Parametric Study for Prestressed Reinforced Concrete Beams Strengthened with Carbon Fiber Reinforced Polymer Laminates

***Hayfaa Dhumad Hasan **Khalid Shaker Mahmoud **Abbas Abd Almged Allawi**

*Ministry of Science and Technology/Directorate of Technical Affairs/Baghdad-Iraq

**Baghdad University/Collage of Engineering/Civil Engineering Department/ Baghdad-Iraq

E mail: haifaadhamad@yahoo.com

Abstract

This research presents a parametric study and a design guideline for the flexural strength of prestressed concrete girders strengthened by CFRP sheet adopting the ACI 318-08, AASHTO LRFD (2004) and ACI committee 440 (2002) procedure. A three-dimensional nonlinear finite element analysis has been used to conduct a numerical investigation on the general behavior of strengthened beams up to failure. ANSYS V. 10.0 software was utilized in this work. Parametric studies are carried out to study the effect of compressive strength of concrete, number of layers of CFRP systems, type of CFRP systems and both type and number of layers of CFRP systems on the behavior of prestressed concrete girders and the load carrying capacity. The design method suggested by ACI 440R-02, the modified equation of ACI 318-08 and AASHTO LRFD (2004) is evaluated based on a comparison made along with previous experimental and with finite element analysis results; these design methods are in a good agreement with results and can be adopted to calculate ultimate capacity of prestressed concrete beams strengthened with CFRP laminates.

Key words: ANSYS Software, Prestressed Beams and CFRP laminates.

دراسة العوامل المؤثرة للعتبات الخرسانية المسلحة المسبقة الجهد المقواة بألياف الكاربون البوليمرية الصفائحية

***هيفاء ضمد حسن **خالد شاكر محمود **عباس عبد المجيد علاوي**

*وزارة العلوم والتكنولوجيا / دائرة الشؤون الفنية / بغداد– العراق

**جامعة بغداد / كلية الهندسة / قسم الهندسة المدنية / بغداد– العراق

الخلاصة

هذا البحث يقدم دراسة العوامل المؤثرة والدليل التصميمي للعتبات الخرسانية المسلحة المسبقة الجهد المقواة بألياف الكاربون البوليمرية الصفائحية باستخدام المواصفة في كل من ACI 440R-02 ,ACI 318-08 و . AASHTO LRFD (2004) تم استخدام التحليل اللاخطي ثلاثي الابعاد بالاعتماد على طريقة العناصر المحددة كوسيلة عددية لدراسة تصرف هذه العتبات لغاية الفشل باستعمال برنامج ANSYS V10.0. و تمت دراسة تأثير كل من قابلية انضغاط الخرسانة و عدد طبقات الياف الكاربون البوليمرية و نوع الياف الكاربون البوليمرية و كل من نوع وعدد الياف الكاربون البوليمرية على سلوك وقيمة الحمل الاقصى للعتبات الخرسانية المسبقة الجهد. أخيراً جرى تقييم طريقة التصميم التي تخص العتبات الخرسانية المسلحة المسبقة الجهد والمقواة بالياف الكاربون البوليمرية والمقترحة من قبل المواصفة في كل من ACI 440R-02 والمعادلة المعدلة من ACI 318-08 و AASHTO LRFD (2004) بموجب النتائج العملية السابقة وطريقة العناصر المحددة. تبين ان هذه الطريقة يمكن أستخدامها لحساب العزم الاقصى للعتبات الخرسانية المسلحة المسبقة الجهد والمقواة بالياف الكاربون البوليمرية.

الكلمات المفتاحية: برنامج انسزز، العتبات المسبقة الجهد و الياف الكاربون البوليمرية الصفائحية.

البحث مستل من رسالة الماجستير للباحث الأول

Introduction

Since the late 1980's, research into the use of Fiber Reinforced Polymer (FRP) for external repair and retrofit of concrete flexural member, has progressed rapidly. Researchers have considered various types of FRP, different application techniques and various loading conditions. Limited research is available on the performance of field applied FRP and on application of FRP materials to prestressed concrete beams. 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.The aim of research is to study the effect of compressive strength of concrete, number of layers of CFRP systems, type of CFRP systems and both type and number of layers of CFRP systems on the behavior of prestressed concrete girders and the load carrying capacity.

Material Properties and Representation Methods

Representation of Concrete

The multilinear isotropic stress-strain curve for the concrete can be obtained using the following equations to represent the uniaxial stress-strain relationship for concrete in compression.

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

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

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

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

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 $0.3f'c$. 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, (Kachlakev, *et al.* 2001).

Cracked Concrete Model

A crack is represented by an infinite number of parallel fissures across that part of the finite element. The cracking of concrete in the present study is modeled as "smeared-cracking model", 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, Chen and Saleeb (1982). 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.

Representation of Reinforcement

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.

Representation 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):

$$\varepsilon_{ps}\le 0.008: \qquad f_{ps}=E_{ps}\varepsilon_{ps} \qquad \text{(MPa)} \qquad \text{……………..5}$$

$\varepsilon_{ps}>0.008:$

(1723.75MPa)strand:

$$f_{ps} = 1710 - \frac{0.4}{\varepsilon_{ps} - 0.006} < 0.98 f_{pu} \quad \text{(MPa)} \quad \ldots\ldots\ldots\ldots\ldots\ldots6$$

(1861.65MPa)strand:

$$f_{ps} = 1848 - \frac{0.52}{\varepsilon_{ps} - 0.0065} < 0.98 f_{pu} \quad \text{(MPa)} \quad \ldots\ldots\ldots\ldots\ldots\ldots7$$

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

Representation 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 Losses

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 Fig. (1). The element is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep.

