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Finite Element Modelling of Strengthened Simple Beams using FRP Techniques: A parametric Study

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Abstract

The main objective of this paper is to study analytically the strengthening of a simple reinforced concrete beams due to excessive uniform loads in flexure, shear and a combination of flexure and shear, using externally bonded FRP sheets technique. A commercial finite element computer program ANSYS has been used to perform a structural linear and non-linear analysis for several models using several schemes of FRP sheets. A parametric study has been performed for a lot of strengthened beams. FE models studies a main parameter of different schemes of FRP sheets in flexure, shear and combination flexure/shear. Comparing the results with a control beam model – simple reinforced concrete beam without strengthening – it is obvious that all strengthened beams have a greater ultimate capacity than the control beam and noticeable enhancement in member ductility. The increasing level differs as a result of the strengthening scheme. The strengthened beam in both flexure and shear gives a higher ultimate load capacity, delay the failure and prevent debonding failure up to a level at which debonding occurs in both longitudinal and wrapped jackets CFRP sheets.

Keywords: R.C. Beam, Strengthening, FRP, CFRP, FE, ANSYS, and Modelling.

1. Introduction

Strengthening of structural members using fiber reinforced polymer (FRP) is one of the most powerful methods to enhance and raise the capacity of an individual members as well as the whole structure to resist the applied loads in its different levels, which are greater than the resistance capacity of the structure without strengthening. Also strengthening improves the mechanical properties of an individual member along with the whole structure up to failure like ductility, cracking behaviour and post buckling behaviour.

Strengthening using externally bonded FRP sheets had been used successfully for strengthening existing reinforced concrete structures and prestressed reinforced concrete structures.

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The benefits of strengthening with FRP became obvious when a large number of reinforced concrete bridges in USA and other countries are structurally deficient by today's standards.

The main contributing factors change in their use, like an increase in load requirements, corrosion deterioration due to exposure to an aggressive environment, or the desire to enhance the structure behaviour under certain load type like cyclic loads. In order to preserve those bridges, rehabilitation is often considered essential to maintain their capability and to increase public safety [1]. Many researchers have found that FRP composite strengthening is an efficient, reliable, and cost-effective means of rehabilitation [1].

Currently in USA, the American Concrete Institute committee 440 (ACI 440) established design recommendations and guidelines for FRP applications to reinforced concrete whether strengthening or design. FRP's are typically organized in a laminate structure, such that each lamina (or flat layer) contains an arrangement of unidirectional fibers or woven fiber fabrics embedded within a thin layer of light polymer matrix material. Fibers are typically composed of carbon, aramid or glass, provide the strength and stiffness. The matrix commonly made of polyester, epoxy or nylon, binds and protects the fibers from damage and transfers the stresses between fibers. There are two additional types of FRP composite, bidirectional fibers which are used commonly for strengthening and design the two-way slab, and the FRP robs which become competitor alternative for reinforcement steel bars.

2. Previous works

2.1. Flexure Strengthening for Simple Beam

Kachlakev et al. [1] studied analytically four models of beams using FE and compare their analytical results with the experimental results. They stated that finite element models using ANSYS computer program had shown a good agreement results with the obtained results from the experimental data. And the proposed flexural strengthening schemes increased beam capacity, enhanced beam mechanical properties like ductility and toughness, and improved cracking behaviour of the strengthened beam.

Ritchie et al. [2] tested 16 under-reinforced beams, 14 beams of them were strengthened mainly in flexure using a several types of FRP plates like aramid, carbon and glass fibers. They chose the beams' reinforcement to ensure that the beams remain under-reinforced before and after strengthening in order to prevent the brittle failure in compression. They stated that for the initial tests, the increase in beam's strength was indeed substantial and the failure mode was separation between concrete itself at the steel reinforcement bars level at the end of FRP length. They tried to change the failure mode by trying different four techniques, proving that using attached FRP sheets to the beam sides improve beam capacity and change mode of failure.

Arduini et al. [3] made two different experimental studies in order to study the behaviour and failure mechanism of flexure beam strengthened with CFRP. The variables were CFRP type’s plates or sheets and configuration of attaching CFRP. They stated that CFRP sheets give better behaviour than CFRP plates, increase beam capacity, and enhance beam ductility and cracking behaviour.

Shahrooz et al. [4] tested existing four 76 years old T-Section R.C. beams using different CFRP strengthening schemes and different CFRP types. The types of CFRP varied between CFRP post-tensioned rods, CFRP unidirectional thick plates, and CFRP woven fabric. They stated that a CFRP plate gives about 10% increase in beam capacity and brittle behaviour. CFRP fabric gives a good behaviour up to the certain maximum values of the applied loads, where the beam didn't fail and the capacity showed 12% increase than the expected capacity.

Pellegrino and Modena [5] tested five full-scale concrete beams strengthened in flexure. The main idea of their effort is to indicate and predict the actual behaviour of reinforced concrete and prestressed reinforced concrete beams strengthened in flexure using ordinary CFRP and pre-tensioned CFRP, with various types of anchorage systems as a main goal idea. They stated that using pre-tensioned CFRP shows a significant increase of first cracking load and failed due to intermediate delaminating of CFRP, and the mechanical end anchorage delays the complete failure point by distinct different.

Brena et al. [6] tested a series of reinforced concrete beams (18 beams) strengthened in flexure using different CFRP composites configurations, and different CFRP types. They stated that all tested specimens gain increase in flexure capacity. Adding transverse straps along the shear span delays or prevent debonding of CFRP. Also they stated that many design assumptions, such as a linear variation of strain with depth are not appropriate for strengthened cross section.

2.2. Shear Strengthening for Simple Beam

As well as in flexural strengthening, Kachlakev et al. [1] studied shear strengthening for the same models. They stated that FE results using ANSYS computer program shown a good agreement with the obtained experimental results; and the proposed shear strengthening schemes gives a little increase in beam capacity but gives a good enhancement in beam ductility.

