EXPERIMENTAL AND NUMERICAL INVESTIGATION OF I-SECTION LIGHTWEIGHT CONCRETE DEEP BEAMS STRENGTHENED WITH CFRP FAILING IN SHEAR

DOI:10.52113/3/eng/mjet/2014-03-01/46-59

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Abstract

The experimental program consisted of testing four I-section reinforced concrete deep beams strengthened with CFRP strips made from lightweight concrete (porcilinate). The experimental program variables include configurations of CFRP. Experimental results obtained from the adopted strengthening CFRP techniques show a significant improvement in the behavior and shear carrying capacity of reinforced concrete deep beams. A stiffer load-deflection response is observed for beams strengthened with CFRP strips as compared with response of control deep beam and the inclined CFRP strips give better enhancement than the vertical CFRP strips in ultimate load, deflection and crack width. Nonlinear finite element analysis is performed using the ANSYS-11. The Comparison between experimental results and numerical results indicates that numerical models can successfully used to simulate similar cases. Where the ultimate numerical load to ultimate experimental load ranged between (88%-96%). And good agreement for (load–deflection) curves between numerical and experimental.

Keywords: ANSYS, CFRP, I-section, Lightweight, Strengthened.

تصرف العتبات الخرسانية العميقة المصنوعة من الخرسانة خفيفة الوزن ذات المقطع (I) والمقواة بألياف الكاربون الفاشلة بالقص

الخلاصة

تضمن الجزء العملي أعداد و فحص (4) نماذج من العتبات الخرسانية ذات المقطع (I) المصنوعة من الخرسانة خفيفة الوزن. تتضمن متغيرات البرنامج العملي ترتيب شرائح ألياف الكاربون بأشكال مختلفة. أظهرت النتائج المختبرية إن استخدام أسلوب التقوية بشرائح ألياف الكاربون يحسن من تصرف وقابلية التحمل للعتبات الخرسانية المسلحة العميقة. وكذلك بينت النتائج المختبرية إن الهطول للعتبات المقواة بألياف الكاربون اقل من العتبات الغير مقواة. واستخدام شرائح ألياف الكاربون بشكل مائل أعطت نتائج (حمل أقصى, هطول, عرض التشقق) أفضل من التقوية بشكل عمودي. استخدمت طريقة العناصر المحددة ثلاثية الأبعاد لاختبار التصرف الإنشائي للعتبات. و قد تم تحليل العتبات بأستحدام أنموذج لاخطي بالاعتماد على الإصدار الحادي عشر من برنامج التحليل الإنشائي (ANSYS- Version 11). أظهرت النتائج المستحصلة من طريقة العناصر المحددة توافقا جيدا مع النتائج العملية حيث تراوحت نسبة الحمل الأقصى التحليلي إلى الحمل الأقصى من التجارب العملية بين (96 - 88%) لجميع العتبات. كذلك تم الحصول على توافق جيد بين منحنيات (القوة – الهطول) للجزء التحليلي و الجزء العملي.

*Received at 12 /3 / 2014 *Accepted at 7 /5 /2014

Introduction

Structural lightweight aggregate concrete is usually defined as a concrete with an oven-dry density of no greater than 2000 kg/m^3 [1]. There are variations in certain parts of the world. For example in Australia structural lightweight concrete is considered to be a concrete made with lightweight coarse and normal weight fines resulting in a saturated surface-dry density of not less than 1800 kg/m^3. In Norway a combination of any types of aggregate can be used for structural concrete provided the resulting concrete: (a) has an oven-dry density of 1200-2200 kg/m^3 and (b) a strength grade of no greater than f'c=85 MPa, if the mix contains lightweight aggregate. In USA, structural light-weight aggregate concrete is considered to be concrete with an air-dry density of less than 1810 kg/m^3 (Newman and Choo, 2003) [2]. Due to the application of Lightweight Aggregate Concrete (LWAC) it is possible to save weight transferred to the substructures and foundations of a bridge or a building and so the construction costs and time could be reduced. In America and in Europe it has been used for a number of structures [3] showing an overall savings in total cost between 10 and 20 % of the equivalent normal–weight structure .The safety and serviceability of LWAC structures cannot be realized without a comprehensive knowledge of this material fundamental properties. Extensive experimentation at several research centers has provided a fundamental understanding of its behavior. Pioneer work has been done at the University of Texas at Austin, the Portland Cement Association in the United States and at the laboratories of the Cement and Concrete Association in England [4], and some researchers work in lightweight concrete such as; Mu'taz, work on naturally available porcelinite concrete has been carried out in several Iraqi universities. In this work an attempt is made to study the structural behavior of porcelinite reinforced concrete beams failing in shear [5]. Yang**,** tested sixteen deep beam specimens, some made of Sand-Lightweight Concrete (SLWC) and others made of All-Lightweight Concrete (ALWC), and compared them with Normal-weight Concrete (NWC) deep beams [6]. Sheelan**,** investigate the effect of adding metakaolin and silica fume, each alone as percentage of cement weight, on properties of lightweight porcelinate aggregate concrete. The experimental results also have been compared with results obtained from normal weight concrete specimens [7]. In this research, the locally available natural porcelinite aggregate is used to produce structural LWAC to be used in the construction. The fundamental behavior in shear of reinforced concrete beams made with aggregate is investigated. Some of the reinforced concrete deep beams may need upgrading or rehabilitation programs so that they can cope with the extra loads. Externally strengthening with advanced composite materials, namely, Carbon Fiber Reinforced Polymers (CFRP), represents the state-of-the-art in upgrading or rehabilitation techniques. CFRP laminates are becoming widely used in upgrading and rehabilitation of reinforced concrete members. CFRP offers the design engineer excellent properties not available in traditional materials. This strengthening composite is light in weight and corrosion resistant and possesses higher strength and stiffness compared to steel. The ease of handling and application gives CFRP an advantage over traditional materials for certain applications.

