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ANALYTICAL INVESTIGATION OF STATICALLY INDETERMINATE FLEXURAL RC SLABS STRENGTHENED USING PRESTRESSED STEEL AND FRP

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الملخص

تقدم هذه الورقة نماذج تحليلية للبلاطات خرسانية المستمرة مدعمة من الخارج بصلب سابق الإجهاد وشرائح بوليمرات مسلحة بالألياف سابقة الإجهاد. هناك حاجة إلى فهم أفضل لسلوك البلاطات الخرسانة المستمرة في الإنحناء كأساس للتصميم يمكن الإعتماد عليه. يتم إجراء الدراسة التحليلية من خلال إعداد نماذج لعشرة بلاطات مستمرة تم اختبارها معمليا سابقا. تم اختبار أربعة بلاطات مستمرة باستخدام شرائح بوليمرات مسلحة بالألياف سابقة الإجهاد الممسوكة وبلاطة أخرى باستخدام شرائح شرائح بوليمرات مسلحة بالألياف سابقة الإجهاد غير الممسوكة. تم تدعيم ثلاث بلاطات بصلب سابق الإجهاد من الخارج ، بينما كانت البلاطتين الباقيتين عبارة عن عينات تحكم. يتم إجراء مقارنة بين نتائج البرنامج و النتائج المعملية. أظهرت نتائج التحلل من البرنامج تطابق شديد من حيث السعة القصوى للبلاطات ، شكل الترخيم ، و شكل الإنهيار النهائي للعينات. استناداً إلى النتائج ، وجد أنه بالنسبة للبلاطات التي تم تدعيمها بصلب سابق الإجهاد ، فإن نسبة الفرق بين الأحمال النهائية للبلاطات التحليلية المعملية هي 8.2٪ و 1.43٪ و 8٪ على التوالي.

ABSTRACT

This paper presents analytical models of continuous RC slabs externally strengthened using prestressed steel strands and prestressed Fiber Reinforced Polymer (FRP) laminates. The behavior of statically indeterminate members with external prestressing to continuous RC slabs is rather complicated. An improved understanding of the flexural behavior of indeterminate concrete members is needed as a basis for a reliable strengthening design. The analytical study is carried out by setting up non-linear finite element models for ten experimentally tested continuous slabs. Four continuous slabs were prestressed using bonded FRP laminates and one using unbonded FRP laminates. Three slabs were strengthened using externally prestressed steel strands and the remaining two slabs were control specimens. A comparison is conducted between the experimental and the non-linear FE results. The FE models captured with reasonable accuracy the ultimate capacity of the slabs, the deflection profile, and the failure mode of all experimentally tested slabs. Based on the results it was found that for the slabs strengthened using prestressed steel strands the ratio of the difference between the ultimate loads of the analytical and experimental slabs are 8.2%, 1.43 % & 8% respectively. The ratio for the slab strengthened using unbonded CFRP at the bottom was 0.98 %.

Keywords: RC slabs; Prestressed steel strands; Prestressed FRP laminates; Non-linear finite element models; Ultimate capacity

INTRODUCTION

Retrofitting and Strengthening are possible by using the traditional materials like concrete and steel. There are many different strengthening techniques for instance increasing the cross section of the member, adding steel plates to the concrete member and fixing it by bolts or adhesively affixed to increase the capacity. Some of these techniques may perform poorly under service conditions and may be highly cost. The use of external prestressed steel bars has been promoted as a method of strengthening and improving serviceability in existing reinforced, precast and prestressed concrete structures because deflection is not reduced much by passive strengthening using fiber-reinforced-polymer composites furthermore the condition of prestressing steel materials can be inspected easily throughout the life of the member [1]. There is a major difference between internally prestressed elements even bonded or unbonded and the externally prestressed one. The effective depth of the steel strands during loading decreases and this must be taken in consideration for strengthening of structural elements. The Externally bonded (EB) non-prestressed fiber reinforced polymer (FRP) used for strengthening of structural elements was widely prevalent in both the application and research part [2-4]. The main important criteria for the design of structural members is to afford the different types of loads acting on the structure and to fulfill serviceability limit states requirements. The advantages of strengthening of the structures using prestressed CFRP appears in order to increase the capacity of the RC members, improving the serviceability limit states and the strength of the structures.

Numerous researchers studied the strengthening of RC members using prestressed CFRP laminates, (El-Hacha 2000) [5] tested RC beams strengthened by EB prestressed and non-prestressed FRP laminates and as a result the prestressed FRP laminates enhanced the stiffness and the flexural capacity of the beams.

(Yail J. Kim, Mark F. Green, R. Gordon Wight 2010) [6] Investigated the Effect of prestressing levels in prestressed CFRP laminates for strengthening concrete beams by an analytical study. The results of this study was that the Load-deflection responses was significantly affected by the prestressing levels in the prestressed CFRP laminates of the strengthened concrete beams. The failure of strengthened beams is primarily due to the rupture of CFRP laminates.

(Hamid Y. Omran 2012) [7] Conducted 3D nonlinear Finite Element (FE) analysis of RC beams strengthened with externally prestressed Near-Surface Mounted (NSM) CFRP strips. The interface between concrete and FRP was taken into consideration by identifying fracture energies of the interfaces and suitable bilinear shear stress-slip and tension stress-gap models to consider de-bonding effect. The results show that de-bonding propagation at ultimate load which is mainly caused by high deflection and crack opening is less for the prestressed beam.

(Rosenboom 2006) [8] Discussed de-bonding of RC beam and observed that de-bonding happens in the EB beam from the crack bottom. High stresses is generated in the FRP plate by increasing the acting load and thus high interfacial shear stresses at the interface between concrete-adhesive results from these high tensile stresses in the FRP plate . As a result of the experimental studies, a numerous analytical models have been conducted and developed to study the shear stress-slip behavior and the bond capacity of FRP-concrete interface.

(Reham El Tahawy 2014) [9] Worked on the evaluation of the bond and the load transfer mechanisms between the FRP material and concrete and the investigation of de-bonding process. The criteria is to evaluate the efficiency of current analytical models. The guiding criteria are the normalized root mean square error (NRMSE) and the coefficient of determination (r2), which is the square of correlation. When the numerical method gives low NRMSE of 0.12 and high r2 of 1.00, therefore, the numerical models can be used for predicting de-bonding failure loads and strains. The proposed model gives NRMSE of 0.17 and r2 of 0.88 to the PE-debonding database, respectively. On the other hand, applying the proposed model to the IC-debonding database gives NRMSE of 0.14 and r2 of 0.99, respectively. Subsequently analytical results statistics give confirmation on the high efficiency of the proposed model compared to other existing analytical models and various design guidelines. The model is considered to be low design model when the strength reduction factor is 0.85.

