



Research Article

**EXPERIMENTAL AND NUMERICAL ANALYSIS OF REINFORCED
CONCRETE BEAM STRENGTHENED USING CARBON FIBER
REINFORCED PLASTIC SHEETS AND BOLTED STEEL PLATE**

Emre ERCAN¹, Bengi ARISOY*², Aybike ÖZYÜKSEL ÇİFTÇİOĞLU³

¹Ege University, Civil Engineering Department, IZMIR; ORCID:0000-0001-9325-8534

²Ege University, Civil Engineering Department, IZMIR; ORCID:0000-0002-2785-0609

³Celal Bayar University, Civil Engineering Department, MANISA; ORCID:0000-0003-4424-7622

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ABSTRACT

This paper presents experimental and numerical study on reinforced concrete (RC) beams with flexural strengthening by carbon fiber reinforced polymer (CFRP) sheets and steel plates. In the study, effect of strengthening on flexural of RC beams is examined. Also, the differences between CFRP sheet and steel plate retrofitting regarding flexural strength of the RC beams are indicated.

For experimental study, seven RC beams were produced. One of the beams is regarded as “control sample”, three of samples were strengthened using CFRP sheets and the other three samples strengthened using steel plates. Four points bending test was conducted, vertical displacements of the beams were measured. Tests results indicated that the beams were strengthened for flexure became vulnerable shear failure and CFRP application was better strength values in flexure than steel plates application. For numerical analysis, three-dimensional finite element modeling of strengthened and non-strengthened reinforced concrete beams is prepared. Reinforced concrete beam is modeled by using hexahedral, steel plate and CFRP sheets are modeled by using tetrahedral elements. Finite element analysis is performed by using ATENA non-linear analysis program. The results of experiments and finite element analysis are compared. Results indicated that the strengthened reinforced concrete beams have larger moment capacity, yet exhibit shear failure. Although, strengthened samples exhibit shear failure, failure is not brittle. Experimental results are also validated by finite element analysis.

Keywords: Reinforced concrete beams, strengthening, carbon fiber polymers, steel plates.

1. INTRODUCTION

Strengthening applications are used extensively in Turkey in order to upgrade reinforced concrete buildings to provide structural safety according to current buildings codes. Besides not being suitable current building codes, necessity of strengthening comes up due to insufficient original design limits, construction errors, poor maintenance or changing in use of the buildings.

Strengthening is mostly done adding reinforced concrete shear wall and jacketing of beams and columns with reinforced concrete. On the other hand, the alternative methods, such as strengthening with steel plates and fiber reinforced plastics (FRP) become widely used because

* Corresponding Author: e-mail: bengi.arisoy@ege.edu.tr, tel: (232) 311 51 81

application is easy and economical. Although the strengthening with FRP or steel plates is easy to apply, economical and used widely, a sufficient code for the FRP and steel plate strengthening technics is not exist and feed backs of the applications are missing. Therefore there is needed to determine or constitute specifications about applications of strengthening technics with FRP and/or steel plates.

Carbon fiber reinforced plastic (CFRP) is one of the type of FRP. It is used commonly in structural rehabilitation, strengthening or retrofitting of reinforced concrete buildings. Academic studies on the subject indicate that using CFRP in structural rehabilitation, strengthening or retrofitting is an effective way to increase the performance of the certain structural members, such as beams or columns [1-15]. Although there are many other studies about subject, only few are cited here. Strengthening columns with CFRP wrapping is much easier than strengthening beams due to physical limitations. In the case of application of strengthening to the beams only, CFRP sheets are connected the member by epoxy, steel plates are connected by studs or bolts. Commercial applications of CFRP strengthening in Turkey are usually practiced for flexure without sufficient shear bonding; steel plate is always applied for flexure, claiming sufficient strengthening is provided. In this study, common "ways" to apply CFRP and steel plates to a beam for strengthening components and its effect are experimentally examined.

2. RESEARCH SIGNIFICANCE

The main objective of this research is to establish an effective approach for commercial applications of strengthening of reinforced concrete buildings. Commercial applications with CFRP and steel sheets in Turkey usually consist of wrapping the column and attaching CFRP component to the bottom face of the beam; ignoring shear vulnerability of the beam at section close to the supports. Here, in this study, it would be exhibited that having strengthen the beam for flexure only would not validate the technique is sufficient. This study is focused on especially the ways of strengthening applications already used in the construction industry in Turkey.

3. ANALYTICAL STUDY

There are three potential failure modes in beams strengthened with bolted steel plate [16-18]:

- steel reinforcement yielding before concrete crashing,
- concrete crashing before yielding of steel reinforcing,
- steel reinforcing yielding followed by rupture or pull out of bolting (since bounding between steel plate and the reinforced concrete beam was provided by only bolting).

