Nonlinear Analysis of External Prestressed Reinforced Concrete Beams with BFRP and CFRP

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Abstract:
The traditional strengthening methods for concrete structure (girders, beams, columns….) consuming time and could be an economical, a new modern repair methods using the Carbon Fiber Reinforced Polymers (CFRP) and Basalt Fiber Reinforced Polymer (BFRP) as a laminate strips or bars,and considered a competitive solution that will increase the life-cycle of repaired structures. This study investigated the strengthen reinforced concrete girder. Nonlinear analysis have been adopted to the models using FEM analysis (ANSYS) to simulate the theoretical results compared with experimental results.Using finite element packages, more efficient and better analyses can be made to fully understand the response of individual structural components and their contribution to a structure as a whole.Three type of material are used in this study as an external prestressed wire (steel, CFRP and BFRP). The prestressed beam is modeled as simply supported beam with two concentrated point load. The results showed that all tested strengthening beam increased the load carryingcapacity of the beams depend on prestressing force. Obtained Result was compared for different type of beam.This study also was enlarged to include using CFRP and BFRPbarwhich are light weight and moredurable, lead to ease of handling and maintenance. The research conducted analytical work to evaluate the effectiveness of concrete beams reinforced normally by the use of CFRP and BFRP bars. The results showed a significant gain in the beam's ultimate capacities using CFRP bars comparing with beam reinforced with BFRP bar and reference beam.
Keywords: Bending Behavior; External prestress, BFRP and CFRP tendon.

الخلاصة

ان الطرق التقليدية في تقوية المنشأت الخرسانية مثل (الجسور والعتبات والاعمدة وغيرها) تستهلك وقتا طويلا وتكون غير اقتصادية . الطرق الجديدة تستخدم الالياف البوليمرية الصناعية ومنها الكاربونية او المصنوعة من البازلت التي تكون على شكل اسياخ او صفائح والتي تعتبر طريقة تنافسية في زيادة عمر المنشأ الخدمي. يهدف هذا البحث لدراسة تقوية عتبات خرسانية مسلحة واعتمدت طريقة التحليل اللاخطي باستخدام طريقة العناصر المحددة بالاعتماد على برنامج (ANSYS) للتحليل الانشائي لمحاكاة النتائج النظرية ومقارنتها مع النتائج العلملية لبحوث سابقة. باستخدام العناصر المحددة بكفاءة عالية لفهم كلي لتصرفوتاثير العناصرالانشائية على كامل المنشأ . ثلاث انواع من حديد التسليح المسبق الجهد كتسليح خارجي تم اعتماده في هذا البحث وهي الحديد والالياف الزجاجية والياف البازلت المصنعة على شكل قضبان. النماذج المستعملة في التحليل هي عتبات بسيطة الاسناد ومحملة بحمل مركز ثنائي. اظهرت النتائجان جميع النماذج التي تم تقويتها زاد مقدار تحملها بشكل اعتمادا على القوى المسلطةالمسبقة الجهد. تم توسعة البحث ليشمل تحليل نماذج من العتبات الخرسانية مسلحة اعتياديا باستخدام قضبان الحديد العادي وقضبان من الالياف الكاربونية وكذلك قضبان من الالياف البازلت والتي تكون خفيفة الوزن موذو متانة مما يسهل التعامل معها في اعمال الصيانة. بينت النتائج تحسن ممتاز في تحمل العتبة باستعمال الالياف الكاربونية مقارن مع العتبات الاعتيادية والعتبات المسلحة باستخدام الياف البازلت.

الكلمات المفتاحية : سلوك الانحناء ،عتبة مسبقة الاجهاد الخارجي ، الياف الكاربون ، الياف البازلت.

1. Introduction.

External prestressing was used usually in old existing bridge need to strengthening and rehabilitation. The practical method in bridges strengthening used external prestressing in the for several decades and proved the efficiency of keepingthe structure integrality andimprove the old structure and working with a good performance comparing with new bridges, This Technology recently was applied into different structural building project such as slabs, beams, composite structures….etc using different material.

The Technology is characterized by several advantages, including the possibility of replacing tendons, reducing web thickness by eliminating internal tendons and the capability of applying precast segmental construction methods. Numerous researches have demonstrated that the behavior of service and ultimate states under static load can be effectively enhanced and the deflection induced by fatigue can be significantly decreased by external prestressing tendons [Aparicio *et.al.;* 2002 and Harajli , 1993].

CFRP bars or plates has been recently investigated by Nordin and Taljsten[Nordin, and Taljsten, 2004), Nordin, and Taljsten, 2006)] applied a prestressed Near Surface Mounted (NSM) system to reinforced concrete beams, the results showed that the ultimate load carrying capacity were highlyimproved, the stress transferring between the FRP to the structure was working effectively.

Basalt fiber tendons (BFRP) have a tensile high strength comparing with steel bar. There is a little research available aboutBFRP tendons and in general BFRP seems to be a rather new structural material. Its look like most of the recent research work about prestressing. Basalt and glass fiberhave been investigated in USA since 1950s [Thorhallsson *et.al.,*2011 and Ross, 2011]. Lopresto *et.al*.;2011) the possibility to replace glass fiber for basalt fibers was studied. Comparing the mechanical and charachterstic difference between glass fiber and basal reinforced plastic laminates where the glass fiber are widley used now. The attention now going for further studies on BFRP fiber material.