(Thiru Aravinthan et al. 2005) [10] conducted an experimental study on nine beams, six specimens are continuous two-span beams and the other three specimens are single-span beams. The main aim of this study is to discuss the flexural behavior of beams strengthened by large eccentric tendons, the strand linear transformation didn't affect the behavior of the beams in flexure in the elastic and post elastic loading ranges and with the increase in mid-span deformation the stress in strands increases proportionally until the strand is yielded.

EXPERIMENTAL INVESTIGATION

The database presented in this study is comprised of two experimental works conducted by previous researchers of continuous two span reinforced concrete slabs strengthened by either externally bonded (EB) fiber reinforced polymers (FRP) laminates or externally prestressed steel strands. The 1st database is composed of five specimens of continuous two span RC slabs, three slabs externally strengthened using prestressed steel strands, one slab strengthened using unbonded CFRP laminates and the remained one is control slab [11]. The 2nd database includes five specimens of continuous two span RC slabs, four slabs externally strengthened using bonded CFRP laminates and the remained one is control slab [12]. Figures 1-9 shows the details of the tested slabs.

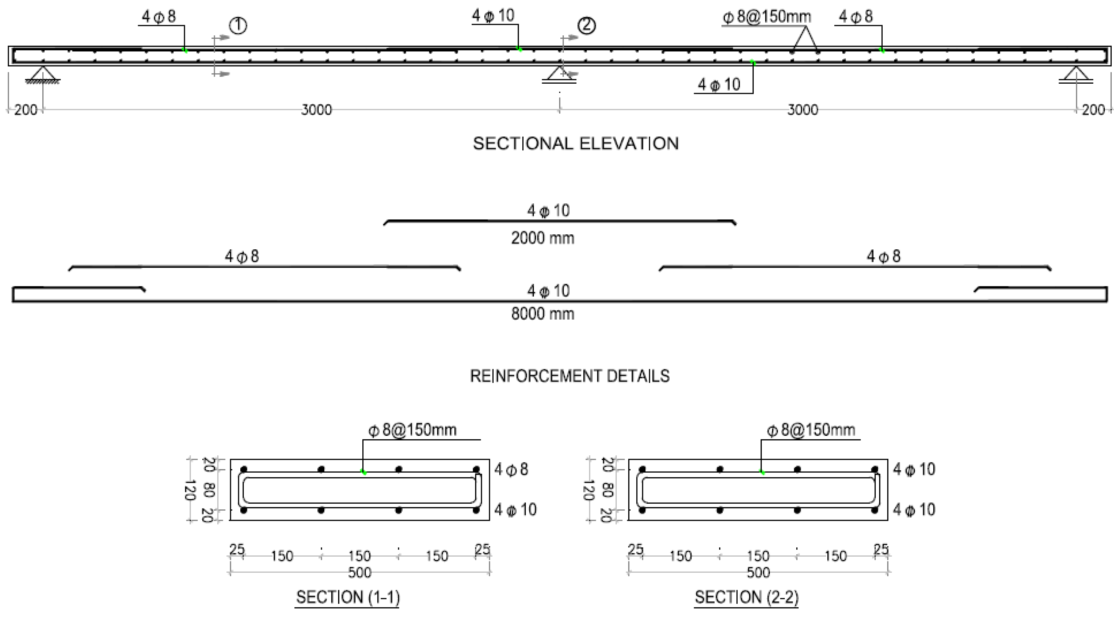


Figure 1. Concrete dimensions and reinforcement details of test specimens [11]

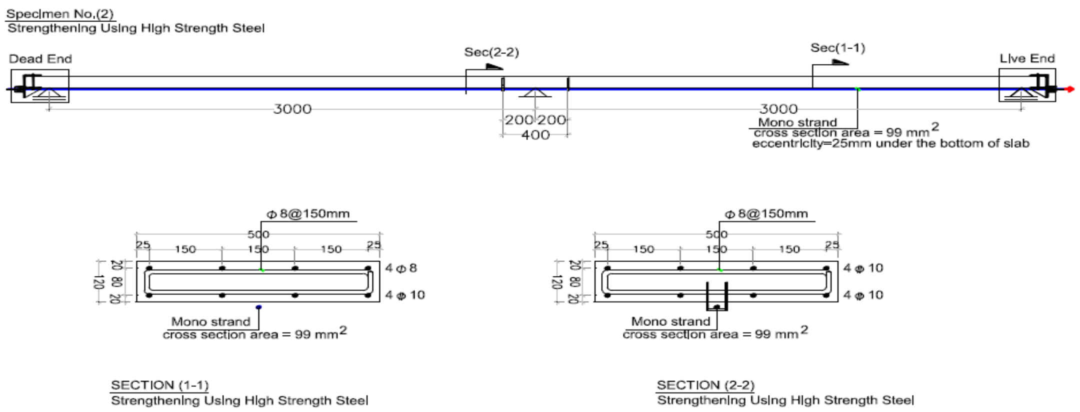


Figure 2. Specimen No. 2 strengthened by prestressed steel strand [11]

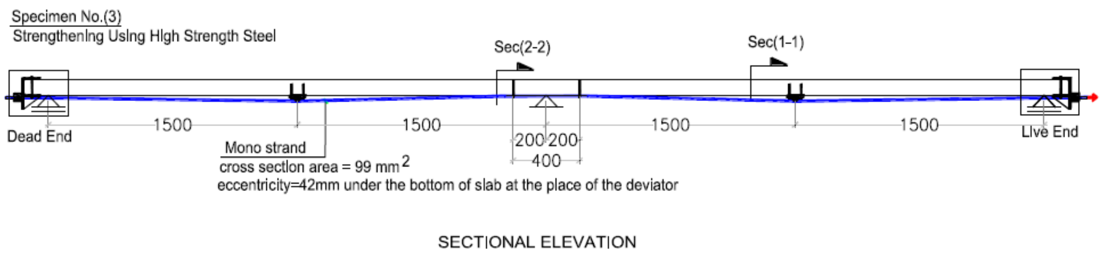


Figure 3. Specimen No. 3 strengthened by prestressed steel strand [11]