Experimental Work

The main purpose of the test program is to generate data and provide information about the effect of CFRP that are attached by special epoxy material to increase their shear capacity and structural behavior of I-section reinforced concrete deep beam (lightweight concrete) under monotonic load. Standard tests according to the American Society for Testing and Materials (ASTM) [8,9,10] and Iraqi specifications [11,12] are carried out to determine the properties of materials. All of these tests have been conducted in the Structure Laboratories for the College of Engineering in Basrah University.

Concrete Mix Proportions

A total of (3) trial mixes were produced to find the mix proportions containing porcelinite aggregate so that the lightweight aggregate concrete should have an oven-dry density < 2000 kg/m^3, and a compressive strength > 15.0 MPa [13]. These mixes were designed in accordance with ACI Committee 211. As discussed later, 12.5 mm maximum size aggregate were chosen for the mixes. Four beams which are made of LWC. It was used a mix of 1:1.031:0.978 (by weight) cement, sand, LWA (Porcelinite) respectively and the water cement ratio was 0.41. This mix was selected to give a cylinder compressive strength of about 20.0 MPa at age of 28 days and slump of about 50 mm with density about 1841 kg/m^3.

Beams Details

The experimental program consisted of testing four made from lightweight concrete (porcilinate as coarse aggregate). Beams designed to fail in shear with (a/d =1) as a deep beams. The first beam (**L.C.M**) was not strengthened with CFRP to serve as a reference beam (control beam). The remaining three deep beams (**L.C.M.1**, **L.C.M.2** and **L.C.M.3**) study how the configuration of CFRP affect the shear behavior of strengthening I-section light weight deep beams under monotonic load. Figure (1) shows the control of the tested beam. Table (1) shows the description of the tested beams.

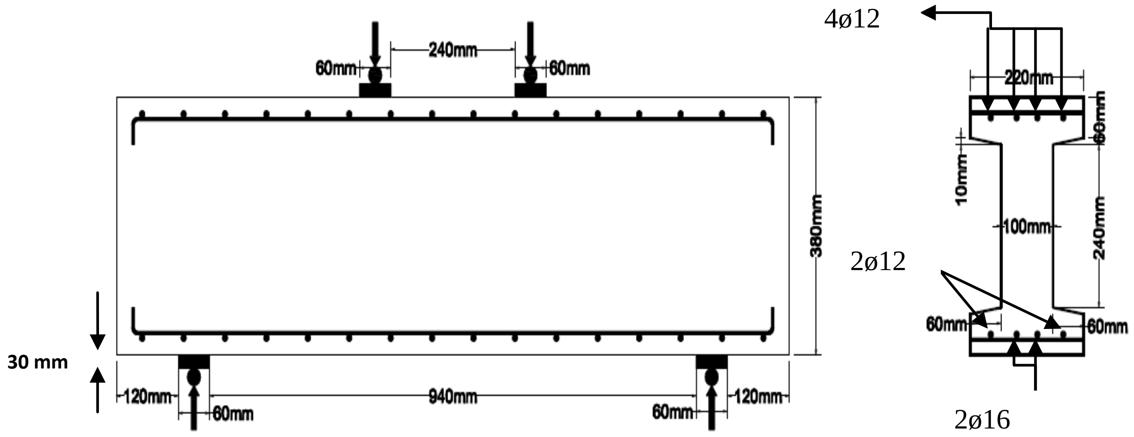


Fig. (1): Reference deep beam (control beam) without strengthening.

Table (1): Details the description of the tested beams

Beam No.	Details of strengthening
L.C.M	Reference beam (control beam) without strengthening
L.C.M.1	strengthened with two opposite side with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
L.C.M.2	strengthened in the U configuration with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
L.C.M.3	strengthened with two opposite side with 45° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)

Experimental Results & Discussion

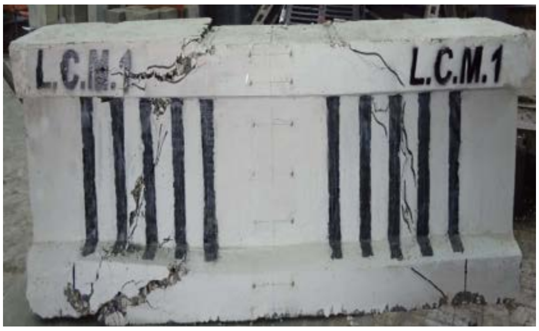
At 15.7 to 29.9% of failure load. The first diagonal shear crack was occurred and developed suddenly in the web and propagated toward the top and bottom flanges at which point they turned and ran horizontally along the longitudinal compression and tension reinforcements located at the interface between the web and flanges. But this load did not cause failure. This means, there is reserve strength in these deep beams after the appearance of shear crack. The inclined crack became wider gradually with increasing load. At load levels close to failure, development new shear cracks parallel inclined crack extended upwards as load increased. The final failure is due to the destruction of the portion of concrete between these two cracks which acts like a strut between the load and the support points. For beams strengthened with CFRP they have same behavior of the control beam.

