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Cement and Concrete Composites

Elixir Cement & Con. Comp. 62 (2013) 17696-17700

ISSN: 2229-712X

Behavior of reinforced concrete deep beams strengthened with CFRP sheets

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ARTICLE INFO

Article history:
Received: 15 July 2013;
Received in revised form:
20 August 2013;
Accepted: 4 September 2013;

Keywords
Carbon fiber Reinforced concrete,
Deep beam,
Light weight aggregate,
High strength.

ABSTRACT

The principal objective of this paper is to investigate the behavior and load carrying capacity of reinforced concrete (indirectly loaded flanged deep beams) strengthened with carbon fiber reinforced polymer (CFRP) strips in shear. Using three types of concrete (normal strength concrete, high strength concrete, light weight concrete) group three consists of five indirectly loaded flanged deep beams (with light weight concrete) to investigate the effect of different strengthening case on the behavior and load carrying capacity of the deep beam like, three sides strengthening with CFRP (V shape), and strengthening the two opposite sides of deep beam, one side strengthening of deep beam, (L shape) strengthening.

Introduction

The structure may have to carry larger loads at a later date, or fulfill new standards. In extreme cases a structure will have to be repaired due to an accident. A further reason can be found that errors have been made during the design or construction phase resulting in need for strengthening the structure before usage. If any of these situations will arise; it needs to be determined whether it is more economic to strengthen the existing structure or to replace it. In comparison to building a new structure, strengthening an existing one is often more economic [i].

Externally strengthening with advanced composite materials, namely, carbon fiber reinforced polymers (CFRP), represents the state-of-the-art in upgrading or rehabilitation techniques. Depending on the member type, the objective of strengthening may be one or a combination of several of the following [ii,3]:

Increasing axial, flexural or shear load capacities; increasing stiffness for reduced deflections under service and design; increase the remaining fatigue life and to increase durability against environmental effects.

In spite of their promise, concern must be taken to existing materials. In some cases it can be difficult to reach the areas that need to be strengthened. Further, the existing documentation of the structure is often very poor and sometimes even wrong. Furthermore, when strengthening is going to be undertaken, all failure modes must be evaluated. For example, a flexure strengthening can lead to a shear failure instead of giving the desired carrying capacity. Also, it should be noted that not only the failure mode of the strengthened member is important. If a critical member in a structure is strengthened, another member can become the critical one and the whole structure must therefore be investigated **[2,3]**.

FRP should not be used in the condition of the largely deteriorated substructure; in case of substantial corrosion of the mild-steel reinforcement and in case of no-mild-steel reinforcement to provide ductile behavior **[4]**.

When the shear span/depth ratio of simply supported beams is less than 2, or less than 2.5 for any span of a continuous beam, it is customary to define these beams as deep [5]. The ACI building code 318R-02 [5] define deep beams as members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports, and have either with clear span equal to or less than four times the overall members' depth, or regions of beams loaded with concentrated loads within twice the member depth.

Reinforced concrete deep beams are widely used in many structural engineering applications, such as transfer girders, pile caps, offshore structures (caisson), shear walls, wall footings, floor diaphragms, and complex foundation system as shown in Fig. (1) [6,7].

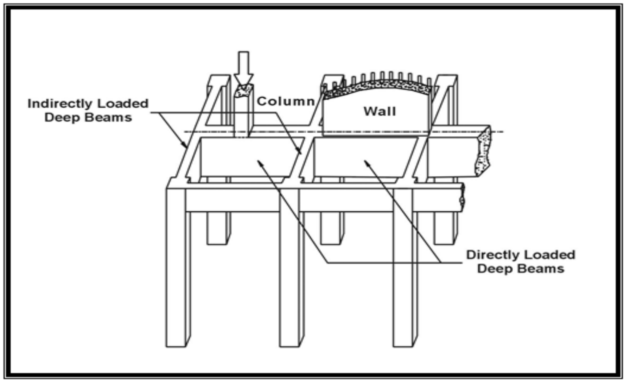

Fig. 1. Directly or indirectly loaded deep beam [5]

Details of Tested Beams:

Seven simply supported of indirectly loaded flanged deep beams (with normal strength concrete), (TNS) where (T: flanged deep beam, S: strengthened) first beam (T1) was not strengthened with CFRP to serve as a reference beam (control beam), The remaining (6) deep beams (TS2, TS3, TS4, TS5, TS6, TS7) study how the length and orientation of CFRP affect the shear behavior of strengthening indirectly loaded flanged deep beams. Three different lengths of CFRP were used and the orientation of CFRP was also varied keeping the amount of CFRP as in 90°by using 30mm width of CFRP. Table (1) shows

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the description of the tested beams, and Fig. 2 (**a-g**) shows the control & strengthening scheme of the (TS) group tested beams.

