The Effect of Carbon Fiber Reinforced Polymer Length on the Strengthened of Concentrically loaded Reinforced Concrete Beams : Finite Element Analysis

Nada S. Assi
Building and Construction Engineering Department, University of Technology/Baghdad, Iraq
Email :aliabbas.n@gmail.com

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ABSTRACT :

Carbon fiber reinforced polymer (CFRP) plates are commonly used to increase the ultimate strength of concrete structures in flexure. CFRP plates are also an effective means of rehabilitation and strengthening of concrete structures. In this paper an analysis model is presented for reinforced concrete beams externally reinforced with CFRP plates using finite elements method adopted by ANSYS. The finite element models using a smeared cracking approach for concrete and elastic shell elements for the CFRP plates. The results obtained from the ANSYS finite element analysis are compared with the experimental data for four beams with different conditions from research , three of which were externally strengthened with different amounts of CFRP reinforcement by changing the length of CFRP plate. The comparisons are made for load-deflection curves at mid-span over a span of 2000 mm, failure load and the optimum length of CFRP plate that can be used for flexural strengthening and achieve the adequate load – carrying capacity. The results obtained from the ANSYS finite element analysis were calculated at the same location for the experimental test of the beams. The accuracy of the finite element models is assessed by comparison with the experimental results, which are to be in good agreement. The load-deflection curves from the finite element analysis agree well with the experimental results in the linear range, but the finite elements results are slightly stiffer than that from the experimental results. The maximum difference in ultimate loads for all cases is 11%. The optimum length of CFRP plate equal to 83% of the full span length, obtained from the finite element analysis shows good agreement with that from the experimental test. Four additional models are used to find that 80% of the full span length is quite enough to be optimum length and beyond which the increase in the ultimate capacity is small and can be neglected to reduce the cost of the material.

Keywords: Finite Element Modeling (FEM), Reinforced Concrete Beams, CFRP plate, flexural strengthening, optimum length.

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

تأثير طول الياف الكاربون البوليميرية على مقاومة الأعتاب الخرسانية المسلحة : تحليل بطريقة العناصر المحددة

الخلاصة

تستخدم صفائح الياف الكاربون البوليميرية CFRP في زيادة تحمل المنشآت خرسانية التي تتعرض الى احمال الانحناء و كذلك تعتبر وسيلة فعالة في اعادة تأهيل وتقوية المنشآت الخرسانية. في هذا البحث تم تقديم نموذج محاكاة للعتبات خرسانية مقواة بصفائح الياف الكاربون البوليميرية باستخدام برنامج الـ ANSYS الذي يعتمد طريقة العناصر المحددة في التحليل. تم استخدام العنصر المرن والعنصر ذو التشققات المنتشرة في تمثيل صفائح CFRP والخرسانة على التوالي، تم مقارنة النتائج المستخرجة باستخدام برنامج ال ANSYS مع النتائج العملية لأربع أعتاب ثلاثة منها تم تقويتها بأطوال مختلفة من صفائح الـ CFRP، وكانت المقارنة تتضمن منحني القوة – الهطول لفضاء طوله 2000 ملم , احمال الفشل والطول الامثل لتلك الصفائح والتي تم استخدامها لتقوية الانحناء والحصول على قابلية تحمل مناسبة. اظهرت النتائج تطابق جيد وخصوصا في الجزء الخطي من المحني بين منحنيات القوة – الهطول المستخرجة من التحليل بواسطة العناصر المحددة والنتائج العملية ولكن النتائج المستخرجة من التحليل بواسطة العناصر المحددة أظهرت صلابة اكثر, اما اقصى فرق في احمال الفشل في جميع الحالات كان 11% . كما تم الحصول على تطابق جيد بنسبة الطول الامثل لل CFRP والبالغ 83% من طول الفضاء الكلي بين النتائج العملية والتحليل بواسطة العناصر المحددة. كما استخدمت اربعة نماذج إضافية لاعتاب خرسانية لإيجاد ان 80% من طول الفضاء الكلي يكفي لكي يكون الطول الامثل واي زيادة في طول الصفائح يؤدي الى زيادة صغيرة في الاحمال من الممكن اهمالها لتقليل من كلفة المواد.