The results from the two-points loading tests on the I-section reinforced concrete deep beams made with lightweight concrete are summarized in Table (2) and the shear crack patterns of these deep beams after failure are shown in Figures (2) to (5).

Table (2): Ultimate Loads of the Beam Specimens

Group No.	Beam designation	First crack load (kN)	Ultimate applied load (kN)	Percentage increase in ultimate load with respect to reference beam
1	**L.C.M**	50.0	319.0	-----
	L.C.M.1	70.0	370.0	16%
	L.C.M.2	120.0	402.0	26%
	L.C.M.3	85.0	387.6	21%

Fig. (2): Shear cracks pattern of L.C.M beam.



Fig(3): Shear cracks pattern of L.C.M.1 beam.

Fig. (4): Shear cracks pattern of L.C.M.2 beam.

Fig(5): Shear cracks pattern of L.C.M.3 beam.

Cracking and Ultimate Loads

The I-section lightweight reinforced deep beam, which is made with natural sand as fine aggregate and crushed porcelenite as coarse aggregate. The I-section deep beam designated as L.C.M was taken as a control deep beam. The beam was tested without any strengthening by CFRP strips where the first crack appear at 50kN and failed with total ultimate load was 319kN as shown in table (2). In the specimen L.C.M.1, when the applied load reached approximately (70kN), shear crack suddenly appeared throughout the shear span, with increasing load, shear crack was widening and propagating until failure occurred, because the diagonal crack became wide (the main shear crack), at a total applied load of 370kN. In beam specimen L.C.M.2**,** the diagonal shear cracks started to appear at about 120kN. With increasing load, more diagonal cracks in both shear spans of the beam were observed, at the applied load 402kN the diagonal crack rapidly propagated toward the loading point and failure occurred. The strengthened beam (L.C.M.3) which was strengthened by vertical CFRP strips with a U configuration has 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 (85kN), and then the crack width increased till the CFRP failed (by debonding failure) with total load (387.6 kN).

Load Versus Mid-span Deflection Results

Deflection of reinforced lightweight (Porcelinite) concrete beams is an important design consideration because of the relatively low modulus of elasticity of this material. If the deflections of lightweight and normal weight beams of the same compressive strength are compared, the deflection of the lightweight beams are from 15 to 35 percent larger than those of the normal weight beams [4].

Four reinforced lightweight concrete I-section 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 L.C.M on the behavior of load versus mid-span deflection curves for these deep beams at different loading stages is presented in this section. Figure (6) shows the load-deflection curves of tested deep beams. From Figure (6), it can be observed that the load versus mid-span deflection response for L.C.M beam (control beam) can be explained as following; in the first stage of loading, the applied load (applied shear force) was carried by the concrete only which was the same in all beams till the appearance of the first diagonal crack. It can be noticed that a change in slope of the curves occurred after the formation of inclined cracking because the formation of the first major inclined crack significantly reduced beam stiffness, therefore the deflection was increased. There was a drop in deflection curve was due to the shear crack appeared at 50 kN after that beam continued in carrying capacity with the new slope till failure. Finally, as the applied load reaches near its ultimate value, the rate of increase in deflection is substantially exceeding the rate of increase in the value of the applied loads. The strengthened beams had a similar behavior to that of the reference beams at the earlier loading stage. With increasing load the shear cracks were formed and increased causing a reduction in the stiffness of strengthened beam specimen. After that the CFRP strips resisted the applied shear force. This was clear because the curve continued with the same inclination.

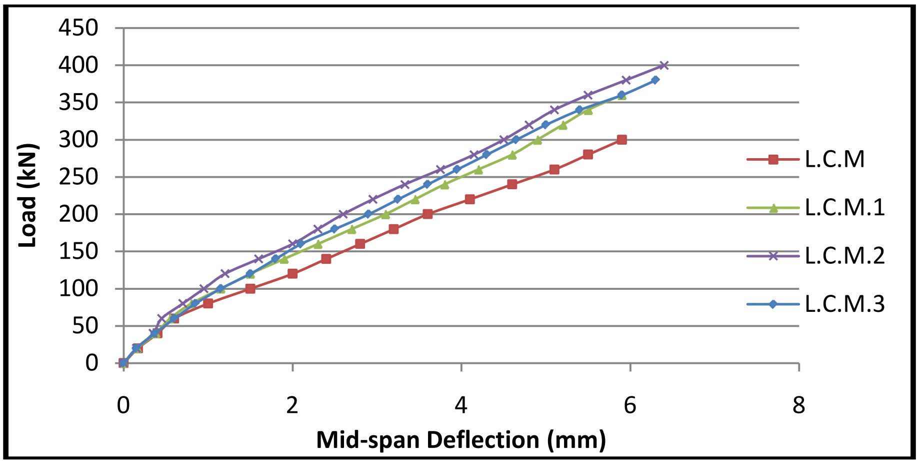


Fig. (6): Experimental load versus mid-span deflection curves

Numerical Applications

Although traditional empirical methods remain adequate for ordinary design of reinforced concrete members, the wide dissemination of computers and the development of the finite element method have provided means for analysis of much more complex systems in a much more realistic way. As part of the research, a total of four FE models are established and the numerical solutions are correlated with the experimental results. The FE models are created using the Finite Element (FE) code ANSYS 11. The models have the same geometry, dimensions, and boundary conditions of the tested I-section reinforced concrete deep beam specimen. The objective of this section is to discuss the possibilities of finding best model in practical use for I-section reinforced concrete strengthened with CFRP. It reports the results of some analyses performed using the reinforced concrete models of the general purpose FE code ANSYS.