In designing the beam, one of the failure modes should be chosen, and then failure should be checked by using strain limitations. On the other hand, in this study, since the problem is "upgrade the existence beam" not to "design", so that the analysis is made for the present situation. For the reinforced concrete beam strengthened by bolted steel plate, rupture or pull out of bolting before the steel reinforcing yielding failure mode assumption was made. Bending moment capacity (M_r) of the beam is determined by using stress and strain profile given in Figure 1, and by the Eqs.s 1 to 5. In Eq. 2, $T_s(d-a/2)$ represents moment capacity of reinforced concrete beam without any strengthening. Flexural and shear stress in any level in profile are determined by mechanics of materials.

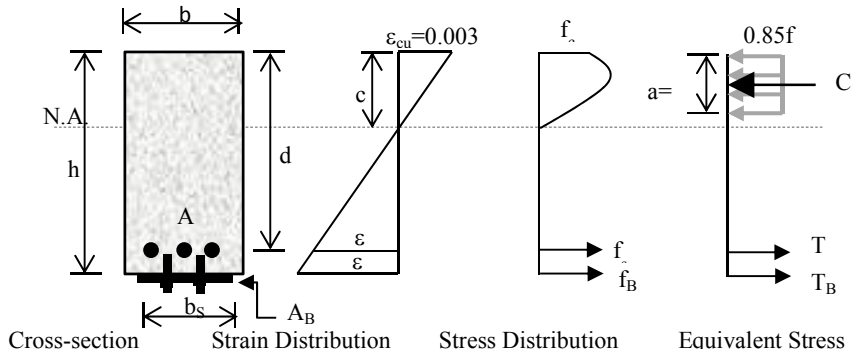


Figure 1. Assumed stress and strain profile of the beam strengthened with bolted steel plate

$$C_c = T_s + T_B \tag{1}$$

$$M_r = T_s \left(d - \frac{a}{2} \right) + T_B \left(h - \frac{a}{2} \right) \tag{2}$$

$$a = \beta_1 c \tag{2 - a}$$

$$C_c = 0.85 \phi_c f_c a b \tag{3}$$

$$T_s = \phi_s A_s f_s \quad \text{with } f_s < f_y \tag{4}$$

$$T_B = \phi_B A_B f_B = \phi_B n \pi \frac{D^2}{4} f_B \tag{5}$$

where C_c is compression force in concrete block in compression region, T_s is tension force in reinforcing steel in tension region, T_B is shear force in bolts in tension region, M_r is bending moment capacity of the beam, f_c is compressive strength of concrete, A_s is cross section area of reinforcing steel, f_s is tension strength of the reinforcing steel, A_B is cross section of the bolts, f_B is shear strength of bolts, n is number of bolts in section, D is diameter of the bolts, β_1 is concrete compressive block factor, ϕ_c , ϕ_s , ϕ_B are safety factors for concrete, steel reinforcement and bolts, respectively.

In the case of strengthening with CFRP sheets, there are four potential failure modes plate [16-18]:

- steel reinforcing yielding before concrete crashing,
- concrete crashing before yielding of steel reinforcing,
- steel reinforcing yielding followed by CFRP rupture,
- CPRP de-bonding.

Same approach in the case of strengthening with bolted steel is used for the case of strengthening CFRP sheets. The rupture of CFRP before the steel reinforcing yielding failure mode assumption was made, and bending moment capacity (M_r) of the beam is determined by using stress and strain profile given in Figure 2, and by the Eq.s 6 to 8.

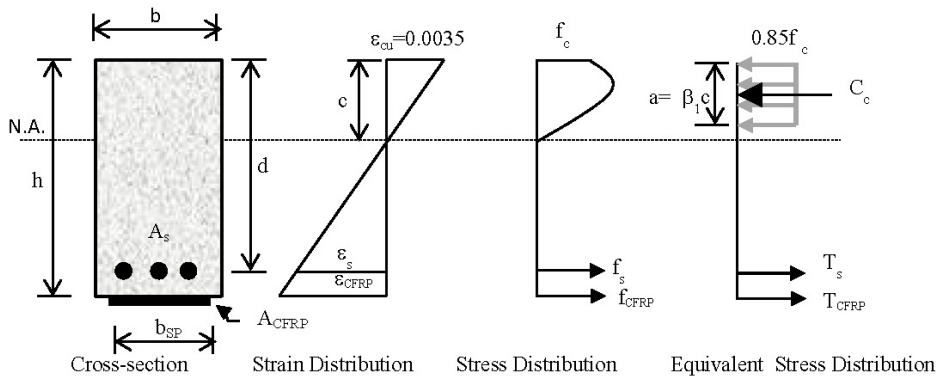


Figure 2. Assumed stress and strain profile of the beam strengthened with bolted steel plate [16-18]

$$C_c = T_s + T_{CFRP} \quad (6)$$

$$M_r = T_s \left(d - \frac{a}{2} \right) + T_{CFRP} \left(h - \frac{a}{2} \right) \quad (7)$$

$$T_{CFRP} = \phi_{CFRP} A_{CFRP} f_{CFRP} = \phi_{CFRP} A_{CFRP} E_{CFRP} \epsilon_{CFRP} \quad (8)$$

where C_c is compression force in concrete block in compression region, T_s is tension force in reinforcing steel in tension region, T_{CFRP} is shear force in CFRP sheet in tension region, M_r is bending moment capacity of the beam, A_{CFRP} is cross section of the CFRP sheet, f_{CFRP} is tension strength of CFRP, E_{CFRP} is modulus of elasticity of CFRP, ϵ_{CFRP} is elastic strain of CFRP, ϕ_{CFRP} is safety factor for CFRP sheets.