INTRODUCTION

Strengthening, upgrading and retrofitting of existing structures are among the major challenges that modern civil engineering is currently facing. One of the most promising answers to these needs is the using fiber reinforced polymer FRP composite material[1]. Carbon fiber reinforced polymer (CFRP), Glass fiber reinforced polymer (GFRP) and Aramid fiber reinforced polymer (AFRP) … ext. There may be several reasons for the need to strengthen and upgrade structures, such as expired design life, changes in functionality, potential damage caused by mechanical actions and environmental effects, more stringent design requirements and original design and of structure:

- Increase the bending moment capacity of beams and slabs by adding fiber composite materials to the tensile face.
- Increase the shear capacity of beams by adding fiber composite materials to the sides in the shear tensile zone.
- Increase the axial and shear capacity of columns by wrapping fiber composite materials around the perimeter.

In the last years, fiber reinforced polymer (FRP) composites have been used for strengthening structural members of reinforced construction errors [2,3]. Three basic principles underlie the strengthening of concrete structures using fiber composite materials, which are the same irrespective of the type concrete bridges, which are deficient or obsolete due to changes in their use or consideration of increased loadings [4]. Many researchers have found that FRP composites applied to the reinforced concrete members provide efficiency, reliability and cost effectiveness in rehabilitation[5,6,7]. Carbon fiber reinforced polymer (CFRP) laminates has proved to be an effective means of upgrading and strengthening reinforced concrete (RC) beams.

Many studies used the carbon fibers reinforced plastic for the strengthening but the plate of length equals to the full span length which is expensive rather than the shorter one that able to give the similar load – carrying capacity. This paper aims to present finite element model to establish the optimum length of CFRP plate that can achieve the optimum load – carrying capacity to more reduce the cost effectiveness.

A large number of available software like sap2000, LUSAS, and ANSYS etc incorporate finite elements based analysis. In this paper an attempt has been made with ANSYS (*version 11*) [8] software to bring into focus the versatility and powerful analytical capabilities of finite elements technique by objectively modeling the complete

response of test beams. The finite elements model uses a smeared cracking approach to model the reinforced concrete and elastic shell elements to model the Carbon fiber reinforced polymer . This model can help to confirm the theoretical calculations as well as to provide a valuable supplement to the laboratory investigation of behavior.

Finite Element Modeling

The finite elements analysis calibration study included modeling a reinforced concrete beams with the dimensions and properties corresponding to beams tested in previous research [9].

Concrete

Solid65 element was used to model the concrete. The following properties must be entered in ANSYS:

- Elastic modulus (Ec).
- Ultimate uniaxial compressive strength (fc').
- Ultimate uniaxial tensile strength (modulus of rupture, fr) = $0.7\sqrt{f'c}$ [10]
- Poisson's ratio (v) = 0.2.
- Shear transfer coefficient (βt) which is represents conditions of the crack face. The value of βt ranges from *0.0* to *1.0*, with *0.0* representing a smooth crack (complete loss of shear transfer) and *1.0* representing a rough crack (no loss of shear transfer) [8].
- Compressive uniaxial stress-strain relationship for concrete.

Reinforcing steel

Modeling of reinforcing steel in finite elements is much simpler than the modeling of concrete. A Link8 element was used to model steel reinforcement. A perfect bond between the concrete and steel reinforcement considered. However, in the present study the steel reinforcing was connected between nodes of each adjacent concrete solid element, so the two materials shared the same nodes. The same approach was adopted for CFRP laminates. A Poisson's ratio of 0.3 is used for the steel reinforcement.

CFRP Laminates

FRP composites are materials that consist of two constituents. The constituents are combined at a macroscopic level and are not soluble in each other. One constituent is the reinforcement, which is embedded in the second constituent, a continuous polymer called the matrix. The reinforcing material is in the form of fibers, i.e., carbon or glass, which are typically stiffer and stronger than the matrix. The FRP composites are orthotropic materials; that is, their properties are not the same in all directions. A Shell 63 element was used to model CFRP Laminates. The high strength epoxy is used to attach CFRP sheets to the experimental beams supported the perfect bond assumption[2,11,12]. In the present study linear elastic properties of CFRP Laminates are assumed .