ANSYS Finite Element Model

a- SOLD65 Element Description

SOLID65 is used for the 3-D modeling of solids with or without reinforcing bars (rebar). The solid is capable of cracking in tension and crushing in compression. In concrete applications, for example, the solid capability of the element may be used to model the concrete, while the rebar capability is available for modeling reinforcement behavior. Other cases for which the element is also applicable would be reinforced composites (such as fiberglass), and geological materials (such as rock). The element is defined by eight nodes having three degrees of freedom at each node: translations of the nodes in x, y, and z-directions. Up to three different rebar specifications may be defined._The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep. The rebars are capable of tension and compression, but not shear. They are also capable of plastic deformation and creep. This 8-node brick element is used, in this study, to simulate the behavior of concrete (i.e. plain concrete). The element is defined by eight nodes and by the isotropic material properties. The geometry, node locations, and the coordinate system for this element are shown in Figure (7) [14].

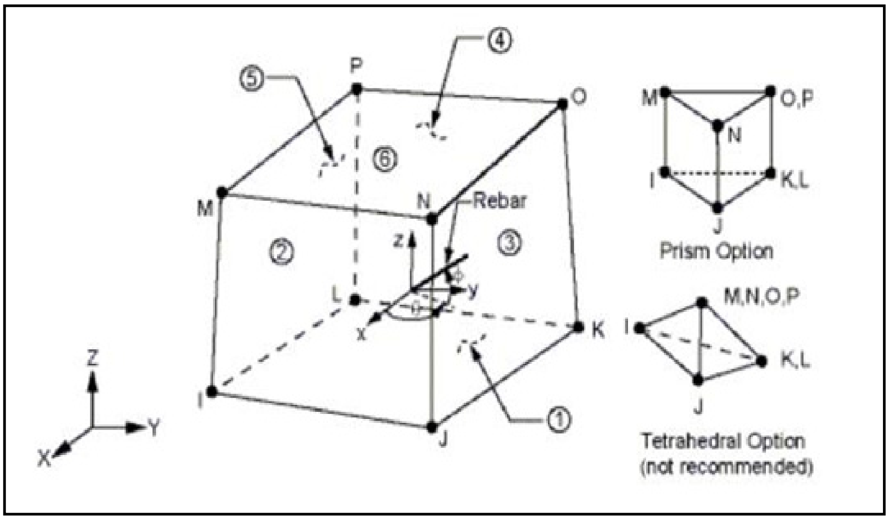


Fig. (7): brick element geometry [14]

b- Solid 45 Element

Soild 45 is used for the 3-D modeling of structural members. The element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities. The geometry, node locations, and the coordinate system for this element are shown in Figure (8). The element is defined by eight nodes and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. In present study, this element is used to represent steel bearing plates located at supports and under the applied loads.

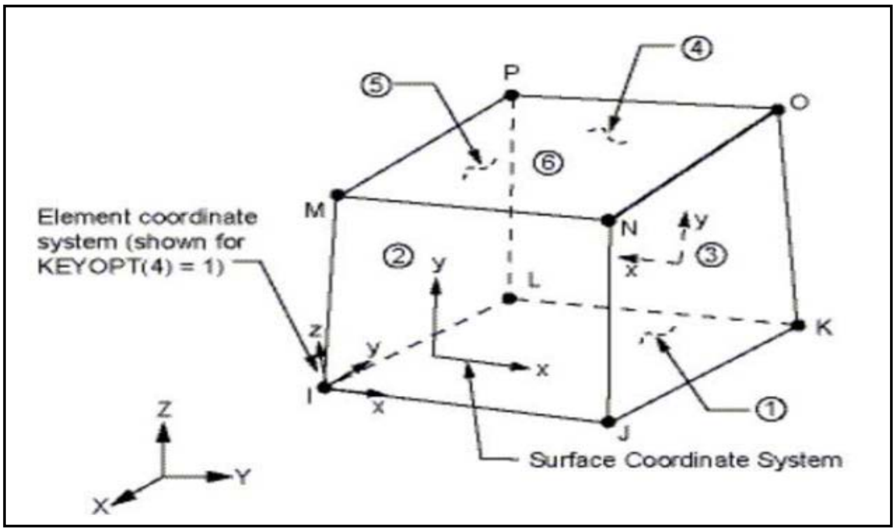


Fig. (8): Solid 45 element [14]

c- LINK8 Element Description

LINK8 is a spar (or truss) element which may be used in a variety of engineering applications. This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations of the nodes in x, y, and z-directions. As in a pin-jointed structure, no bending of the element is considered. Plasticity, creep, swelling, stress stiffening, and large deflection capabilities are included. This element is used, in this study, to simulate the behavior of steel reinforcement which works as main steel reinforcement in resisting the flexural stresses. The geometry, node locations, and the coordinate system for this element are shown in Figure (9) [14].