Bousselham and Chaallal [7] tested and studied extensive experimental investigations on reinforced concrete T-beams retrofitted in shear using externally bonded CFRP. Twenty two tests performed on 11 full-scale T-beams. Results showed that the contribution of the CFRP to the shear resistance was not in proportion to the CFRP thickness (stiffness) provided and it depends on internal transverse steel reinforcement. They made a comparison for shear resistance values predicted by ACI 440.2R-02, CSA S806-02 and FIB TG9.3 guidelines with the test results. They concluded that the guidelines fail to capture the important aspects, such as the presence of the transverse steel and beam effective depth.

Pellegrino and Modena [8] tested and studied full-scale beams strengthened in shear using U-wrapped CFRP. Based on observed results, they developed an analytical model that allows estimating the interaction contributions to the shear capacity of the strengthened beams. They concluded that the experimental values of CFRP shear contribution and those obtained from their model are always less than the analytical proposal of ACI committee 440-02. The steel shear contribution is always greater than that calculated with ACI code.

Challal et al. [9] conducted 28 tests on 14 T-bridge girders strengthened in shear using epoxy-bonded bi-directional U-wrapped CFRP fabrics. They stated that for unwrapped specimens, the values for nominal shear predicted by ACI were underestimated by 40% to 80%. For wrapped specimens, the maximum shear force as well as the mid-span deflection generally increased with the number of CFRP layers. They found that the optimum numbers of plies to achieve the maximum gain in shear resistance are dependent on the internal shear steel reinforcement provided.

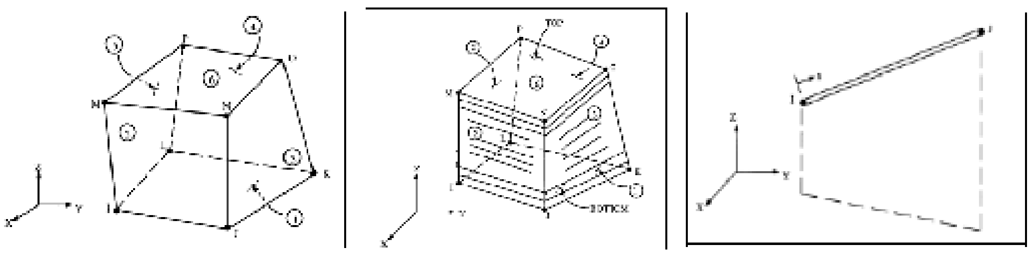
Triantafillou [10] tested and studied 11 reinforced concrete beams strengthened in shear with CFRP plies at various area fractions and fiber configurations. He stated that strengthening of reinforced concrete beams in shear using epoxy-bonded composite materials in the form of laminates or fabrics appears to be a highly effective technique. Design of FRP- strengthened members can be treated in analogy with the design of internal shear reinforcement. They also, stated that an effective FRP strain is used in the formulation, contrary to most of the existing theories. This strain is not constant, but decreases as the FRP axial rigidity decreases.

2.3. Flexural and Shear Strengthening for Simple Beam

Sheikh et al. [11] studied and tested full-size to near-full-size model specimens simulating simple beams damaged in existing building. The damaged specimens repaired using combination of unidirectional and wrap sheets of CFRP and GFRP. They stated that the test results showed that FRP is effective in strengthening for flexure as well as shear. But this combination causing over reinforcing in flexure, which was reason for shifting the failure to shear mode. Shear strengthening increasing the ultimate displacement tenfold and toughness 26 times. They explained that FRPs were effective in enhancing strength in both flexure and shear, and no premature delamination of FRP observed in the test specimens.

3. Finite Element Modelling

ANSYS computer program has been used for the finite element modelling. SOLID65 element is used to model the plain concrete material, since it has a capability of both cracking in tension and crushing in compression. SOLID65 element is defined by 8 nodes with three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element material is assumed to be initially isotropic. The most important aspect of this element is the treatment of nonlinear material properties, where concrete is capable of directional cracking and crushing besides incorporating plastic and creep behaviour. The LINK8 element used to model the reinforcing steel bar. It is a uniaxial tension-compression member that can include nonlinear material properties. The element comprises two nodes with three degree of freedom at each one. The elastic-perfectly plastic representation is assumed for the reinforcing steel bars. The SOLID46 layered structural solid element is used to model the CFRP materials. The element comprises 8 nodes with three degree of freedom at each node. The element material is assumed to be orthotropic and no slippage is assumed between the element layers (perfect interlaminate bond). Whereas, CFRP sheets are brittle materials, the stress-strain relationship is roughly linear up to failure. Consequently, in this study it is assumed that the stress-strain relationships for the CFRP laminates are linearly elastic. The elements are shown in Figure 1.



a) SOLID65 b) SOLID46 c)LINK8, 3-D spar

Figure 1: Used modelling elements

The suggested stress-strain relationship for the concrete represents both the ascending and descending portions. This relation provides two parameters, one to adjust the ascending portion and the other to control the descending portion. Because of its simplicity and experimental validation, the stress-strain relation suggested by Ghoniem [12] is utilized in the present study, as shown in Figure 2. This relation is given as:

$$Y = \frac{mX}{1 + \left[m - \frac{n}{(n-1)} \right]^2 X + \frac{X^n}{(n-1)}}$$

Where:

$Y = f / f_c'$ the ratio of concrete stress to the ultimate concrete strength
$X = \varepsilon / \varepsilon_o$ the ratio of concrete strain to the strain at Y = 1
$m = E_o / E_{sc}$ the ratio of initial tangent modulus to the secant modulus at Y= 1
n = a factor to control the slope and curvature of the descending portion.
The parameters (m) and (n) are given below and are based on test data

$m = 1 + (17.9 / f_c')$, f_c' in N/mm^2, $n = (f_c' / 6.68) – 1.85 > 1.0$

In this case the secant modulus is given as $E_{sc} = E_o / m$

Cracking and crushing are the most significant factors contributing to nonlinear behaviour of concrete. The crack modelling adopted by ANSYS program is the smeared crack representation. Where shear transfer coefficient (β_t) is represent the shear strength reduction factor for the subsequent loads, which induce sliding (shear) across the crack face. If the crack closes, then all compressive stresses normal to the crack plane are transmitted and only a shear reduction factor (β_c) for a closed crack is introduced. Typical shear transfer coefficients range from zero, representing a smooth crack, to one, representing a rough crack. In the present analysis, β_t was taken (0.1) and β_c was taken (0.8).

