Non - Linear Analysis of Restressed Reinforced Concrete Beams Strengthened wtth Carbon FiberReinforced Polymer Laminates

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Abstract

This research was devoted to investigate the behavior and performance of prestressed concrete beams strengthened with externally bonded Carbon Fiber Reinforced Polymer (CFRP) laminates in bending. **ANSYS V. 10.0** software was utilized in this work. Material nonlinearity due to cracking and crushing of concrete, nonlinear stress-strain response of concrete, a smeared crack model with tension stiffening of the concrete between cracks and with post-cracking shear transfer were included. Also, the short term prestress losses were considered. The concrete was simulated by 8-node brick elements with three translation degrees of freedom at each node. The reinforcing bars, prestressing strands and Carbon Fiber Reinforced Polymer (CFRP) laminates were idealized as axial members with two nodes and one translation degree of freedom at each node. Several examples of prestressed concrete beams strengthened with CFRP laminates were analyzed and compared with available experimental studies. Good agreements between the results were obtained.

Keywords: Non-linear, Finite element, ANSYS software, Prestressed beams and CFRP laminates.

التحليل اللاخطي للعتبات الخرسانية المسلحة المسبقة الجهد المقواة بألياف الكاربون البوليمرية الصفائحية

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الخلاصة

الغرض من هذا البحث هو التحري عن تصرف واداء العتبات الخرسانية المسلحة المسبقة الجهد والمقواة بالياف الكاربون البوليمرية والمعرضة الى احمال الانحناء . أستخدام التحليل اللاخطي ثلاثي الابعاد بالاعتماد على طريقة العناصر المحددة كوسيلة عددية لدراسة تصرف هذه العتبات لغاية الفشل باستعمال برنامج (**ANSYS V10.0**). في هذا البرنامج جرى الاخذ بنظر الاعتبار اللاخطية للمادة الناتجة عن تشقق وانسحاق الخرسانة والتصرف اللاخطي لعلاقة الاجهاد-الانفعال للخرسانة واستخدام أنموذج الشق المنتشر مع أعتماد أنموذج تصلب الشد للخرسانة بين الشقوق وانتقال القص. ايضاً تم الاخذ بنظر الاعتبار وجود الخسائر قصيرة المدى. تم تمثيل الخرسانة بأستخدام عناصر طابوقية ثلاثية الابعاد ذات ثمانية عقد. وتم تمثيل كل من حديد التسليح الاعتيادي و حديد التسليح مسبق الجهد و الياف الكاربون البوليمرية بأستخدام عناصر محورية ثنائية العقد. وتم تحليل عدد من العتبات الخرسانية المسبقة الجهد المقواة بألياف الكاربون البوليمرية ومقارنتها مع الدراسات العملية المتوفرة. أظهرت نتائج المقارنة بأنها أعطت نتائج جيدة.

الكلمات المفتاحية: التحليل اللاخطي، العناصر المحددة ، برنامج انسزز، العتبات المسبقة الجهد و الياف الكاربون البوليمرية الصفائحية.

البحث مستل من رسالة الماجستير للباحث الاول .

Introduction

Prestressed concrete bridge girders sometimes become structurally deficient for several reasons including corrosion of reinforcing bars or prestressing strands and changes in load requirements. In general, it is more economical to strengthen deficient girders than to replace them, Carbon Fiber Reinforced Polymer (CFRP) laminates are particularly suited for this purpose. The CFRP laminates are externally bonded to the girders and provide additional tensile resistance, which can improve flexural and shear strength. This rehabilitation technique can provide several advantages which include light weight, high strength to weight ratios, high stiffness, resistance to corrosion, good fatigue characteristics and relative ease to installation. Previous laboratory researches have shown that external application of CFRP in the tension zone of a flexural member can dramatically increase the flexural capacity of the member. The externally applied CFRP adds to the tensile capacity of the existing internal non-prestressed or prestressed tension reinforcement thereby, increasing the flexural capacity. The high tensile strength of CFRP materials provides significant increased capacity for relatively small amounts of added material.

Material Properties and Modeling Methods

Modeling of Concrete

In ANSYS V10.0 (2005) computer program requires the uniaxial stress-strain relationship for concrete in compression, which can be obtained using the following equations to compute the multilinear isotropic stress-strain curve for the concrete, (Kachlakev, *et al.* ,2001).

$$E_c = 4700\sqrt{f'c} \qquad \text{……………1}$$

$$f = \frac{E_c \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_o}\right)^2} \qquad \text{……………2}$$

$$\varepsilon_o = \frac{2f'c}{E_c} \qquad \text{……………..3}$$

$$E_c = \frac{\sigma}{\varepsilon} \qquad \text{……………4}$$

where:

σ = stress at any strain ε, N/mm^2.

ε = strain at stress f .

ε_o = strain at the ultimate compressive strength $f'c$.