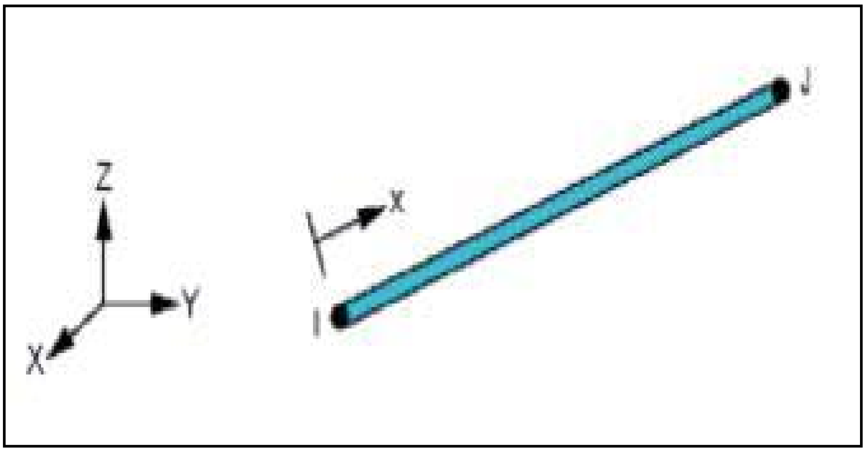


Fig. (9): LINK8 geometry [14]

d- SHELL41 Element Description

SHELL41 is a 3-D element having membrane (in-plane) stiffness but no bending (out-of-plane) stiffness. It is intended for shell structures where bending of the elements is of secondary importance. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions. The geometry, node locations, and the coordinate system for this element are shown in Figure (10). This element has variable thickness, stress stiffening, large deflection, and a cloth option, this element is used to simulate CFRP shear for all beams [14]. Full bond was assumed between CFRP and concrete surface.

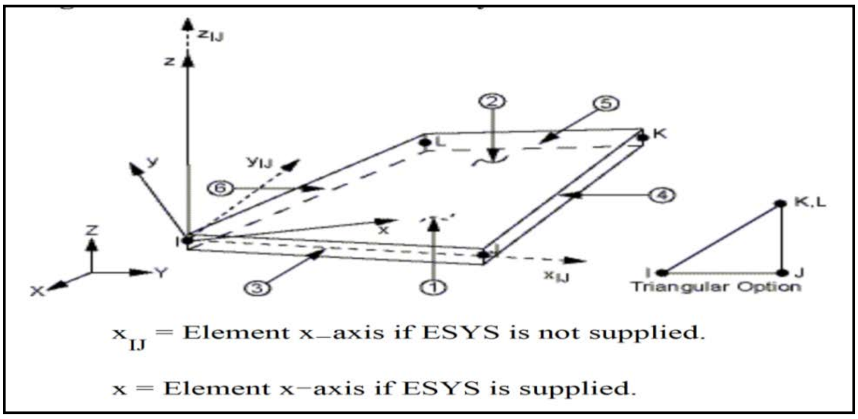


Fig. (10): SHELL41 geometry [14]

Geometry

The I-section reinforced concrete deep beam, plates, and supports were modeled by creating nodes on the working plane of ANSYS 11. Then elements created through nodes with auto-numbering of elements. By taking advantage of the symmetry of the beams, a half of the full beam was used for modeling. This approach reduced computational time and computer disk space requirements significantly. Half of the entire model is shown in Figure (10). The zero values for the Z-coordinates coincide with the lower-left corner of the cross-section for the concrete I-beam; see Figure (11) due to symmetry, only one loading plate and one support plate are needed. Link8 elements were used to create the flexural and shear reinforcement. The element type number, material number, and real constant set number for the ANSYS models were set for each mesh.

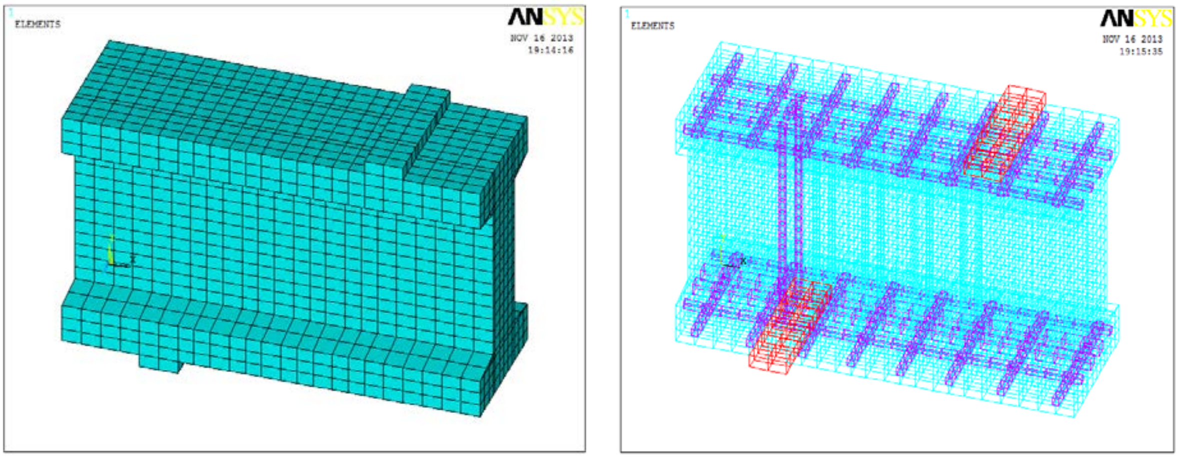


Fig. (11): Typical half symmetry finite element model

Loads at Failure

Table (3) compares the ultimate loads for the full-size beams and the final loads from the FE simulations. In general, the predicted ultimate loads obtained by ANSYS give good agreement with experimental results. ANSYS underestimates the strength of the tested beams by (4%-12%). One reason for the discrepancy is that Toughening mechanisms at the crack faces may also slightly extend the failures of the experimental beams before complete collapse. The finite element models do not have such mechanisms. For comparing the load carrying capacity of the beams, the finite element models have the same sequence as the actual beams.

