Nonlinear Behavior of Steel-Concrete Composite Beams Curved in Plane with CFRP Strips Bonding

Dr. Ahmed F. Kadhum

Abstract

This paper deals with the behavior of structural steel-concrete composite beams curved in plane. The analytical investigation included the use of three dimensional nonlinear finite elements to model the performance of the composite beams strengthened with CFRP strips by using (ANSYS 11.0) computer program. The numerical results showed very good agreement with the experimental results reach to 100% before the strengthening, while the increase in strength after the curved strengthened with CFRP strips 32% for the curve beam with L/R equal to 0.05 and 48% for the curve beam with L/R equal to 0.10 and 53% for the curve beam with L/R equal to 0.25.

Keywords: Composite beam, Curved beam, Shear connector, ANSYS program, Finite element, CFRP strips**.**

التصرف اللاخطي للعتبات المركبة المنحنية أفقيا و المتكونة من عتبة حديد و بلاطة كونكريتية مقواة بأشرطة الياف الكربون فايبر

الخلاصة

هذا البحث يتعامل مع تصرف العتبات المركبة المنحنية في المســـتوي الأفقـــي. البحــث التحليلي يتضمن استخدام العناصر المحددة اللاخطية لتمثيل كفاءة العتبات المركبة المقواة باشرطة الكربون فايبر بواسطة برنامج (ANSYS 11.0). النتائج التحليلية اظهرت تطابق جيد جدا مع النتائج العملية تصل الى نسبة 100% قيل التقوية في حين كان مقدار الزيادة في المقاومة عنــد تقوية العتبات المركبة المنحنية بالياف الكربون فايبر 32% للعتبة المنحنية بنسبة L/R مســـاوية الى 0.05 و 48% للعتبة المنحنية بنسبة L/R مساوية الى 0.1 و مقدار الزيادة 53% في العتبة المنحنية بنسبة L/R مساوية الى 0.25.

Introduction

Fiber reinforced polymer (FRP) materials are commonly used for the repair and strengthening of concrete structures. Due to the success of this technique, several researchers have investigated the use of externally bonded carbon FRP (CFRP) materials to strengthen steel beams. A number of different approaches have been investigated to assess the effectiveness of various CFRP materials for the strengthening and repair of steel bridges and structures, including of overload girders [1].

Hafez, 2008 [2] presented a nonlinear three-dimensional finite element analysis has been used to predict the load-deflection behavior of horizontally curved composite beams of concrete slab and I-section steel beam with shear connectors using the analysis system computer program.

Rizkalla et al, 2003 [3], proposed the use of a new high

* **Building & Construction Engineering Department, University of Technology / Baghdad**

Eng. & Tech. Journal, Vol.28, No.12, 2010

Nonlinear Behavior of Steel-Concrete
Composite Beams Curved in Plane
with CFRP Strips Bonding

modulus carbon fiber reinforced polymer (CFRP) for strengthening of steel structures includes extensive research to select the resin for wet lay-up of carbon fiber sheets and the adhesive for bonding of procured laminates strips. Test results of the first scaled monopole tower showed a 25% increase in stiffness in the elastic range over the same monopole before strengthening. This paper summarizes also the remaining program, including the strengthening of other monopoles and a steel-concrete composite girder to be strengthened using different techniques.

Al-Saidy et al., 2005 [4], presented the results of an experimental study on the behavior of strengthened steel-concrete composite girders using Carbon Fiber Reinforced Polymer (CFRP) plates. Strengthening was achieved by attaching the CFRP plates to the bottom flange and in some beams the CFRP plates were also attached to the beam web. Two different types of CFRP plates were used, being mainly different in the tensile modulus of elasticity. Shear stress distribution along the bond line between CFRP plates and steel was recorded and reported. The test results showed that using light weight CFRP plates could enhance the strength and stiffness of steel-concrete composite girders up to 45% of the original strength.

Rizkalla et al, 2006 [5], presents the details and relevant finding of an experimental program which was conducted in three phases to investigate the behavior of steel-concrete composite bridge girders strengthened with new high modulus carbon fiber reinforced polymer (HM

CFRP) materials. In the first phase, the feasibility of various HM CFRP strengthening systems was examined. The second phase investigated the behavior of the strengthened beams under overloading conditions. The fatigue durability of the strengthening system was investigated in the third phase. Based on the findings of experimental program, simplified design guidelines are presented for the design and analysis of steel-concrete bridge girders strengthened with HM CFRP materials.

In this paper analytical study achieved by proposing I-girders curved in plane (are frequently employed in structures such as highways bridges, interchanges in large urban areas and balconies of buildings) tested by Liew et al. [6], strengthened with CFRP strips and then study the behavior of these composite curved beams and the amount of increasing in the strength.

Cases Study:
Various types of horizontally curved composite beams with available experimental results have been analyzed (SP1, SP2, and SP3) with span length to radius of curvature (L/R) ratios ranging from 0.05 to 0.25 were tested to failure under a concentrated load applied at midspan by Liew et al. [6]. Each specimen was 6.2 m long simply supported over a span 6 m and consisted of main girder and three secondary beam. The main girder and secondary girders were made of UB356×171×57 kg/m. the concrete slab of all specimens was normal

weight concrete slab with overall thickness of 100 mm. The width of the slab was 1500 mm, two layers of welded mesh (8 mm diameter bars spaced at 150 mm center to center in orthogonal directions) were used along the entire length of the concrete slab in all specimens [6].   Figure (1) shows the typical geometry of the specimens while Table 1 and Table 2 summaries the geometric and material properties respectively as shown below.