Moment capacities given in Eq.(2) for reinforced concrete beam strengthened with bolted steel, in Eq.(7) for reinforced concrete beam strengthened with CFRP are for the assumption that the samples exhibit fully flexural behavior. Analytic calculations for samples introduced experimental study section are completed step by step according to reference ISIS Design Manual No.4 [16] and ACI440 [18].

4. EXPERIMENTAL STUDY

In experimental study, seven RC beams were produced. All the beam specimens are 250 by 150 mm in cross section and 1500 mm in span length Reinforcing detail of the sample is given in Figure 3. Samples were designed to exhibit ductile behavior to emphasize effect of flexural strengthening on behavior under static load. The both strengthening, with CFRP and with steel plates, were applied to increase flexure behavior whether the sample needed flexural strengthening or not. The reason behind such application is that because commercial applications are performed without questioning the capacity of structural member.

One of the seven samples was regarded as “control sample”, the three samples were strengthened using FRP sheets and the other three samples were strengthened using steel plates. Four points bending test was conducted, mid span displacements were measured.

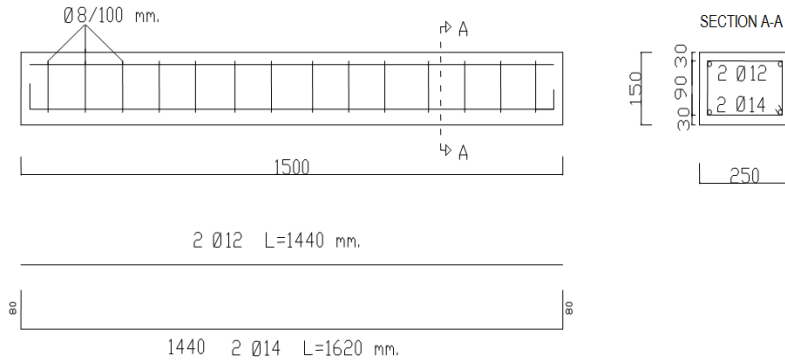


Figure 3. Design of reinforced concrete beam samples [19]

Materials used and their properties are listed in Table 1. Concrete was commercially available ready to mix concrete manufactured according to local building codes TS EN 206-1. The other materials were provided from market. Materials properties of concrete were provided by testing cylinder samples suitable to ASTM C873.

Table 1. Material properties of concrete, steel rebars and FRP sheets.

Material	Dimensions (mm)	f_c^* (MPa)	f_v^{**} (MPa)	f_u^{***} (MPa)	E^+ (GPa)
Concrete		25	--	-	30
Reinforcing steel		-	420	500	200
CFRP sheets	$t=0.12$	-	-	4100	235
Steel plates (with bolted connection)	$t=5.0$ $w=250$	-	235	260	206
M10 bolt				140 (shear strength)	200

* Compression strength, ** Yielding strength, *** Ultimate strength, + Modulus of elasticity, t is thickness, w is wideness, M10 bolt with 10mm diameter

4.1. Strengthening

Two types of strengthening techniques were applied: strengthening using steel plates and strengthening using CFRP sheets. In steel plate application, bolting was used. 5mm thick, 250mm wide and 1200mm long steel plate was bolted to the RC beam with 12 M10 bolts. Schematic location of bolts and picture of strengthened member with steel plate are given in Figure 4 and 5, respectively.

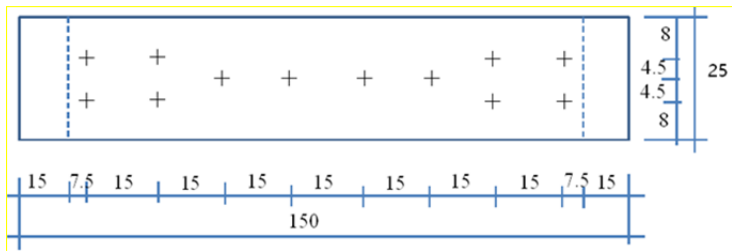


Figure 4. Application of steel plates (units are cm) [19]



Figure 5. Member strengthened with steel plate [19]

Two layers of fiber sheet were applied. CFRP sheets were applied as the steel plates had been: CFRP sheets were applied only bottom surface of beam. Application of the CFRP was properly and carefully completed (Figure 6). All rules were applied to have best bonding. At the both end of the beam, CFRP sheets were wrapped two layers of CFRP sheets to eliminate immediate debonding (Figure 7).