Numerical Analysis

In order to validate the numerical representation of the reinforced concrete beams strengthening with carbon fiber reinforced polymer (CFRP), the finite elements representation using ANSYS program has been applied to practical sections and the results will be compared with the experimental results reported by A. A. Elhameed, N. Shafiq and M. F. Nuruddin [9].

Geometry and materials properties.

Four beams with different conditions (all beams were overdesigned for shear to avoid conventional shear failure and to isolate shear behavior form flexure behavior) will be analyzed using the proposed ANSYS finite elements model. *Table(1)* shows all beams evaluated in the present study.

Table (1): Beams evaluated in the study.

Symbol	Description	CFRP thickness (mm)
CB1	As built beam (control beam) [9].	------
CB2	The effective length of CFRP plate represent 67% of the total span length[9].	1.2
CB3	The effective length of CFRP plate represent 83% of the total span length[9].	1.2
CB4	The effective length of CFRP plate represent 100% of the total span length[9].	1.2

The geometry of all beams is shown in Figure (1) and (2) , and the material properties adopted in the analysis are given in Table(2). The finite element mesh, boundary condition and loading regions of all beams are shown in Figure(3).

Table (2): Material Properties of Selected Beams.

Material	Property	Values
Concrete	Compressive strength (MPa) Modulus of elasticity (GPa)	69 34
Steel bars	Tensile strength (MPa) Modulus of elasticity (GPa)	460 230
CFRP plates	Tensile strength (MPa) Modulus of elasticity (GPa)	2100 150