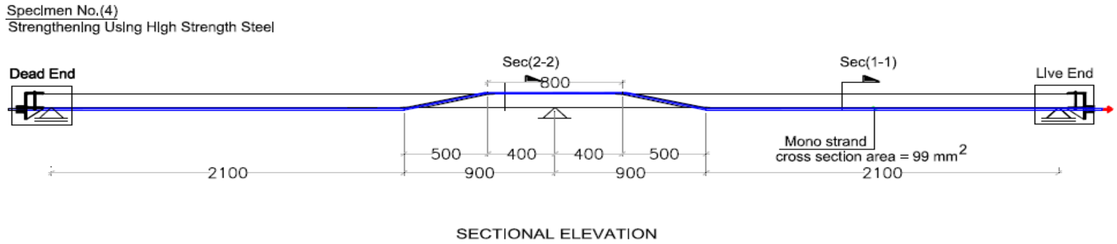


Figure 4. Specimen No. 4 strengthened by prestressed steel strand [11]

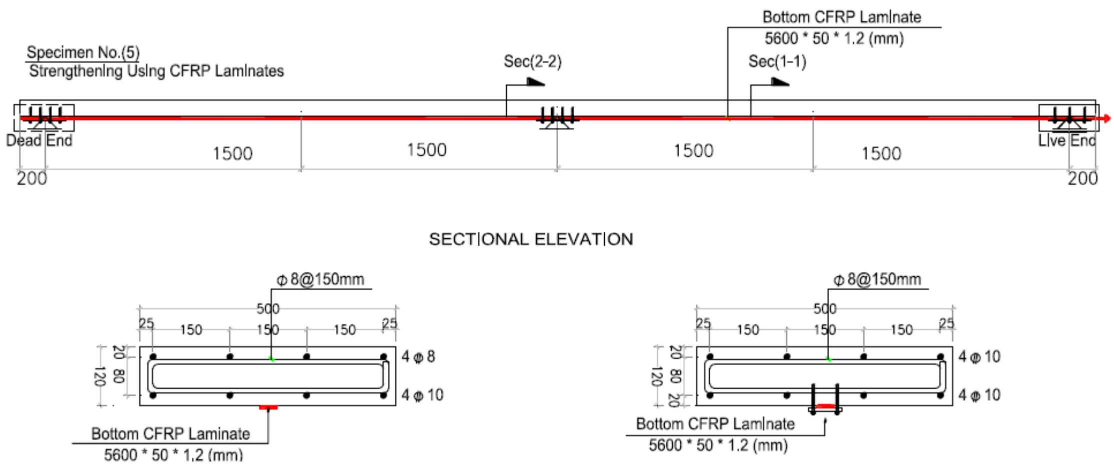


Figure 5. Specimen No. 5 strengthened by prestressed unbonded CFRP laminate [11]
Figure 6. Specimen No. 6 strengthened by prestressed bonded CFRP laminate [12]

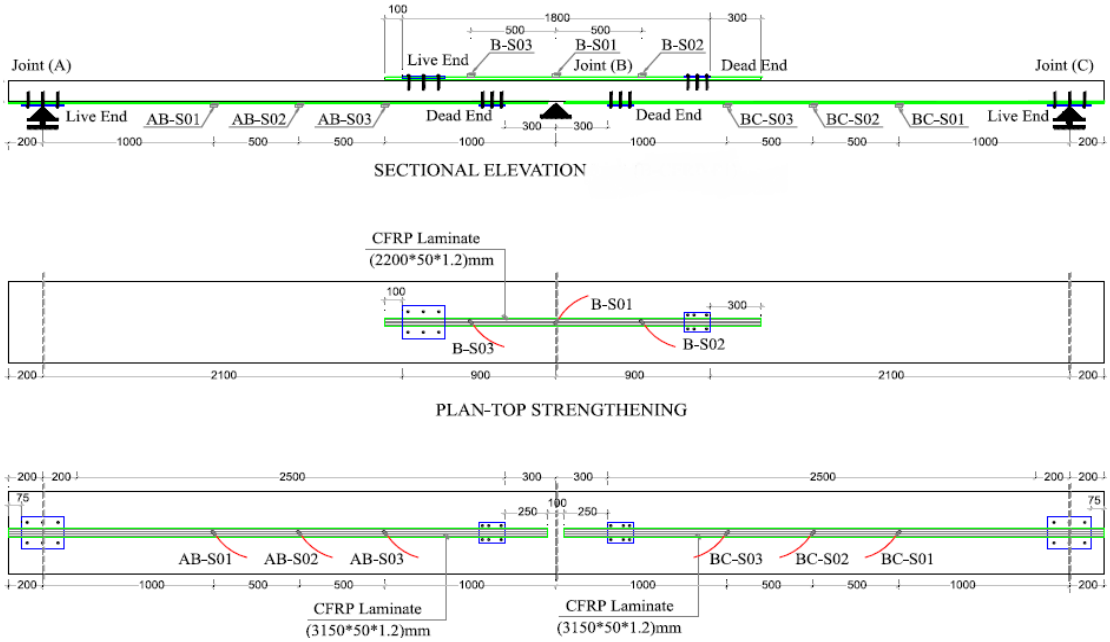


Figure 7. Specimen No. 7 strengthened by prestressed bonded CFRP laminates [12]

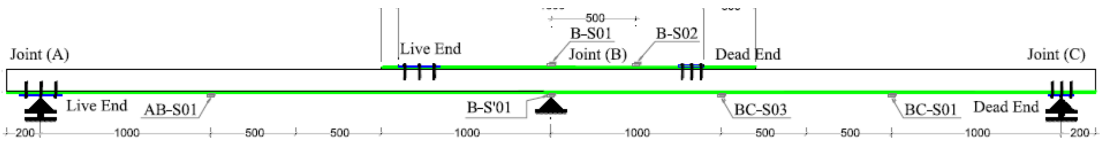


Figure 8. Specimen No. 8 strengthened by prestressed bonded CFRP laminates [12]

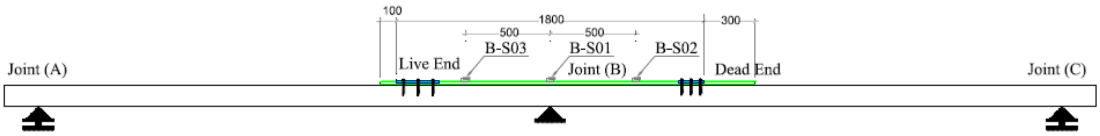


Figure 9. Specimen No. 9 strengthened by prestressed bonded CFRP laminate [12]

NUMERICAL INVESTIGATION

ATENA software [13] is used in analyzing of ten continuous RC slabs strengthened using prestressed steel strands and prestressed CFRP laminates in order to verify the analytical models. The validation of the numerical models is achieved by comparing FE models results with the experimental results.