Figure 6. Application of CFRP sheets at flexure section [19]



Figure 7. Application of CFRP sheets at support sections [19]

4.2. Testing

Beams were simply supported over a clear span of 1300 mm and tested under four-point bending, as shown in Figure 8. The load was applied using 500 kN capacity load cell with a loading rate of 1 kN/ min. All beams were instrumented to measure displacements on the mid span.

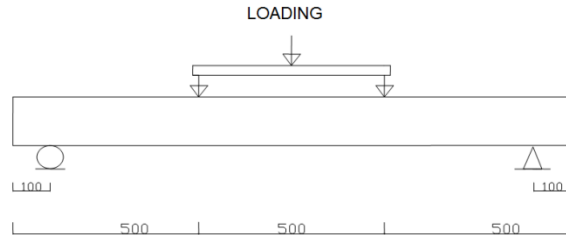


Figure 8. Loading configuration [19]

4.3. Findings

4.3.1. Failure modes and load-displacement response

Control specimen exhibited flexural failure, as expected. Flexural cracks formed parallel to each other in the mid span until the beam failed due to yielding of longitudinal reinforcing in tension region and crushing concrete in compression region as seen in Figure 9. Fracture load capacity of the beam is 97.1 kN, and the flexural moment capacity of beam at fracture is 19.4kN-m. The theoretical moment capacity of the beam calculated from mechanics of the cross section is 12kN-m. The beam exhibited larger flexural capacity than theoretical. Load-displacement curve of the sample is given in Figure 10. The sample exhibited considerably large ductility.

Modulus of rupture (MOR) of the sample at the loading point is determined by Eq. 9.

$$MOR = \frac{3Pl'}{bd^2} \quad (9)$$

where P is applied load, l' is distance between support and the nearest loading point, b is width and d is height of the beam. Modulus of rupture calculated for CONTROL beam is 20.71 MPa. (for P=97.11 kN, l'=0.4m, b=0.25m, d=0.15m). Flexural strength of all the samples tested is given in Table 2, at section 4.



Figure 9. Failure of control sample [19]

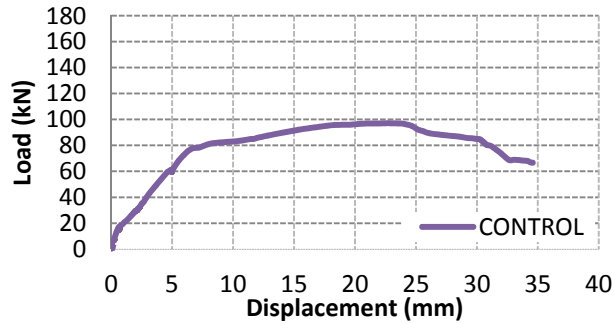


Figure 10. Load-deflection curves of CONTROL sample

The Figure 11 exhibits the while parallel cracks becomes shear cracks at about supports and progress to the compression region, the concrete at compressive region is crashed.



Figure 11. Close view of fracture in CONTROL sample [19]

4.3.1. Steel plate strengthened specimen

Specimens strengthened with steel plates exhibited semi ductile failure. The beams failed at support regions due to concrete crashing initiated by shear effect (Figure 12). All the samples were failed due to concrete crashing immediately after either pulling out or rupturing of bolting (Figure 13). The capacity of the beam was limited by the shear capacity although the beam was retrofitted to the flexure. Load-deflection curves are shown in Figure 14. Strengthened samples had larger load carrying capacity than CONTROL sample. On the other hand, one of the beams (Figure 12-a), fractured in shear following same pattern with the others, was exhibited relatively better ductility as seen in Figure 15. The sample has 138.94kN fracture load capacity, indicating bolting and bounding conditions are important parameters comparing fracture load capacity of other two samples that are 130.11 kN and 124.1 kN. If the failure in bolting was prevented, the sample might have exhibit flexural failure. Flexural strength of the samples are 29.64, 27.76, and 26.47 MPa calculated according to Eq. 11. Average load carrying capacity is increased according to control specimen, but since the failure mod was semi-ductile, bounding technique should be improved.

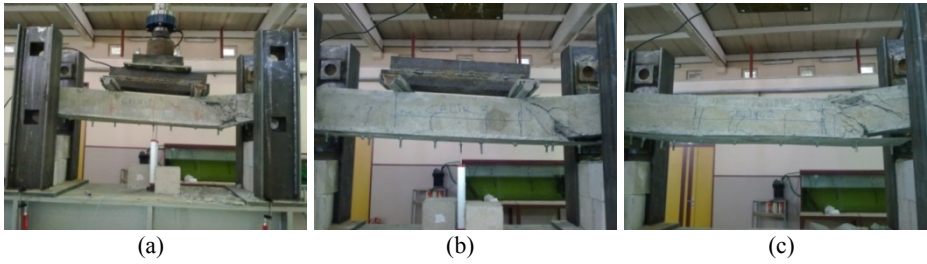


Figure 12. Failure of the three samples strengthened with steel plate [19]



Figure 13. Pull-out of bolts at near support [19]

Figure 13 indicates severe concrete crushing after failure of bolting member. Two of the samples exhibit such behavior, one of the sample exhibits concrete failure without failure in bolting having smaller amount increase in both moment capacity. Although mentioned increase may not considered large increase, load-displacement curves (Figure 14) indicates samples exhibit ductile behavior, meaning reinforcing in the beam is still working.