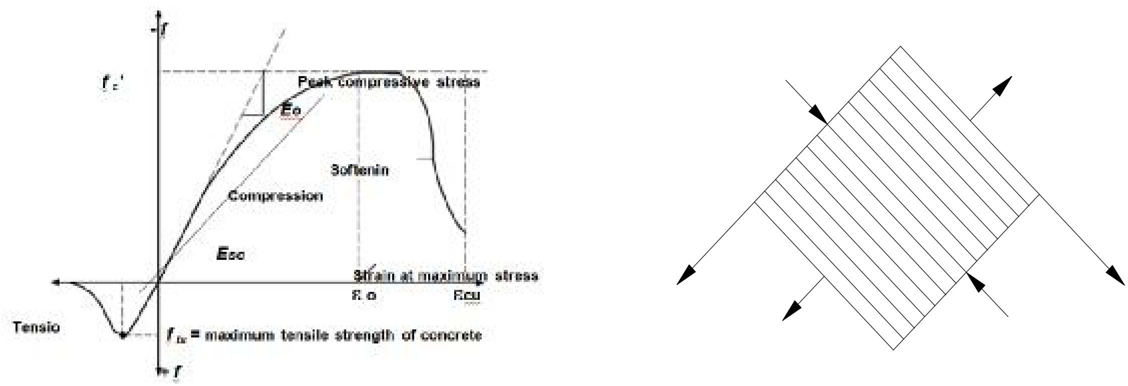


Figure 2: a) Stress-strain curve b) Smeared crack

The concrete model material predicts the failure of brittle materials. Both cracking and crushing failure modes are accounted for. The failure criterion of concrete due to a multi-axial stress state can be expressed in the form: $\frac{f}{f_{cu}} - S > 0.0$

Where

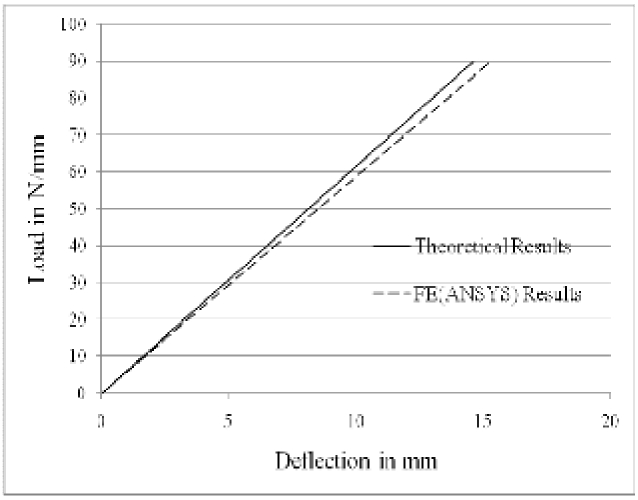
f function of the principal stress state (f_{xp}, f_{yp}, f_{zp}) in the principal directions
S failure surface expressed in terms of principal stresses.
f_{cu} uniaxial crushing strength

The material will crack if any principal stress is tensile with a crack plane normal to this principal stress, while crushing will take place only if all principal stresses are compressive.

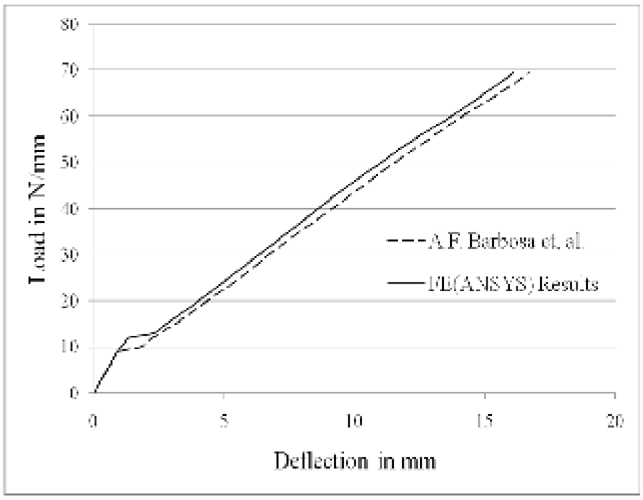
4. Computer Modelling Verification

Verification of FE results pass through a gradual path. First verification level was a simple beam without reinforcement bars compared with theoretical well known formulas and was analyzed linearly. Second verification level was done and compared in accordance with a published paper [13], who made FE models to analyze a certain reinforced concrete beam nonlinearly. Also verification levels third to fifth were done and compared in accordance with a published paper of Kachlakev et al.[1], who made FE models with nonlinear analysis. Three cases of reinforced concrete beam were presented, the first was non-strengthened beam, the second was beam strengthened in flexure, and the third was beam strengthened in shear. Moreover, they made a comparison study with published experimental results.

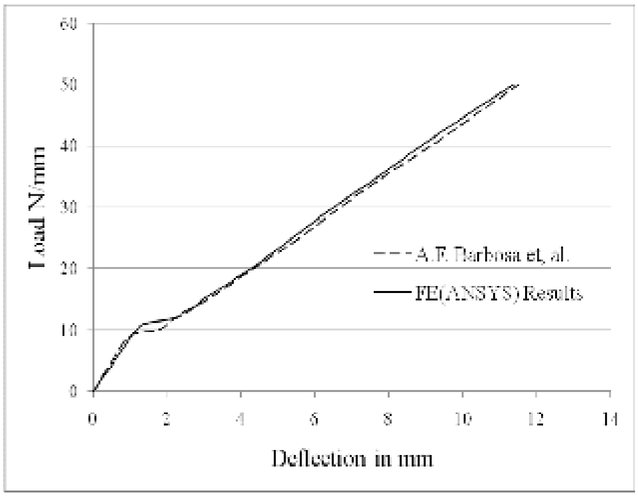
Figure 3 shows the verification results in form of comparison curves for each verification level.