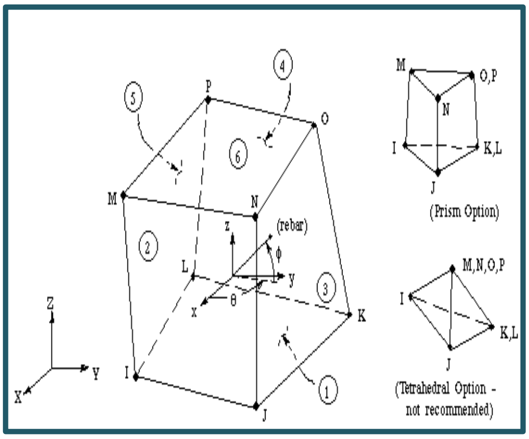


Figure (1) Solid 65 Elements Used for concree, (ANSYS V10.0 (2005)).

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), Fig. (2)

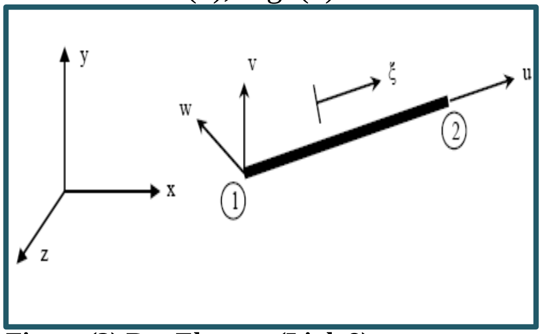


Figure (2) Bar Element (Link 8), (ANSYS V10.0 (2005)).

Bond Representation Between Materials

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, (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.

Parametric Study

The parametric study is carried out to investigate the behavior of simply supported prestressed concrete girders having different types of CFRP system, layers and the compressive strength of concrete. For the parametric study, one or two parameter is assumed to vary while the others are kept constants in order to clarify the effect of the parameter considered. Four prestressed concrete girders (Rosenboom, *et al.*) 2004), S5 Girder, Rosenboom, O. A. (2006), EB2S and EB7S girders and Rosenboom, *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 Fig. (3) Due to symmetry, one half of each girder was modeled as shown in Fig. (4) All models were supported vertically at the end and horizontally at the beam's centerline with roller supports as shown in Fig. (5) Detail of the experimental girder shown in Fig. (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 used in the parametric study are summarized in table (1). The material properties of each type of CFRP system used in the parametric study are given in table (2).

Table (1) Parameters Used in the Parametric Study

Parameters	Case 1	Case 2	Case 3
The compressive strength of concrete (f'c), (MPa)	40	50	60
No. of layers of CFRP system	1	2	4
Type of CFRP system	MBrace MBrace EB900	Replark (Mistsubishi) Grade HM	Sika SikaWrap Hex.100G

Table (2) Material Properties for CFRP System Used in the Parametric Study

Type of CFRP system		Tensile strength, f_{uf} (MPa)	Thickness, t_f (mm)	Modulus of elasticity, E_f (MPa)	Elongation at failure, ε_{uf} (mm/mm)
System 2	MBrace MBrace EB900	1730	0.353	88000	2%
System 3	Replark (Mistsubishi) Grade HM	1900	0.14	640000	0.3%
System 4	Sika SikaWrap Hex.100G	600	0.36	26100	2.2%

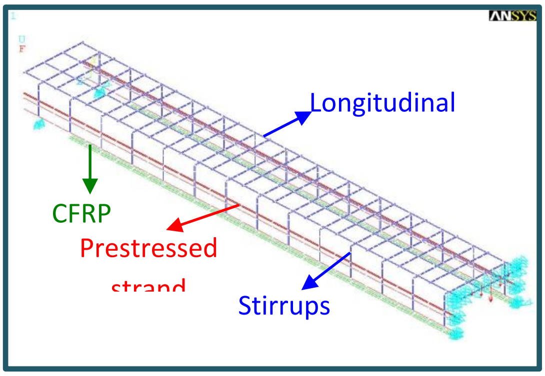


Figure (3) The Used of Link 8 Elements in Each Girder

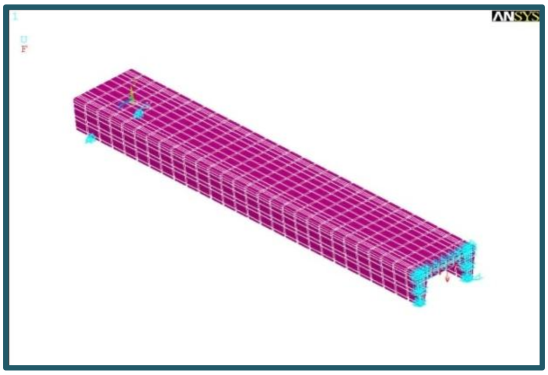


Figure (4) Finite Element Mesh and Boundary Conditions Used for the Girders.

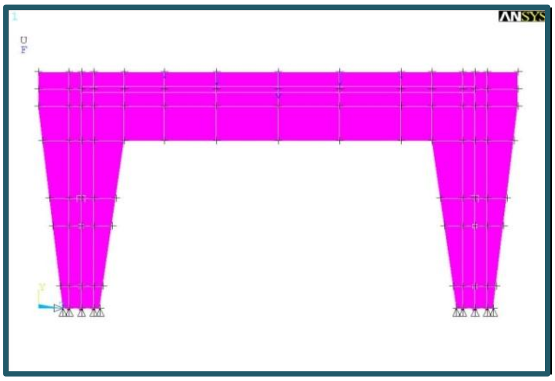


Figure (5) Finite Element Mesh and Boundary Conditions Used for the Girders at End.