Element Models

In ATENA [13], the concrete slabs, steel plates used in loading, supports, adhesive layers are modelled by 20 nodes solid three-dimensional (3D) brick. The steel reinforcement, CFRP and steel cables are modelled by two-node truss element.

Material Models

“CC3DNonLinCementitious2” material is used in modelling concrete in ATENA [14]. The parameters of the material are based on different codes and recommendations. The modulus of elasticity for all specimens are modified according to ACI code [15]. This material assumes that before reaching the concrete compressive strength a hardening branch is reached (Figure 10- Material state 3). (Figure 10- Material state 4) the mentioned figures showed that in compression concrete is considered a strain-softening material, while before cracking the behavior of concrete in tension is linear elastic (Figure 10-Material state 1). Crack opening is represented by an imaginary crack model [14] based on fracture energy and a crack-opening law (Figure 10-Material state 2). The failure criteria of the concrete material is performed by a biaxial stress failure as in Figure 11. In the 3d model the 3d stress state of the concrete is computed automatically by using predictor- corrector formula. “CCReinforcement” is used in modelling steel cables, CFRP and steel reinforcement [14]. A bilinear stress-strain relationship is used to represent reinforcement bars in a discrete form. While CFRP is modeled by using a linear stress-strain relationship also in the form of discrete bars embedded in the adhesive material. 3D elastic isotropic material is used to model both the steel plates and the adhesive layer.

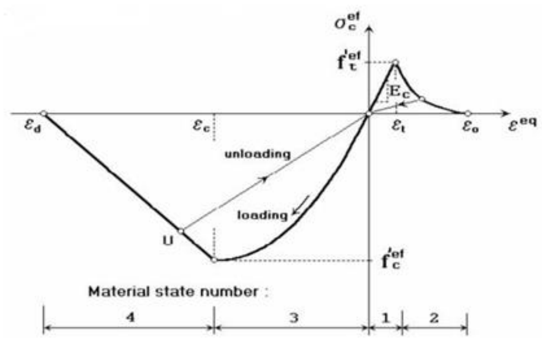


Figure 10. Uniaxial stress-strain relationship for concrete [14]

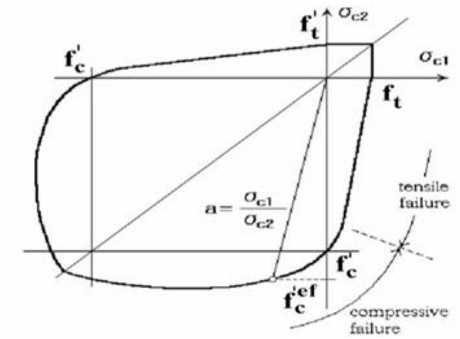


Figure 11. Biaxial failure functions for Concrete [14]

For the simulation of the interface between the concrete and CFRP, a contact element is defined which is called "gap" contact element. The relationship employed for the interface is a bilinear bond stress-slip [16], the tangential stiffness is defined as shown in Figures 12 and 13, while for introducing the normal direction stiffness the tensile behavior of the concrete is used as shown in Figure 13. Failure due to debonding is considered to occur when the interface principal tensile stress between concrete and CFRP reach the concrete tensile strength.

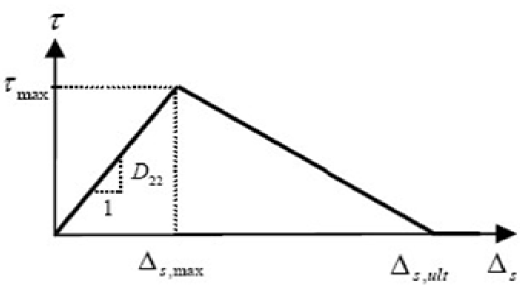


Figure 12. Bilinear bond-slip model [16]

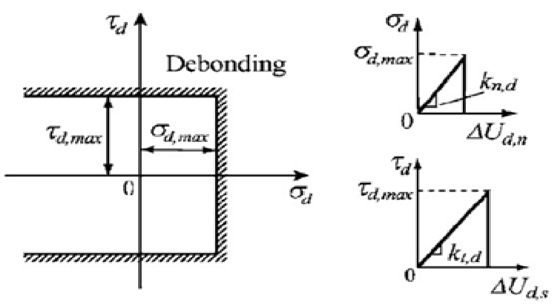


Figure 13. FRP debonding model [14]

ANALYTICAL INVESTIGATION OF TEST SLABS

In this paper, the flexural behavior of continuous RC slabs strengthened using prestressed steel strands and prestressed CFRP laminates is presented. FE models was completed and verification of the experimental results with the FEM results comprises the ultimate load capacity, cracking load, load-deformation curve and debonding load values for the bonded CFRP slabs.

For the control specimen Sp1, the FEM results shows high convergence with the experimental one as the first cracking load, Elastic peak load and ultimate load of the model is found to be 21, 80 and 114 KN respectively while the tested slab load values are 18, 79.8 and 114.8 KN respectively with variation in ultimate capacity load equals to 0.7% which shows the great agreement in the results. Figure 14. Shows load deflection-deflection curve of tested slabs and FEM.

For the slabs (Sp2, Sp3 and Sp4) strengthened using prestressed steel cables, the ultimate capacity of the slabs Sp2, Sp3 and Sp4 from the FEM are 156, 172, 207 KN respectively compared with the experimental results which are 170.5, 174.5 and 225.1 respectively with variation in results equals to 8.2%, 1.43% and 8% respectively. For the cracking and elastic peak loads the comparison is summarized in table 1.a, b, c. Figures 15, 16, 17 showed the flexural behavior of the strengthened slabs.