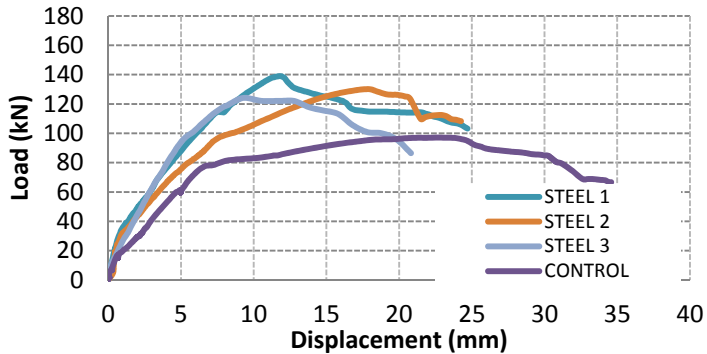


Figure 14. Load-displacement curve of steel plate strengthened

4.3.1. CFRP strengthened specimen



Figure 15. Load-displacement curve of steel plate strengthened [19]

Specimens strengthened with CFRP sheets exhibited both ductile and semi-ductile failure. One of the beams exhibited flexural failure (Figure 16-a), other two exhibited shear failure (Figure 16-b,c). Although flexural strengthening member (CFRP sheet) was hold by at about support section by CFRP sheets in each samples, it is proven that attention paid during application is important.

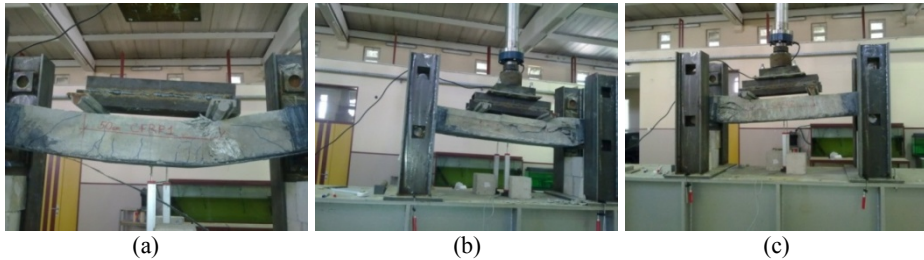


Figure 16. Failure of the three samples strengthened with CFRP sheets [19]



Figure 17. Failure of the three samples strengthened with CFRP sheets [19]

Fracture load and flexural strength capacities of the samples are given in Table 2. Detailed discussion will be made in section 6.

Load-deflection curves of samples with CFRP sheets are shown in Figure 18. Average load carrying capacity is increased according to control specimen. Although the load-deflection curve indicates that as if all the samples exhibit ductile behavior, the failure was shear failure in two of the samples. On the other hand, if retrofitting applied sufficient enough, the flexural capacity of the sample might be increased.

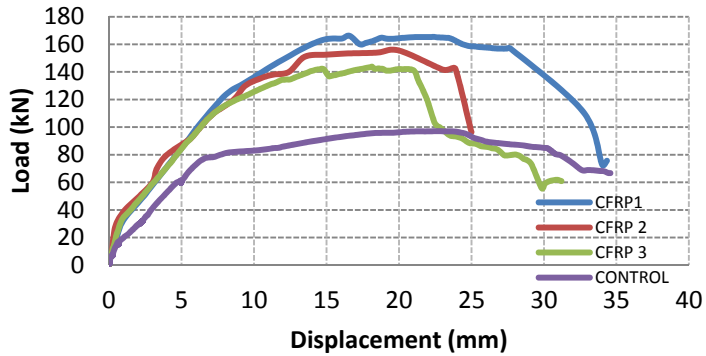


Figure 18. Load-displacement curve of CFRP strengthened samples

Tests results indicated that the beams were strengthened for flexure became vulnerable shear failure and FRP application was better strength values in flexure than steel plates.

5. FINITE ELEMENT MODELING

Finite element (FE) analysis of the RC beam strengthened with CFRP sheets and strengthened with bolted steel plate is completed by using ATHENA [20]. structural analysis software. Mesh seeding is done to determine the optimum mesh size [21-23].

The concrete part of the model is composed of 8008 Hexahedral elements, longitudinal and strips are composed of 88 linear elements and the loading and the support plates are composed of 808 tetrahedral elements. The reinforced concrete beam strengthened bolted steel plate is modeled using 2560 tetrahedral elements. The 12 bolts that provide connection between steel plate and concrete are modeled as linear elements. The CFRP under the beam is modeled also as linear elements as explained in ATENA Program Documentation Part 4-9. Figure 19, 20 and 21 shows the FE models of the Control, Steel plated and CFRP applied models of the samples, respectively.