EI-Hcha and Couture (2007) haveshowed that due the modulus of FRP tendons lower than a corresponding steel tendon, losses for prestressed FRP tendon because of the elastic shortening, creep and shrinkage of concrete will be less than for prestressed of steel tendons [EI-Hacha & Coutre, 2007].

Eyþór and Jónas (2015)have studied the test of prestressed concrete with internal basalt rods and also studied the columns strengthened by wrapping fiber-reinforced composite sheets around the columns to increase their strength andductility. Theresults showed the sample strengthening with prestressed BFRP barincreasing strength and ductile for both the beams and the columns.

Kim, Shi and Green (2008) studied ductility and 2 cracking behaviour of prestressed concrete beams strengthened with prestressed CFRP sheets by constructing FE model in ANSYS. Their main conclusion was that the ANSYS model presented acceptable crack widths under service loads when compared to the tested beams. However, the FE model did not represent the stiffness of the beams well enough after the beams started cracking and some differences were also noticed in the ductility indices between the test beams and the FE model.

Chen et alhave conducted the strengthening of Reinforce concrete slabs using CFRP, GFRP and BFRP. The FRP materials were added in different layer to RC slabs with glue material (epoxy resin), the FEM analysis result using ANSYS had compared with experimental results shows good agreement with minor difference in ultimate deflection load results.

CFRP, has been successfully used in concrete structures as prestressing reinforcement several concrete bridges prestressed by CFRP reinforcement were built in Japan, Europe and Canada. The non-corrosive characteristics of CFRP reinforcement. In addition to its high strength-to-weight ratio, good fatigue properties and low relaxation losses are properties that significantly increase the service life of the structures. The current practice is to keep the jacking stresses within 60 % of the nominal tensile strength of FRP prestressing reinforcement [report of the JSCE (1993)].

Different recent studies reveal that BFRPs have no any creep rupture under tensioned up to approximately 52% from the ultimate allowable stress and perform efficiently as cables forlong-span bridges. Moreover, BFRPs and their hybrid tendonsalso show superior performance under marine environment.These advantages allow their potential application asprestressing tendons. Therefore, the combination of external prestressingtechnology and BFRP tendons should be a promising way to realize a new prestressing method [Wang *et.al.*,2014 , Wang and Wu; 2010 , Wang *et.al.*, 2014].

Extensive analytical and experimental works have been devoted to the application of external prestressing in structures . Most works were related to the flexural behavior of externally prestressed beams, in particular, the prediction of stress increasein the tendons at ultimate limit state and secondordereffects due to variations in eccentricity of the external tendons. Also, past worksfocused mainly on statically determinate structures, that is, simply supported beams, and the application of the method in strengthening continuous beams, which are commonly seen in practice, has not been adequately addressed [Desayi and Krishnan ;1964 , ANSYS Release 12, (Harajli and Kanj ;1991) , Naaman and Alkhairi 1991 , Aravinthan *et.al.*, 1997 , Tanand 1997 , Harajli, and *et.al.,* 1999].

2. Finite Element Model Simulation

ANSYS software was used in this study to simulate the models. Three-dimensional model created to represent the geometricand material nonlinear behavior pretstressed and normal reinforced concrete beam.

The Geometry of beam are given in Fig. (1). This model have been adopted by Wang *et. al.* [Xin Wang (2015)].

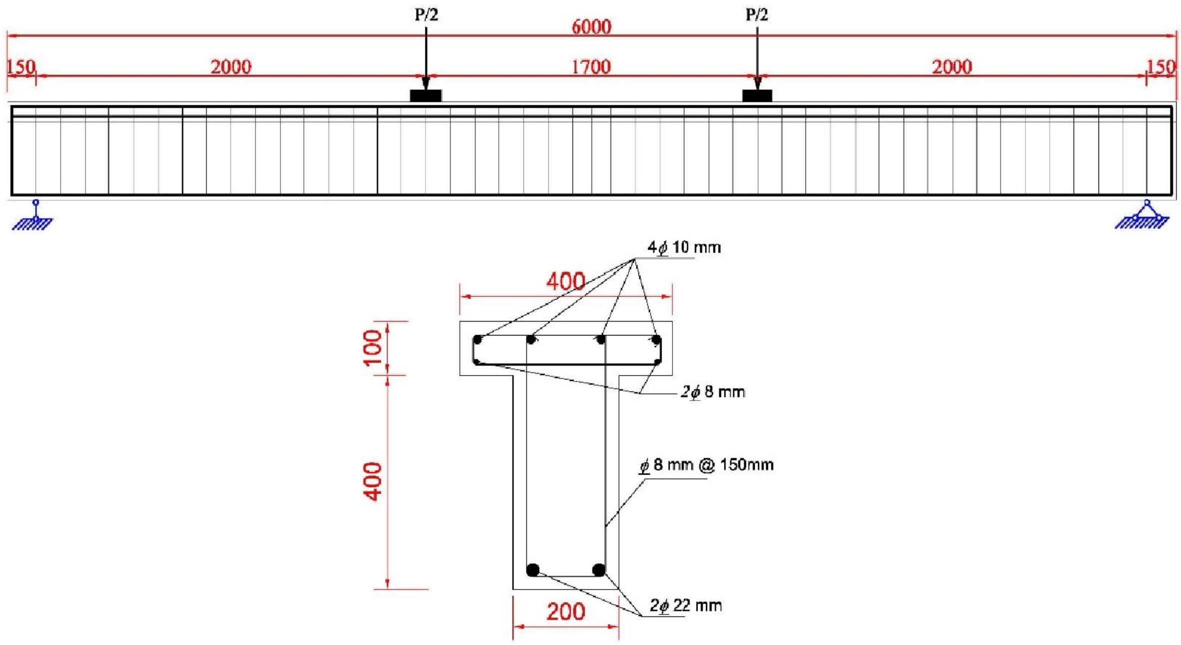

Fig.(1) The geometry detail of models (dimension in mm)[Xin Wang (2015)].