Table (3): Comparison between Experimental and Numerical

Beam Designation	Numerical First Crack Load(kN)	Numerical Failure Load(kN)	Experimental Failure Load(kN)	P_u(Num.)/P_u(Exp.)
L.C.M	42.12	280.8	319.0	0.88
L.C.M.1	54.29	337.0	370.0	0.91
L.C.M.2	77.06	371.5	402.0	0.92
L.C.M.3	53.35	373.2	387.6	0.96

Crack Patterns

In ANSYS 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:-

1- Cracking is shown with a circle outline in the plane of the crack.
2- Crushing is shown with an octahedron outline.
3- If the crack has opened and then closed, the circle outline will have an X designation through it.

The ANSYS program records a crack pattern at each applied load step. In general, flexural cracks occur early at midspan. When applied loads increase, vertical flexural cracks spread horizontally from the midspan to the support. At a higher applied load, diagonal tensile cracks appear. Increasing applied loads induces additional diagonal and flexural cracks. Finally, compressive cracks appear at nearly the last applied load steps. Figures (12) to (15) show the evolution of crack patterns for the model of four beams as were recorded in ANSYS program.

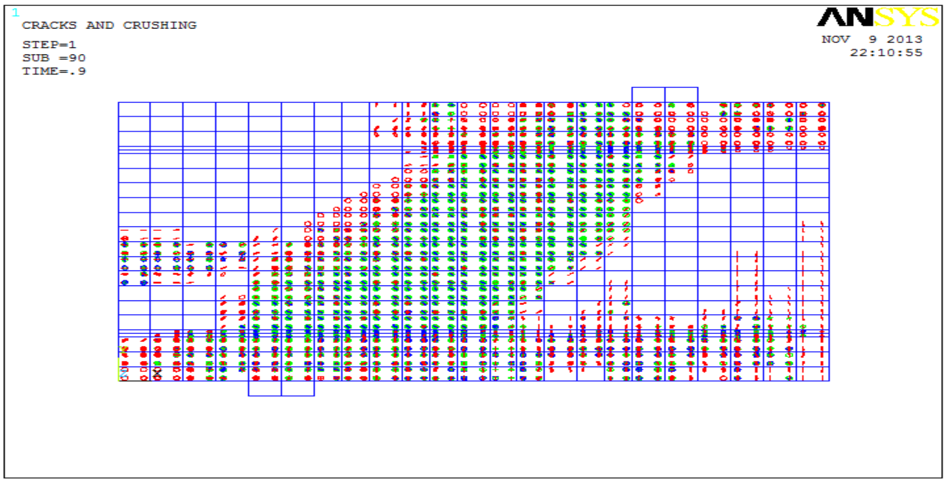


Fig. (12): Numerical crack patterns of L.C.M at load 280.8 KN

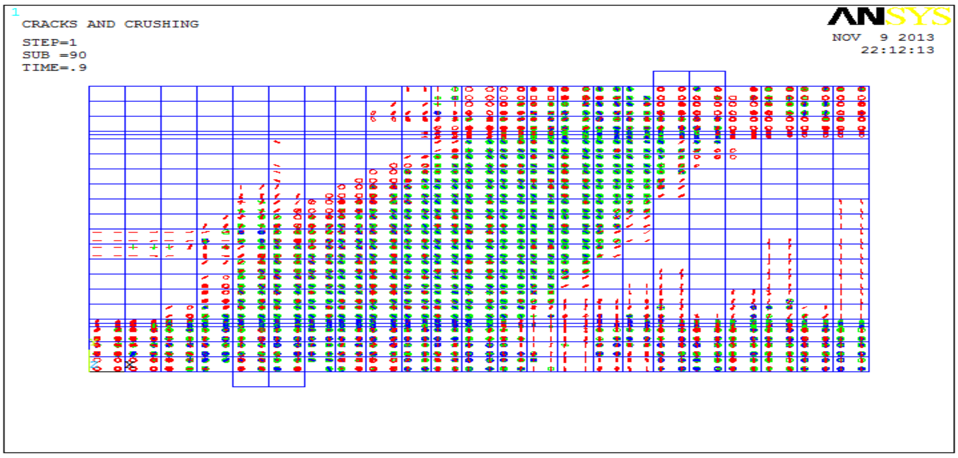


Fig. (13): Numerical crack patterns of L.C.M.1 at load 337.0 KN

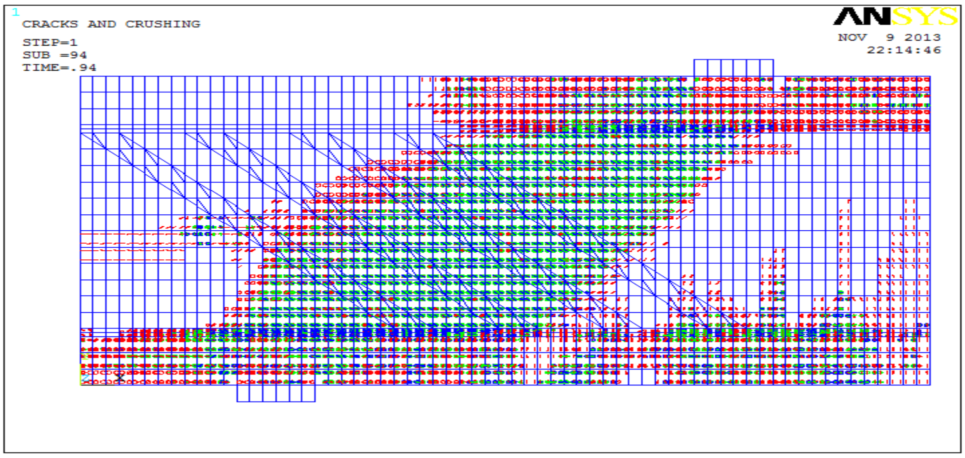


Fig. (14): Numerical crack patterns of L.C.M.2 at load 371.5 KN

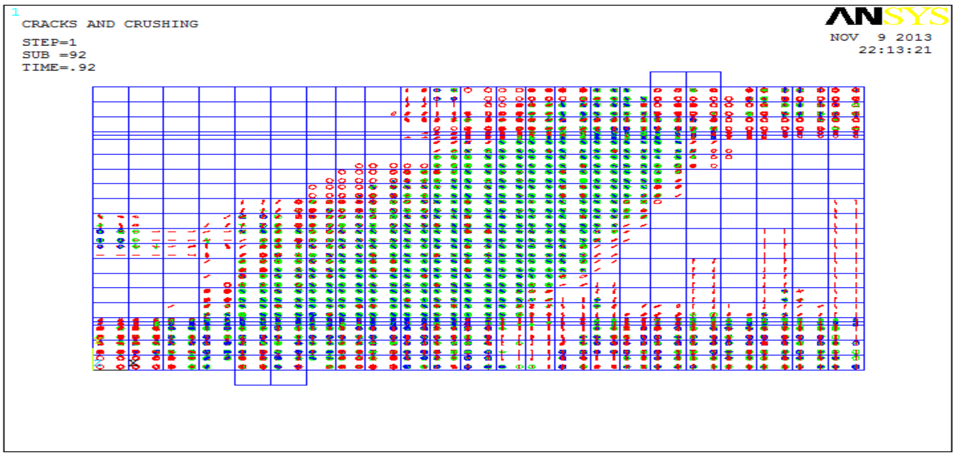


Fig. (15): Numerical crack patterns of L.C.M.3 at load 373.2 KN