The multilinear isotropic stress-strain curve implements the first point of the curve to be defined as $0.3 f'c$. The multilinear curve is used to help with convergence of the nonlinear solution algorithm. The other point are calculated from equation 2 with ε_o obtained from equation 3, strain was selected and the stress was calculated for each strain.

Cracked Concrete Model

The cracking of concrete in the present study is modeled as “smeared-cracking model”. In this approach, it is assumed that the concrete becomes orthotropic after the first cracking has occurred with zero modulus of elasticity in the direction normal to the crack, Chen and Saleeb (1982). A crack is represented by an infinite number of parallel fissures across that part of the finite element. In the present study, two coefficients of shear strength reduction are used, thus (β_o) is introduced for the case of opened crack and (β_C) is introduced for the case of closed crack. Values of β_o and β_C are always in the range of $1 > \beta_C > \beta_o > 0$, ANSYS V10.0, (2005). These values depend on the texture of the cracked surface.

Modeling of Reinforcement

Modeling of reinforcing steel in connection with the finite element analysis of reinforced concrete members is much simpler than the modeling of concrete. The steel bars are long and relatively slender, and therefore, they can be assumed to transmit axial force only. In the current work, the embedded reinforcement model with an elastic-linear work hardening model is adopted to simulate the uniaxial stress-strain behavior of reinforcing steel bars.

Modeling of Prestressed Strands

The material properties for prestressing steel were modeled using multilinear isotropic stress-strain curve developed using the following equation, Wolanski, A. J. (2004):

$$\varepsilon_{ps} \leq 0.008: f_{ps} = E_{ps}\varepsilon_{ps} \text{ (MPa)} \quad \ldots\ldots\ldots 5$$

$\varepsilon_{ps} > 0.008$:

(1723.75MPa)strand:

$$f_{ps} = 1710 - \frac{0.4}{\varepsilon_{ps} - 0.006} < 0.98 f_{pu} \text{ (MPa)} \quad \ldots\ldots\ldots 6$$

(1861.65MPa)strand:

$$f_{ps} = 1848 - \frac{0.52}{\varepsilon_{ps} - 0.0065} < 0.98 f_{pu} \text{ (MPa)} \quad \ldots\ldots\ldots 7$$

The values obtained from equations (5, 6 and 7) entered into ANSYS V10.0.

Modeling of CFRP Sheets

The material properties for CFRP sheets were modeled using a bilinear isotropic stress-strain curve up to at the ultimate strain of CFRP sheets. The local coordinate system for the FRP sheets (link8 elements) is defined where the x direction is the same as the fiber direction, while the y and z directions are perpendicular to the x direction.

Short Term Prestress Losesses

In the present study, three types of short term prestress losesses are used, Frictional losses, elastic shortening loss and anchorage loss.

Formulation of Finite Element Concrete Idealization

In the current research, three-dimensional 8-node solid elements (SOLID 65) in **ANSYS V10.0** are used to model the concrete. The element has eight corner nodes, and each node has three degrees of freedom in x, y and z as shown in figure (1). The element is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep.

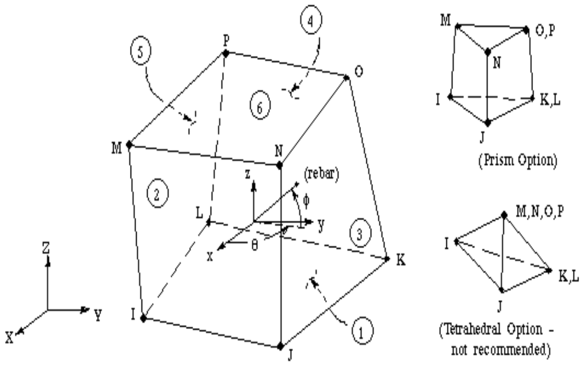


Figure (1) Solid 65 elements used for concrete, (ANSYS V10.0 (2005)).

Reinforcement and CFRP Idealization

The steel reinforcement, prestressed strands and CFRP sheets are represented by using “bar elements” (Discrete representation). The one-dimensional two-node bar element is in effect of a uniaxial tension-compression element with one degree of freedom at each node. The axial normal stress is assumed to be uniform over the entire element. The element x-axis is oriented along the length of the element from node (1) towards node (2), figure (2).

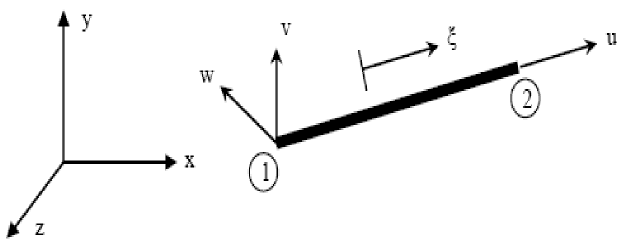


Figure (2) Bar Element (Link 8), (ANSYS V10.0 (2005)).