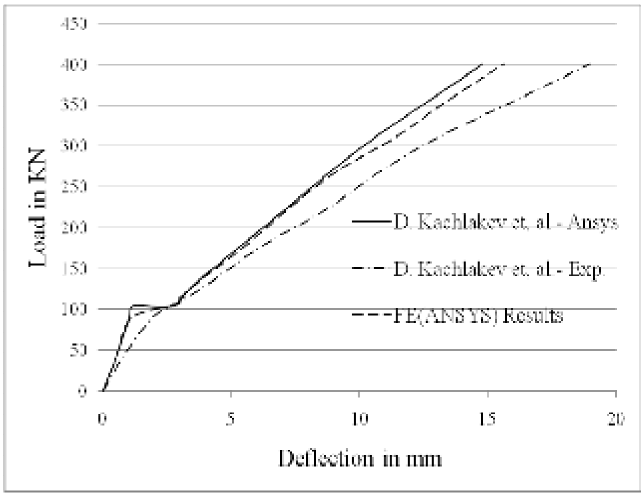
1) First verification level



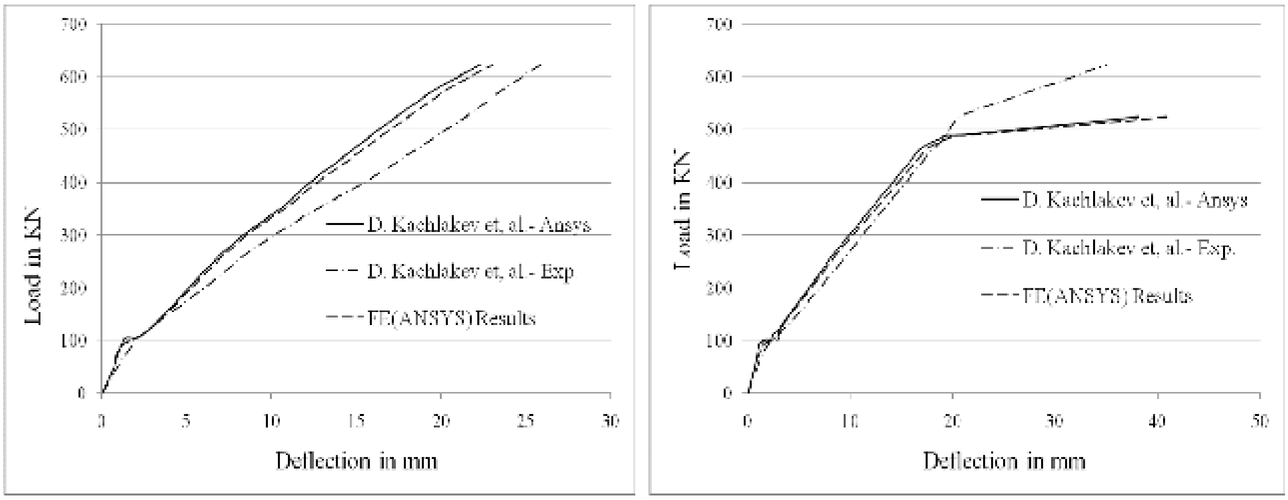
2-a) Second verification level– case I



2-b) Second verification level– case II



3) Third verification level, non-strengthened beam



4) Fourth verification level, flexure strengthened 5) Fifth verification level, shear strengthened

Figure 3: Comparison curves for different verification levels

Modelling of structural reinforcement concrete elements using FE (ANSYS) prove the ability of modelling and analyzing the reinforced concrete elements in all circumstances including strengthening cases. Since the above verification levels' results had shown a good agreement between FE modelling procedures using ANSYS and the results from published papers. Therefore, the parametric study gets corroboration and consolidation.

5. A Parametric Study

The model used in this study is a full-scale simple beam in residential building. Its cross section has dimensions of 0.50X0.2m and its cross section is a T-sec shape; as shown in Figure 4. Slab contributory portion is taken as 300mm from each beam side as in Egyptian Code 2007 and slab reinforcement is ignored in this study due to its small effect. Concrete properties are F_{cu} = 30MPa, F_t = 2.7MPa, E_c = 20000MPa, and ν = 0.2. Steel properties are F_y = 360MPa, E_s = 210000MPa, ν = 0.3, and st 36/52. CFRP properties are, F_u = 958MPa, E_x = 62000MPa, $E_y = E_z$ = 4800MPa, $G_{xy} = G_{xz}$ = 3270MPa, G_{yz} = 1860MPa, $\nu_{xy} = \nu_{xz}$ = 0.22, and ν_{yz} = 0.3. The model loaded with uniform distributed load as shown in figure (1-5).