Load-Deflection Plots

The deflections for the experimental beams were measured at mid-span at the center of the bottom face of the beams. For ANSYS, deflections are measured at the same location as for the experimental beams. Figures (16 to 19) show the load-deflection plots from numerical and experimental results. Good agreement was noticed between numerical and experimental results for **L.C.M** beam as shown in Figure (16). For the all beams, the finite element load-deflection plots in the linear range are stiffer than the experimental plots by 12% - 35%. The diagonal cracking loads for all models from the finite element analyses are higher than those from the experimental results by 12% - 29%. After diagonal cracking, the stiffness of the finite element models is again higher than that of the experimental beams by 9% - 21%.

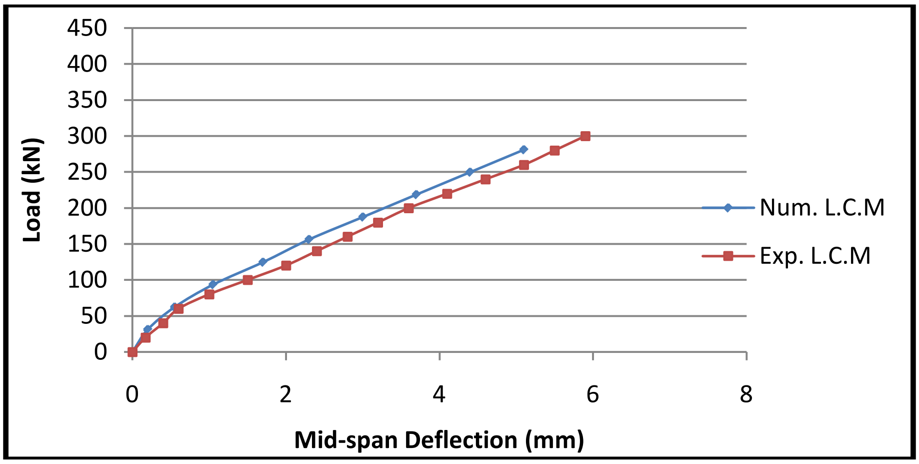


Fig. (16): Load versus mid-span deflection curve for L.C.M

There are several factors that may cause the higher stiffness in the finite element models. Micro cracks produced by drying shrinkage and handling are present in the concrete to some degree. These would reduce the stiffness of the actual beams, while the finite element models do not include micro cracks. Perfect bond between the concrete and steel reinforcing is 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 reinforcement is lost. Thus, the overall stiffness of the actual beams could be lower than what the finite element models predict, due to factors that are not incorporated into the models.