Effect of the Compressive Strength of Concrete (f'c)

To investigate the effect of the compressive strength of concrete (f'c) on the behavior of the four considered girders, two cases of (f'c) for each girder are used in addition to the compressive strength of concrete value used in the experimental work for the girder. The results show that the increase in the compressive strength of concrete (f'c) caused an increase in the load carrying capacity. Fig. (7) shows the effect of compressive strength of concrete (f'c) on the load-deflection curve. Comparison for the ultimate load capacity of members strengthened with CFRP sheets and having compressive strength (f'c) of 40MPa with having compressive strength (f'c) of 50 and 60MPa shows:

- Case 2 and case 3 caused an increase of 15.9% and 23.9% respectively, in the load carrying capacity for S5 girder of Rosenboom, *et al.* (2004).
- Case 2 and case 3 caused an increase of 18.94% and 28.4% respectively, in the load carrying capacity for EB2S girder of Rosenboom, (2006).
- Case 2 and case 3 caused an increase of 1.09% and 6.5% respectively, in the load carrying capacity for EB7S girder of Rosenboom, (2006).
- Case 2 and case 3 caused an increase of 6.6% and 6.6% respectively, in the load carrying capacity for EB2S girder of Rosenboom, *et al.* (2007).

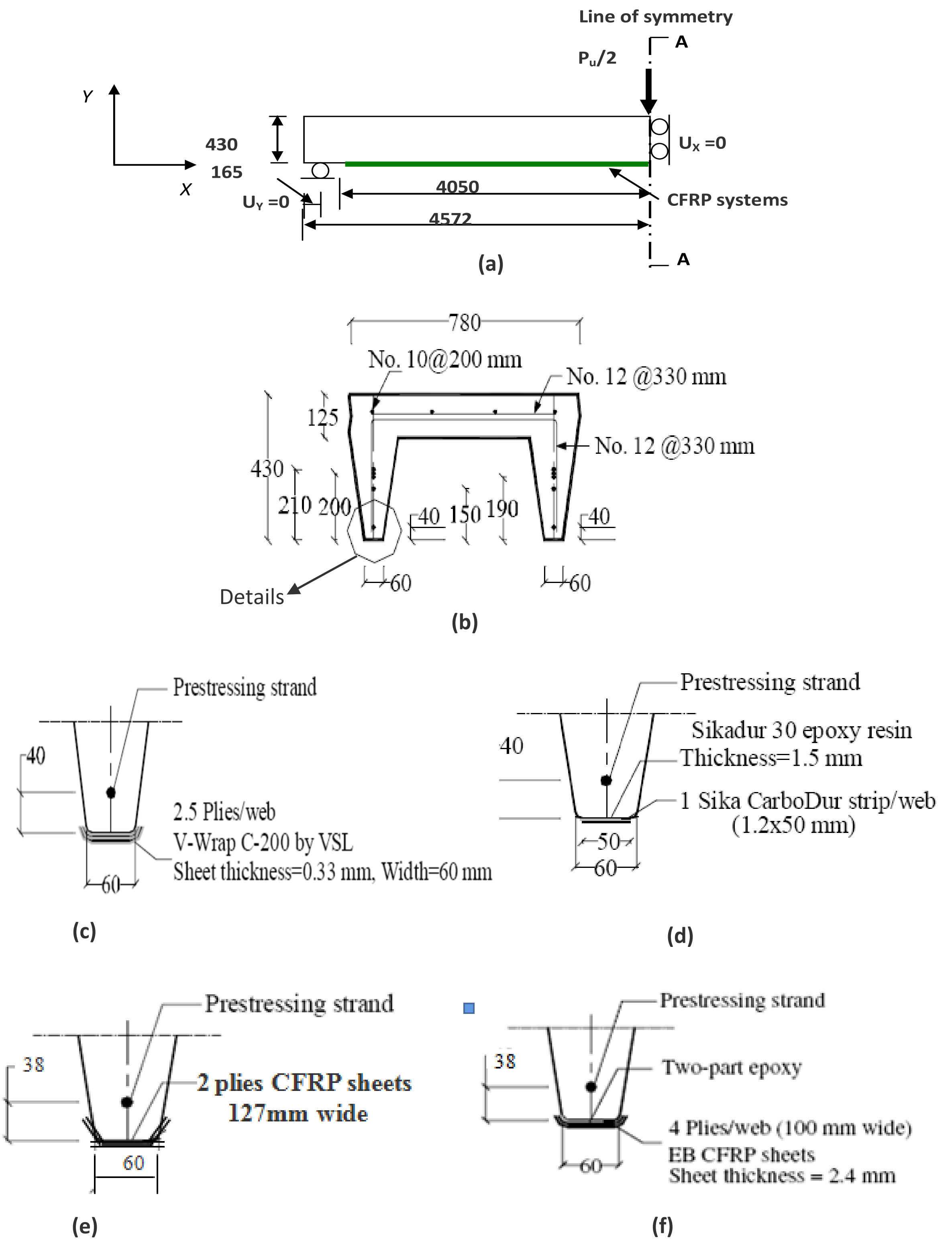


Figure (6) Plan and cross-section of C-Channel

(a) Plan of C-Channel

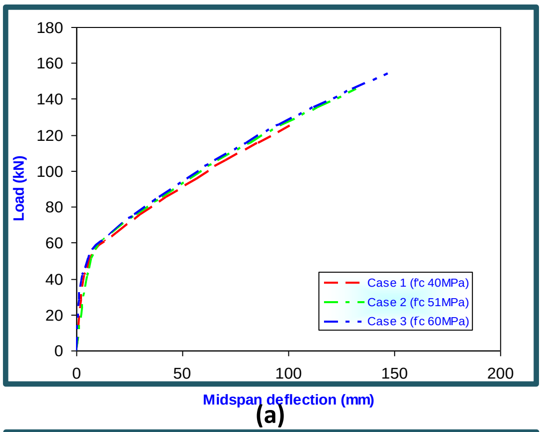
(b) Section A-A

(c) Detail A, Rosenboom, *et al.* 2004, S5 girder

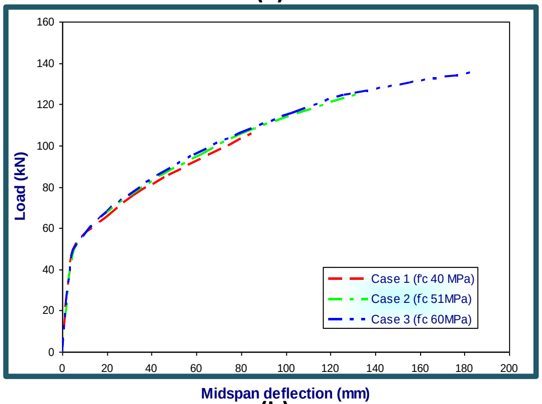
(d) Detail B, Rosenboom, 2006, EB2S girder

(e) Detail C, Rosenboom, 2006, EB7S girder

(f) Detail D, Rosenboom, *et al.* 2007, EB2S girder