Table (1) Material properties.

Material	Type/ Size	Elastic Modulus (MPa)	Compressive strength (MPa)	Yield stress (MPa)	Ultimate stress (MPa)
Concrete	--	32500	40.5	-	-
Steel (Stirrup)	D8 mm	2.1×10^5	--	240	385
Steel (upper)	D10 mm	2.1×10^5	--	275	375
Steel (lower)	D22 mm	2.0×10^5	--	340	450
Steel tendon	12 mm	2.1×10^5	--	580	1760
BFRP tendon	12 mm	48200	--	--	1192
CFRP tendon	12 mm	1.6×10^5	--	--	2800
CFRP bar	12 mm	135×10^5	--	--	1680
BFRP bar	12 mm	47×10^5	--	---	1000

3. Constitutive Material Curves.

3.1 Concrete in Compression

The stress –strain curve of concrete was used in this research to represent the linear (elastic) and nonlinear (plastic) behavior of concrete. The concrete is assumed to be homogeneous and isotropic. The relationship of stress-strain curve of concrete in compressive (uniaxial)for concrete modeling is predicted from the following equations:

$fc=\varepsilon Ec$ $\quad for \quad 0\leq\varepsilon\leq\varepsilon 1$ (Ross,2011)

$fc=\varepsilon Ec/ (1+ (\varepsilon/\varepsilon_0)^2$ $\quad for \quad \varepsilon 1\leq\varepsilon\leq\varepsilon_0$

$\varepsilon_0=2\, fc/Ec$ $\quad for \quad \varepsilon_0\leq\varepsilon\leq\varepsilon cu$

Where:

fc = stress at any strain ε, N/mm^2,

ε_0=strain at the ultimate compressive strengthfc'.

εcu= ultimate compressive strain,

$\varepsilon 1$= strain corresponding to 0.3 fc'

The multi-linear isotropic stress- strain requires the first point of the curve to be defined according to Hooke's law:

$E = \sigma/\varepsilon$

$\sigma = 0.3fc'$

Fig. (2) showing the constitutive curves of concrete in compression used in this research.

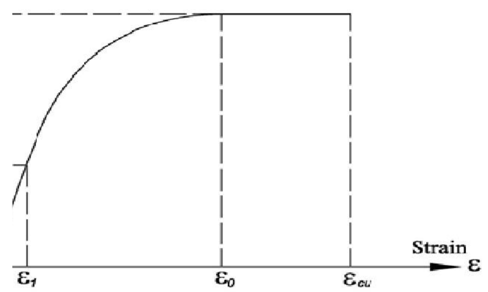

Fig. (2) stress-strain curve of concrete (Compression).

3.2 Concrete in Tension

The stress–strain relationship for concrete in tension assumes that the tensile stress increases linearly with an increase in tensile strain up to concrete cracking. After concrete cracking, the tensile stress decreases linearly to zero as the concrete softens. The bond between the concrete and reinforcing bars was simulated approximately by the tension stiffening model, which defines the stress–strain relationship for concrete in tension after cracking. Fig (3) present the relationship between stress and strain of concrete in tension.

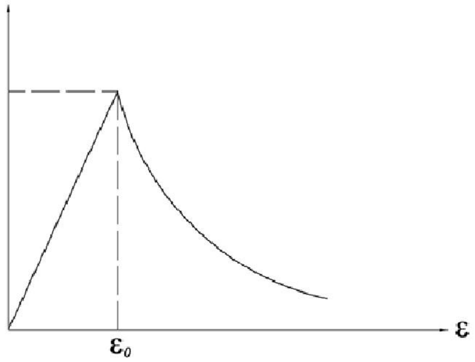

Fig. (3) stress-strain curve of concrete (Tension)

3.3 Steel properties

A perfect-plastic stress-strain curve model was adopted in this research to simulate the behavior of the steel reinforcement. The parameters including yielding strengthf_y, modulus of elasticityE_s, (Table 1) and Poisson's ratio ν = 0.2 are used to define this model. The stress–strain curve relationship is shown in Fig. (4), according to the formulas:

$f_s = E_s.\varepsilon_s \varepsilon_s \leq \varepsilon_{sy}$

$f_s = f_{sy} \varepsilon_s > \varepsilon_{sy}$

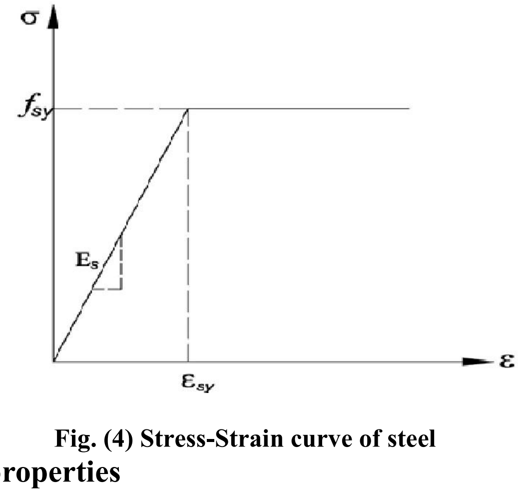

Fig. (4) Stress-Strain curve of steel

3.4 BFRP and CFRP properties

The stress–strain relationship of BFRP and CFRP bars can be obtain by equation:

$f_f = E_f.\varepsilon_f \varepsilon_f \leq \varepsilon_{fu}$

Where:f_f and ε_f are the stress and strain of FRP(BFRP or CFRP), respectively, E_f is the modulus of elasticity of FRP (BFRP or CFRP) while the $\varepsilon_{fu}$is the ultimate strain of FRP.