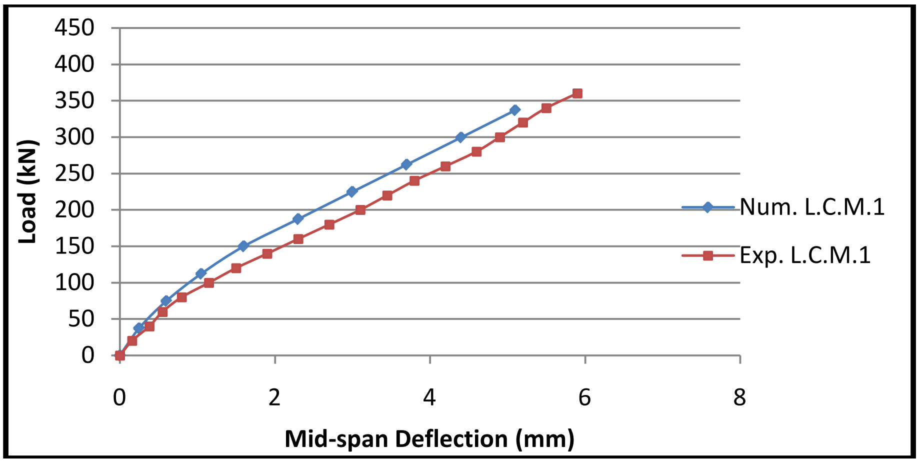


Fig. (17): Load versus mid-span deflection curve for L.C.M.1

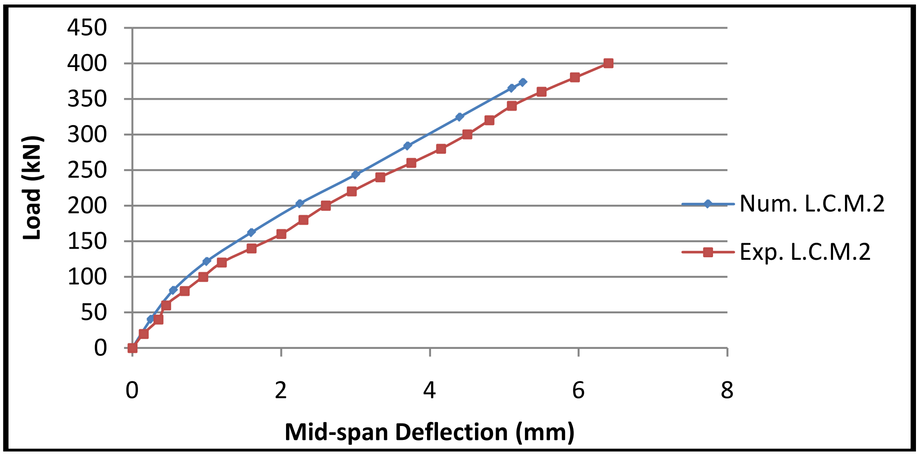


Fig. (18): Load versus mid-span deflection curve for L.C.M.2

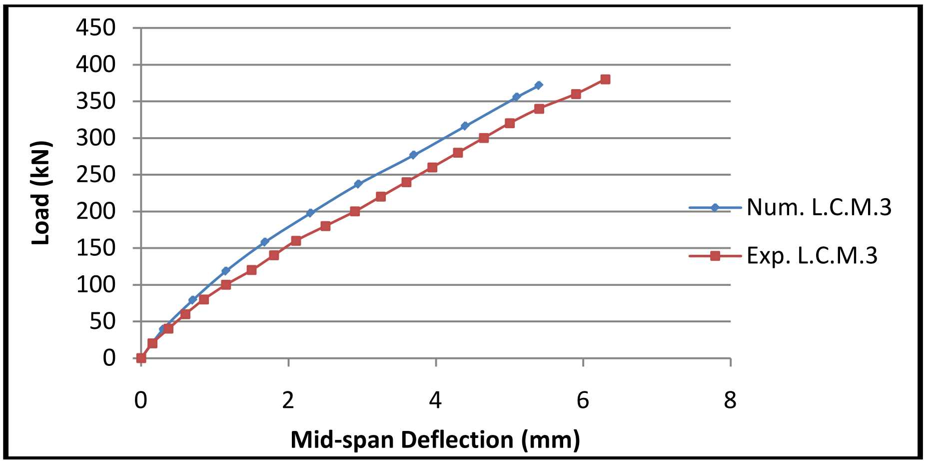


Fig. (19): Load versus mid-span deflection curve for L.C.M.3

Conclusions

Based on the results obtained from the experimental work and by finite element analysis for the externally strengthened reinforced concrete beams with CFRP laminates under different monotonic loading, the following conclusions are presented:-

1) The increase in the ultimate load of the strengthened beams ranged between 16% to 26% under monotonic load compared to reference beam.

2) According to the observations through the beams test, the presence of external CFRP laminates on the surface of the tested beams. The presence of strengthening was delayed and restrained cracking propagation which caused increase in load carrying capacities prior to and beyond the first cracking and the initial shear cracks appear at higher loads in case of strengthened beams.
3) A stiffer load-deflection response is observed for reinforced concrete deep beams strengthened with CFRP strips as compared with response of control deep beam.
4) The inclined CFRP strips give better enhancement than the vertical CFRP strips in ultimate load, deflection and crack width.
5) The finite element model showed that the CFRP strips did not reach to their ultimate tensile strength before overall failure of the beams. The maximum difference between experimental and computed ultimate load capacities for the conventional reinforced concrete beams was 12%, while the maximum difference in ultimate load capacities for the strengthened beams were 9%.
6) In general, the behavior of the finite element models represented by the load-deflection curves show good agreement with the corresponding experimental curves. However, the finite element models show a slightly stiffer response in the linear range and relatively stiffer response in the nonlinear ranges.

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