Bond Representation between Materials

The bond between CFRP sheets and concrete is an issue that is in need of attention. The importance of bond is that it is the means for the transfer of stress between concrete and CFRP in order to develop composite action. The type of concrete surface preparation and quality of concrete affect the bond of CFRP sheets. The delamination and peeling failure modes are directly related to the properties of the bond between the FRP and concrete substrate, Miller, B. D. (1999). The epoxy adhesive was not included in the model. In previous studies, perfect bond between materials was assumed thus, slip induced in the adhesive is ignored. Perfect bond between steel reinforcement and concrete and between concrete and FRP laminates are assumed to occur. To simulate the perfect bonding of the CFRP sheets with concrete, the nodes of link 8 elements were connected to the nodes of solid 65 elements at the interface so that two materials shared the same nodes.

Verification with Experimental Results

Four prestressed concrete girders (Rosenboom, O. A. *et al.* ,(2004), S5 Girder, Rosenboom, O. A. (2006), EB2S and EB7S girders and Rosenboom, O. A. *et al.* ,(2007), EB2S girder) were modeled using 8-node brick elements, *(2072 solid 65 elements)* and *(932 link 8 elements)* for each longitudinal bar, stirrups, prestressed strands and CFRP systems as shown in figure (3). Due to symmetry, one half of each girder was modeled as shown in figure(4). All models were supported vertically at the end and horizontally at the beam's centerline with roller supports as shown in figure(5). Detail of the experimental girder shown in figure (6). No point load are applied in the first load step, the initial prestrain was applied to the beams, (the initial strains for real constant for prestressing strands were determined from effective prestress (F_{pe}) and the modulus of elasticity (E_{ps})). Upward camber was observed in each beam In the next step, the concentrated load was applied as a line load distributed on nodes at the top of girders at midspan. Uniform increments of load have been used for applying the external load. The nonlinear analysis is conducted using full Newton-Raphson method. A convergence tolerance of (5%) is used. Different values for shear transfer parameters are used for each girder to obtain acceptable results. The parameters are summarized in table (2).

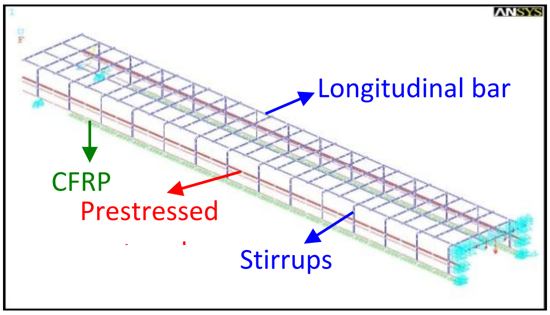


Figure (3) The used of link 8 elements in each girder.

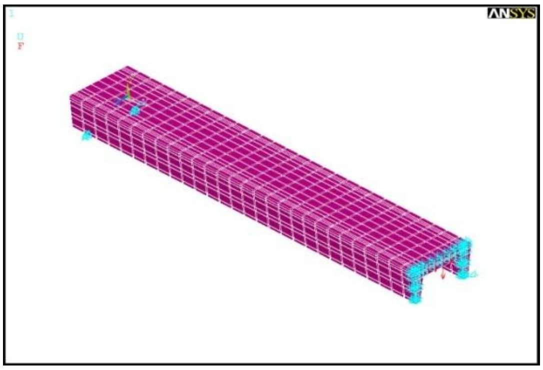


Figure (4) Finite element mesh and Boundary conditions used for the girders.

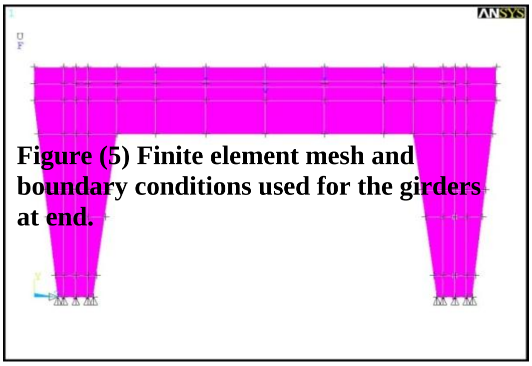


Figure (5) Finite element mesh and boundary conditions used for the girders at end.