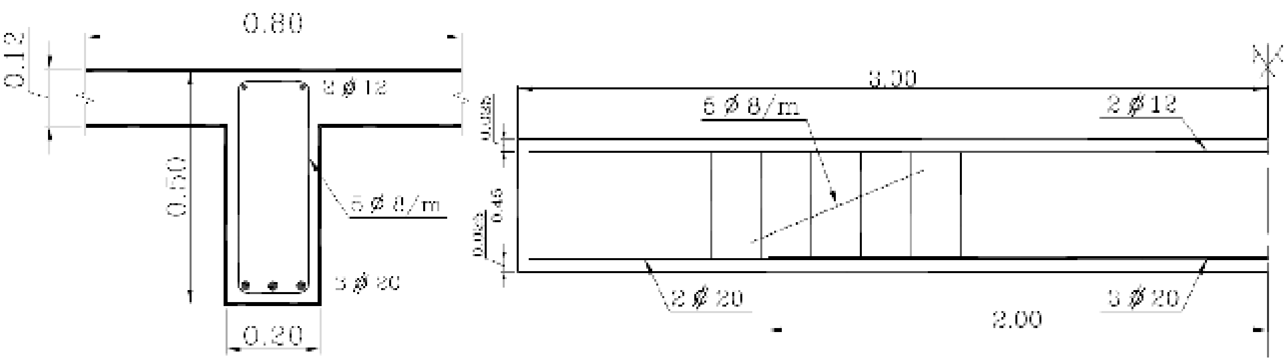


Figure 4: Studied beam cross sections details

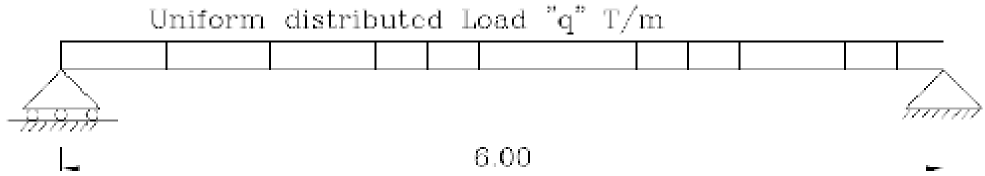


Figure 5: Loading type

Models from F.1 to F.8 represent the flexure strengthened schemes. Model F.1 is strengthened in flexure using 1 ply of CFRP attached to beam soffit along full beam span. Model F.2 is strengthened in flexure using 2 plies of CFRP attached to beam soffit along full beam span. Model F.3 is strengthened in flexure using 3 plies of CFRP attached to beam soffit, 2 of them along the full span and the third one attached along the middle two thirds (2 m right and left the beam centre with total 4m). Model F.4 is strengthened in flexure using 4 plies of CFRP attached to beam soffit, 3 of them along the full span and the fourth one attached along the middle two thirds (2 m right and left the beam centre with total 4m). Model F.5 is strengthened in flexure using 5 plies of CFRP attached to beam soffit, 3 of them along the full span, the fourth one is attached along the middle two-thirds (2 m right and left the beam centre with total 4m), and the fifth one attached along middle zone (1.2 right and left the beam centre with total 2.4m). Model F.6 is strengthened in flexure using 2 plies of CFRP attached to beam soffit along full beam span with leg 25 mm attached to beam sides. Model F.7 is strengthened in flexure using 2 plies of CFRP attached to beam soffit along full beam span with leg 50 mm attached to beam sides. Model F.8 is strengthened in flexure using 2 plies of CFRP attached to beam soffit along full beam span with leg 75 mm attached to beam sides.

Models from S.1 to S.6 represent the shear strengthened schemes. Model S.1 is strengthened in shear using 2 plies of CFRP attached perpendicular to the beam along the first and the last quarters (1.5 m from each end) without continuity under beam soffit. Model S.2 is strengthened in shear using 2 plies of CFRP attached perpendicular to the beam along the first and the last quarters (1.5 m from each end) with continuity under beam soffit. Model S.3 is strengthened in shear using 2 plies of CFRP attached perpendicular to the beam along the first and the last thirds (2.0 m from each end) with continuity under beam soffit. Model S.4 is strengthened in shear using 2 plies of CFRP attached perpendicular to the beam along the first and the last thirds (2.0 m from each end) with continuity under beam soffit and with anchorage leg 100 mm attached to the slab soffit. Model S.5 is strengthened in shear using 4 plies of CFRP attached perpendicular to the beam along the first and the last thirds (2.0 m from each end) with continuity under beam soffit.

Model F/S is strengthened in both flexure and shear. Using 4 plies of CFRP attached to beam soffit, 3 of them along the full span and the fourth one attached along the middle two thirds (2 m right and left the beam centre with total 4m) as flexure strengthening set. Two plies of CFRP attached perpendicular to the beam along the first and the last thirds (2.0 m from each end) with continuity under beam soffit as shear strengthening set.

Figure 6 shows grouped load-deflection curves for flexural strengthened beams F.1 to F.5. It's obvious that by increasing the number of CFRP plies a significant increase in beam capacity become noticeable and beam ductility increases dramatically. In model F.1, beam capacity increased by 8.3% compared to the control beam and the ductility increased but not significantly. In model F.2, beam capacity increased by 15% compared to the control beam and the ductility increased noticeably. In model F.3, beam capacity increased by 24.5% compared to the control beam and the ductility increased noticeably. In model F.4, beam capacity increased by 39% compared to the control beam and the ductility increased dramatically. In model F.5, beam capacity increased by 53.3% compared to the control beam and the ductility increased dramatically. It's noticed that for all beams strengthened in flexure with different CFRP plies configurations, the effect of CFRP started when beam reinforcement start yielding and cracked load didn't affected anyway. Figure 8 shows crack patterns at ultimate stage for flexural strengthened beams F.1 to F.5. It's obvious that increasing number of CFRP plies make the beam exhibit a wide propagation of cracking whether flexure cracks or shear cracks. It's noticed that for beam models F.4 and F.5 which strengthening in flexure using 4 plies and 5 plies respectively, the strengthened beam exhibits higher levels in strength capacity and dramatically increase in beam ductility and sustainability. But in the other hand, these models vulnerable to sudden failure if a certain debonding level between CFRP plies and concrete surface take place. Which, it can be occur due to shown excessive cracks as showed in Figure 8. This is undesired in concrete structures. Consequently, it's highly recommended during design the flexure strengthening for concrete elements to determine existing conditions for the strengthened member and evaluate, estimate proper limit level for strengthening in order to prevent undesired failure mechanisms.

Figure 7 shows grouped load-deflection curves for flexural strengthened beams F.2, F.6, F.7 and F.8. It's obvious that by extend CFRP to be attached to beam sides, a little increase in beam capacity gained and also increase in beam ductility. It's clear that increasing height of the attached leg to beam sides causing strain decreased for same stress level. That indicates a delay in cracking propagation, as showed in Figure 8. Which mean delaying in failure and shifting failure mode, as agreed with many other researchers Kachlakev et al.[1], Ritchie et al.[2], Arduini et al.[3]. This feature is important to control cracking propagation in flexural strengthened beams with higher number of CFRP plies. And it will be useful to enhance concrete member behaviour in resisting cyclic and seismic loads.