(a)



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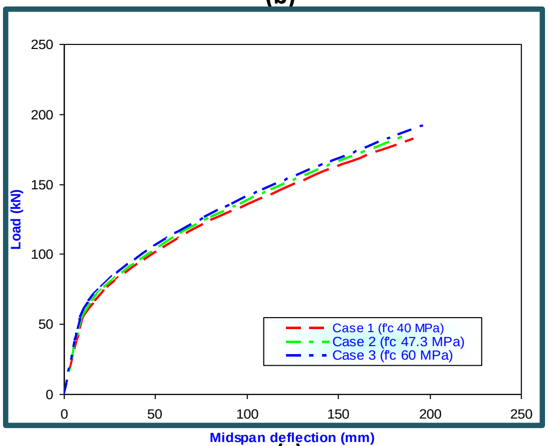

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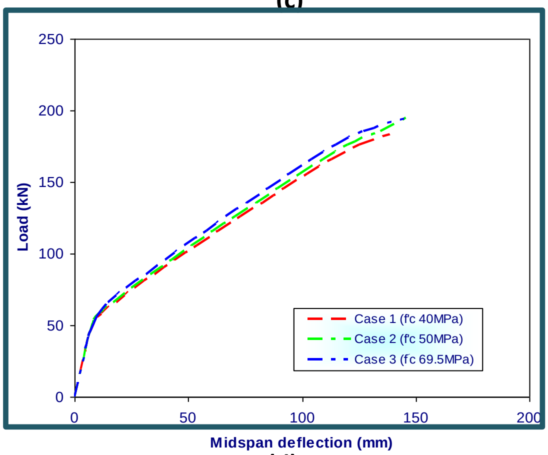


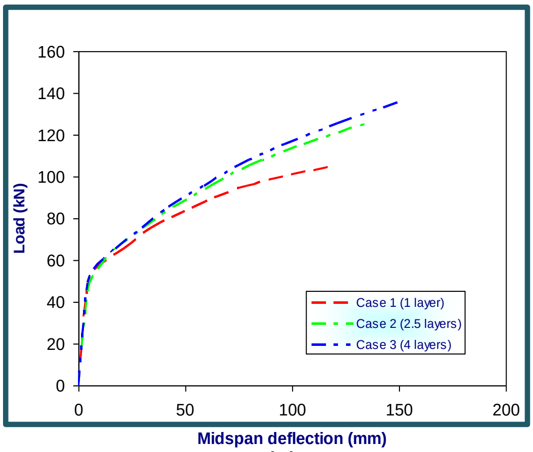
(d)

Figure (7) Effect of Compressive Strength of Concrete (f'c) on load-deflection Relation
(a) Girder S5, Rosenboom, *et al.* (2004)
(b) Girder EB2S, Rosenboom, (2006)
(c) Girder EB7S, Rosenboom, (2006)
(d) Girder EB2S, Rosenboom, *et al.* (2007)

Effect of Number of Layers of CFRP Sheets

To investigate the effect of number of layers of CFRP sheets on the behavior of the four considered girders, two cases of layers number for each girder are used in addition to the references number of layers used for the girder. The results show that the increase in number of layers of CFRP sheets applied to prestressed concrete girders caused an increase in the load carrying capacity. Fig. (8) shows the effect of number of layers of CFRP sheets on the load-deflection curve. Comparison of one layer of CFRP sheet with two and four layers of CFRP sheets of the investigated girders are as follows:

- Case 2 and case 3 caused an increase of 15.9% and 30.5% respectively, in the load carrying capacity for S5 girder of Rosenboom, *et al.* (2004).
- Case 2 and case 3 caused an increase of 18.94% and 28.4% respectively, in the load carrying capacity for EB2S girder of Rosenboom, (2006).
- Case 2 and case 3 caused an increase of 73.5% and 82.7% respectively, in the load carrying capacity for EB7S girder of Rosenboom, (2006).
- Case 2 and case 3 caused an increase of 69.14% and 17.3% respectively, in the load carrying capacity for EB2S girder of Rosenboom, *et. al.* (2007).