The headed shear studs used in these specimens are (19 mm diameter, 75 mm long) for the top flange of the main girder and the secondary beams.

Finite Element Analysis:

A three-dimensional finite element model (ANSYS software compute program release 11.0) with the following characteristics had been used in the study:

1. Concrete slab – modeled by Solid-65 element with or without reinforcing bars (rebar). The solid element is capable of considering cracking in tension and crushing in compression [7]. The element is defined by eight nodes having three degrees of freedom at each node: translation in the nodal x, y and z-directions.   The geometry, node locations, and the coordinate system for this element are shown in Figure (2).

2. Steel flange and web and CFRP strips – modeled by Shell-63 element has both bending and membrane capacities. Both in-plane and normal loads are permitted. The element has six degrees of freedom at each node: translations in nodal x, y and z-

directions and rotations about the x, y and z-axes. Stress stiffening and large deflection capacities are included. The element is defined by four nodes, the thickness, elastic foundation stiffness, and the orthotropic material properties. The geometry, nodal locations, and the coordinate system for this element are shown in Figure (3).

3. Shear connectors between concrete slab and steel flange– modeled by Link-8, the 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translation in the nodal x, y and z-directions. As in a pin-jointed structure, no bending of the element is considered. Plasticity, creep, swelling, and large deflection capabilities are included. The element is defined by two nodes, cross-sectional area, an initial strain, and by the material properties. The geometry, node locations, and the coordinate system for this element are shown in Figure (4).

4. An adhesive force which occurs between the concrete slab and the surface of the top flange of the steel section simulated by Contact-52, this element represents two surfaces which may maintain or break physical contact or may slide relative to each other. The element is capable of supporting only compression in the normal direction to the surface and

Eng. & Tech. Journal, Vol.28, No.12, 2010

**Nonlinear Behavior of Steel-Concrete
Composite Beams Curved in Plane
with CFRP Strips Bonding**

shear (Coulomb friction) in the tangential direction. The element has three degrees of freedom at each node: translations in the nodal x, y, and z-directions. The element is defined by two nodes. The geometry, node locations, and the coordinate system for this element are shown in Figure (5).

A typical three-dimensional model with elements used in the study is shown in Figure (6).

Material Modeling:

In the present section, and as required within the model of this study, a description of the constitutive relationships for the material and structural components such as; concrete slab, steel beam, shear connectors and CFRP strips are given. The constitutive model of the nonlinear behavior should be in such a form that it could be easily incorporated into numerical analysis (finite element) procedure to simulate structural behavior.

1. **Concrete:** The concrete material model predicts the failure of brittle materials. Both cracking and crushing failure modes are accounted for access to this material model, which is available with the reinforced concrete element SOLID65 [7]. In ANSYS, the criterion for failure of concrete due to a multiaxial stress state can be in the form

$$\frac{F}{f_c} - S \geq 0 \qquad \ldots (1)$$

where:

F = a function of the principal stress state (σ_{xp}, σ_{yp}, σ_{zp})

S = Failure surface expressed in terms of principal stresses.

2. **Steel:** The rebars, steel beams, and shear connectors are modeled as elastic-plastic material and when compared with concrete; this material is much simpler.

for the *Reinforcing Steel (Rebars)*. The reinforcement in SOLID65 has uniaxial stiffness only and is assumed to be throughout the element. Directional orientation is accomplished through user specified angles.

The steel material by ANSYS is modeled by two parts; linear elastic material model and the required values are:

- Elastic modulus (E_s)
- Poisson's ratio (v)

while the second part is bilinear inelastic to represent the stress-strain behavior of material as shown in Figure (7), and the input data which are needed for ANSYS are:

- Yield stress (f_y)
- Tangent modulus (E_{tan})

For the *Steel Beam Modeling* Shell type element 63 is used to model the steel section of the composite beams; the material can have orthotropic properties corresponding to the element coordinate directions [7].

The input data of material properties in the ANSYS program are the modulus of elasticity E_x, E_y, and E_z (one value required), Poisson's ratios v_{xy}, v_{yz}, and v_{xz} (one value

2311

Eng. & Tech. Journal, Vol.28, No.12, 2010

**Nonlinear Behavior of Steel-Concrete
Composite Beams Curved in Plane
with CFRP Strips Bonding**

required), and the shear modulus G_{xy}, G_{yz}, and G_{xz} (one value required),

In addition, the yield stress (f_y) and the tangent modulus (E_{tan}) are required for the bilinear inelastic stress-strain behavior as in the reinforcing steel (rebars).

3. CFRP (Carbon Fiber Reinforced Polymer)

Carbon fiber reinforced polymer (CFRP) which is used in this study, is in the from of thin unidirectional strips with linear elastic behavior up to failure without any significant yielding or plastic deformation, and leading to reduced ductility [8] as shown in Figure (8), and the strengthened is achieved through the width of the face of the bottom flange.