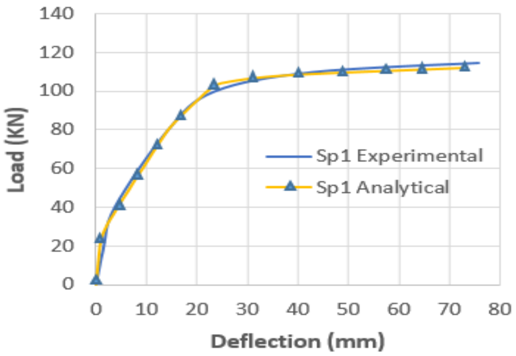


Figure 14. Load-deflection relationship for Sp1

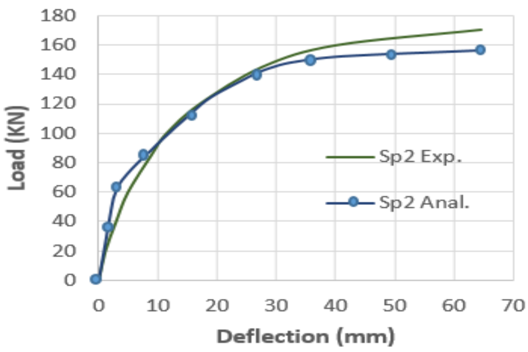


Figure 15. Load-deflection relationship for Sp2

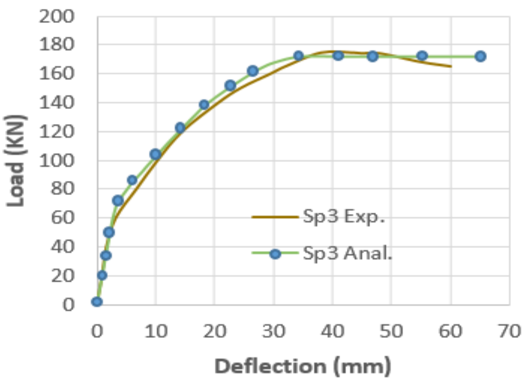


Figure 16. Load-deflection relationship for Sp3

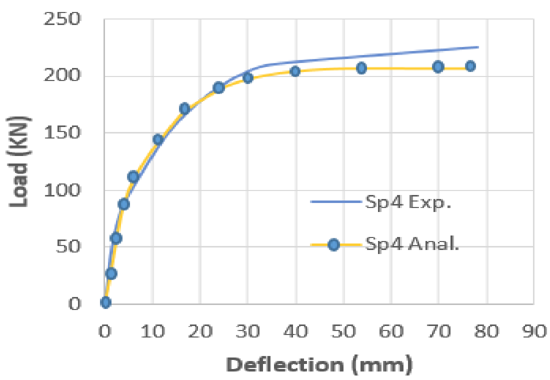


Figure 17. Load-deflection relationship for Sp4

Specimens	Cracking load KN		Failure load KN		% Load Enhancement= Anal./control	Theoretical / Exp.
	Exp.	Analyt.	Exp.	Analyt.		
SP1 control	**18**	**21**	**114.8**	**114**	**—**	**0.70%**
SP2	**49**	**45.5**	**170.5**	**156**	**35%**	**8.20%**
SP3	**60**	**64**	**174.5**	**172**	**49.80%**	**1.43%**
SP4	**80**	**76**	**225.1**	**207**	**67.20%**	**8.00%**
SP5	**44.9**	**42.5**	**142.6**	**144**	**20.20%**	**0.98%**

Table 1.a. Comparison between finite element model results and experimental results

Specimens	**Elastic peak loadal**		**Δe Elastic peak load**		**Δf Failure load**		**Δf / Δe Ductility index**	
	Experimental	**Analytical**	**Experimental**	**Analytical**	**Experimental**	**Analytical**	**Experimental**	**Analytical**
SP1 control	**79.8**	**81**	**14.27 mm**	**14.5 mm**	**76.3 mm**	**73.5 mm**	**5.346**	**4.526**
SP2	**145.3**	**140**	**27.37 mm**	**26.40 mm**	**64.9 mm**	**64.7 mm**	**2.371**	**2.45**
SP3	**139.5**	**142**	**21.46 mm**	**19.55 mm**	**43.45 mm**	**41.57 mm**	**2.024**	**2.126**
SP4	**194.6**	**189**	**25.50 mm**	**24.96 mm**	**78.30 mm**	**77.02 mm**	**2.427**	**3.085**
SP5	**121.3**	**125**	**26.53 mm**	**25.43 mm**	**99.80 mm**	**101.4 mm**	**3.761**	**3.98**

Table 1.b. Comparison between finite element model results and experimental results

Specimens	**Stiffness at cracking load (KN/mm)**		**Stiffness at Elastic load (KN/mm)**		**Stiffness at Failure load (KN/mm)**	
	Experimental	**Analytical**	**Experimental**	**Analytical**	**Experimental**	**Analytical**
SP1 control	**15**	**16.552**	**5.592**	**5.586**	**1.505**	**1.551**
SP2	**12.405**	**22.75**	**5.309**	**5.303**	**2.627**	**2.411**
SP3	**18.182**	**20.645**	**6.500**	**7.263**	**4.016**	**4.138**
SP4	**25**	**23.75**	**6.034**	**7.572**	**2.875**	**2.688**
SP5	**18.708**	**20.238**	**4.572**	**4.915**	**1.429**	**1.420**

Table 1.c. Comparison between finite element model results and experimental results

Table 1

For the slabs (Sp5, Sp6, Sp7, Sp8, Sp9) strengthened using prestressed CFRP laminates, Sp5 is the slab strengthened from the bottom chord only by unbonded CFRP laminates it was observed that the cracking, elastic and ultimate loads for the FEM are 42.5, 125, 144 KN respectively while the tested slab are 44.9, 121.3, 142.6 respectively and the variation in the ultimate load between the analytical and experimental results is 0.98 % as shown in figure 18. For the bonded slabs it was observed that the failure happened in all the specimens in the FEM was by debonding of the CFRP from the concrete which

agreed with the experimental results. Table 2. Shows the loads at which debonding took place and comparison between FE results and the experimental. Figures 19, 20, 21 shows the load-deflection curves for the tested slabs and FEM.