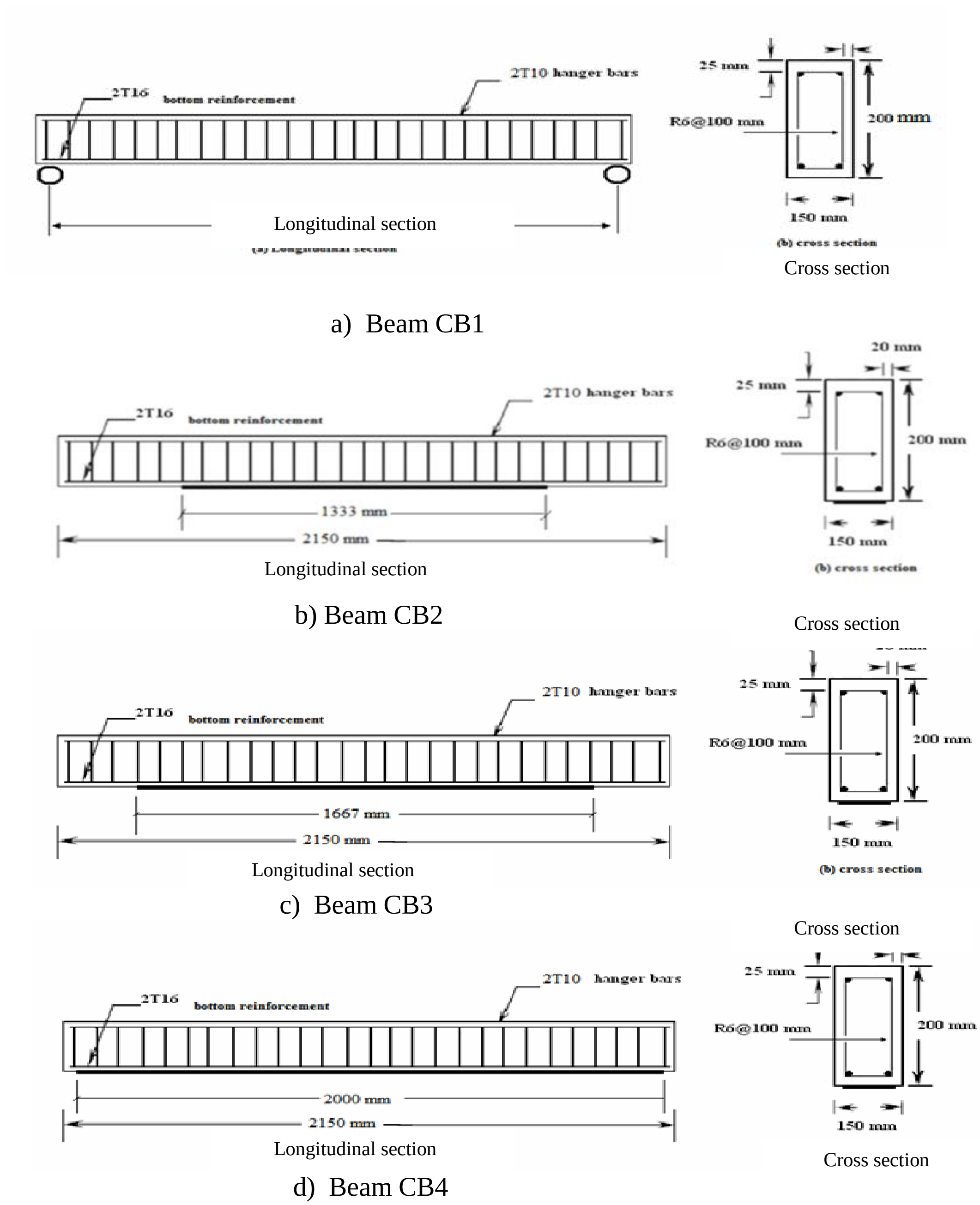


Figure (1): Geometrical properties of analyzed beams[9].

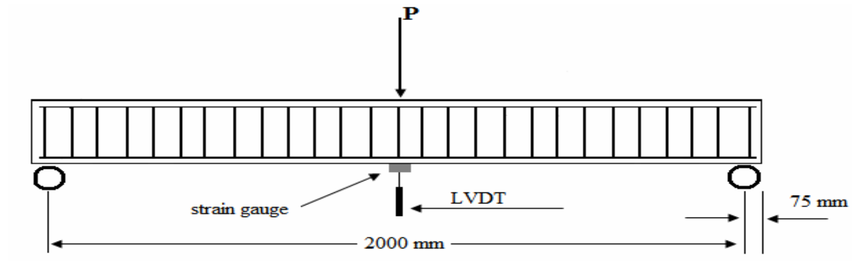


Figure (2): Loading reigns of analyzed beams[9].

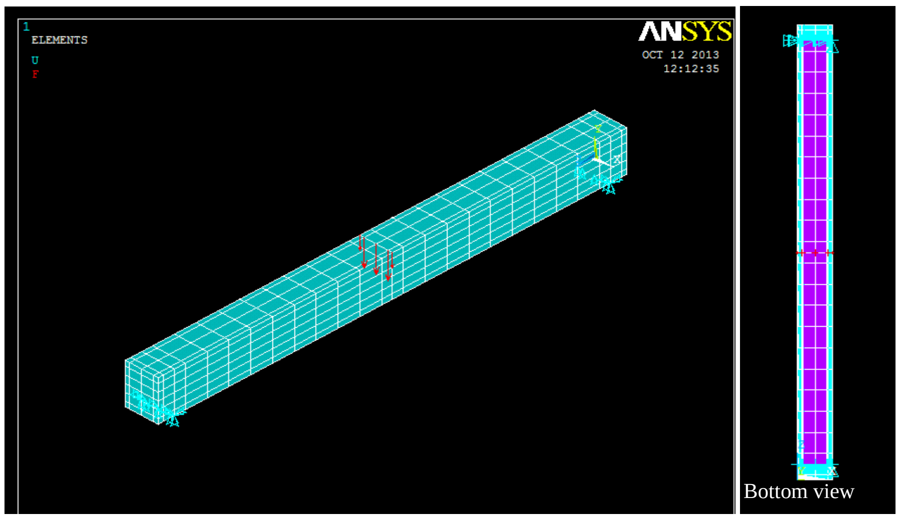
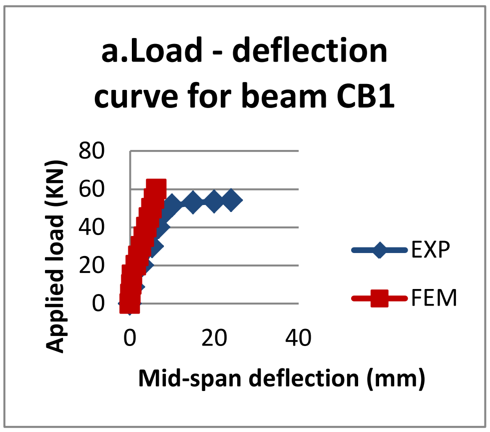