Table 1. Shows group flanged deep beams tested

Beam No.	Details of strengthening
T1	Reference beam (control beam) without strengthening
TS2	Strengthened with 90° CFRP strips (the depth of CFRP 300mm in the web)
TS3	Strengthened with 90° CFRP strips (the depth of CFRP 250mm in the web)
TS4	Strengthened with 90° CFRP strips (the depth of CFRP 200mm in the web)
TS5	Strengthened with 45° CFRP strips (the depth of CFRP 300 in the web)
TS6	Strengthened with 45° CFRP strips (the depth of CFRP 250 in the web)
TS7	Strengthened with 45° CFRP strips (the depth of CFRP 200mm in the web)

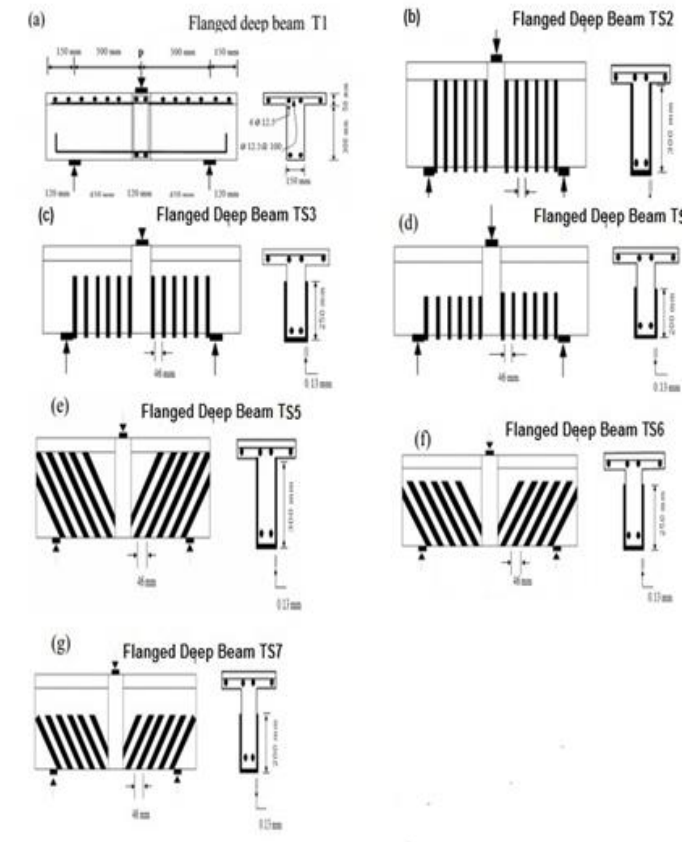

Fig (2) group of Flanged deep beam strengthed with 90^{0}& 45^{0} CFRP strips with deffernt length

Test Set-up and Instruments:

Torsee's Universal Testing machine with a capacity of 2000 KN was used to apply the load. The beam was loaded from the top of the mid-span. The load was applied in increments, with approximately fifteen load steps to failure. At each load increment, the total applied load on the beam, mid-span deflection, and crack width were measured. The cracks were plotted and marked. A test was terminated when the total load on the specimen started to drop off. The total time to failure in a test was approximately two hours. Fig. 3, and Fig. 4 Shows the test setup.