For nonlinear solution, ANSYS "Newton-Raphson" approach to solve nonlinear problems .in this approach, the load is subdivided into a series of the load increments. The load increments can be applied over several load steps.

The concrete element was modeled by using the 8-noded brick elements (SOLID 65). Eight nodes with three degrees of freedom at each node, translation in the x, y, and z directions. This element have the capability of predicting cracks in tension and in three orthogonal directions, crushing in compression, and plastic deformation.

The steel bars, were modeled using element type (LINK8). This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension compression element with three degrees of freedom at each node: translations of the Nonlinear Analysis of simply supported beam.

The BFRP tendon, CFRP tendon and prestress steel wire were simulated using element type (LINK 10). This element is a 3-D spar element have the unique feature to a bilinear stiffness matrix and has three degrees of freedom at each node, translations in the nodal x, y and z directions. ANSYSLINK10 elements are capable of dealing with only tension or only compression by assigning certain parameters forcable elements.

Fig. (5) show the external prestress technique with eccentricity 50 cm from substrate of beam. The end anchorage of prestressed wire was tied with steel plate at the end of beam to avoid any load concentration on concrete and this plate was modeled in ANSYS using element type Solid 45.

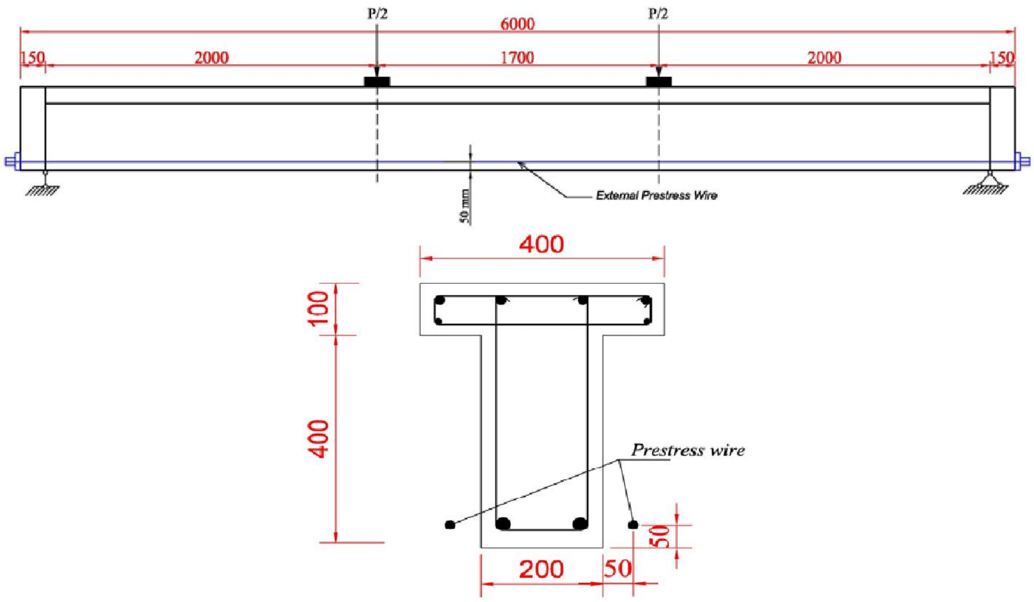

Fig. (5) Beam model with external prestress-wire (mm).

4. Beam models

The first beam model was reference concrete beam with normal reinforcement (steel bars) as shown in Fig. (1).The second model beam was strengthened with external steel tendons and the tendonswere placed as can be seen in Fig. (5). The tendons were placed in the lowerpart of the beam and the tendons were only fixed at theends and the tendons will always remain at the same level as theendpoints. This is an effectiveway to place the tendons and the tendons are always fixed at the endpoints.The others model will be either normal reinforced or strengthening with prestressed BFRP and CFRP tendons. Table (2) presents the all strengthening beams adopted in this study.

Table (2) Type of strengthening beam models

Beam No.	Type of Reinforcement	
	Main Steel bar	External prestress tendon
C0	2 ϕ22mm	---
PS	2 ϕ22mm	2 ϕ12 mm steel wire
PB	2 ϕ22mm	2 ϕ12 mm BFRP wire
PC	2 ϕ22mm	2 ϕ12 mm CFRP wire
NB	2 ϕ22 BFRP bar mm	---
NC	2 ϕ22 CFRP bar mm	----

4.1 Finite element model

Fig. (6) shows the finite element model (C0-referemce beam) normally reinforced with steel bar and the finite element model of prestress beam are shown in in Fig. (7)