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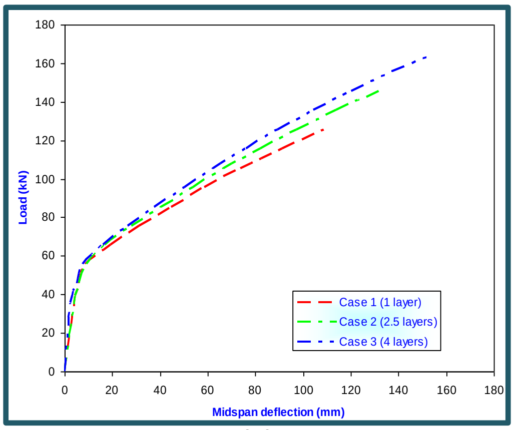

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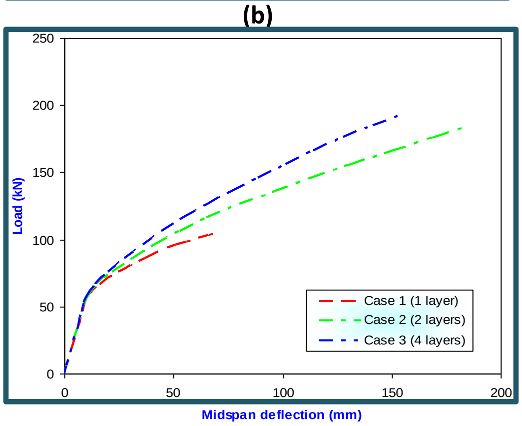

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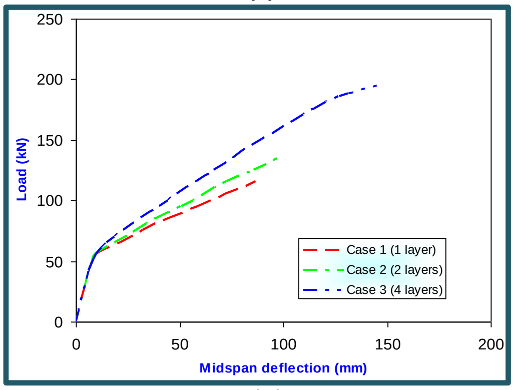


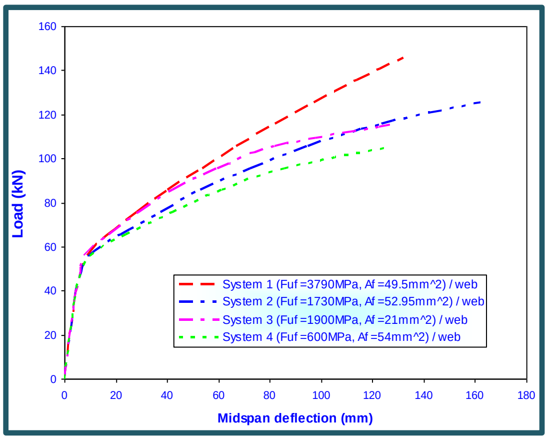
(d)

Figure (8) Effect of Number of Layers of CFRP System on Load-deflection Relation
(a)Girder S5, Rosenboom, *et al.* (2004)
(b) Girder EB2S, Rosenboom , (2006)
(c) Girder EB7S, Rosenboom , (2006)
(d)GirderEB2S, Rosenboom, *et al.* (2007)

Effect of System Type of CFRP

To investigate the effect of type of CFRP system on the behavior of the four considered girders, three different types of CFRP system for each girder are used, the material property of CFRP system of the three systems are shown in table (2). The results show that changing type of CFRP system (i.e. changing F_{uf} and A_f) effects on the load carrying capacity. Fig. (9) shows the effect of type of CFRP sheets on the load-deflection curve. System 4 has minimum tensile strength as compared with the other systems. Failure mode for all system is rupture of CFRP sheets. Comparison of system 1 is the strengthening type used in experimental work with three different system of CFRP sheets of the investigated girders are as follows:

- System 2, system 3 and system 4 caused a decrease of 13.7%, 20.6% and 27.5% respectively, in the load carrying capacity for S5 girder of Rosenboom, *et al.* (2004).
- System 2, system 3 and system 4 caused a decrease of 7.96%, 15.9% and 23.88% respectively, in the load carrying capacity for EB2S girder of Rosenboom, (2006).
- System 2 caused an increase of 0.49% in the load carrying capacity. System 3 and system 4 caused a decrease of 42.3% and 47.78% respectively, in the load carrying capacity for EB7S girder of Rosenboom, (2006).
- System 2, system 3 and system 4 caused a decrease of 15.3%, 25.5% and 30.7% respectively, in the load carrying capacity for EB2S girder of Rosenboom, *et al.* (2007).