Shell63 has elastic capability which makes this element appropriate to simulate the CFRP strips. The input material data by ANSYS are the modulus of elasticity and Poisson's ratio.

Finite Element Results and Discussions:

The idealization of the curved composite beams is done by subdividing the structure into a number of elements as shown in Figure (9).

The word *loads* in ANSYS terminology includes boundary conditions and externally or internally applied forcing functions for example: loads, displacements U_x, U_y, and U_z (DOF constraints), forces, pressures.

For the tested beam in this study the displacements (DOF constraints) U_x and $U_y = 0$ to represent the hinge end, while the other end is a roller so just $U_y = 0$. It is worthy to mention here that for the edge nodes $U_z = 0$ against transverse slip.

For the three composite curved beams SP2, SP3, and SP4 are analyzed by finite element (ANSYS program 11.0) and the load-deflection curves of the numerical solution for the three curved beams before and after strengthened with CFRP strips were plotted by using GRAPHER 1.09 program software and compared with experimental results by Liew et al. [6] as shown in Figures 10 through 18. From Figures 10 and 13 it can be seen that there is intersection between the experimental and analytical curves before and after strengthening, the reason for this behavior is that the curves of the composite curved beams be stiffer after the strengthening with CFRP strips. The analytical values of the ultimate loads of three beams are summarized along with the corresponding experimental values in Table 3. The comparisons between experimental and finite element values are also presented in the table.

From the table it can be seen that curved composite beams strengthened with CFRP strips in general showed a significant increase in the ultimate load by about 53% for the beam SP4 and this increase increasing with the L/R increase, and figures 11, 12, 14, 15, 17, and 18 of the stress variation reflect this behavior with red region increase.

Conclusions

ANSYS (11.0 release) was adopted to simulate the three curved campsite beams for finite element

solution. The experimental composite beams constituents (like; concrete slab, steel beam, shear connectors, and CFRP strips) were simulated by the special elements of ANSYS, as an example, concrete by SOLID65, steel section and CFRP strips by SHELL, etc, the following conclusions can be adopted:

1. The three-dimensional finite element (ANSYS 11.0) models used to represent the composite curved beams are found efficient to simulate these composite beams.

2. In general it can be said that there was good agreement between the analytical and the experimental load-deflection curves at the midspan reach to 100% before the strengthening, while the increase in strength after the curved strengthened with CFRP strips 32% for the curve beam with L/R equal to 0.05 and 48% for the curve beam with L/R equal to 0.10 and 53% for the curve beam with L/R equal to 0.25.

3. For the curved composite beams strengthened with CFRP strips the increase in the strength reach to 53% especially to the curved beam with L/R equal to 0.25 the reason for this behavior is the CFRP strips prevent the bottom flange of main steel beam from bending and twisting and do not effect much the ultimate strength.

References:

[1]-Rizkalla S. and Dawood M., "High Modulus Carbon Fiber Materials for Retrofit of Steel Structures and Bridges" Proc ACUN-5 "Development in Composites: Advanced, Infrastructural, Natural and Nano-composites", UNSW, Sydney, Australia, www4.ncsu.edu, 11-14 July, 2006, pp 1-10.

[2]-Hafez, Alaa Adnan, "Analysis Up To Failure of Horizontally Curved Composite Steel Beam And Concrete Slab With Partial Interaction By Brick And Shell Elements", M.Sc. thesis, Building and Construction Engineering Department, University of Technology, 2008.

[3]-Rizkalla S., Schnerch D., Stranford K. and Lanier B., "Use of High Modulus Carbon Fiber Reinforced Polymers (CFRP) For Strengthening Steel Structures", Department of Civil, Construction, and Environmental Engineering, North Carolina State University, www4.ncsu.edu, NC, USA, 2006, pp. 1-11.

[4]-Al-Saidy A.H., Klaiber F.W., and Wipf T.J., "Strengthening of Steel-Concrete Composite Girders Using Carbon Riber Reinforced Polymer Plates", Construction and Building Materials, Elsevier, pp. (295-302), 2007, pp. 295-302.

[5]-Dawood M., Sumner E., Rizkalla S., and D. Schnerch, "Strengthening Steel Bridges with New High Modulus CFRP Materials", www4.ncsu.edu, 2005, pp. 1-8.

[6]-V. Thevendran, S. Chen, N. E. Shanmugam, and J. Y. Richard Liew, "Experimental Study on Steel-Concrete Composite Beams Curved in Plane", Engineering Structures, Elsevier, 2000, pp. (877-889).

[7]-ANSYS, Inc., "ANSYS Help", Release 8.0, Documentation, Copyright 2003.

Eng. & Tech. Journal, Vol.28, No.12, 2010

Nonlinear Behavior of Steel-Concrete
Composite Beams Curved in Plane
with CFRP Strips Bonding

[8]- "Externally bonded FRP Reinforcement for RC Structures", Technical report on the design and use of externally bonded fiber reinforced polymer reinforcement (FRP ERP) for reinforced concrete structures prepared by a working party of the Task Group 9.3 FRP (Fiber Reinforced Polymer) reinforcement for concrete structures, Sprint-Digital-Druck Stuttgart, July, 2001,130 pp.