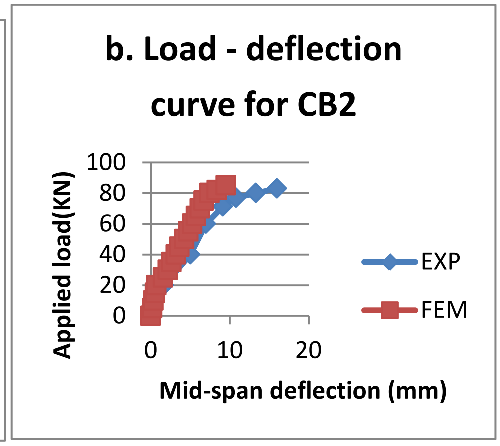
Figure (3): Finite element modeling for Selected Beams.

Load deflection curves

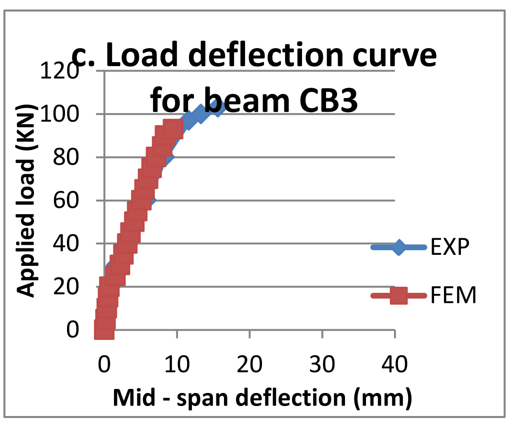
The experimental and numerical load-deflection curves obtained for the beams are illustrated in *Figure(4)*. The curves show good agreement in finite element analysis with the experimental results throughout the entire range of behavior and failure mode, for all beams the finite element model is stiffer than the actual beam in the linear range. Several factors may cause the higher stiffness in the finite element models. The bond between the concrete and steel reinforcing is assumed to be perfect (no slip) in the finite element analyses, but for the actual beams the assumption would not be true slip occurs, therefore the composite action between the concrete and steel reinforcing is lost in the actual beams. Also the microcracks 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 microcracks due to factors that are not incorporated into the models. After the initiation of flexural cracks, the beam stiffness was reduced and the linear load –deflection behavior ended when the internal steel reinforcement began to yield.



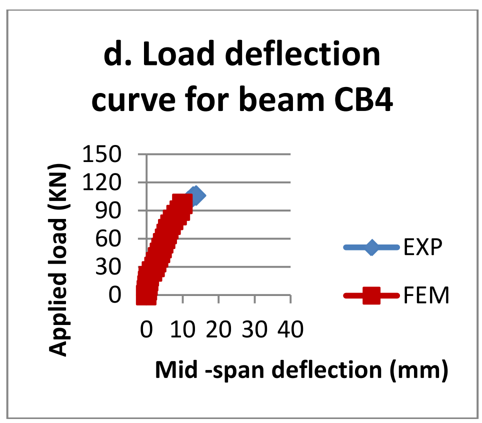
a) CB1



b) CB2



c) CB3



d) CB4

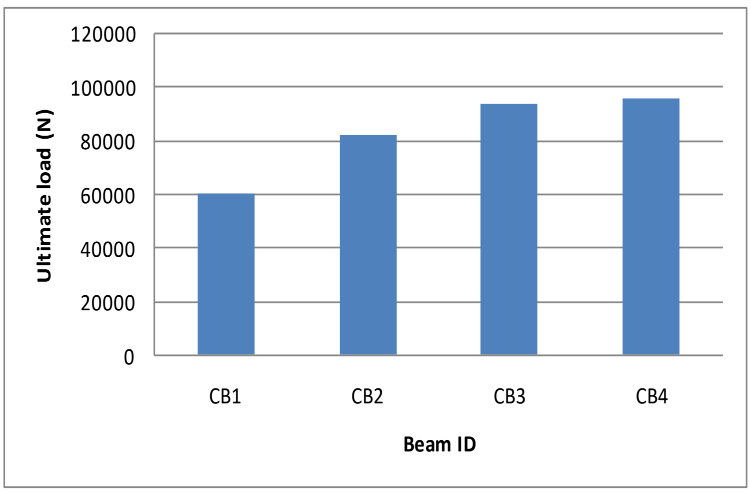
Figure (4) : Load deflection curves.