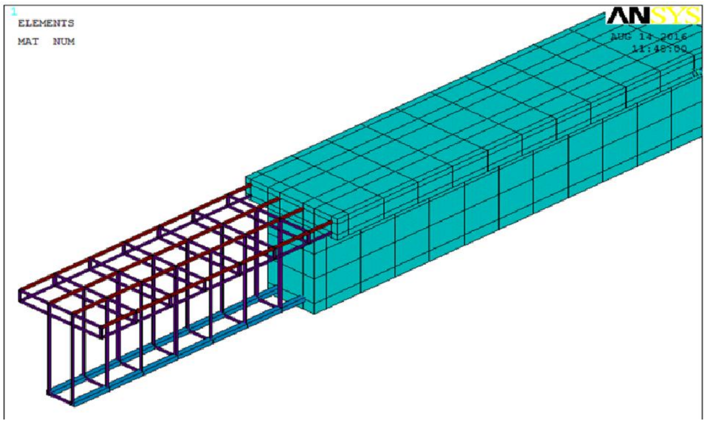

Fig. (6).Finite element model ofReinforced concrete beam

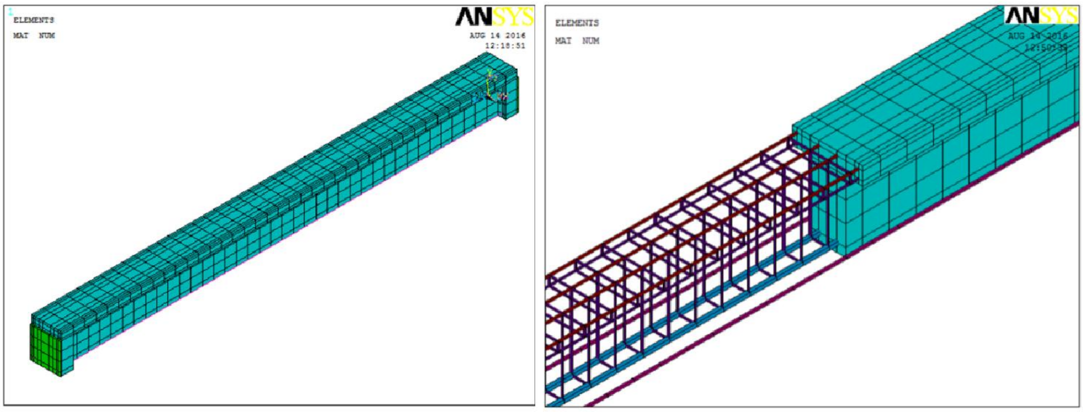

Fig. (7) Finite Element model of Prestress-beam model in ANSYS

5. Results and Discussion

5.1 Load Deflection Curve for prestressed Beams

The load deflection curve of different type of prestress case are shown in Fig. (8) it is necessary to conduct the vertical displacement at mid span of each model of substrate face of the Models, the maximum vertical deflectionat ultimate applied load was predicted at each step till the failure load occurred.The experimental and numerical curves obtained for the composite beam.

The finite element results are predicted by ANSYS solutions are listed in Table (3).It can be noted from Fig.(8) that the control beam (C0) non prestressed with maximum deflection value 37.5 mm at ultimate load 123 KN while the beam with prestressed wire (PS model) (steel wire) has 60 mm vertical deflection at ultimate load of 271 KN. The behavior of PC model are so close from PS model with ultimate applied load 264.6 KN with vertical displacement equal to 40 mm. Reinforced concrete beam with external prestressed BFRP bar predicting ultimate load 172 KN with deflection value 44 mm. The improvement of in theoretical ultimate applied load were 220%, 215% and 139% of PS, PC and PB model respectively comparing with (control beam) C0 model.

The deformation increment (vertical deflection) were 160%,106%, and 117% of PS, PC and PB model respectively comparing with (control beam) C0 model, this show that the high deformation ability can be occurred through using steel bar as external prestress wire, and with small extra deformation with using CFRP and BFRP external bars comparing with control beam (C0).

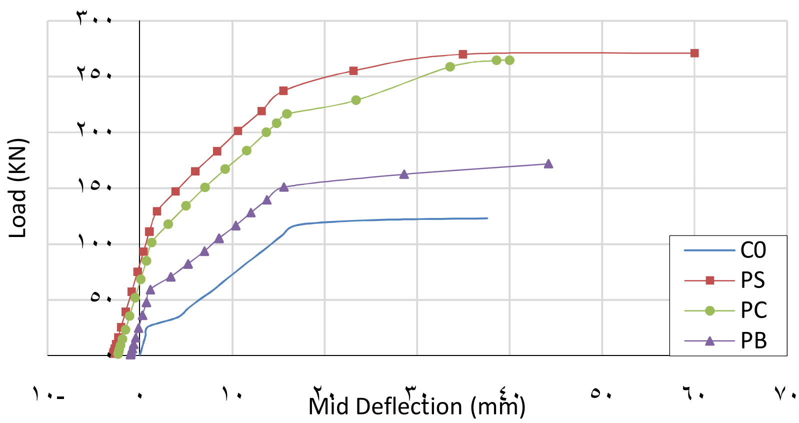

Fig. (8) Load deflection curve of external presterss bar.

The Fig. (9) shows the initial prestress force of PS model before start applied force keeping the tension stress at the top surface under the permissible stress without causing any crack surface due to prestress force. The initial cracks are shown in Fig. (9) with load value 129.6 KN while the while the beam pretressed with BFRP tendon initially cracked at 83.4 KN and the beam prestressed with CFRP bar show the initial crack at 109 KN and the reference beam (non pretressed beam) the initial crack was at load value 34.5 KN.