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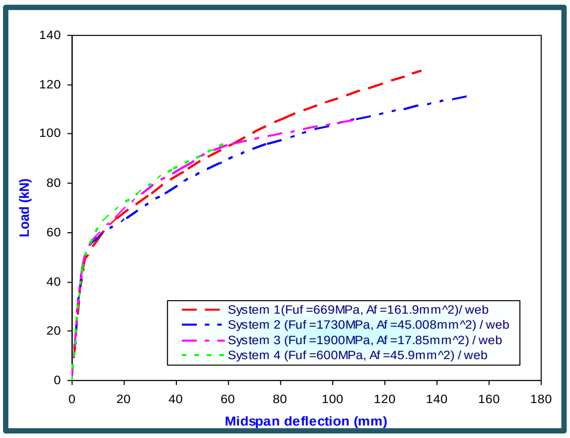

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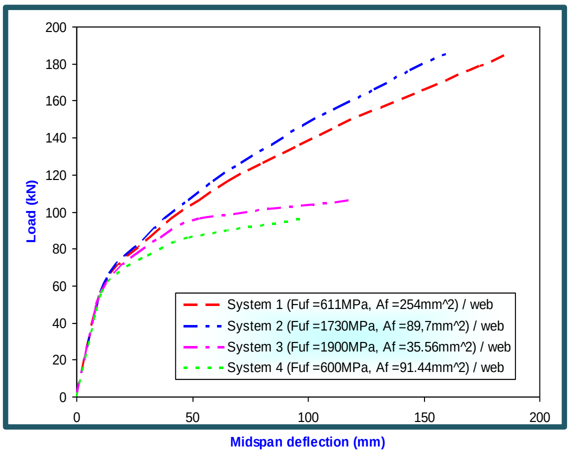

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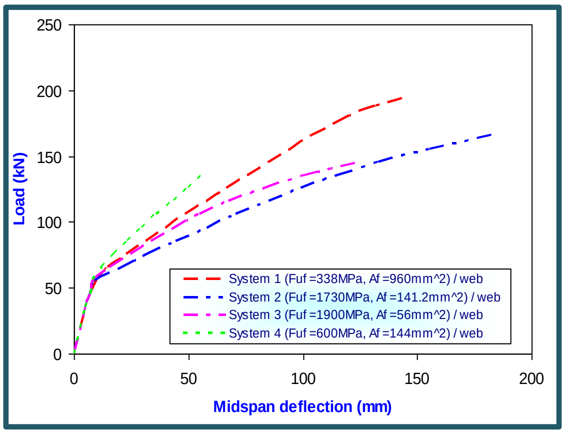

(d)

Figure (9) Effect of type of CFRP System on Load-deflection Relation
(a) Girder S5, Rosenboom, *et al.* (2004)
(b) Girder EB2S, Rosenboom, (2006)
(c) Girder EB7S, Rosenboom, (2006)
(d) GirderEB2S, Rosenboom, *et al.* (2007)

Effect of Strength and CFRP Systems on the Prestressed Concrete Members Behavior

In order to investigate the effect of changing the type of CFRP system as shown in table (2), and number of layers (multiple layers, more than 10 possible for CFRP sheets can used, Nordin (2003)), 6 layers of CFRP sheets are used in this research. The study of the effect of these parameters on the behavior of the all girders that are analyzed has been investigated.

The results show that the changing number of layers and type of CFRP system (i.e. changing F_{uf}, A_f and No. of layers) effects on the load carrying capacity. Fig. (10) shows the effect of type of CFRP sheets on the load-deflection curve. Failure mode for all system is rupture of CFRP sheets. Comparison of system 1 is the strengthening type used in experimental work with three different system of CFRP sheets with 6 layers of the investigated girders are as follows:

- System 2 caused an increase of 6.87% in the load carrying capacity. System 3 and system 4 caused a decrease of 6.87% and 20.6% respectively, in the load carrying capacity for S5 girder of Rosenboom, *et al.* (2004).

- System 2 caused an increase of 7.96% in the load carrying capacity. System 4 caused a decrease of 15.9% in the load carrying capacity for EB2S girder of Rosenboom, (2006).

- System 2, system 3 and system 4 caused an increase of 5.34%, 4.79% and 0.45% respectively, in the load carrying capacity for EB7S girder of Rosenboom, (2006).

- System 2 caused an increase of 2.2% in the load carrying capacity. System 3 and system 4 caused a decrease of 15.33% and 25.55% respectively, in the load carrying capacity for EB2S girder of Rosenboom, *et al.* (2007).

