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An Innovative Efficient Strengthening For Reinforced Low Strength Concrete Cantilever Slabs

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Abstract : *External prestressing is commenly used with notable effectiveness to increase and upgrade the flexural capacity of Reinforced Concrete (RC) beams and slabs. However, the major practical difficulty associated with external prestressing is that, it must be applied to relatively high strength concrete elements which may not be met in many cases where geometry and properties of concrete and steel reinforcement of existing member can't be modified. Hence the designer has no control on the existing structural elements that need repair. This research is aims to develop and evaluate an innovative strengthening technique for low strength concrete slabs. This method is based on applying a thin layer of Engineered Cementitious Composites (ECC) in the compressive side of RC slabs prior to the application of the external prestressing tendons. The role of the proposed ECC layer is to avoid the early concrete crushing in compression side, and consequently increase the efficiency of the external prestressing. To investigate the efficiency of the proposed strengthening technique, a total of nine RC slabs cast by low concrete strength (compressive strength = 15 MPa). Application of external prestressing solely would induce brittle failure by abrupt crushing in concrete at the low strength compressed soffit. For That purpose, two different thicknesses of ECC layer were considered in the first group of the experimental program. Strengthening process at three different levels of sustained loading was also taken into account through the second experimental group. The present study indicated that the proposed hybrid strengthening technique was is a very powerful tool for enhancing the capacity of the considered case study. Evaluation of some of the existing analytical formulae of tendon stress was finally made. In addition, a proposed prediction formula of the ultimate tendon stress for the case of the studied hybrid strengthening technique was presented.*

Keyword : *External prestressing, Cementitious Composites, Strengthening, RC slabs.*

I. Introduction

Strengthening and/or upgrading of concrete structures by using external prestressing have been considerably used for several application. External prestressing may be defined as a prestress introduced by tendons located outside a section of a structural member, only connected to the member through end-anchorages with or without deviators. The main advantages of using this technique are; higher utilization of small sectional areas, ease in inspection of the tendons and in their replacement and low friction losses [1, 2, 3, 4]. This type of prestressing can be applied to both new and existing structures that need to be strengthened due to several reasons such as: changes in use, deficiencies in design or construction phase and structural degradation. At present, the application of external prestressing to deteriorated, overloaded or aging existing structural members using unbonded tendons is proving to be a very effective and promising in strengthening structural elements or systems [5, 6, 7, 8, 9, 10]. Even in well designed concrete members cracking is the main cause of failure as it can lead to loss of structural integrity allowing partial or total collapse mechanisms to occur.

The applications of external prestressing rehabilitation techniques have shown to not only increase the life expectancy of the member or system, but to increase the flexural strength considerably, resulting in reduced deflection and cracks widths [11, 12]. However, in RC slabs of low concrete strength, the increase of the flexural strength that external prstressing can provide is limited by the maximum allowable compressive stress in the compressed part of the slab [13, 14]. This restriction reduces the effectiveness of the strengthening, thus limiting the use of the external prestressing technique.

The idea of the present work is based on utilizing the beneficial properties of an easy used ductile high strength cement based material to be applied to the compression side, thus reducing the developed stresses on the low strength concrete at the compression side and consequently increase the efficiency of the strengthening technique. ECC is a special category of the new generation of high-performance fibre-reinforced cementitious composites. It is a micromechanically designed material that uses a micromechanical model to tailor-make the required properties. By using this micromechanical tool, the fibre amount used in the ECC is typically less than

2% by volume. The use of fibres gives better compressive behaviour and better tensile crack-bridging properties (15, 16, 17]. ECC's high tensile ductility, deformation compatibility with existing concrete and self-controlled micro-crack width lead to their superior durability under various mechanical and environmental loading conditions such as fatigue, freezing, chloride exposure and drying shrinkage [18, 19]. Many investigators tried several mixes of ECC [20, 21, 22, 23, 24, 25] where some of them used spraying for its application which suited the current research.

In this paper, the experimental program is demonstrated. Constituent materials and mixes design are elaborated. Discussion of the results is presented in terms of mode of failure, cracking pattern, crack openning, load-displacement relationships, strain development and toughness. Predictions of tendon stress by particular analytical formulae are tested against the experimental results.

