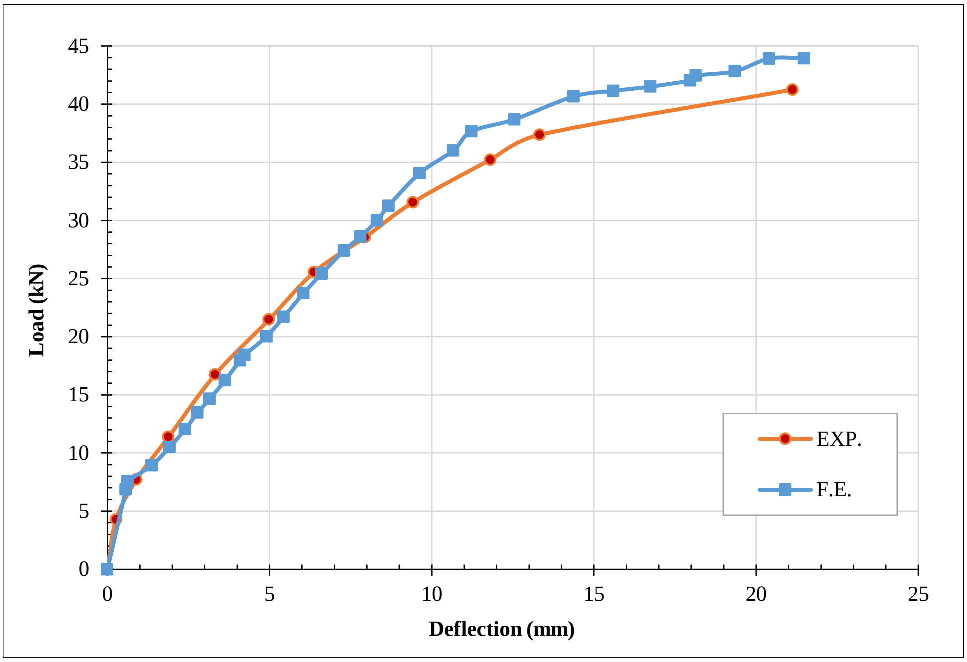


Figure 14. Load-deflection curves for experimental and numerical of conventional reinforced concrete beam

After increasing the reinforcing steel ratio from 0.692% to 1.38% and 2.075%, the results of numerical analysis were presented in Figure 15.

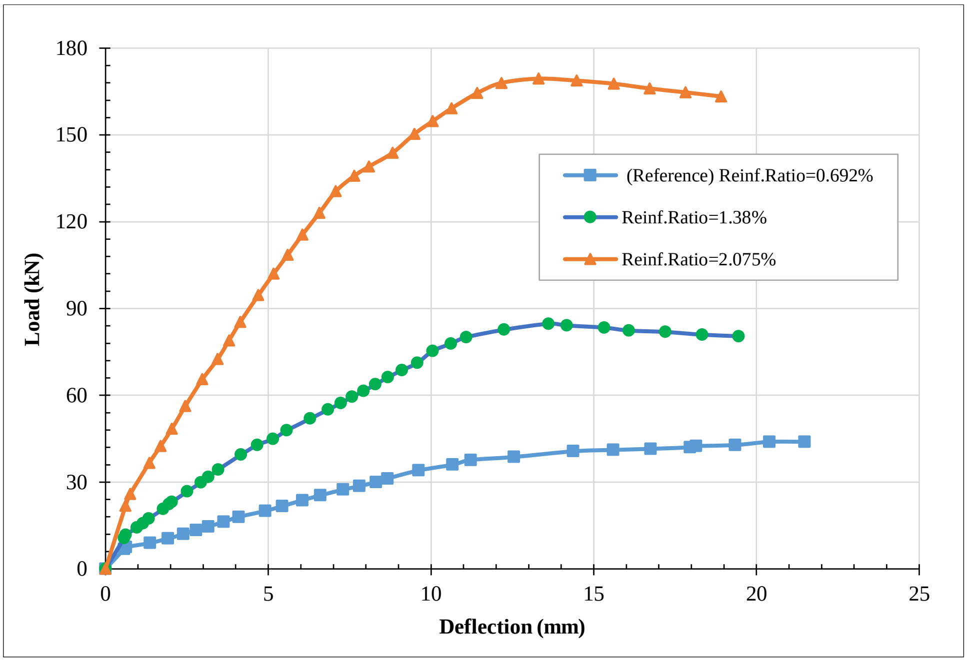


Figure 15. Load-deflection curves for strengthened reinforced concrete beam with different reinforcement ratios (F.E. method)

From Figure 15, it can be noticed that the flexural strength of the beam increased, as the ultimate load rose by 92% and 285% when the rebar ratio was increased to 1.38% and 2.075%, respectively. The load–deflection curve also shows, in contrast to beams strengthened with steel plate and CFRP sheets, a more ductile behavior, as it continues to carry loads beyond the curve's peak, exhibiting a greater deformation capacity before failure. This indicates a gradual failure behavior, which is desirable in most structural applications.