Failure load

The failure load obtained from the numerical solution for most beams is slightly smaller than experimental load. The mid – span deflections for all strengthened beams are smaller than of control specimens at their failure loads. The values of the maximum deflections decrease as the stiffness of the beam increases due to the increase in the amount of strengthening material. The final loads for the finite element models are the last applied load step before the solution diverges due to numerous cracks and large deflections. *Table(3)* shows comparison between the ultimate loads of the experimental beams and the final loads from the finite element models, and the ultimate capacity of the strengthened beams with ultimate capacity of the control beams. All the strengthened beams exhibited higher load – carrying capacity when compared to the unstrengthened control beam. The ultimate failure loads for all beams are shown in Figure(5).

Table (3) : Comparsions between experimental and finite element ultimate loads.

Beam	Experimental ultimate load (kN)	Numerical ultimate load (kN)	% Difference
CB1	54.07	60	-11
CB2	83.03	84	-1.2
CB3	103.12	93	9.7
CB4	106.06	96	9.4



Figure(5): Ultimate loads for the analysis beams (FEM)

Beams CB1 which was not strengthened with CFRP plates and was kept as the control specimen, exhibited small cracks at and around the loaded point and failed in flexure by crushing of concrete in compression zone; the cracks started at the tension sides and increased in width and length with applied loads The failure loads for CB1

60KN. The failure mode for beam CB2 which was strengthened with CFRP strip of 1333 mm length, 66.7% of the total length was a hybrid of flexural and interfacial debonding of the CFRP plate. The ultimate load for CB2 was 84 KN. Beam CB3 was strengthened with CFRP plates of length 1667 mm, 83% of the total span length, failed in the same behavior as beams CB2 but with higher load – carrying capacities. The ultimate load for CB3 was 93 KN which was 55% and 11% higher than CB1 and CB2 respectively. Beams CB4 which were strengthened with CFRP plate of length 2000 mm, full span length, had the highest ultimate load over all the strengthened beams. The failure mode for this beam was similar to CB2 and CB3. The ultimate load for CB4 was 96 KN which were 58.3%, 13.1% and 3.2% higher than CB1, CB2 and CB3 respectively. The increase in the ultimate load for this beam (100% plate length) was 3.2% over beam CB3 (83% plate length) which clarifying the insignificant increase in the strength resulted by extending the length of the CFRP plate length from 83% to 100% of the total span length. The failure modes of the finite element models and the optimum length show good agreement with observations and data from the experimental full-scale beams. Figure (6) shows the failure mode for beam CB2, CB3,and CB4.

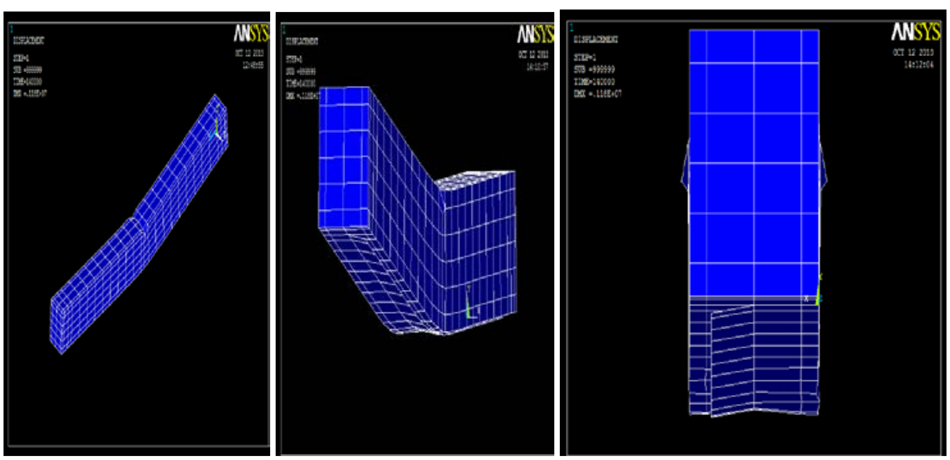
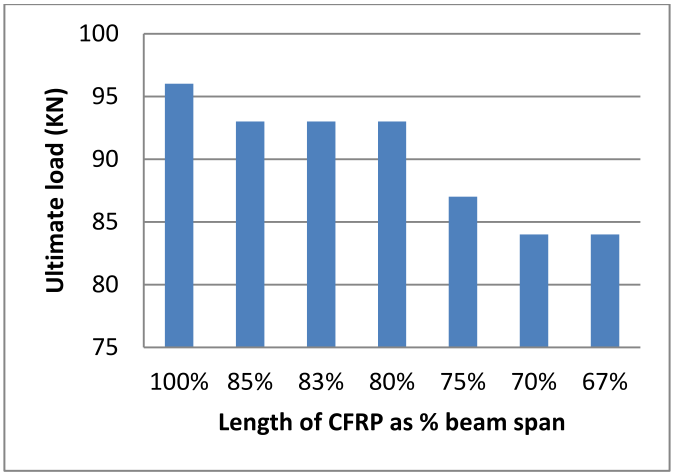