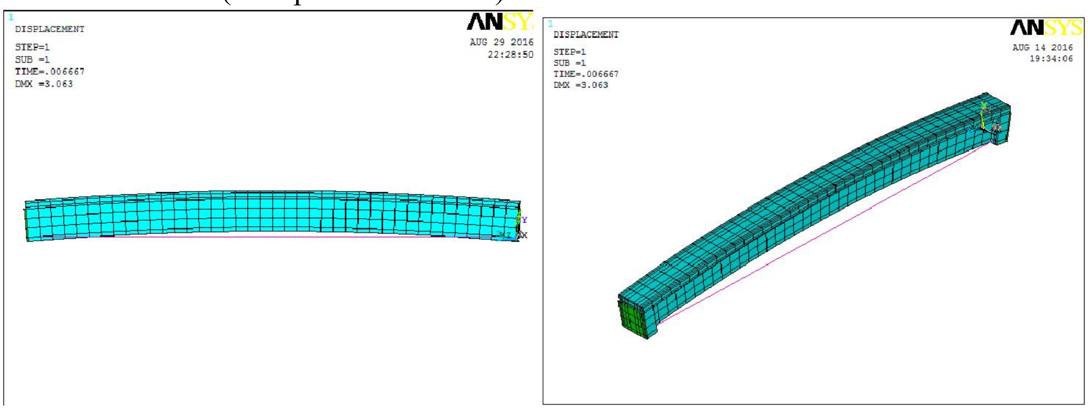

Fig. (9) First step Analysis of external prestress beam (steel tendon)

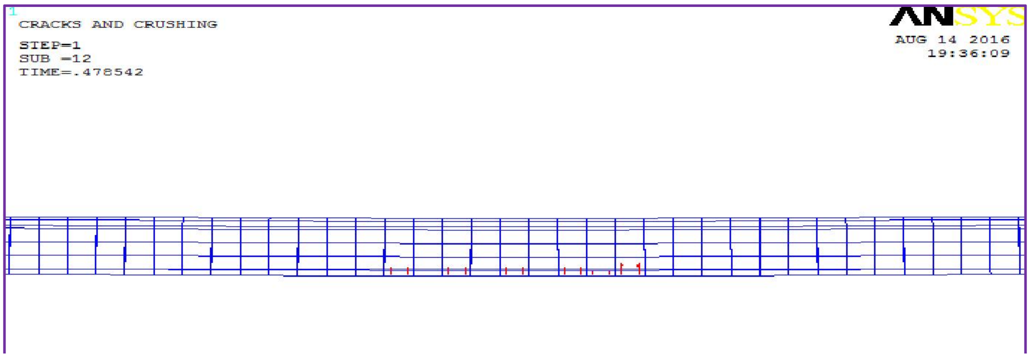

Fig. (10) First crack analysis of external prestress beam (steel tendon)

5.2 Reinforced beam with BFRP and CFRP bars

The FEM results of this research were compared with experimental results by [Xin Wang (2015)]. The theoretical result shows good agreement. The results are listed in Table (3).

Table (3) critical load values of different models.

Model No.	Pcr (KN)	Py (KN)	P Max (KN)	Pcr (KN) [Xin Wang]	Py (KN) [Xin Wang]	P Max KN) [Xin Wang]
CO	34.5	116.3	123.0	32.5	117.5	132.5
PS	129.6	237.2	271.0	--	--	--
PC	109.0	216.6	264.6	--	--	--
PB	83.4	151.1	172.0	70	162	190

5.3 Strain Distribution along Cross -Section

The strain distribution along the height of the cross- section of beams are shown in Fig.(11). Normal RC concrete beam (C0), the strain curve against the depth of beam distribution at (25%) and (50%) of the ultimate load is almost linear along the concrete beam depth as shown Fig. (9).At (75%) and above of the ultimate load the tensile strain at the bottom face of the concrete is reduceddue to cracking. Also, the normal strain at beam bottom face near yielding. Increasing the load levels up to maximum load, the compressive strain at top of concrete beam is continuously increased.

Fig. (12) shows the strain values along the height of beam normally reinforced with BFRP bars (NB). Its noted that the strain value at load any specific load is much higher than the same level of normal reinforced beam (C0), that indicate the highly deformation ability compared with normal steel.

Fig. (13) presents the strain value for beam which reinforced with CFRP bar (NC) and it clearly shows the strain was much less compared with (NB) and (C0) models, this due to the highly stress capacity of CFRP bar and this causes the lower neutral axis

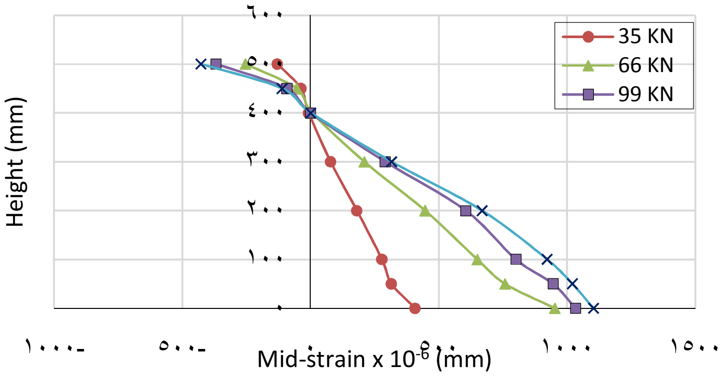

Fig. (11) Strain distribution along the height of beam reinforced normally with steel bar.