The increase in reinforcement ratio with ultimate load increasing has follows the linear relationship with power function of 1.2. This, indicate that the efficiency of this method in strengthened the concrete beams (see Figure 16).

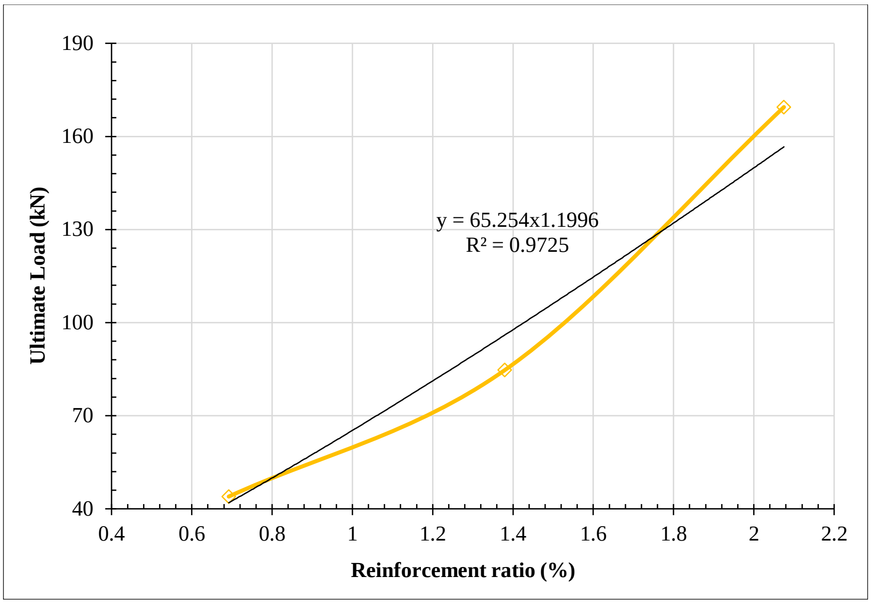


Figure 16. Influential function for external bar strengthening

4. Strengthening Strategy Selection

After studying each strengthening method separately and analyzing all parameters, it was observed that strengthening with steel plates improved the flexural capacity by 17% more than CFRP when using the same thickness, despite the superior tensile properties of carbon fiber. This can be attributed to the nature of anchorage and adhesion between the CFRP or steel plate and the beam surface, where the steel plate provides a stronger bond with the concrete, reducing the likelihood of debonding from the beam’s bottom fiber at higher load levels. Meanwhile, external bars produced the greatest increase and influence on flexural strength. Therefore, they are preferred when a significant enhancement in beam flexure is required. However, the installation complexity and economic considerations of each technique must also be taken into account.

The load-deflection behaviour for all strengthened methods remained similar especially with the absence of post peak stage, where the failure occurred close to the ultimate load. Meanwhile, the external bars demonstrated ductility behaviour make it suitable for structural applications.

5. Conclusion

The flexural capacity of reinforced concrete beams significantly enhanced when strengthened with carbon fibres especially with higher tensile strength. Also, a very limited effect on ultimate capacity when the number of layers was increased due to expected debonding failure. A higher beam strength was achieved using steel plate in strengthening compared to carbon fiber sheets, despite superior tensile strength of carbon fibre sheets. A highest ultimate beam capacity was observed when the beam was strengthened with external bars.

Although strengthening with carbon fiber and steel plates significantly improved the beam’s flexural strength, both exhibited brittle failure due to the absence of a post-peak stage, unlike the external bars, which demonstrated ductile failure and a clear increase in ductility. This distinction should be carefully considered in structural design. The optimal strengthening strategy depends on the design objectives: if the goal is to enhance stiffness and capacity, CFRP or steel plate methods are suitable, particularly when a moderate increase in capacity is sufficient. However, if ultimate capacity and ductility are essential design requirements, external bar strengthening is the more appropriate choice.

6. Declarations

6.1. Author Contributions

Project administration, H.A; formal analysis, R.A. and M.H.; conceptualization, R.A. and H.A.; software, R.A. and M.H.; R.A. and M.H.; resources, R.A. and M.H.; methodology, R.A. and H.A; validation, R.A., H.A., and M.H; data curation, R.A. and M.H.; writing—original draft preparation, R.A. and M.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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