[9]-Breňa S. F., Bramblett R. M., Benouaich M. A., Wood S. L., and Kreger M. E., "Use of Carbon Fiber Reinforced Polymer Composite to Increase the Flexural Capacity of Reinforced Concrete Beams", National Technical Information Service, Springfield, Virginia, USA, www.utexas.edu, April, 2001, 229 pp

Table (1) Geometric property of test specimens [6]

Specimens	B(mm)	D (mm)	t_f(mm)	t_w (mm)	Ls	R(mm)	L/R
SP2	1500	358	12.9	8	6200	120000	0.05
SP3	1500	358	13.0	8	6200	60000	0.10
SP4	1500	358	12.9	8	6200	24000	0.25

Table (2) Material property of test specimens [6]

Specimens	E(GPa)	F_y (MPa)	F_u (MPa)	F_{cu}(MPa)	E_c(N/mm^2)
SP2	220.0	371	522	29.0	21480
SP3	200.0	370	491	35.7	21000
SP4	212.5	352	535	39.0	18280

**Table (3) Comparison of ultimate loads predicted by ANSYS with
experimental values**

Specimens	Ultimate Load P_u (kN)			$\dfrac{(P_u)_{ANSYS}}{(P_u)_{EXPT}}$	$\dfrac{(P_u)_{ANSYS+CFRP}}{(P_u)_{EXPT}}$
	$(P_u)_{ANSYS}$	$(P_u)_{ANSYS+CFRP}$	$(P_u)_{EXPT}$		
SP2	448	591.2	448	1	1.32
SP3	460	681.8	460	1	1.48
SP4	438	672.2	438	1	1.53
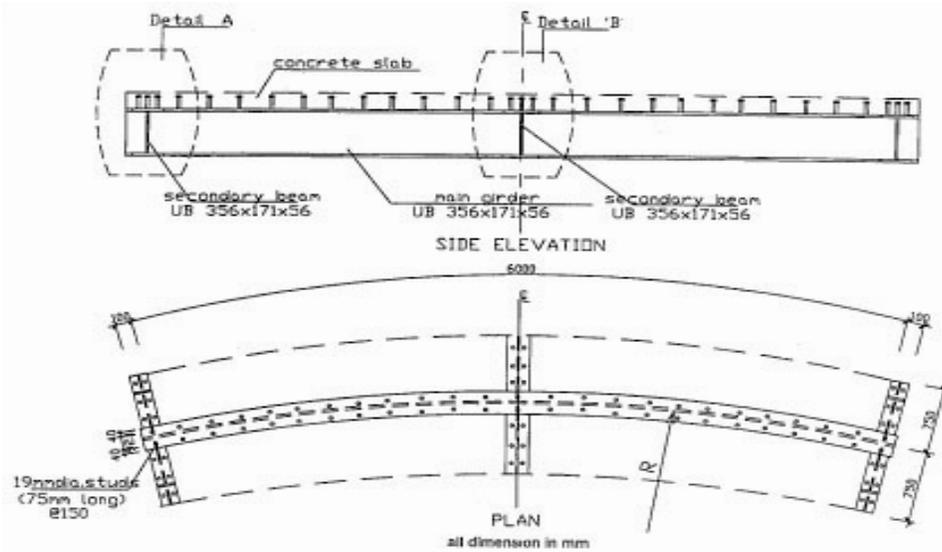
Figure (1) Details of a typical specimens; structural steel components [6]
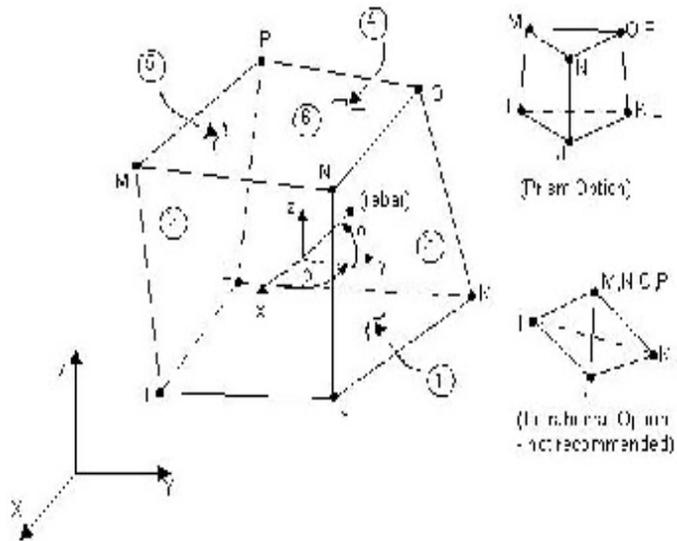
Figure (2) Solid-65 geometry [7]
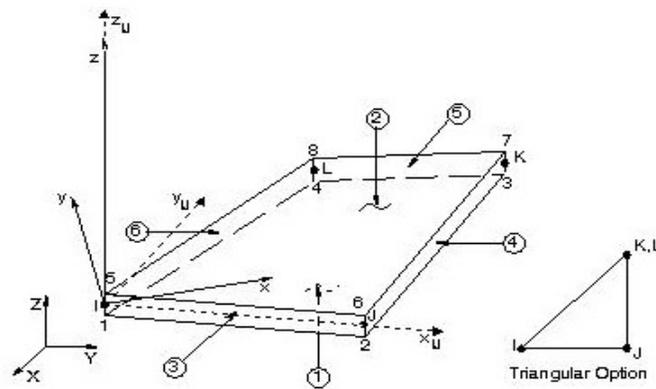
x_{IJ} = Element x-axis if ESYS is not supplied.

x = Element x-axis if ESYS is supplied.