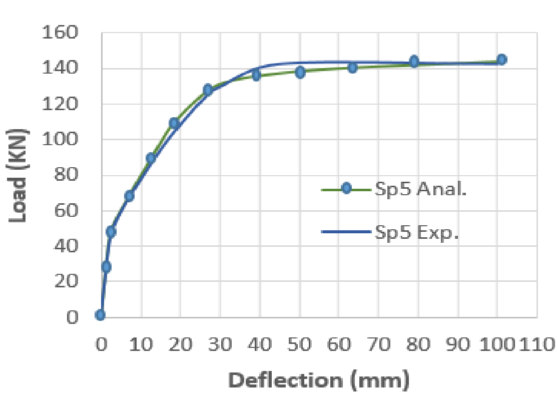


Figure 18. Load-deflection relationship for Sp5

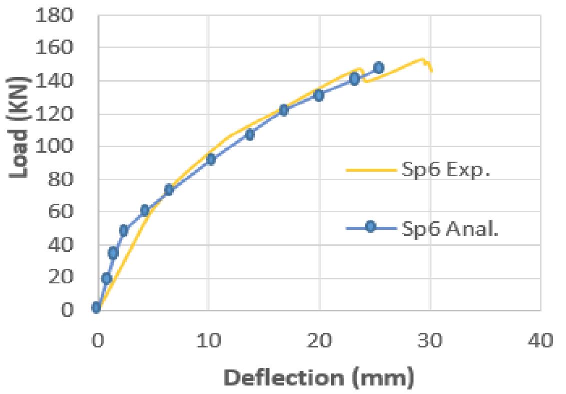


Figure 19. Load-deflection relationship for Sp6

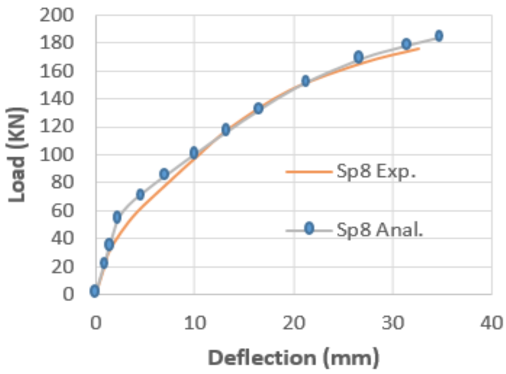


Figure 20. Load-deflection relationship for Sp8

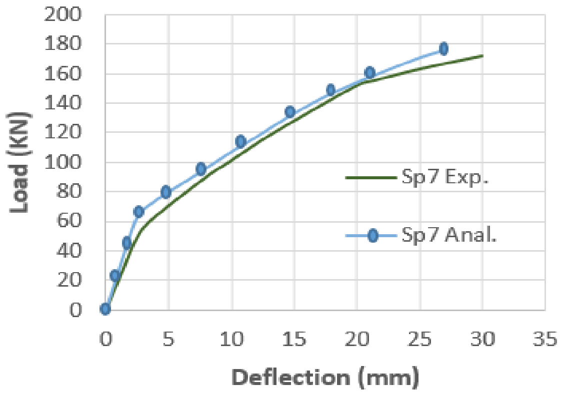


Figure 21. Load-deflection relationship for Sp7

Specimens	Debonding loads		Debonding zone	
	Experimental	Analytical	"Experimental"	"Analytical"
Sp6	147.1 KN	149 KN	Bottom IC debonding	Bottom IC debonding
Sp7	155.1 KN	147.5 KN	Top CFRP Middle and near the live end anchor	Top CFRP Near the live end anchor
	173.3 KN	181 KN	Left CFRP by slipping from live end anchor	Left CFRP, IC debonding near live end anchor
Sp8	146.7 KN	148 KN	At the top CFRP laminate	At the top CFRP laminate
Sp9	107 KN	106 KN	Slipping from dead end anchor	Near the live end anchor

Table 2. Shows the loads causing debonding for Sp.6, Sp7, Sp8, Sp9

The conclusion from the previous results is that the finite element analysis results converges with the experimental results and the ratio of the error of the cracking, elastic and ultimate loads between the FEM and the tested slabs are small. The flexural behavior of the modelled slabs agreed and gave good predictions against the experimental one. Subsequently there is a good verification between the FEM results and the experimental results which permits the possibility of conducting parametric study and give reliable results.

Parametric study

There are several parameters that are involved in this study to investigate the flexural behavior of prestressed slabs even by steel strands or CFRP laminates. The parameters are:

1- Concrete compressive strength and its effect on the ultimate capacity and the slab ductility,
2- Effect of prestressing levels and the possible failure criteria,
3- Effect of changing cross section area of cables and
4- Finally effect of number of CFRP layers on both the ultimate capacity and slab ductility.

The first parameter (Concrete compressive strength) which includes the changing of the concrete compressive strength, the study is conducted on the slabs strengthened by prestressed steel cables (Sp2, Sp3, and Sp4). The values of Fcu are 30 MPa, 50 MPa and 70 MPa, the results are summarized in table 3. And Figures 22, 23, 24.