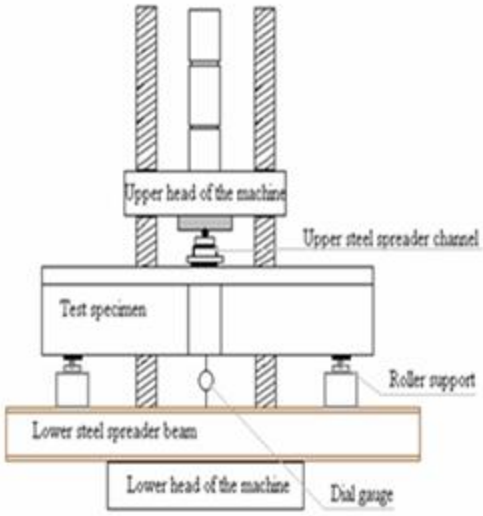

Fig. 3: Test setup

Fig. 4: Test arrangement

Experimental Results

Behavior of beams under loading and crack pattern:

The ultimate load and percentage increase in ultimate load with respect to reference beam are shown in Table (2). The deep beam designated as T1 was taken as a control deep beam. The beam was tested without any strengthening by CFRP strips. In the specimen T1 cracks were observed close to the middle of the span. When the applied load reached approximately (95kN), shear crack suddenly appeared throughout the shear span (from the support towards the loading point). With increasing load, shear crack was widening and propagating until failure occurred because the left diagonal crack became very wide (the main shear crack) and reached the loading point at a total applied load of 240kN. The strengthened beams (TS2, TS3 and TS4) which were strengthened by vertical CFRP strips with length (300,250 and 200mm) respectively had the same behavior of the control beams except that the inclined crack was delayed more than the control beam. The inclined crack appeared when the load reached approximately (112 kN), then the crack width increased till the CFRP failed (by debonding failure with CFRP strips separated from concrete). The beams failed (in shear failure) in beams (TS5, TS6 and TS7) which were strengthened by inclined CFRP strips with length (300,250 and 200mm) respectively. Beams strengthened by inclined CFRP strips showed the same behavior except that the load failure was higher. Change in length of CFRP strips may result in different behaviors of strengthening beams with respect to vertical and inclined CFRP strips. The longest CFRP presents a high stiffness and high load while when the CFRP strips do not cover the full depth of the beam, the length required to the bound the CFRP strips on the concrete decreases and the crack crosses not within the all CFRP strip or pass through the end of the CFRP strip length. The shear crack patterns of these deep beams after failure are shown in Figs from (4.1 to 4.7)

Table 2: Ultimate Loads of the Beam Specimens

Beam designation	Ultimate applied load (kN)	Percentage increase in ultimate load with respect to reference beam
T1	240	-----
TS2	338.4	41%
TS3	328.8	34%
TS4	312	30%
TS5	364.8	52%
TS6	340.8	42%
TS7	326.4	36%

Fig(4-1) shear crack pattern after testing deep beam TS2

Fig (4-2) shear crack pattern after testing deep beam TS2

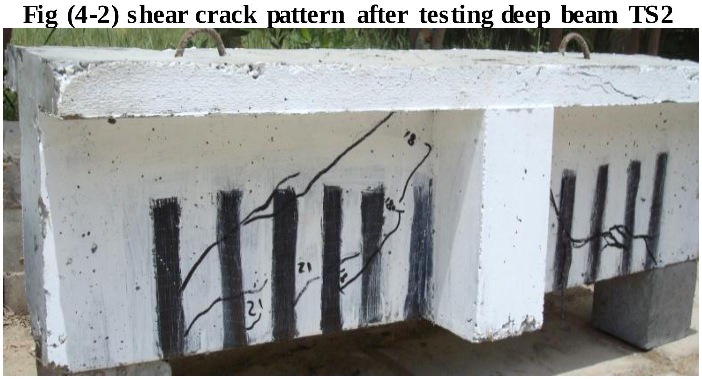

Fig (4-3) shear crack pattern after testing deep beam TS3

Fig (4-4) shear crack pattern after testing deep beam TS4

Fig. (4-5) shear crack pattern after testing deep beam TS5

Fig (4-6) shear crack pattern after testing deep beam TS6

Fig. (4-7) shear crack pattern after testing deep beam TS7

Load versus Mid-Span Deflection Results:

Seven reinforced concrete deep beams under two point loads were strengthened by CFRP strips to examine the effect of strengthening patterns on their behavior and ultimate load capacity. Experimental investigation on the behavior of load versus mid-span deflection curves for these deep beams is presented in the Fig (5) .