Figures 10 show grouped load-deflection curves for shear strengthened beams S.1 to S.5. Grouped two by two to compare and show the effect of change CFRP plies configuration in beam capacity and ductility. It's obvious that in shear strengthening CFRP didn't affect the beam capacity significantly. Beams S.3, S.4 and S.5 show increase in beam capacity by little values varied between 8 to 15%, and enhanced beam ductility significantly. Figure 10-b shows that continuity of CFRP plies under beam soffit didn't affect beam capacity but enhance beam ductility slightly. Figure 10-c shows that extend CFRP plies to be attached to first and last beam thirds affect beam capacity little and enhance the beam ductility noticeably. Figure 10-d shows that extend CFRP plies to be attached to slab soffit didn't affect beam capacity but enhance the beam ductility slightly. Figure 10-e shows that increase CFRP plies didn't affect beam capacity but enhance the beam ductility. It's obvious that shear strengthening using CFRP plies by various plies number and varied configurations didn't affect beam capacity significantly but enhanced beam ductility noticeably. It's clear that CFRP strengthening didn't act as a major parameter in shear strengthening for this certain structural beam element. While, shear reinforcement steel and beam geometry act this rule. The effect of the attached CFRP acts with these effective parameters only to enhance the structural element ductility. This conclusion is agreed with the other researchers [7-10]. Figure 9 shows the crack pattern at ultimate stage for shear strengthened beams.

Figure 11 shows grouped load-deflection curves for control beam, flexural strengthened beam F.4, and flexure/shear strengthened beam. It's obvious that strengthening the beam using combination of CFRP plies, longitudinal plies for flexure and warped CFRP jacket for shear, increase beam capacity noticeably and enhance beam ductility. The increase in beam capacity reaches 63% from control beam and 17% from strengthened beam F.4. But this strengthened beam exhibit a high level of cracking propagations, as shown in Figure 12, which can lead to suddenly failure. This is not desirable in concrete structures.

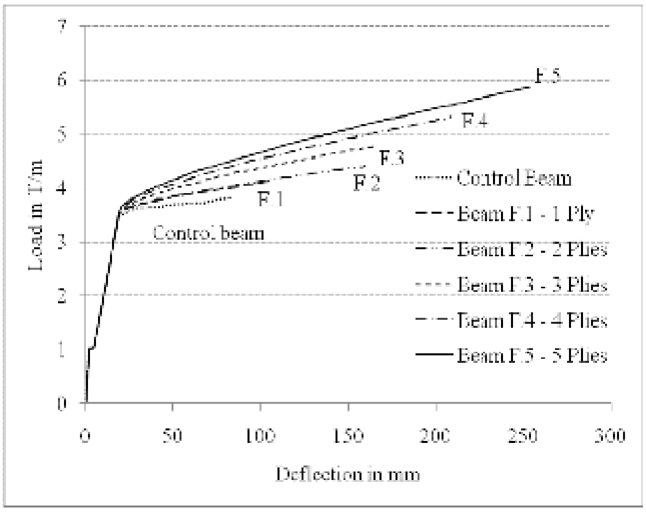


Figure 6: Load-deflection curves F.1: F.5

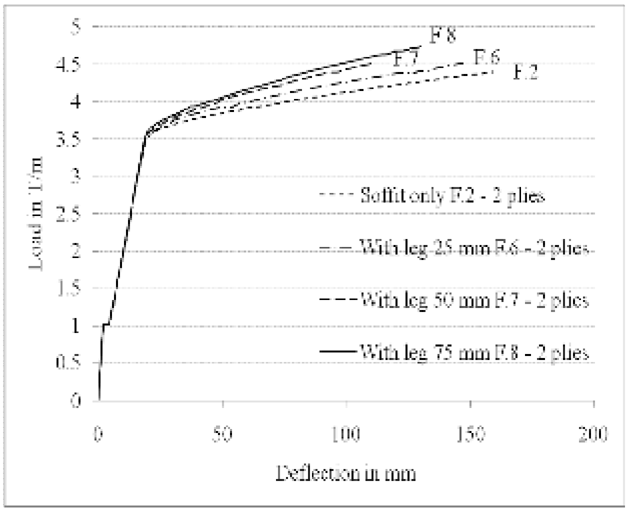
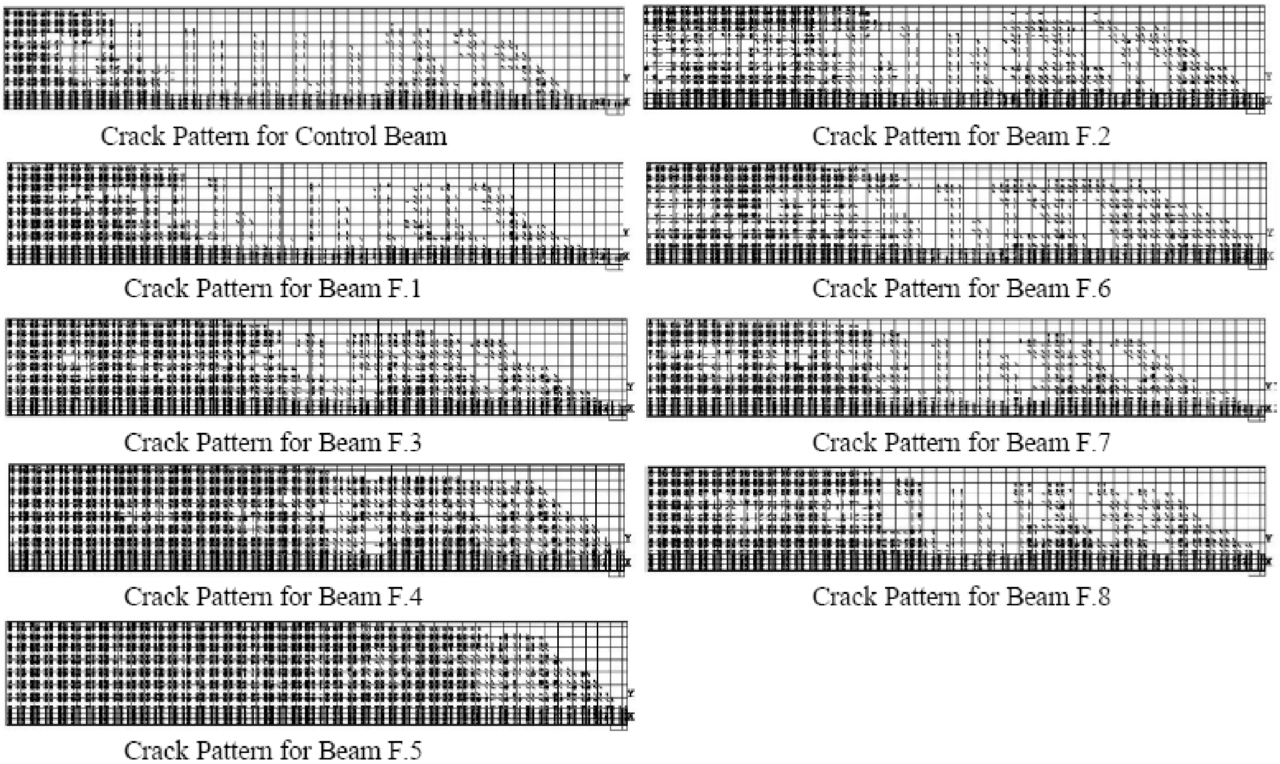