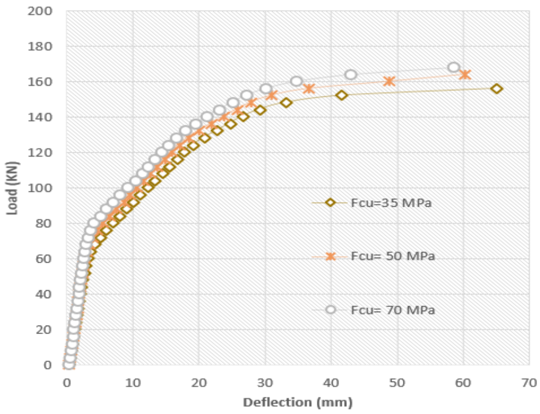


Figure 22. Load-deflection for different Fcu for Sp2

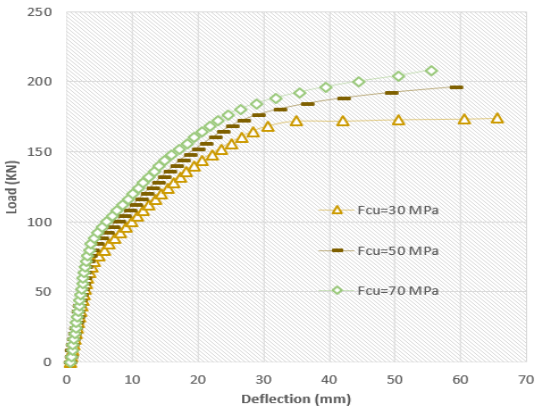


Figure 23. Load-deflection for different Fcu for Sp3

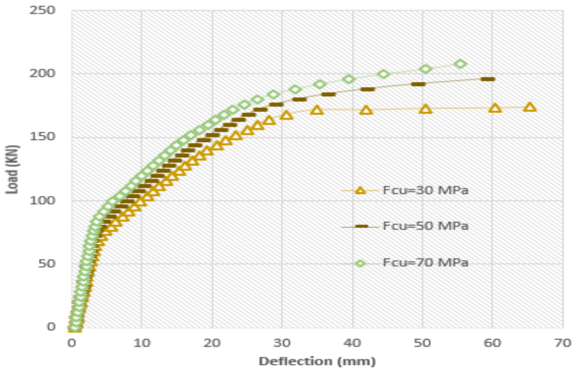


Figure 24. Load-deflection for different Fcu for Sp4

Specimens	Failure Load		
	Fcu=30 Mpa	Fcu=50 Mpa	Fcu=70 Mpa
SP. 1	156 KN	164 KN	172 KN
SP. 2	172 KN	196 KN	216 KN
SP. 3	207 KN	212 KN	232 KN

Table 3. Comparison between Specimens Sp2, Sp3, Sp4 with respect to different Fcu values

The previous results showed that by increasing the concrete compressive strength the ultimate capacity of the slab increases and the brittleness increases and it was observed that the failure occurred for the slabs F30, F50 and F70 is crushing of concrete in addition to by increasing the concrete compressive strength, the stress in the steel strands decrease for all the slabs.

The second parameter (effect Prestressing levels) which discuss the effect of changing the prestressing level, this study is conducted on the prestressed steel strands slabs (Sp2, Sp3, Sp4), the slabs are subjected to different prestressing ratios %F_{pe} equals to 45%, 55%, 60% and 70% from the ultimate strength of the strand F_{pu}. It is cleared that by increasing the prestressing ratio the behavior of the slabs prior to cracking is the same as well as the ultimate capacity of the slabs increases with a decrease in the ductility of the slab. The maximum camber in the slab increases and the stress in the strands increases without rupture. The failure in all the slabs is crushing of concrete in the compressive zone of the intermediate support. These results are presented in table 4. And figures 25, 26 and 27.

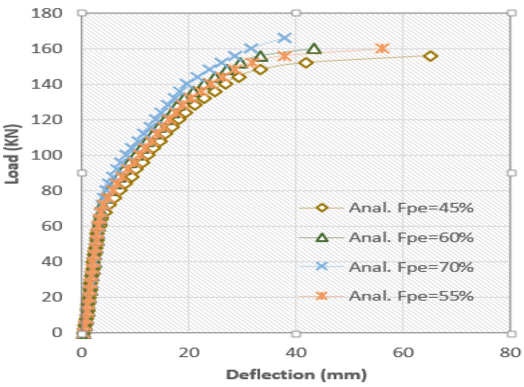


Fig. 25. Load-defl. For prestressing levels for Sp2

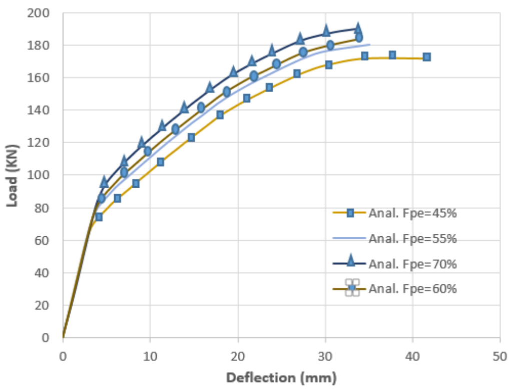


Fig. 26. Load-defl. For prestressing levels for Sp3

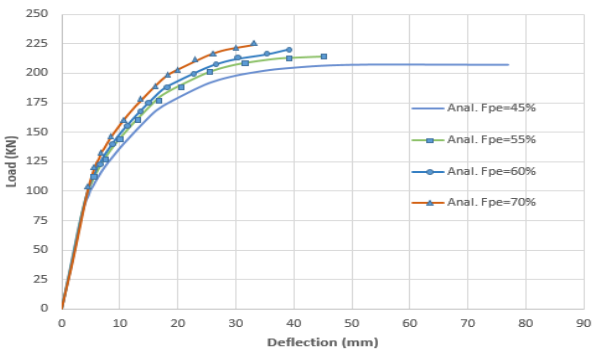


Figure 27. Load-defl. for prestressing levels for Sp3

	% Fpe = 0.55 Fpu				% Fpe = 0.45 Fpu			
Specimens	Failure mode	Maximum camber (mm)	Maximum stress in cable at failure (Mpa)	Ultimate load (KN)	Failure mode	Maximum camber (mm)	Maximum stress in cable at failure (Mpa)	Ultimate load (KN)
Sp2	Crushing	1.348	1350.6	159	Crushing	1.096	1180	156
Sp3	Crushing	1.697	1422.5	180	Crushing	1.361	1242.2	172
Sp4	Crushing	2.05	1484.4	212	Crushing	1.64	1328.6	207

	% Fpe = 0.60 Fpu				% Fpe = 0.70 Fpu			
Specimens	Failure mode	Maximum camber (mm)	Maximum stress in cable at failure (Mpa)	Ultimate load (KN)	Failure mode	Maximum camber (mm)	Maximum stress in cable at failure (Mpa)	Ultimate load (KN)
Sp2	Crushing	1.861	1599.5	164.5	Crushing	1.503	1437.8	162
Sp3	Crushing	2.268	1680	190	Crushing	1.884	1535.6	183.5
Sp4	Crushing	2.75	1802.4	224	Crushing	2.28	1598	218

Table 4. Comparison between Specimens Sp2, Sp3, Sp4 with respect to different prestressing level

The third parameter (effect of number of strands) showed the effect of increasing the number of strands on the flexural capacity of the slabs in the specimens (Sp2, Sp3), the addition of two strand of the same cross section area 98.7 mm2 instead of one strand only increases the ultimate load for Sp2 from 156 KN to 180 KN and Sp3 from 172 KN to 212 KN, subsequently it enhances the flexural capacity of the slab Sp2 and Sp3 by 57.9 % and 86 % with corresponding deflection 35.4 mm and 26.9 mm instead of 64.9 mm and 43.45 mm for Sp2 and Sp3 respectively as shown in figures 28, 29.