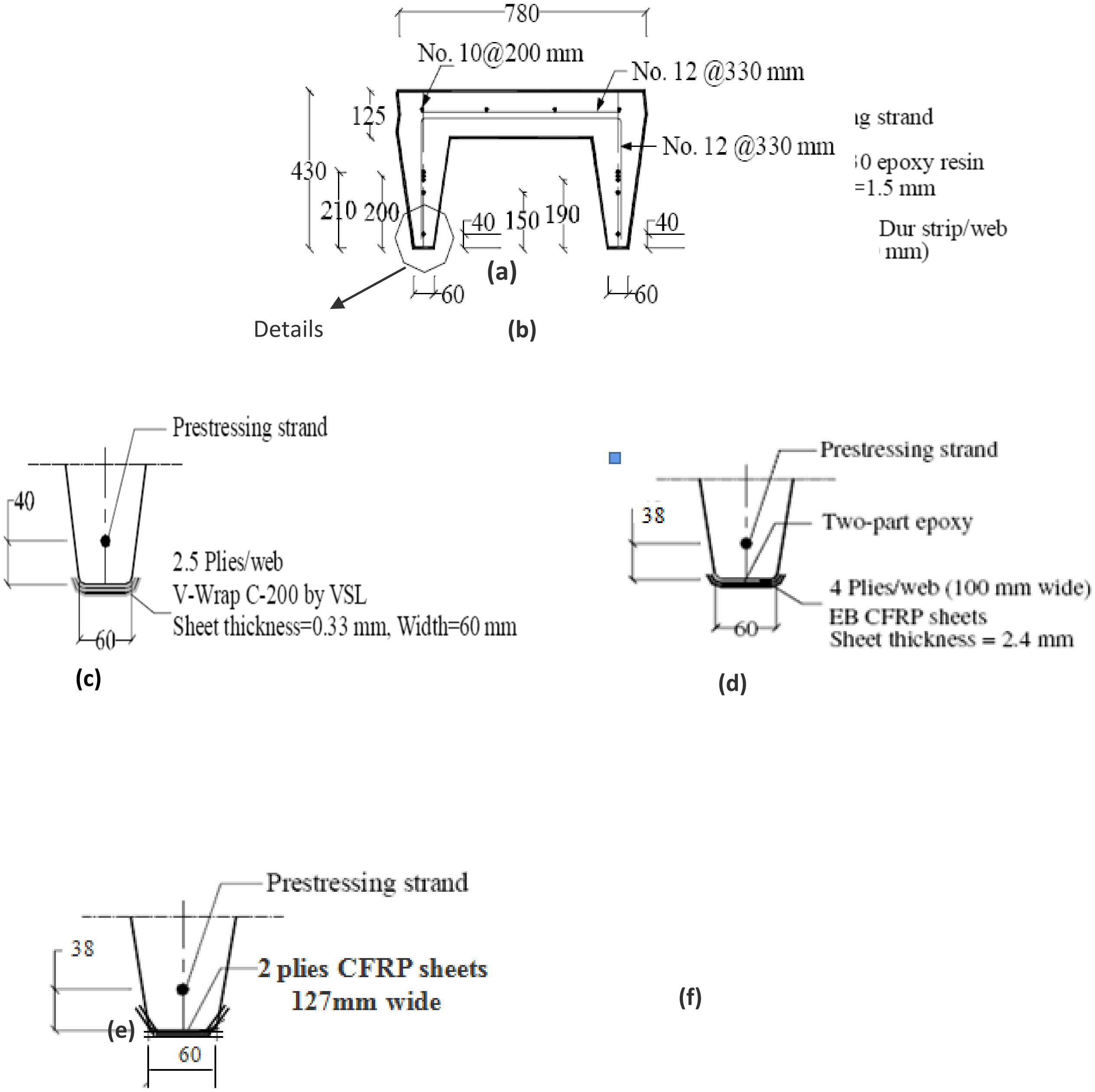


Figure (6) Plan and cross-section of C-Channel

- **(a) Plan of C-Channel**
- **(b) Section A-A**
- **(c) Detail A, Rosenboom, O. A. *et al.* 2004, S5 girder**
- **(d) Detail B, Rosenboom, O. A. 2006, EB2S girder**
- **(e) Detail C, Rosenboom, O. A. 2006, EB7S girder**
- **(f) Detail D, Rosenboom, O. A. *et al.* 2007, EB2S girder**

Rosenboom, O. A. *et al.* ,(2004) S5 Girder

The simply supported prestressed concrete girder, tested by Rosenboom, O. A. *et al.*, (2004), is one of the tested five girders. The girder was a C-Channel type prestressed concrete bridge girder. The girder had ten 1724 MPa (seven-wire stress relieved prestressing strands, five in each web), and a 125 mm flange with minimal reinforcing as shown in figure (6). The material properties are given in table (2). The girder was designed to achieve 30 percent increase in strength. The girder was strengthened with Externally Bonded (EB), two and a half 50 mm wide plies of VSL V-Wrap C-200 sheets per web bonded using VSL saturant. Failure occurred due to rupture of the sheets at midspan. The EB CFRP sheets achieved an increase in the ultimate load capacity of 10%. Figure (4) shows the experimental and numerical curves obtained for girder S5. The midspan externally applied load is plotted against the midspan deflection. For this girder, the failure load obtained by experimental work and that predicted by the finite element solutions are given in table (1). It can be noted from figure (7) and table (1) that the finite element solutions are in good agreement with the experimental results throughout the entire range of loading. Failure mode from FEA results was rupture of CFRP sheets. Figure (8) show the Deflection shape due to loading steps that explained in perverse item.