Figure (3) Shell (63 and 143) geometry [7]
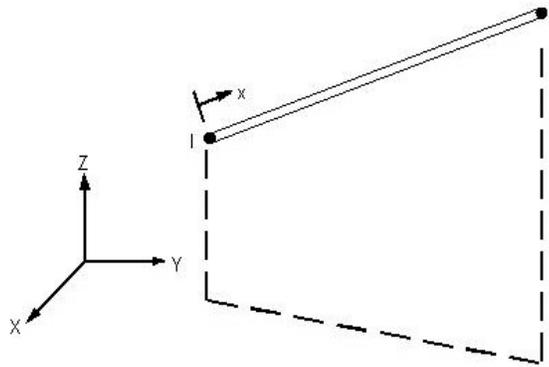
Figure (4) Link-8 geometry [7]
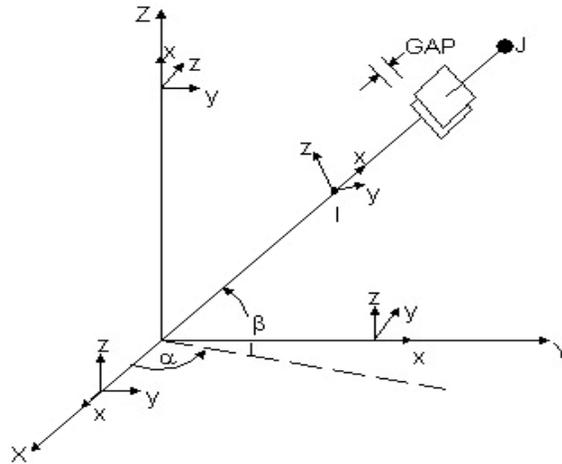
Figure (5) Contact-52 geometry [7]
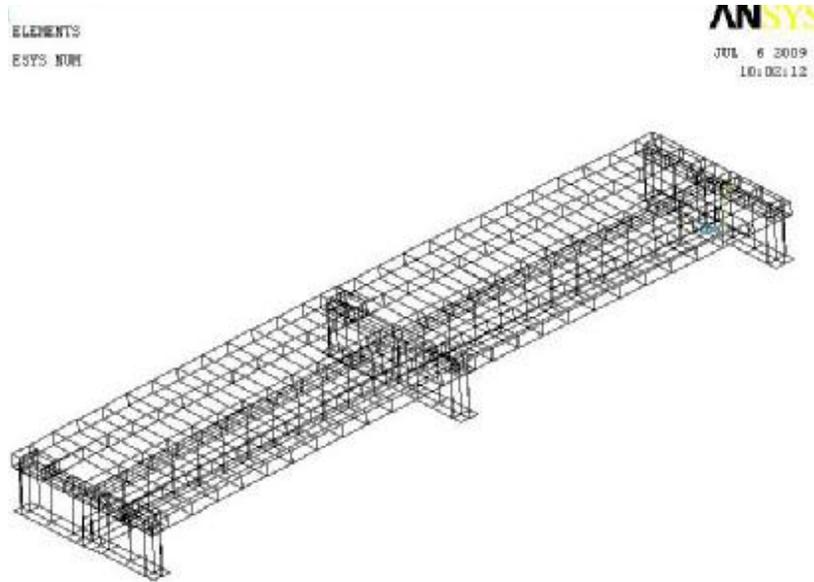
**Figure (6) Typical finite element mesh for composite beams curved in plane
(ANSYS program 11.0)**
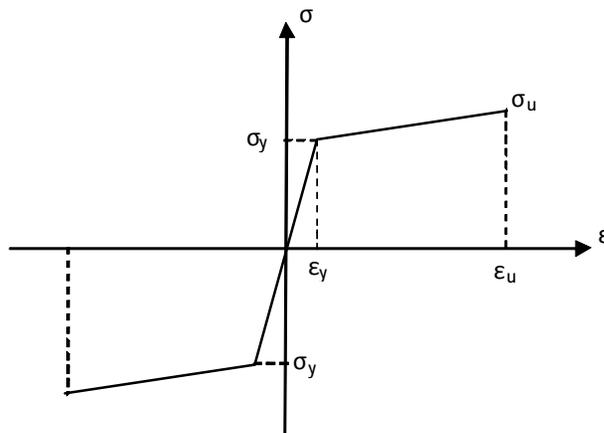
Figure (7) Idelized uniaxial stress-strain relationships for steel [7]