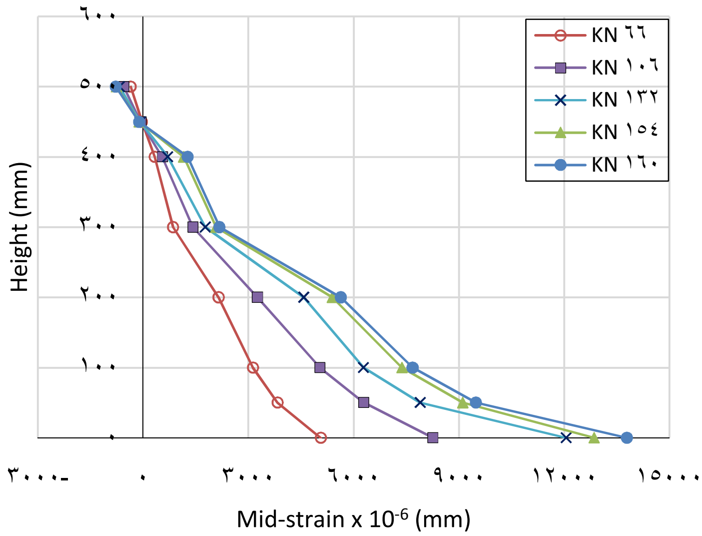

Fig. (12). Strain distribution along the height of beam reinforced normally with BFRP bar.

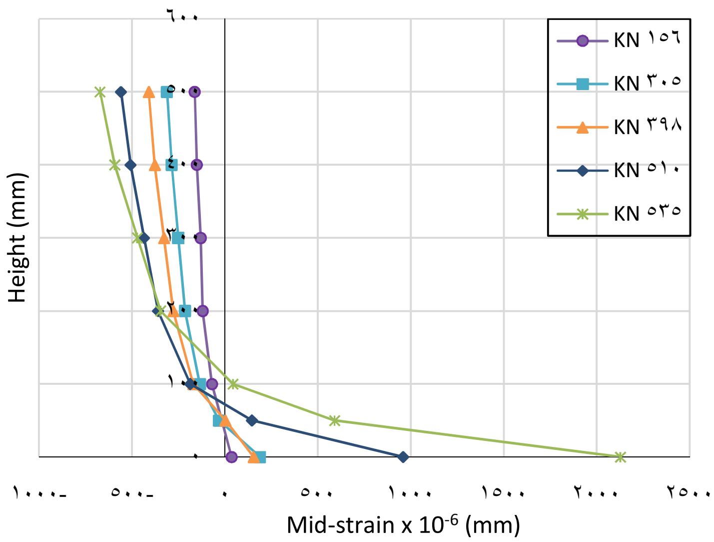

Fig. (13). Strain distribution along the height of beam reinforced normally withCFRP bar.

The deflection-load curve is presented in Fig. (14), shows the improvement in beam loading capacity using CFRP bar is larger than normal bar (C0) and BFRP bar beam reinforcement (NB),while high deformation appeared in model (NB) compared with others models .

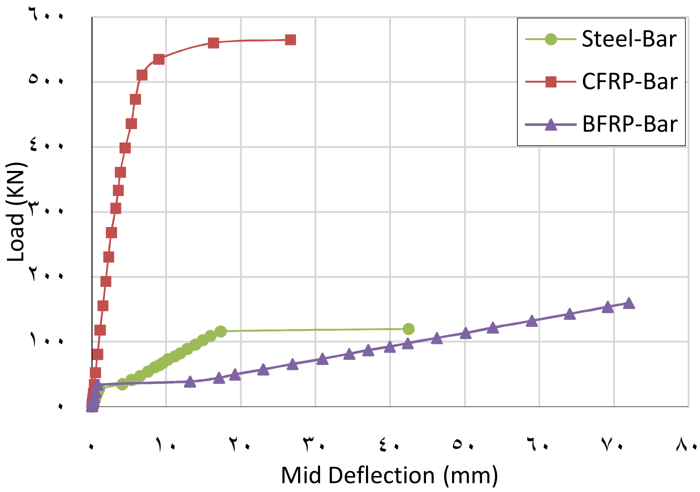

Fig.(14) Load Deflection Curve for different type of reinforcement.

6. Conclusion

1. The prestressed beam models for different kind of external prestressed are modelled quite well using finite element analysis (FEA) showing different behavior with varying modified rates.
2. Results obtained from finite element analysis arewellagreement to the experimental results obtainedfrom previous work.
3. Using Finite element analysis of external prestress tendon using BFRP and CFRP barsgives advantage of to calculate the strain, stress and deflection and the propagation of cracks through the beam at different points which explain the appropriate method to predict the flexural behavior.
4. The flexural behavior of deflection is investigated in depth. FEM software ANSYS are used to model the same beams to evaluate the validity of the FEM method comparing with previous work and its fit well with the experimental result and there is some deviation of experimental result.
5. Prestressed beams were usedCFRPand BFRP as external tendon compared with normal steel tendon. The FEM result showed that the using the steel tendon is improved the loading capacity of reinforced beamhigher compared with beam strengthening with BFRP tendon. Beam strengthen with CFRP has a good result and almost close to the beam strengthen with normal steel tendon due to a good properties and highly tensile yield and ultimate stress.
6. The beams that were prestressed with an external tendon showed significant increases in boththeir yield load and ultimate load compared with the control beam. In particular, the ultimate loads of the beams strengthening with steel tendon increased by 220%, while beam strengthening with CFRP tendon improved the ultimate load215%, and140% for beam strengthen with BFRP tendon.
7. This study was enlarged to including behavior of beam reinforced normally with steel bar, CFRP bar and BFRP bar, result shows a significant modified of ultimate capacity

compared with reference beamwhile the beam reinforced with BFRP bars has a very little increasing in ultimate capacity. This could be due to the lower modulus of elasticity of BFRP material while CFRP material have higher modulus of elasticity.