Figure 7: Load-deflection curves F.2, F.6:F.8



Crack Pattern for Control Beam

Crack Pattern for Beam F.2

Crack Pattern for Beam F.1

Crack Pattern for Beam F.6

Crack Pattern for Beam F.3

Crack Pattern for Beam F.7

Crack Pattern for Beam F.4

Crack Pattern for Beam F.8

Crack Pattern for Beam F.5

Figure 8: Crack patterns for beam models, F.1:F.8

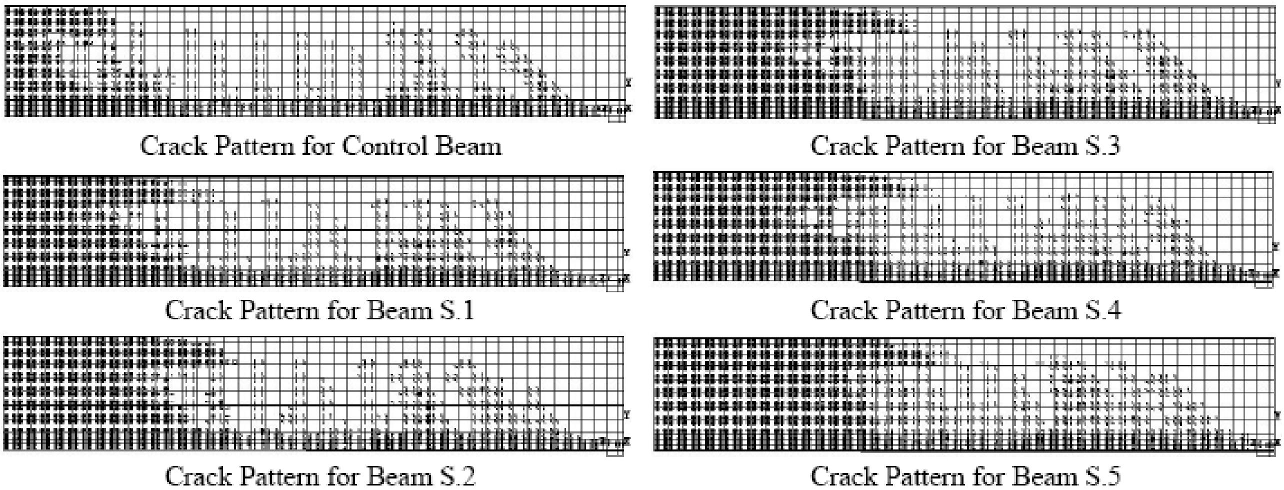


Figure 9: Crack patterns for beam models, S.1:S.5

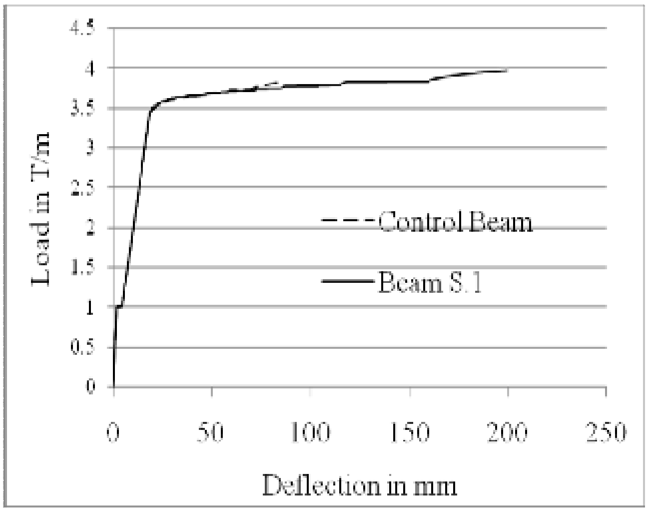


Figure 10-a
Comparison Control beam with Beam S.1

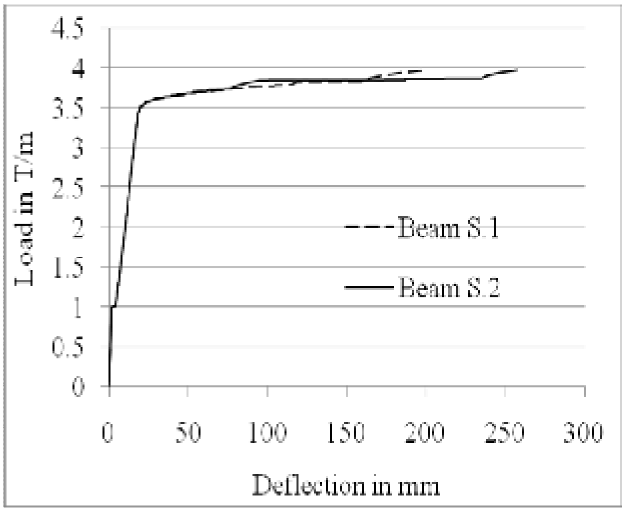


Figure 10-b
Comparison beam S.1 with Beam S.2

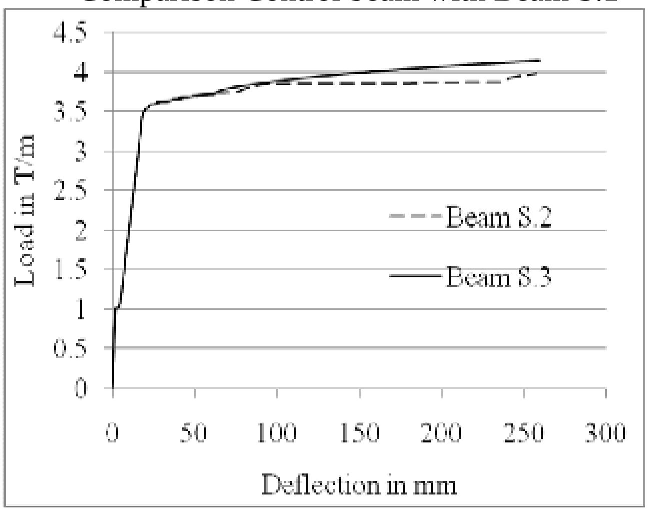


Figure 10-c
Comparison beam S.2 with Beam S.3

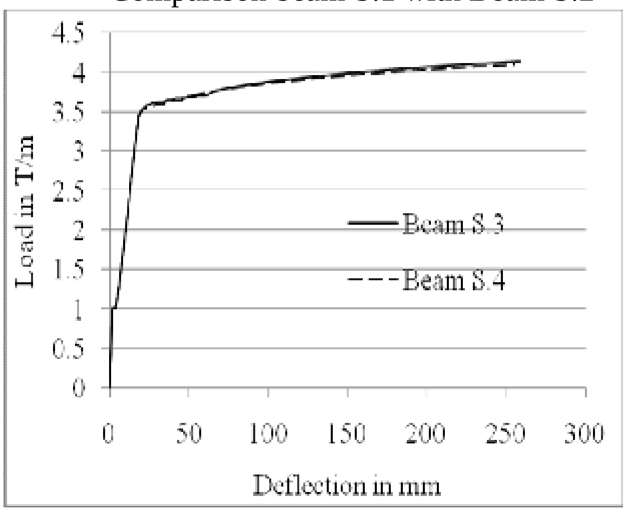


Figure 10-d
Comparison beam S.3 with Beam S.4

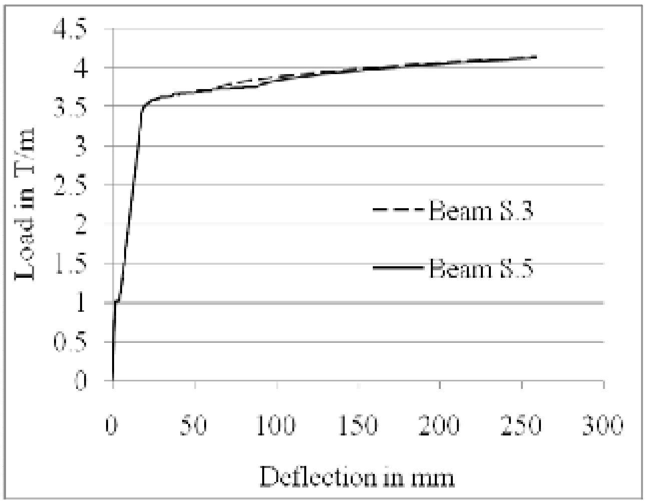


Figure 10-e
Comparison beam S.3 with Beam S.5

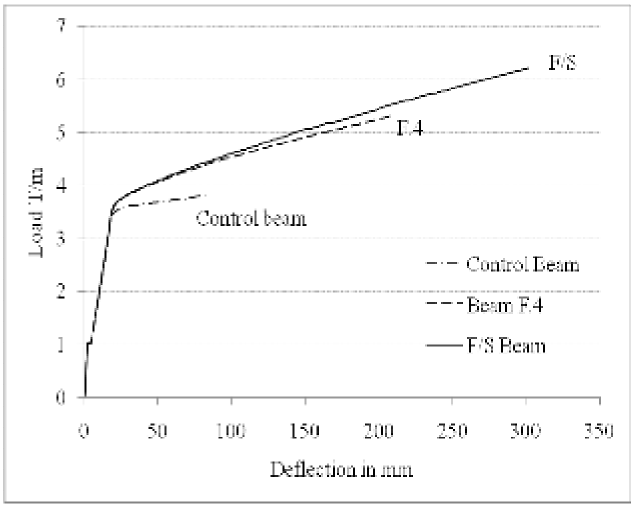


Figure 11: Load-deflection curves F.4, F/S

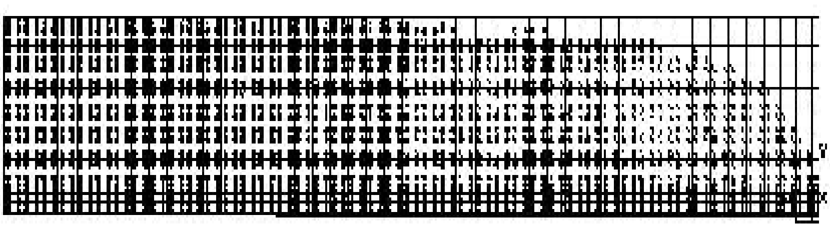


Figure 12 Crack patterns for beam model F/S

6. Conclusion

Increasing number of CFRP plies in flexure strengthening increase the beam capacity and beam ductility significantly. While, same increase of CFRP plies in shear strengthening didn't affect beam capacity, but enhancing the beam ductility. For flexure strengthening, attaching CFRP leg to beam sides enhances beam cracking behaviour and changes failure mode. In shear strengthening CFRP act to enhance the ductility of the structural members. General conclusions conducted from the parametric study sorted below:

1) For flexure strengthening, one ply and two plies schemes didn't give a significant development compared to three, four and fife plies scheme, that gives a high noticeable increase in beam capacity and dramatically increase in beam ductility.
2) In flexure strengthening, it's recommended to extend the CFRP plies by attaching legs to beam sides, in order to delay and control the cracks and failure mode.
3) Shear strengthening of this certain beam didn't affect beam capacity significantly, even increasing number of CFRP plies. But it enhances beam ductility significantly.

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