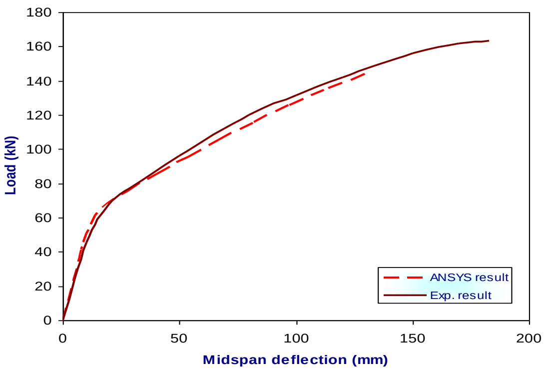
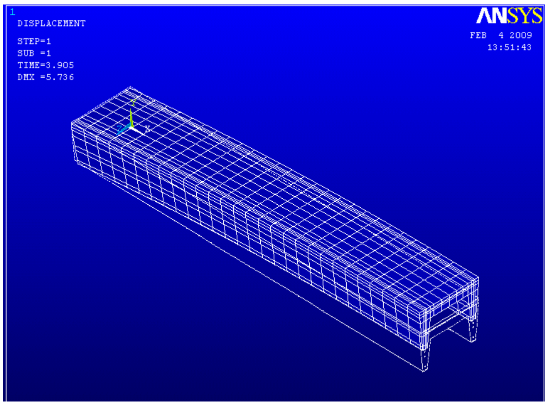
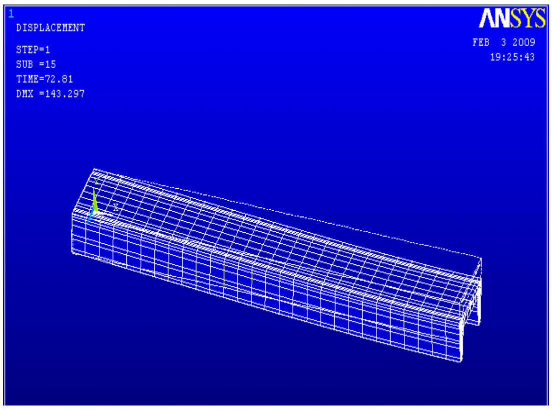


Figure (7) Rosenboom, O. A. *et al.* (2004) S5 girder, experimental and numerical load- deflection curves



a- **Upward camber**



b- Downward deflection

Figure (8) Deflection shape for Rosenboom, O. A. *et al.* ,2004, S5 girder

Rosenboom, O. A. (2006) EB2S Girder

The simply supported prestressed concrete girder, tested by Rosenboom, O. A. (2006), is one of the eleven girders that were tested under static loading. The girder was a C-Channel type prestressed concrete bridge girder. The girder had ten 1724 MPa (seven-wire stress relieved prestressing strands, five in each web), and a 127 mm flang with minimal reinforcing as shown in figure (6). The material properties are given in table (2). The girder is designed to achieve 20 percent increase in strength. The girder was strengthened with Externally Bonded (EB), two and a half 51 mm wide plies of VSL C-200 wet lay-up sheets per web bonded using VSL resin. Failure occurred due to rupture of the sheets at midspan. The EB CFRP sheets achieved an increase in the ultimate load capacity of 10%.

The finite element load-deflection curve, obtained for the EB2S girder, is shown in figure (9) along with corresponding experimental results. The behavior obtained using the numerical models is approximately similar to the reported experimental observations throughout the whole loading process as can be seen from the load-deflection curve. Failure mode from FEA results was rupture of CFRP sheets. Table (1) shows the experimental and the analytical load-carrying capacity of the EB2S girder and the differences between them. Figure (10) show the Deflection shape due to loading steps that explained in perverse item.