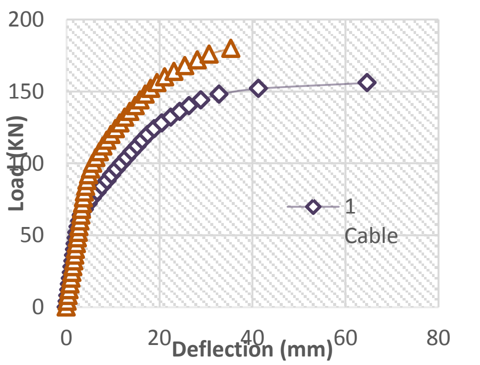


Fig. 28. Effect of no. of cables on behavior of Sp2

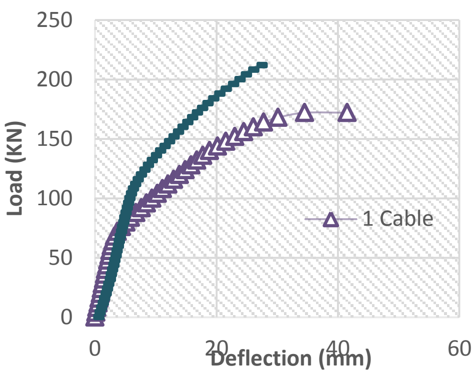
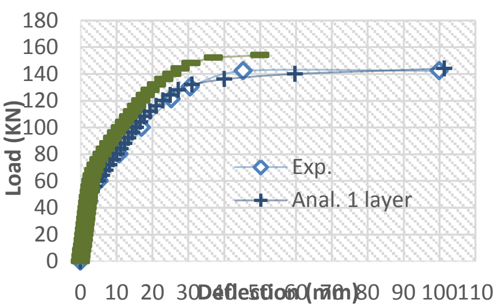


Fig. 29. Effect of no. of cables on behavior of Sp3

The fourth parameter (effect of number of CFRP layers) discussed the effect of increasing number of CFRP layers on flexural behavior of the slabs (Sp5, Sp6). For Slab Sp5 by increasing the number of layers by 2 layers instead of one layer the ultimate load increases from 144 KN (1 layer) to 154 KN by ratio 7% which is small ratio accompanied by decrease in deflection from 101.4 mm to 49.8 mm subsequently decreasing in the slab ductility as shown in figure 30. And table 5. For slab Sp6 (bonded CFRP) it was observed that increasing the number of CFRP layer by 2 layers delayed the debonding of the bottom CFRP from load 149 KN to 168 KN and the ductility of the slab is nearly the same as the deflection at failure for 1 layer CFRP is 25.3 mm while for the 2 layer specimen is 20.7 mm, therefore the addition of layers of CFRP enhanced the flexural behavior of the slab as shown in figure 31.



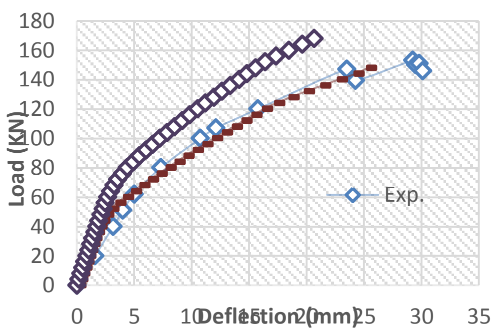


Fig. 30, 31. Effect of inceasing no. of layers of CFRP laminates on behavior of Sp5, Sp6 respectively

	Cracking	Ultimate	Strain of CFRP at failure	Stress of CFRP at failure
Experimental	**44.9**	**142.6**	**0.00875**	**1443.75**
Analytical 1 layers	**42.5**	**138**	**0.008967**	**1479.555**
Analytical 2 layers	**48**	**154**	**Upper layer =0.007726**	**Upper layer =1288 Mpa**
			Lower layer =0.008198	**Lower layer =1366 Mpa**

Table 5. Comparison between results of experimental, Analytical with 1 & 2 layers of CFRP laminates

Conclusions

The following main points can be concluded based on results extracted from these investigation:

1- The finite element analysis proved its efficiency in the estimation of the ultimate load for the continuous RC slabs which exhibited in the results of the models compared with the experimental results as for specimens Sp1, Sp2, Sp3, Sp4 and Sp5 the ratio between the theoretical and the experimental ultimate loads are 0.7% , 8.2%, 1.43%, 8% and 0.98% respectively.

2- For the slabs strengthened using prestressed bonded CFRP laminates, the ratio between the theoretical and the experimental first debonding loads for slabs Sp6, Sp7, Sp8 and Sp9 are 1.3% , 5.0%, 0.80% and 0.93% respectively, it is clear that the finite element model give reliable values.

3- The ultimate capacity of the tested slabs increased by increasing the concrete compressive strength accompanied by decrease in ductility of the slabs, for Fcu equals to 30 MPa, 50 MPa, 70 MPa for slabs Sp2, Sp3, Sp4.

4- The effect of changing the prestressing level is significant, by increasing the prestressing level the ultimate capacity increases with an increase in the slab brittleness, for slabs Sp2 & Sp3 the maximum prestressing level without the occurrence of rupture in the strands may reach 75% from ultimate strength of the strand, while in Sp4 the maximum prestressing level is found to be 70% from the ultimate strength.

5- The effect of increasing the number of strands results in increasing the ultimate capacity of the slabs by a great ratio for both Sp2 & Sp3.

6- Finally by increasing the number of CFRP layers, the unbonded CFRP Sp5 is not greatly affected by this increase as the ultimate capacity increases by 7%. While for the bonded CFRP its effect clarified clearly in the delay of debonding and without an obvious difference in ductility between the slab with one layer and the slab with two layers.

Further investigations is proposed to be conducted to study the effect of strengthening large scale slabs with externally prestressed steel strands and prestressed CFRP laminates by its analysis in two directions under different loading schemes (point loading, uniform loading and cyclic loading).

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