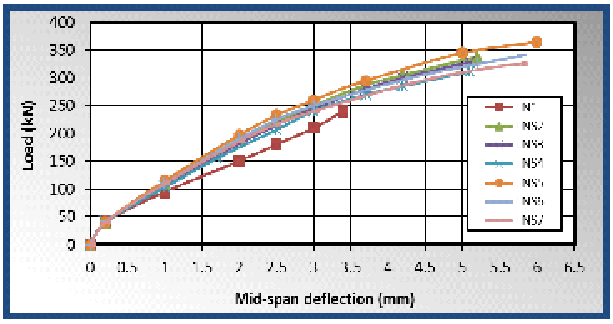

Fig.5 Experimental load versus mid –span deflection curve for one group

Concrete Cracking:

For each load increment, crack width of the major inclined crack at mid-depth of the beam was measured by means of crack detection pocket microscope. Figure (6) show load versus crack width for all tested beams. The main observations noted from crack width measurements are listed below: At low load level flexural cracks firstly initiated from the mid span bottom and grew upward. The shear cracks initiated at the middle of shear span. They are inclined and start from the middle of the height. They propagate toward support and load, with load increasing flexural cracks stopping, but shear crack continuing until failure occurs. By inspecting the curves of the load-crack, it can be observed that, the presence of CFRP tends to reduce number of cracks even at the same loads compared with reference beam.

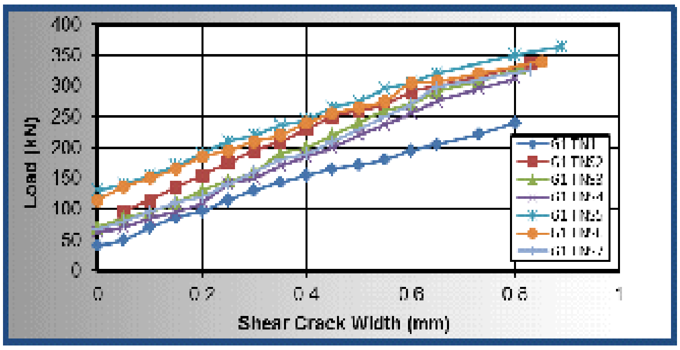

Fig.6: Load versus crack width of flanged deep beams group one.

Strains in CFRP Strips:

Although demec points were placed at different positions along CFRP strips, the strain values indicated in the figures of this section are those obtained at regions with maximum strain values. From testing, it can be observed that the maximum strain values along each strip occur at regions intersecting the diagonal shear crack.

Figs (7) show the development of maximum strains which was recorded in strip at every loading step for all deep beams. From the curves shown in Fig (7) it can be observed that the strain in the CFRP strips was very small before the initiation of the diagonal shear cracks and began to increase very quickly after the formation of the shear crack.

Referring to the strains measured in CFRP strips, which are shown in curves of Figures (7), it can be noticed that, the load strain curve tends to be straight line at low load level, but when load increases the rate of strain increment would be higher. The maximum strains occurred at the 2nd or 3rd strip for all tested beams. This is because initial shear crack originated at the shear span, where 2nd and 3rd strip is located.

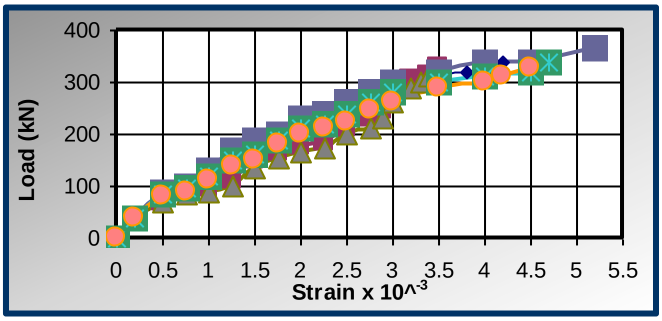

Figure (7): Development of tensile strain in CFRP strips of deep beam

Numerical Applications:

A nonlinear finite element analysis has been carried out to analyze the concrete deep beams, which are reinforced by CFRP strips tested in this study. The analysis is performed by using ANSYS computer program (Version 13) which is running under system manager program (Windows seven) with applying the geometrical and material modeling.

In this section, verification is done in order to check the validity and accuracy of the finite element procedure. The ability of the constitutive finite element analysis method to simulate the behavior of this type of members is demonstrated through the analysis of the tested beams. The results obtained by using finite element method are compared with the experimental results through the load-deflection curves, ultimate loads and crack patterns to check the validity and accuracy of this numerical method.