Eng. & Tech. Journal, Vol.28, No.12, 2010

**Nonlinear Behavior of Steel-Concrete
Composite Beams Curved in Plane
with CFRP Strips Bonding**
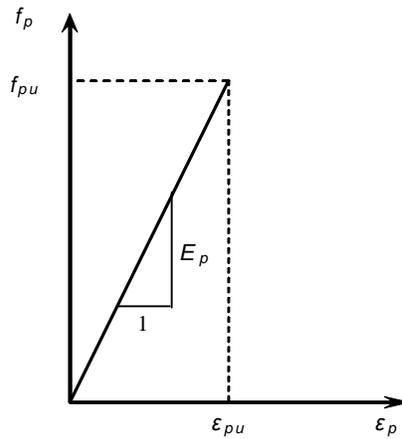
Figure (8) Idealized stress-strain relationship for CFRP composites [9]
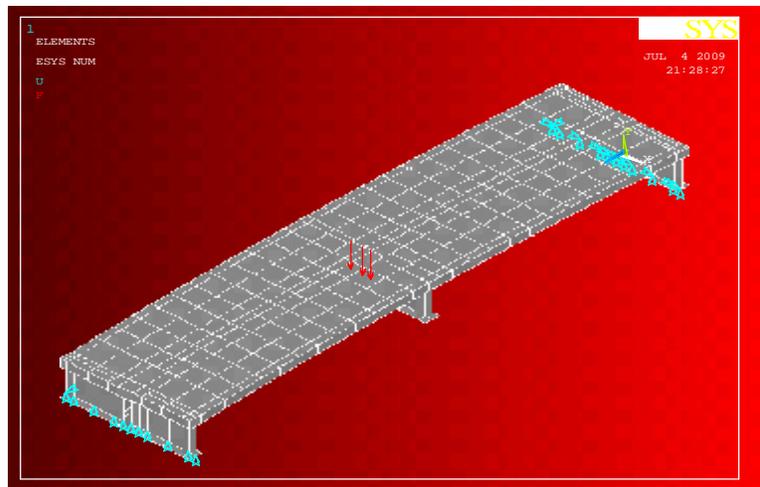
**Figure (9) ANSYS mesh of the curved composite beam (ANSYS program
11.0)**
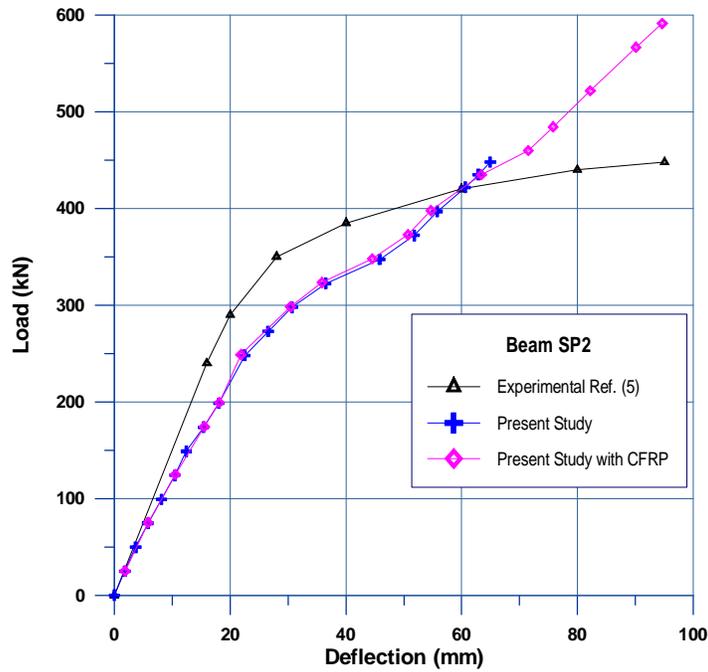
**Figure (10) Load-Deflection relationship: analytical-experimental
comparison of beam SP2**
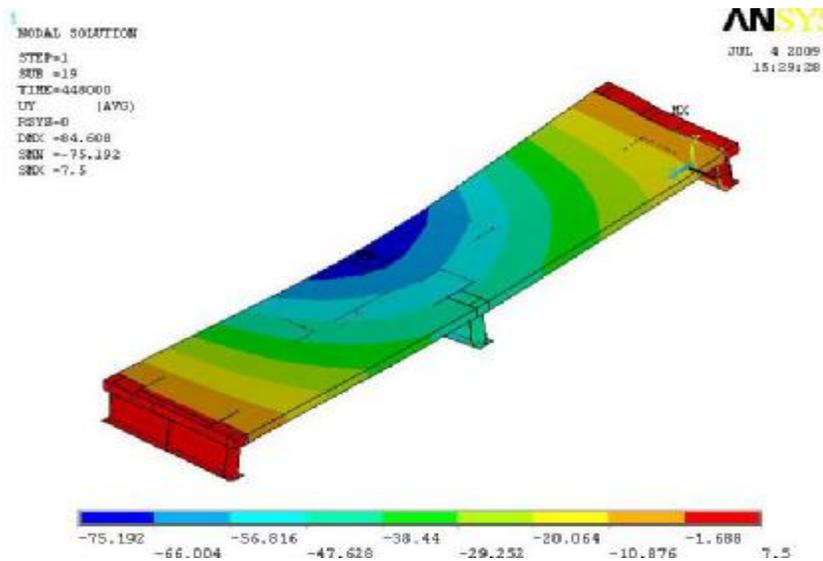
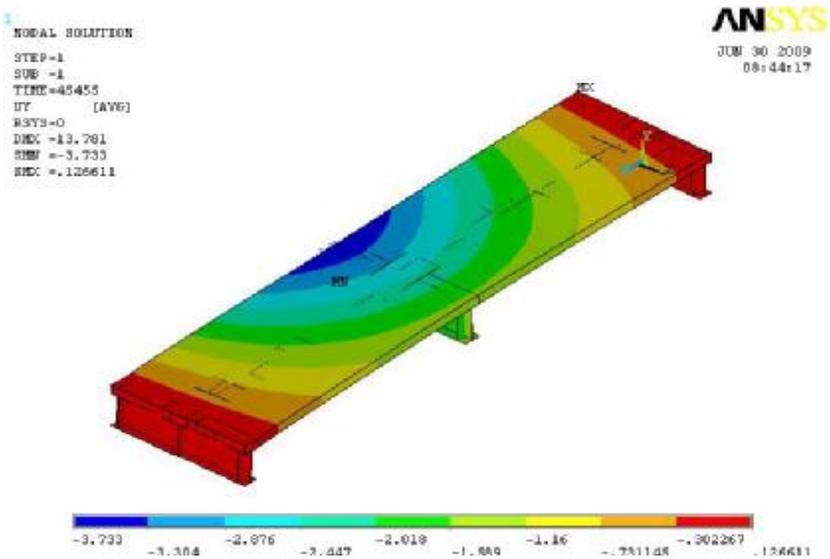**Figure (11) Stress variation along the translation-Ux (X-axis) of beam SP2**