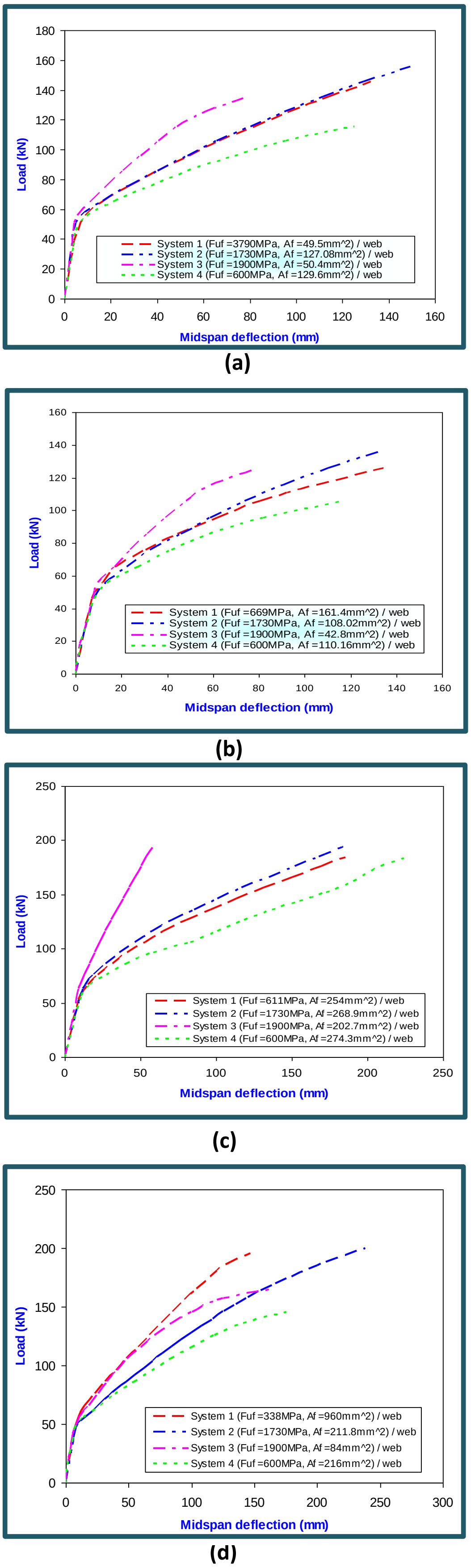

Figure (10) Effect of type of CFRP System and Number of layers on load-deflection Relation
(a)Girder S5, Rosenboom, *et al.* (2004)
(b) Girder EB2S, Rosenboom, (2006)
(c) Girder EB7S, Rosenboom, (2006)
(d) GirderEB2S, Rosenboom, *et al.* (2007)

Design Guidelines for the Flexural Strength of each Girder

The predicted nominal flexural capacity for the girders was based on ACI 318-08 building code. The nominal flexural capacity has been calculated using the following formula,

$$M_n = A_{ps} f_{ps}\left(d_p - \frac{a}{2}\right) \qquad \text{.........} \ 8$$

where f_{ps} is taken from (ACI 318-08, Eq. 18-3) or from (AASHTO LRFD (2004), item 5.7.3)

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f'_c} + \frac{d}{d_p}(\omega - \varpi)\right]\right) \qquad \text{.........} \ 9$$

where:

$\gamma_p = 0.4$ for $\frac{f_{py}}{f_{pu}}$ not less than 0.85 (stress-relieved wire and strand)

$$\beta_1 = 0.85 - \frac{0.05(f'_c - 28)}{7} \geq 0.65 \qquad \text{.....} \ 10$$

$$\varpi = A'_s f_y / bdf'_c \qquad \text{.........} \ 11$$

$$\omega = A_s f_y / bdf'_c \qquad \text{.........} \ 12$$

Since there was no mild tension steel in the girders and the effect of the compression steel in the flange was negligible, f_{ps} is simplified to:

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f'_c}\right]\right) \qquad \text{....} \ 13$$

To take the contribution of the CFRP flexural reinforcement into account, the expression of (f_{ps}) is modified to be:

$$f_{ps} = f_{pu}\left(1 - \frac{\gamma_p}{\beta_1}\left[\rho_p \frac{f_{pu}}{f'_c} + \frac{A_f . f_{fu}}{bd_f f'_c}\right]\right) \qquad \text{..........} \ 14$$

For internal force equilibrium, the depth of the concrete compression block is:

$$a = \beta_1 c = \frac{\sum A_{ps} f_{ps} + A_f f_{fu}}{0.85 f'_c b} \qquad \text{....} \ 15$$

And if a<h_f then the section is designed as a rectangular section, otherwise it is designed as flanged section. The calculated values of (a) were found to be less than the flange thickness (h_f) therefore, the section is considered as a rectangular section.

The nominal capacity of the CFRP strengthened prestressed concrete girders are computed as given in (ACI 440.2R-02, Eq. 9-11):

$$M_n = \sum A_{ps} f_{ps}\left(d_p - \frac{a}{2}\right) + \psi_f A_f f_{fu}\left(d_f - \frac{a}{2}\right)$$

……. 16

where;

ψ_f is a reduction factor, in case of the flexural-strength contribution of the CFRP reinforcement equal to 0.85. Comparison between experimental and calculated CFRP nominal moment capacity for the girders is shown in table (3). Comparison between FEA and calculated CFRP nominal capacity for the girders for 48 cases with different parameters is shown in table (4).The plotted results in Fig. (11) and Fig. (12) are in good agreement with results, which lead to adopt ACI 318-08 expression to calculate moment capacity of prestressed concrete girders strengthened with CFRP laminate.

Table (3) Comparison Between Experimental and Calculated CFRP Nominal Capacity Using Eq. (16) for the Girders

Girders	Experimental ultimate moment capacity, kN.m	Calculated CFRP moment capacity, kN.m, (Eq. 16)	FEA ultimate moment capacity, kN.m
Rosenboom, O. A. *et al.* (2004) S5 girder	359.2	352.86	320.8
Rosenboom, O. A.(2006) EB2S girder	359.6	277.45	276.7
Rosenboom, O. A.(2006) EB7S girder	423.7	306.64	405.88
Rosenboom, O. A. *et al.* (2007)EB2S girder	520.026	456.06	431.22

Discussion the Reasons for Difference Loads Carrying Capacity of Girders

- Increased carrying concrete compression force (f'c) in each of the three cases increased in load carrying capacity of the girder strengthened with CFRP sheets. So that the concrete has become more resistant and to withstand pressure stresses resulting from the download. The more concrete compression force increased the amount incurred.
- Concrete is defined as unable to resist tensile strength because of weakness incurred in tensile stresses and fragile nature. when using carbon fibers and linked in the tensile region (under the girder) leads to increased carrying concrete to resist tensile strength concrete exposed parts. And to increase the number of fiber layer increases carrying concrete to resist.
- The use of multiple types of carbon fibers, which vary in their characteristics and advantages of each other in terms of carrying maximum tensile stress and the thickness of the fiber (which leads to increase the area used). When an increased carrying tensile strength without increasing area of carbon fiber dose not mean increasing the carrying concrete. And do not forget that the convexity of the concrete due to prestressing force has an effect on the failure of fiber and because in the laboratory, the examiner used strengthening process after shedding prestressing force on the girder. As for the process of representation model within ANSYS program, it has been put before shed fiber prestressing force and due to the difficulty and placed after the occurrence of the convexity.
- As for affordability concrete extracted from ACI 440R-02 code must always be greater than affordability concrete extracted from the practical side. And it represents the upper limit may not be waived, it is a condition of design.