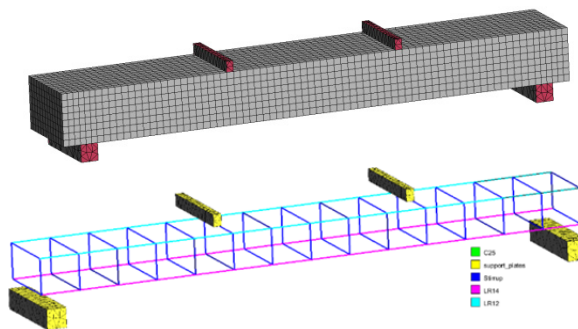


Figure 19. Finite element model of the control sample

The reinforced concrete beam strengthened steel plate and CFRP sheets shown in Figure 20 and Figure 21, respectively, presented upside down in order to present steel plate and CFRF sheets clearly.

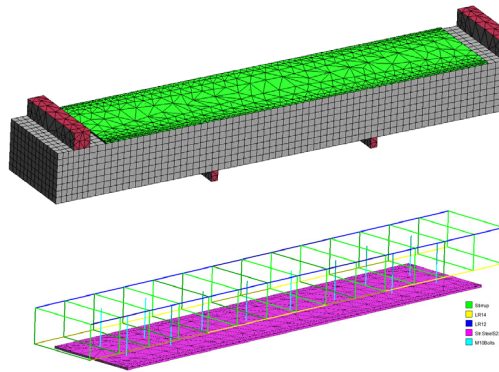


Figure 20. Finite element model of the beam with bolted steel plate (the beam is presented upside down), and reinforcing bars

After analysis, the deformed shape and cracks on the models are presented in following Figures. In Figure 22, the stress contour of concrete beam and reinforcement for CONTROL model is presented.

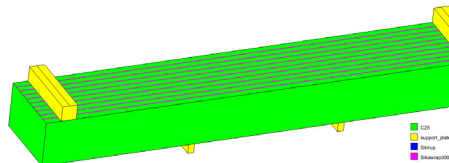


Figure 21. Finite element model of the beam with CFRP (the beam is presented upside down)

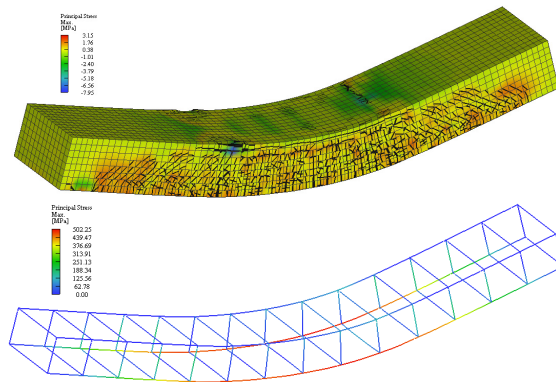


Figure 22. Deformed shape and cracks of control sample at the end of the analysis with maximum principle stress contour for beam and reinforcing bars.

The crack generation under loading of FEM model is very much similar to experimented sample. Even concrete crushing under load point is observed. The stress transformation from concrete to steel rebars is also observed. Maximum stress recorded 7.95 MPa compression in concrete and 502.25 MPa tension in rebars. Tension stress in the rebars is also determined

analytically as 584 MPa using Eq. 10. Calculations are based on mechanics of the beam profile. Since strain measurements were not performed, stresses are not checked by experimentally.

$$\sigma = \frac{T_s}{A_s} \tag{10}$$

where T_s is load in reinforcing bar, A_s is cross section area of reinforcing bar. T_s is determined by using Eq. 4. Figure 23 presents load-deflection curves of testing and FEM analysis of CONTRON sample.

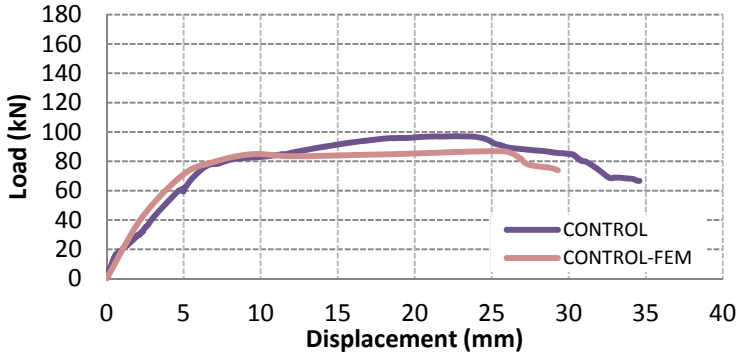


Figure 23. Deformation and stresses in bolts in reinforced concrete beam strengthened bolted steel plate

Figure 24 presents the deformed shape and cracks of the steel plated sample at the end of the analysis with maximum principle stress contour. As shown in Figure the concrete has cracks near the supports as it is in experimental results. Deformed shapes of beam in experiment and FEM analysis are almost identical (compare Figure 13 and Figure 24).