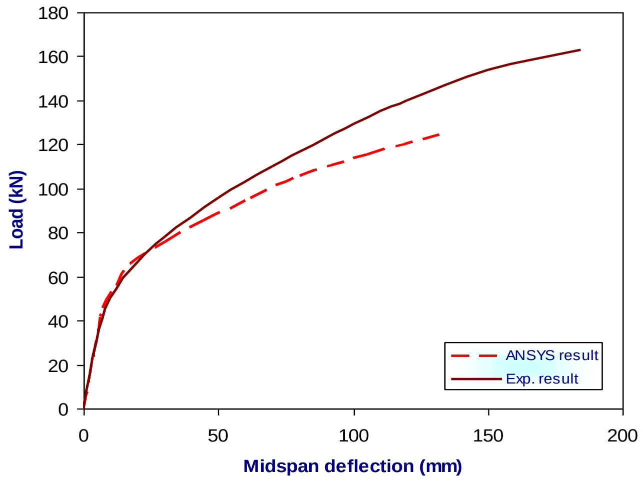
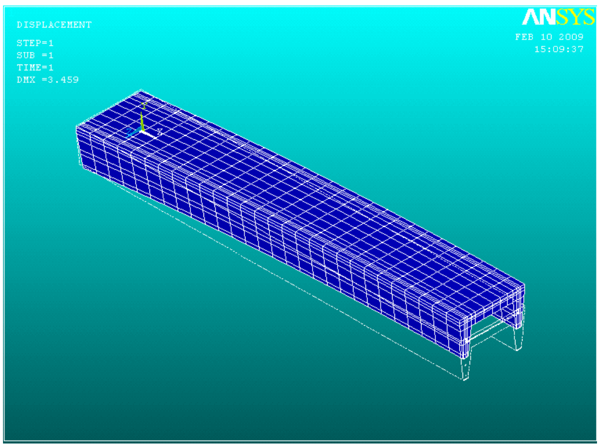
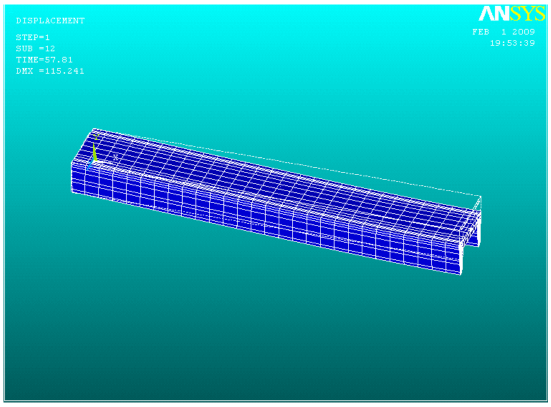


Figure (9) Rosenboom, O. A. 2006, B2S girder, experimental and numerical load - deflection curves



a- **Upward camber**



b- Downward deflection

Figure (10) Deflection shape for Rosenboom, O. A. 2006, EB2S girder

Rosenboom, O. A. (2006) EB7S Girder

The simply supported prestressed concrete girder, tested by Rosenboom, O. A. (2006), is one of the eleven girders that were tested under static loading. The girder was a C-Channel type prestressed concrete bridge girder. The girder had ten 1724 MPa (seven-wire stress relieved prestressing strands, five in each web), and a 127 mm flang with minimal reinforcing as shown in figure (6). The material properties are given in table (2). The girder is designed to achieve 30 percent increase in strength. The girder was strengthened with Externally Bonded (EB), two 127 mm wide plies of Hexcel sheets per web bonded using Sika Hex 306 resin. Failure occurred due to concrete crushing. The EB CFRP sheets achieved an increase in the ultimate load capacity of 30.2%. The main results of the investigation are summarized in table (1), which gives the experimental and analytical load-carrying capacity that can be sustained by the EB7S girder. Whereas, the analytical and experimental load-deflection relationships are drawn together in figure (11). In general, this figure shows acceptable agreement between the finite element solutions and the experimental results. Failure mode from FEA results was rupture of CFRP sheets. Figure (12) show the Deflection shape due to loading steps that explained in perverse item.

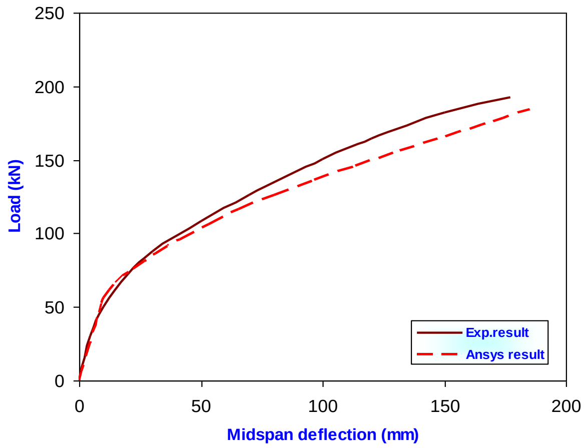
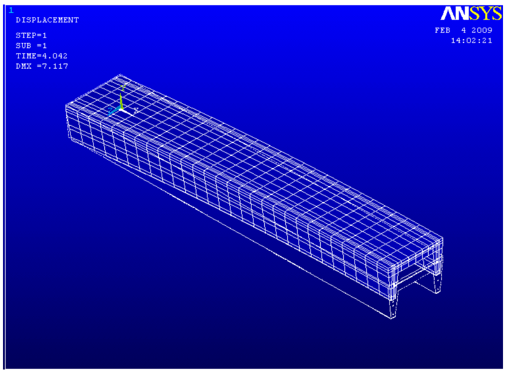
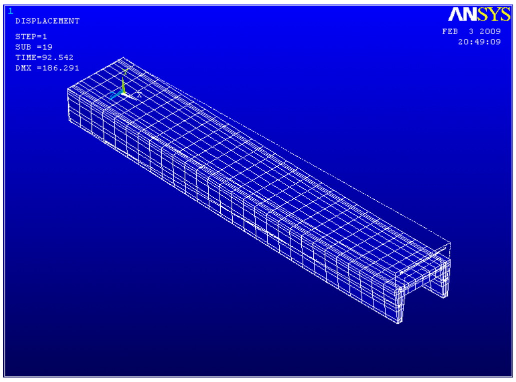