References.

ANSYS Structural Analysis Guide ANSYS Release 12.

Aparicio AC, Ramos G, Casas JR. 2002 “Testing of externally prestressed concrete beams” Eng Struct;24:73–84.

Aravinthan, T., Mutsuyoshi, H., Fujioka, A., and Hishiki, Y. 1997. “Prediction of the ultimate flexural strength of externally prestressed PC beams.” Trans. Jpn. Concr. Inst., 19, 225–230.

CHEN , Z. F. ; L. L. WAN, S. LEE, M. NG, J. M. TANG, M. LIU , L. LEE, “Evaluation of CFRP, GFRP and BFRP Material Systems for the strengthening of RC Slabs” Journal of Reinforced Plastics and Composites, 27(12),1233-1243.

Desayi, P., and Krishnan, S., 1964,"Equation for the Stress-Strain Curve of Concrete", Journal of the American Concrete Institute, Vol. (61), pp. 345- 350.

EI-Hacha, R & Coutre, C. S. 2007 “ Prestressing concrete structure with fibre reinforced polymer” (educational module No. 9) (p. 30). Calgary: ISIS Canada research Network. Retrieved from http://isiscanada.com /education/education.html.

Eyþór R. Þórhallsson, Jónas Þ. Snæbjörnsson 2015, “BASALT FIBERS AS NEW MATERIAL FOR REINFORCEMENT AND CONFINEMENT OF CONCRETE”Conference: Proceedings 22nd Czech Concrete Day , At Litomysl

Harajli M H. 1993 “Strengthening of concrete beams by external prestressing”. J Precast/Prestress Concr Inst ;38(6).

Harajli, M. H., and Kanj, M. Y. 1991 . “Ultimate flexural strength of concrete members prestressed with unbonded tendons.” ACI Struct. J., 88(6), 663–673.

Harajli, M. H., Khairallah, N., and Nassif, H. _1999_. “Externally prestressed members: Evaluation of second-order effects.” J. Struct. Eng., 125(10), 1151–1161.

Kim, Y., Shi, C., & Green, M. 2008 . “Ductility and Cracking Behavior of Prestressed Concrete Beams Strengthened with Prestressed CFRP Sheets”. Journal of Composites for Construction, 12(3), 274–283. doi:10.1061/(ASCE)1090-0268(2008)12:3(274).

Lopresto, V. Leone, C., & De Iorio, I. 2011 “Mechanical Characterisation of basalt fibre reinforced plastic”, Compositics Part B: 42 (2011) 717-723.

Naaman, A. E., and Alkhairi, F. M. 1991 . “Stress at ultimate in unbonded post-tensioning tendons: Part 2—Proposed methodology.” ACI Struct. J., 88(6), 683–692.

Nordin, H., and Taljsten, B., 2004 . “Prestressed Near Surface Mounted Reinforcement (NSMR) for Strengthening Concrete Beams, ” Proceedings of the second international conference on FRP composites in civil engineering, Adelaide, Australia, pp. 447-454.

Nordin, H., and Taljsten, B., 2006 . “Concrete beams strengthened with prestressed near surface mounted CFRP,” Journal of Composites for Construction, V. 10, No. 1, pp. 60-68.

Research Subcommittee on Continuous Fibre Reinforcing Material 1993 . English translation of the report of the JSCE, Japan Society of Civil Engineering, Japan, 120 pp.

Ross, A. “Basalt fiber Alternate to Glass” Composite World Retrieved April 13, 2011, from http://www.compositesworld.com/article /basalt-fibers-alternative-to-glass.

Tan, K. H., and Ng, C. K. _1997_. “Effects of deviators and tendon configuration on behavior of externally prestressed beams.” ACI Struct. J., 94(1), 1–10.

Thorhallsson E.R., Konráðsson A., Kubens S., 2011 ,“Strengthening of concrete columns by wrapping basalt fiber matrix“. Nordic Concrete Research Symposium, pp. 457-462.

Wang X, Shi J, Liu J, Yang L, Wu Z., 2014 “Creep behavior of basalt fiber reinforced polymer tendons for prestressing application”. J. Mater Des; 59: 558–64.

Wang X, Wu G, Wu Z, Dong Z, Xie Q. 2014, “Evaluation of prestressed basalt fiber reinforced polymer and hybrid FRP tendons under marine environment “. J. Mater. Des.;64:721–8.

Wang X, Wu Z. 2010 “Evaluation of FRP and hybrid FRP cables for super long-span cable-stayed bridges “.Compos. Struct.;92 (10):2582–90.

Xin Wang, Jianzhe Shi, Gang Wu, Long Yang, Zhishen Wu. 2015 ” Effectiveness of basalt FRP tendons for strengthening of RC beams through the external prestressing technique “Journal of Engineering Structure, 101 ,34-44.