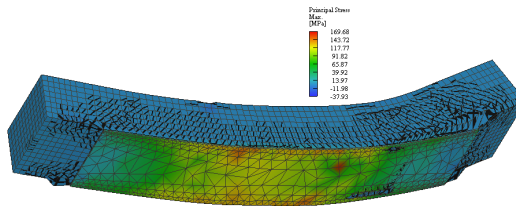


Figure 24. Deformed shaped and cracks of the beam bolted steel plate model at the end of the analysis

FEM analysis also indicates that stress release in plate occurs due do pulling out or rupturing bolts near support. The Figure 25 shows deformation and stresses in bolting members. As it was seen in sample tested (Figure 12 and Figure 13), the bolts near supports are under large tensions. After failure of the bolts near supports, stresses are transferred to insider bolts by plate, so that the stress concentration occurs in plate. Since ultimate failure takes place following by concrete crushing, steel plate and the insider bolts do not have large stresses.

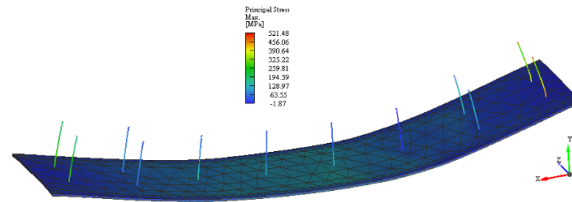


Figure 25. Deformation and stresses in bolts in reinforced concrete beam strengthened bolted steel plate

Figure 26 presents load-deflection curves of testing and FEM analysis of samples with bolted steel plate. Maximum load carrying capacity of the samples tested and the model are in close range. Although, response of the samples tested is ductile and progressive cracking is observed clearly reaching ultimate load having multiple cracks, the model reaches the ultimate load in elastic region, and exhibits ductile behavior after having first crack .

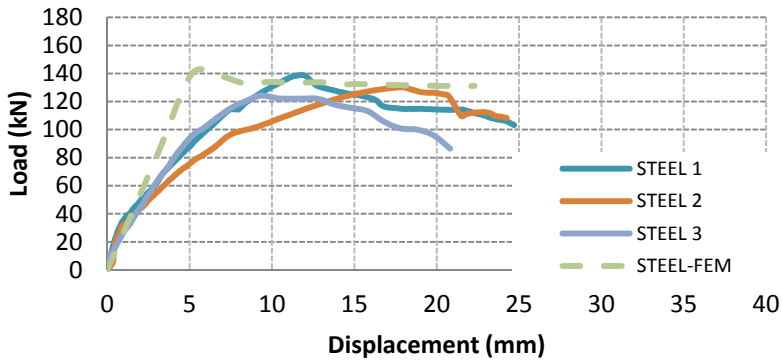


Figure 26. Deformation and stresses in bolts in reinforced concrete beam strengthened bolted steel plate

Figure 27 presents the deformed shape and cracks of the sample with CFRP and principle stress contour in CFRP sheets in FEM analysis. Deformed shapes of beam in experiment and FEM analysis are almost identical (compare Figure 13 and Figure 27). Stress concentration observed in CFRP sheets is close to right side of the beam indicating that CFRP sheet in left side of the beam is fractured and stress moves to the right side.

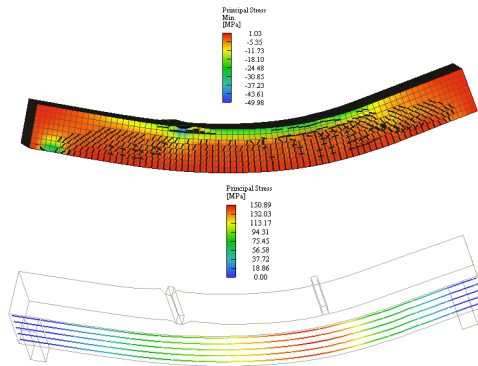


Figure 27. Deformed shape and cracks for the beam with CFRP and stress contour of concrete beam and CFRP sheets

The load-deflection curves of samples with CFRP sheets and model are given in Figure 28.

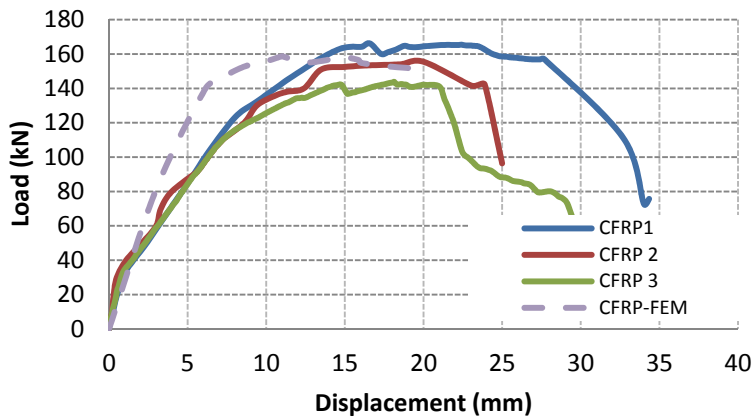


Figure 28. Deformation and stresses in bolts in reinforced concrete beam strengthened bolted steel plate

The result of FEM and the testing are very close each other. It is also observed that the FE model of the beam reaches maximum load with the first cracking, later the curve exhibit rectilinear although tested samples reach the maximum load with multiple cracking.