Figure (11) Rosenboom, O. A. 2006, EB7S girder, experimental and numerical load -deflection curves



a- **Upward camber**



b- Downward deflection

Figure (12) Deflection shape for Rosenboom, O. A. 2006, EB7S girder Rosenboom *et al*., (2007) EB2S Girder

The simply supported prestressed concrete girder, tested by Rosenboom *et al*., (2007), is one of the eight girders that were tested under static loading, five had ten 1724 MPa prestressing strands and three had eight 1862 MPa prestressing strands. The girder was a C-Channel type prestressed concrete bridge girder. The girder had ten 1724 MPa (seven-wire stress relieved prestressing strands, five in each web), and a 127 mm deck with minimal reinforcing as shown in figure (6). The material properties are given in table (2). The girder was designed to achieve 60 percent increase in strength. The girder was strengthened with Externally Bonded (EB), four 100 mm wide plies of wet lay-up sheets per web bonded using. Failure occurred due to rupture of CFRP sheets near midspan. The EB CFRP sheets achieved an increase in the ultimate load capacity of 60%.

The experimental and the numerical load-deflection curves for EB2S girder are shown in figure (13). Excellent agreement is obtained by using the finite element method compared with the experimental results throughout the entire range behavior. Table (1) shows a comparison between the experimental and predicted failure loads. Failure mode from FEA results was rupture of CFRP sheets. Figure (14) show the Deflection shape due to loading steps that explained in perverse item.

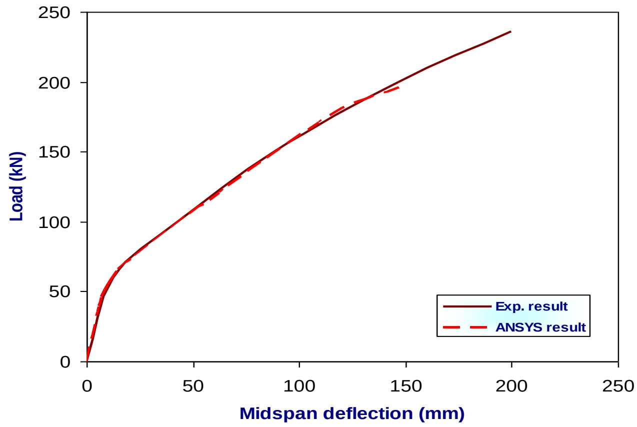
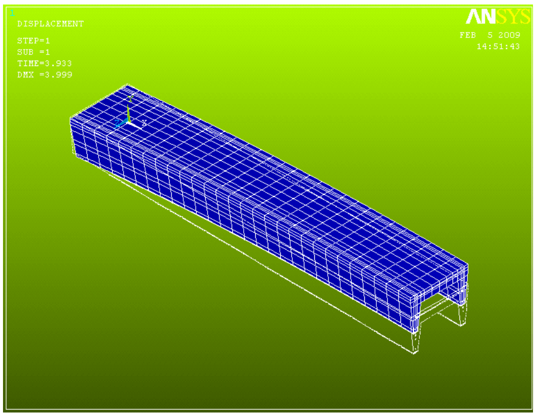
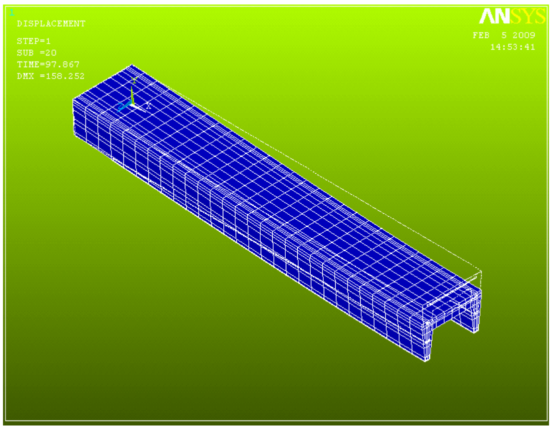


Figure (13) Rosenboom, O. A. *et al.* ,2007, EB2S girder, experimental and numerical load-deflection curves



a- **Upward camber**



b- Downward deflection

Figure (14) Deflection shape for Rosenboom, O. A. *et al.* ,2007, EB2S girder

Table (1) Experimental and redictedfailure loads for the analyzed girders

Results / Girders	Ultimate load from Exp.(kN)	Ultimate load from FEA (kN)	(Exp. Ultimate Load-FEA ultimate load) / Exp. Ultimate Load %	Failure mode
Rosenboom, O. A. *et al.* ,(2007) EB2S Girder	236	195.7	-17.1	Rupture of CFRP sheets
Rosenboom, O. A. (2006), EB7S Girder	192.2	184.2	-4.2	Concrete crushing
Rosenboom, O. A. (2006), EB2S Girder	163.2	125.6	-23.04	Rupture of CFRP sheets
Rosenboom, O. A. *et al.* ,(2004) S5 Girder	163	145.6	-10.7	Rupture of CFRP sheets