Table (4) Comparison Between FEA and Calculated CFRP Nominal Capacity Using Eq. (16) for the Girders considered

Girders / Cases		Rosenboom, O. A. *et al.* (2004) S5 girder		Rosenboom, O. A. (2006) EB2S girder		Rosenboom, O. A. (2006) EB7S girder		Rosenboom, O. A. *et al.*,(2007) EB2S girder	
		FEA nominal moment capacity kN.m	ed CFRP nominal moment capacity kN.m	FEA nominal moment capacity kN.m	ed CFRP nominal moment capacity kN.m	nominal moment capacity	Calculated CFRP nominal moment capacity kN.m (Eq. 16)	nominal moment capacity	d CFRP nominal moment capacity kN.m
Values of f'c	40	276.76	346.22	232.7	272.9	401.4	302.4	404.6	437.6
	50	320.8	352.9	276.8	277.4	405.8	306.6	431.2	446.44
	60	342.8	356.33	298.8	280.13	427.5	311.6	431.2	456.06
Number of bonded layers	1	276.8	279.02	232.7	234	233.9	228.4	254.9	290.22
	2	320.8	352.9	276.8	277.4	405.8	306.6	299.08	345.9
	4	361.4	210.6	298.8	320.7	427.5	301.3	431.2	456.06
Type of CFRP sheets	System 2	276.8	289.9	254.7	257	407.8	252.7	365.12	334.8
	System 3	254.7	255.7	232.7	227.7	233.9	225.2	321.05	278.7
	System 4	232.7	280.8	210.7	223.4	211.9	221.2	299.01	270.6
Type of CFRP sheets with 6	System 2	342.9	373.9	298.8	350.8	427.5	348.7	440.7	384.2
	System 3	298.8	292.7	276.76	259.3	425.3	267.6	365.12	300.3
	System 4	254.7	280.9	232.7	249.22	407.6	255.7	321.05	288.2

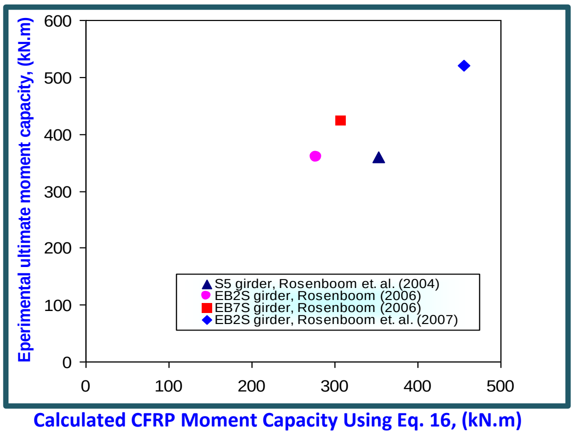

Figure (11) Relation between Experimental and calculated CFRP Nominal Capacity for the Girders

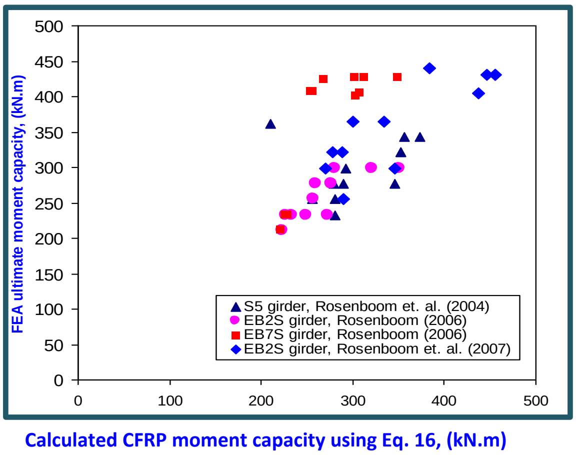

Figure (12) Relation between FEAand Calculated CFRP Nominal Capacity for the Girders

Conclusions

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

2. The ultimate load at failure was found to be increasing as the crushing and strength of concrete is made higher. Comparison for the ultimate load capacity of members strengthened with CFRP and having f'_c of 40MPa with having f'_c of 50 and 60MPa shows:

   *15.9% and 23.9% increase respectively, for S5 girder of Rosenboom, *et al.* (2004).

   *18.94% and 28.4% increase respectively, for EB2S girder of Rosenboom, (2006).

   *1.09% and 6.5% increase respectively, for EB7S girder of Rosenboom, (2006).

   *6.6% and 6.6% increase respectively, for EB2S girder of Rosenboom, *et al.* (2007).

3. The ultimate failure load is found to be larger as the number of layers of CFRP system applied to prestressed concrete girders is increased. Comparison of the one layer of CFRP system with two and four layers of CFRP systems of the investigated girders are as follows:

   *15.9% and 30.5% increase respectively, for S5 girder of Rosenboom, *et al.* (2004).

   *18.94% and 28.4% increase respectively, for EB2S girder of Rosenboom, (2006).

   *73.5% and 82.7% increase respectively, for EB7S girder of Rosenboom, (2006).

   *17.3% and 69.14% increase respectively, for EB2S girder of Rosenboom, *et al.* (2007).

4. The bending strength design method for the strengthened prestressed concrete girders with CFRP recommended by ACI 440R-02, the modified equation of ACI 318-08 and AASHTO LRFD (2004) are in a good agreement with results and can be adopted.

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