6. RESULT AND DISCUSSION

In this section, analytical, experimental and FEM results are discussed. Analytical calculation is based on basic mechanics of beam profile. Constants needed to use are taken from local codes. Maximum load, flexural moment capacities and flexural strengths are summarized in Table 2. The nonlinear FEM analysis and the experimental results regarding both moment capacity and flexural strength are reasonably close each other. On the other hand, analytical results do not give true approach to estimate either moment or flexural strength. Reason of it is, analytical calculation

is based on working the concrete beam and CFRP sheet together without peeling from edges or ruptures in supports due to large shearing forces.

The load-deflection curves are given in Figure 29. In Figure 29, the worst experimental data is chosen to make comparison in order to avoid excess load-deflection curves, and CONTROL, CFRP 3 and STEEL 3 curves represent the experimental results.

Table 2. Maximum load, moment and flexural strength capacities of experimental analytical and FEM analysis

Sample	Max. Load Capacity (kN)			Moment Capacity (kN-m)			Flexural Strength (MPa)		
	Analytic*	FEM	Exp.	Analytic*	FEM	Exp.	Analytic*	FEM	Exp.
Control	58.7	86.86	97.11	11.7	17.58	19.42	12.48	18.75	20.72
Beam with Bolted SteelPlate	71.34	139.75	124.1	14.27	27.95	24.82	15.22	29.81	26.42
			130.1			26.02			27.76
			138.9			27.79			29.42
Beam with CFRP	474.6	158.62	143.8	94.9	31.72	28.76	101.2	33.84	30.68
			155.5			31.1			33.17
			166.2			33.24			35.45

* Analytic results are based on mechanics of beam profile for without deformation

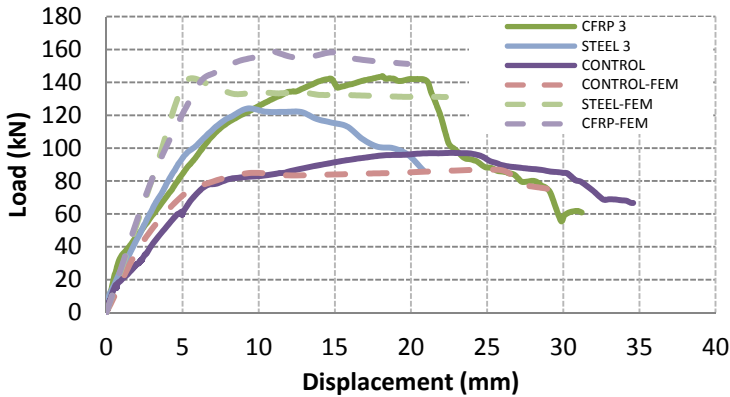


Figure 29. Deformation and stresses in bolts in reinforced concrete beam strengthened bolted steel plate

In Figure 29, although strengthened specimens seem exhibit ductile behavior, in fact samples demonstrate shear failure but not in brittle manner. Increase in load carrying capacity indicate strengthening have large impact on the performance of the beam, yet strengthening beams for only flexure is not enough to have "strengthened" member. All other issues, in this case, such as shear failure and concrete crashing should be considered.

7. CONCLUSIONS

Strengthening of reinforced concrete buildings is still popular in developing countries, because of low cost comparable to rebuild the building. There are hundreds of strengthening applications without considering overall behavior of the structure. Local strengthening technics,

such as strengthening only beams, leads unexpected results. This study expresses the inappropriate strengthening of the beams causes unpredicted failures in beams.

Strengthening the beams in flexure without strengthening shear sections, or strengthening inappropriately, causes shear failure in beam. Although load carrying capacity is increased in beams strengthened in flexural, brittle failure is undesirable. Applying of appropriate shear strengthening to the beam might result large load carrying capacity.

This study is carried out to express effect of two different strengthening technics, strengthened with bolted steel plate and strengthened with CFRP sheets, on flexural behavior of reinforced concrete beam. The following conclusions can be drawn:

1) Reinforced concrete beam without any strengthening exhibited typical flexural behavior. Experimental and FEM analysis results give approximately close moment capacity an flexural strength, yet FEM analysis predicts that behavior of the sample has larger rigidity. Analytical result represents only linear behavior of the beam.

2) Strengthened samples exhibited shear failure, yet flexural moment capacity and flexural strength of the beams are increased.

3) The samples strengthened with CFRP sheets exhibited better behavior regarding both for flexural strength and flexural performance.

4) By improving bolting technics or methods in support sections for the sample strengthened with bolted steel plate might provide better flexural behavior.

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