II. Experimental Program

2.1 Test Specimens

Nine RC slabs, 120 mm thickness, 500 mm width, and 2650 mm long, were cast that were divided into three groups (I, II, and III) in addition to two control unstrengthened slab, S-C (fcu=15 MPa), and S-C* (fcu=40 MPa). The slabs were reinforced by four 10-mm diameter reinforcing bars in the longitudinal direction spaced at 125 mm across the width of the slab. The bars had a clear cover of 20 mm. The transverse reinforcement consisted of 8-mm diameter reinforcing bars spaced at 200 mm. Further details of the tested slabs are given in Table 1.

The slabs of group I were selected to evaluate firstly the efficiency of external prestressing in strengthening both low and ordinary strength reinforced concrete cantilever slabs. Secondly, specimens of group II were designed to investigate the efficiency of strengthening low strength reinforced concrete cantilever slabs using an innovated hybrid strengthening technique. The proposed technique composed of a thin layer of ECC cast to compression side prior the application of external prestressed bars in tension side as illustrated in Figures 1&2. The strengthening technique was designed to reach to about 60% target gain. The slabs of group III were chosen to evaluate the efficiency of using the proposed strengthening technique to repair cracked slabs. Group III consisted of three reinforced concrete cantilever slabs that were preloaded by 35%, 65% and 85% of the ultimate load of control slab, prior to the application of the proposed strengthening technique. Figure 3 shows crack pattern of specimen S-20-85 after preloading and before strengthening.

Specimens of G-II and G-III were demoulded at an age of 2 days, and their bottom surfaces (compression side) were washed out using a retarder to obtain rough surfaces. The slabs were then covered with wet towels for additional 26 days. At the age of 28 days, ECC strengthening layer was cast to compression side of each slab. After 28 days from the application of the ECC layer, each slab was externally prestressed using two stainless steel 12 mm diameter bars located directly at the slabs' top surface. The bars were set to the ends of the concrete slab via two steel anchoring plates 20 mm thickness. The prestressing was conducted using end nuts at the two ends of each bar as shown in Fig. 1. The prestressing area of the two bars was 226 mm2 and carried a prestressing force of 22 kN each (about 20% of its ultimate strength), with a total prestressing force of 44 kN. Local slab crushing at end zones was avoided by using two L-shape steel plates at slabs ends as shown in Fig. 1.

2.2 Material Properties

The average compressive (cubic) strength of the concrete used to make the slabs, at an age of 28 days, was 15 MPa for all specimens expect the two slabs S-C* , and S-0-0*, it was 40 MPa. Mix proportions of the used concrete are illustrated in Table 2. Four 10-mm diameter steel bars having a yield tensile strength of 480 MPa were used as flexural reinforcement, while eight 8-mm diameter steel bars having a yield strength of 262 MPa were used as secondary reinforcement. Two high strength stainless steel 12-mm diameter bars were used for each prestressed slab. The used bars have an ultimate strength of 978 MPa and an ultimate strain of 0.5%.

The mix proportions of the ECC used as a strengthening material in this study are listed in Table 3. The water to binder ratio (W/B) was 0.20. Ordinary Portland cement having a density of 3.14 g/cm3 was used, and 15% of the design cement content was replaced by silica fume. Quartz sand with diameter less than 0.5 mm was used as a fine aggregate. High strength Polypropylene (PP) fiber was chosen for ECC and its volume in mix was 1.5%. The average compressive strength at an age of 28 days was designed to be 55 MPa.