Loads at Failure:

Table (2) compares the ultimate loads for the full-size beams and the final loads from the finite element simulations. In general, the predicted ultimate load obtained by ANSYS-13 gives agreement with experimental result. In most of the beams, the finite element ultimate load overestimated the experimental results by (3% - 12%).

There are several factors that may cause the higher stiffness in the finite element models. Microcracks produced by drying shrinkage and handling are presented in the concrete to some degrees. These would reduce the stiffness of the actual beams, while the finite element models do not include microcracks. Perfect bond between the concrete and steel reinforcing are assumed in the finite element analyses, but the assumption would not be true for the actual beams. As bond slip occurs, the composite action between the concrete and steel reinforcing is lost.

Table 2. Comparison between experimental and numerical ultimate load of the analyzed deep beams

Beam Designation	Numerical Failure Loads(KN)	Experimental Failure Loads(KN)	P(Num.)/ P(Exp.)
TN1	256.8	240	1.07
TNS2	365.4	338.4	1.08
TNS3	364.9	328.8	1.11
TNS4	324.4	312	1.04
TNS5	375.7	364.8	1.03
TNS6	380.8	340.8	1.12
TNS7	349.2	326.4	1.07

Crack Patterns:

In ANSYS computer program, the cracking or crushing types of fracture in concrete elements appear as circles at locations of these cracking or crushing, the shape of each crack and crush in concrete element is summarized as follows

Cracking is shown with a circle outline in the plane of the crack,

Crushing is shown with an octahedron outline.

If the crack has opened and then closed, the circle outline will have an X designation through it.

A cracking sign appears when a principal tensile stress exceeds the ultimate tensile strength of the concrete and appears perpendicular to the direction of the principal stress. The cracking sign appears perpendicular to the direction of the principal stress as illustrated.

The cracking signs in Figure (8.1) and (8.2) are explained below:

Sign of the flexural crack.

Sign of the compressive crack.

Sign of the diagonal tensile crack.

Sign of two cracks (the first crack is diagonal tensile crack and the second crack is compressive crack, it's shown with a green circle outline).

Sign of three cracks (the first and second cracks are diagonal tensile cracks and the third crack is compressive crack, it's shown with a blue circle outline).

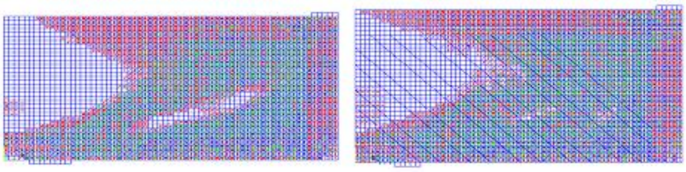

Fig. (8.1) Numerical crack patterns of T1
(8.2) Numerical crack patterns of TS5

Conclusions:

Based on the overall results obtained from the experimental work and the finite element analysis for the externally strengthened or repaired reinforced concrete deep beams by CFRP strips failing in shear, the following conclusions can be drawn as follows:

In general higher ultimate loads were achieved for deep beams strengthened with CFRP strips as compared with unstrengthened control deep beam and it is not necessary to cover the entire depth of the beam with CFRP strip when strengthening for shear if the shear crack crossed the strips not close to strips end and within the length of CFRP strips.

A decrease in the width of cracks due to presence of CFRP strips is occurred and the average of this decrease is about 65 % of the crack width of the control deep beams at ultimate load levels.

A stiffer load-deflection response is observed for reinforced concrete deep beams strengthened with CFRP strips as compared with response of control deep beam.

The finite element model (ANSYS -11 [96]) used in the present work is able to simulate the behavior of externally strengthened reinforced concrete deep beam strengthened with CFRP strips in shear. The numerical ultimate loads are in overestimated with those obtained from experimental work and it was found the ratio of numerical ultimate load to experimental ultimate load ranged between 1.03 and 1.12.

The crack patterns obtained from the finite element models are similar to the crack patterns observed in the experimental work, where all the analyzed deep beams fail in diagonal shear cracks with a mode of failure similar to that occurred in the experimental test.

Acknowledgments:

This study was performed in the structures Laboratory at the University of Basrah, Iraq. An expression of gratitude is presented to the staff of Structural materials laboratory and the library for their assistance in preparing the study.

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