Discussion of strengthening approach

In laboratory the experimental girder strengthened with CFRP sheets after applying prestressing force as compared with the design girder using ANSYS programs, all elements (concrete, prestressing strand, steel and CFRP sheets) modeled before applying the initial prestrain. Upward camber was observed in each beam, and herein only FEA values are available since the beams were not instrumented during the prestressing operation in the laboratory. Thus, the load-displacement response of each beam starts from zero displacement. So that the displacement obtained from the FEA was shifted to give a fair comparison to the experimental data. In the next step, point load was applied. So that this procedure effected on the failure load that predicted by the finite element solutions.

Table (2) Material properties andparameters used for the analyzed girders.

	Property	Definition	Rosenboom, O. A. *et al.*(2007), EB2S Girder	Rosenboom, O. A. (2006), EB7S Girder	Rosenboom, O. A. (2006), EB2S Girder	Rosenboom, O. A. *et al.* (2004), S5 Girder
Concrete	f'_c	Compressive strength, (MPa)	69.5	47.3	51	51
Concrete	E_c	Young's modulus, (MPa)	39182.33	32324.25	33564.7	33564.7
Concrete	f_t	Tensile strength, (MPa)	5.2	4.3	4.45	4.45
Concrete	ν_c	Poisson's ratio	0.2	0.2	0.2	0.2
Concrete	γ_c	Concrete density, (kN/m^3)	24	24	24	24
Concrete	ε_{uc}	Ultimate compressive strain, (mm/mm)	0.003	0.0032	0.0026	0.0026
Mild Steel	f_y	Yield stress, (MPa)	ϕ12 400* ϕ10 400*	ϕ12 358 ϕ10 358	ϕ12 358 ϕ10 358	ϕ12 400* ϕ10 400*
Mild Steel	E_s	Young's modulus, (MPa)	200000*	204495	204495	200000*
Mild Steel	ν_s	Poisson's ratio	0.3	0.3	0.3	0.3
Shear Transfer Parameters	β_o	for opened crack	0.2	0.25	0.25	0.25
Shear Transfer Parameters	β_c	for closed crack	0.9	0.7	0.8	0.8
Prestressing Strand	E_{ps}	Elastic modulus, (MPa)	200000	193060*	193060*	193060*
Prestressing Strand	f_{py}	Yield stress, (MPa)	1465.4	1465.4	1465.4	1465.4
Prestressing Strand	ν_{ps}	Poisson's ratio	0.3	0.3	0.3	0.3
Prestressing Strand	D	Diameter used, (mm)	9.525*	9.525*	9.525*	9.525*
CFRP	ε_{in}	Initial strain in Prestressing strand, (mm/mm)	0.0052	0.0054	0.0054	0.00544
CFRP	f_{fu}	Tensile strength, (MPa), Manufacturer	338	611	669	3790
CFRP	E_f	Young's modulus, (MPa)	46486	64900	50490	228000
CFRP	ν_f	Poisson's ratio	0.22*	0.22*	0.22*	0.22*
CFRP	b_f	Width of CFRP, (mm)	100	127	51	60
CFRP	t_f	Thickness of CFRP, (mm)	2.4	1	1.27	0.33
CFRP	ε_f	Ultimate tensile strain (mm/mm) Experimental	0.0117	0.0102	0.0129	0.0117
CFRP	Type of CFRP systems		Wet lay-up sheets	Hexcel sheets	VSL C-200 wet lay-up sheets	VSL v-200 wet lay-up sheets

$E_c = 4700\sqrt{f'_c}$ $f_t = 0.62\sqrt{f'_c}$ *Assumed value

Conclusions

1- Comparisons of the FEA results with the available experimental data show that maximum difference was 10.7%, 23.04%, 4.2% and 17.1%, respectively for the four strengthened prestressed concrete girders.

2- The finite element method adopting ANSYS program can be used to investigate the behavior of prestressed concrete beams strengthened with CFRP laminates.

Recommendations for Future Work

The bending behavior of prestressed concrete members strengthened with externally bonded CFRP requires further investigations. The areas, which are to be of particular importance, are listed here in:

1. Further studies should focus on the bond behavior of externally bonded CFRP system for prestressed concrete members.
2. The torsional and shear behavior of prestressed reinforced concrete beam strengthened with CFRP laminates need to be investigated.
3. Further studies should focus on the behavior of repaired prestressed concrete members with externally bonded CFRP system.
4. The experimental shear behavior of prestressed concrete members strengthened with CFRP sheets need to be investigated.

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