Eng. & Tech. Journal, Vol.28, No.12, 2010

Nonlinear Behavior of Steel-Concrete Composite Beams Curved in Plane with CFRP Strips Bonding
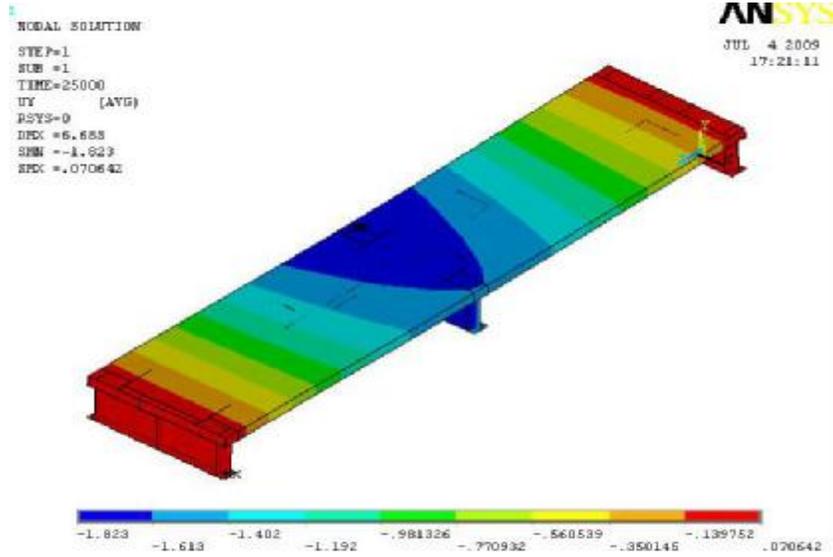
Figure (12) Stress variation along the translation-Ux (X-axis) of beam SP2 with CFRP strengthening
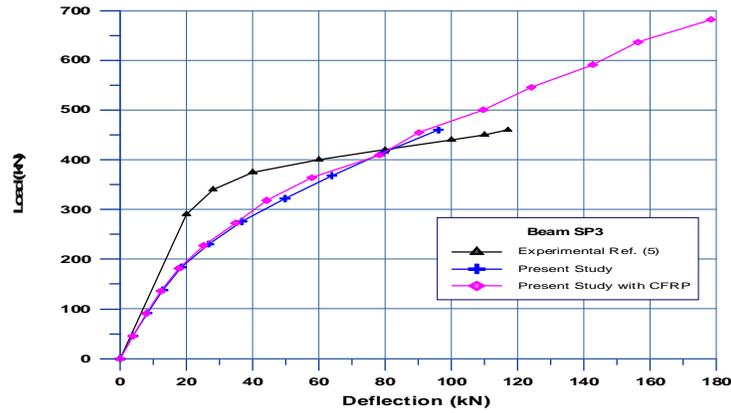
Figure (13) Load-Deflection relationship: analytical-experimental comparison of beam SP3
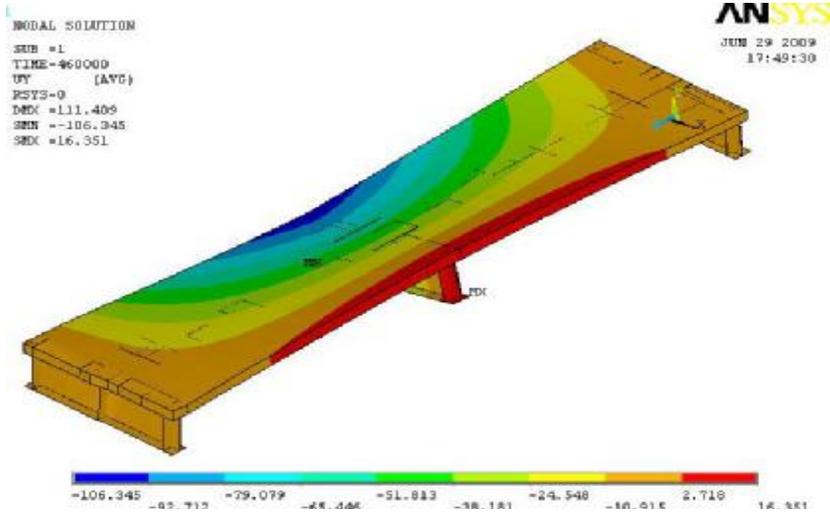
Figure (14) Stress variation along the translation-Ux (X-axis) of beam SP3