Figure (6):The failure mode for beam CB2, CB3,and CB4.

Optimum length

The finite element model obtained from this numerical study can be used to predict the behavior of reinforced concrete beam strengthed with CFRP and find the optimum length of CFRP plates. Seven reinforced concrete beam models were used to investigate the optimum length with different length of CFRP plates, 67%, 70%, 75%, 80%, 83%, 85% and 100% of the total span length. The ultimate failure loads and the load-mid span deflection relationship of all beams shown in figure (7) and figure (8) respectively. As it can be seen from Figure(13); comparisons have shown that 80% of the total span length can achieve similar ultimate loads than that obtained by using 100% (full span length); which justifying the use of this length as the optimum length of CFRP composite.



Figure(7) : Comparisons of the ultimate failure loads .

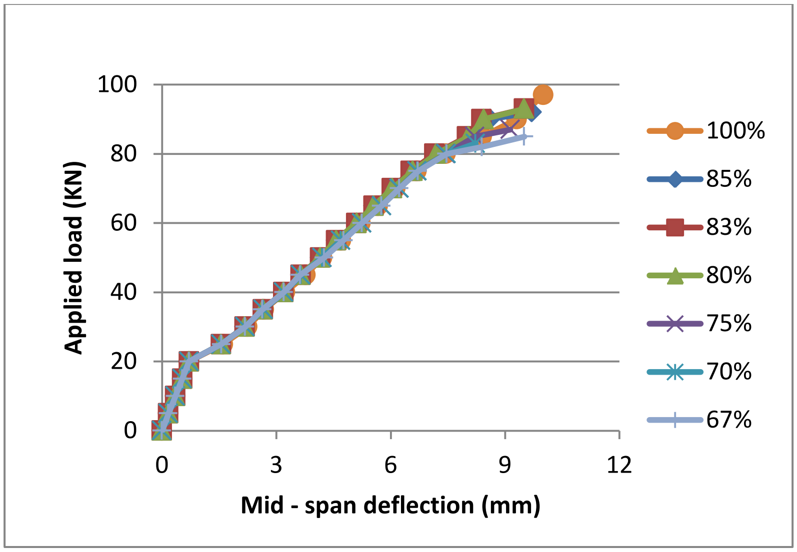


Figure (8) : Comparisons of the load-mid span deflection relationship.

CONCLUSIONS

The numerical solution was adopted to evaluate the optimum length of CFRP plate in simple, cheap and rapid way compared with experimental full scale test. The general behavior of the finite element models show good agreement with observations and data from the experimental full-scale beam tests. The CFRP plate bonding is an effective for external strengthening of reinforced concrete beams. An increase in the load – carrying capacity up to 58.3% over the control specimens was obtained. All the strengthened beams have mid – span deflections smaller than those of the control specimens at their failure loads. The values of the maximum deflection decrease as the stiffness of the beam increases due to the increase in the amount of strengthening material. The 80% of the total span length can be considered as the optimum length and beyond which the increase in the strength is negligible. An increase of 3.2%, in the strength, was obtained when the plate length was 100% of the total span length. The present finite element model can be used in additional studies to develop design rules for strengthening reinforced concrete members using CFRP plates.

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