**Figure (15) Stress variation along the translation-Ux (X-axis)
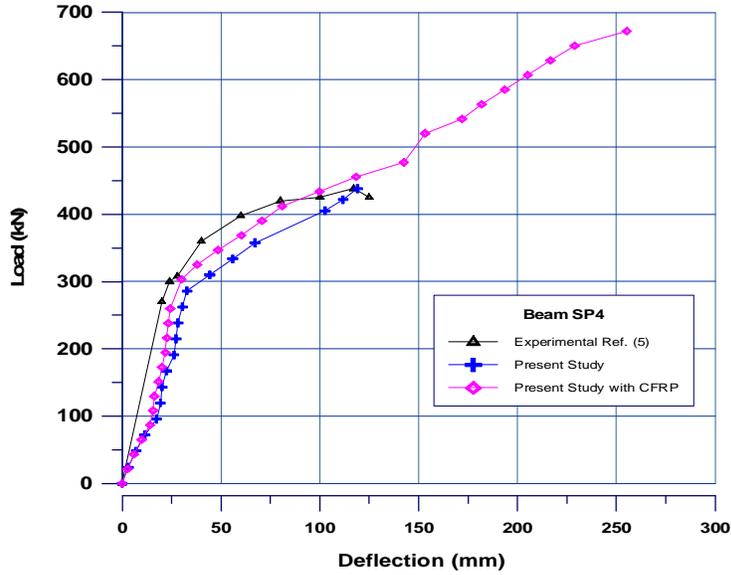of beam SP3 with CFRP strengthening**

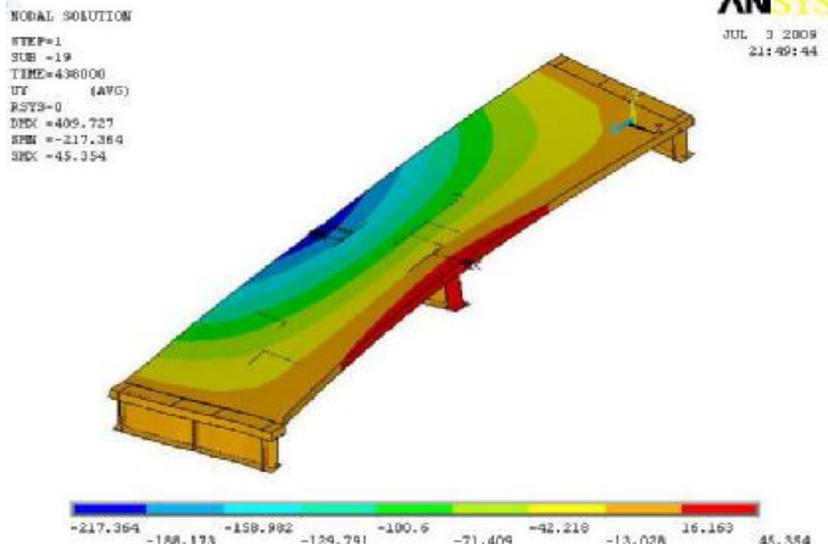**Figure (16) Load-Deflection relationship: analytical-experimental comparison of beam SP4**

Figure (17) Stress variation along the translation-Ux (X-axis) of beam SP4
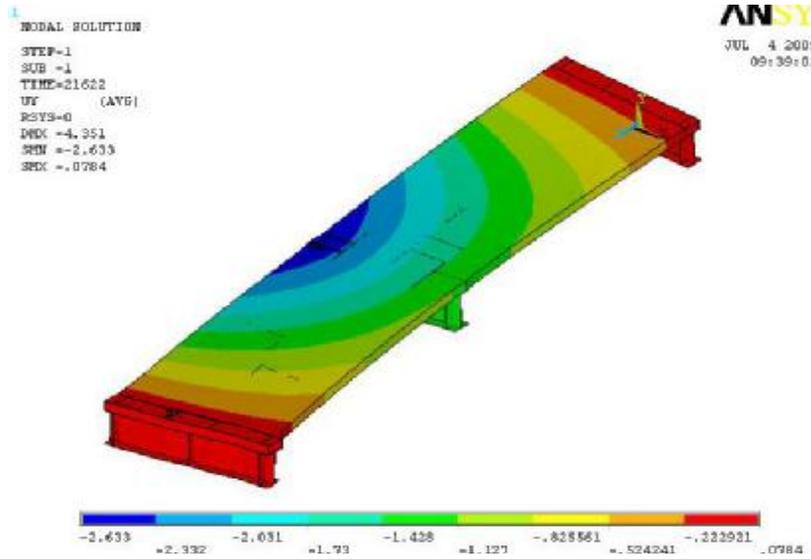
**Figure (18) Stress variation along the translation-Ux (X-axis)
of beam SP4 with CFRP strengthening**