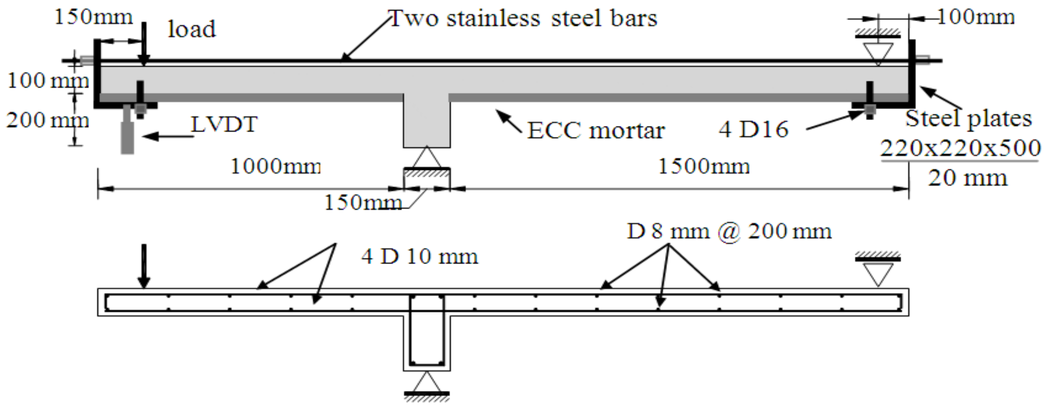

Fig. 1: Test setup and specimens' details.

Fig. 2. The proposed hybrid strengthening technique.

Fig. 3. Crack pattern of specimen S-20-85 after preloading and before strengthening.

Table 1: Description o f test slabs

	slab	f_{cu} (MPa)	Internal reinforcement (mm^2)	External prestressing		ECC thickness (mm)	Preloading level%
				Area (mm2)	Initial force (kN)		
Reference	S-C	15	314	--	--	--	--
	S-C*	40	314	--	--	--	--
G-I	S-0-0	15	314	226	44	--	--
	S-0-0*	40	314	226	44	--	--
G-II	S-20-0	15	314	226	44	20	--
	S-40-0	15	314	226	44	40	--
G-III	S-20-35	15	314	226	44	20	35%
	S-20-65	15	314	226	44	20	65%
	S-20-85	15	314	226	44	20	85%

Table 2: Mix proportions of the used concrete

Cubic Strength (MPa)	Water (kg/m^3)	Cement (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)
15	210	240	1165	680
40	190	475	1140	570

Table 3: Mix proportions of ECC

Water/binder ratio	Water (kg/m^3)	Cement (kg/m^3)	Silica fume (kg/m^3)	Sand (kg/m^3)	Super plasticizers (kg/m^3)	Polypropylene fiber (kg/m^3)
0.2	292	1243	223	149	14.9	14.6

2.3 Test Setup And Procedure

All the tested slabs were loaded in three-point bending. They were loaded with a concentrated load at the cantilever end. The slabs were positioned under a hydraulic actuator that was mounted on a steel reaction frame. The actuator and load cell were positioned at a distance of 150 mm from the free end. Steel plates and adjustable rollers were used to distribute the load at the top surface of the slab. To record the compression strain in the extreme concrete fibers at the section of maximum moment, a strain gauge was bonded to the concrete surface of each slab. The maximum strains in inner steel were recorded using one strain gauge bonded to each bar at the position of maximum bending moment. Displacements at loading point and the supports were measured using LVDT (stroke = 50mm, sensitivity = 0.005mm). An automatic data acquisition system was used to monitor loading, displacements and strains. The instrumentation used to monitor the behavior of the slabs during testing is shown in Figure 1.

III. Test Results And Discussion

The obtained experimental results are presented and subsequently discussed in terms of the observed mode of failure, ultimate loads, load deflection behavior, external prestressing force, and cracking behavior.

3.1 Ultimate loads and Modes of Failure

The crack pattern of the tested slabs after failure is shown in figure 4. The two control slabs exhibited a conventional ductile flexural mode of failure which were initialy by yielding of steel reinforcement followed by crushing of concrete in the compression zone. The two slabs S-0-0 and S-0-0* which were strengthened by externally prestressing failed by tension cracking followed by crushing of concrete in the compression zone which was preceded by yielding of the steel reinforcement without rupture of the strengthening bars. The hybrid strengthened slabs failed by flexural cracking followed by crushing of concrete in the compression zone then local de-bonding between concrete and the ECC strengthening layer at the crushed zone. Also according to the strain monitoring realized during the test, the main reinforcement yielded and no rupture occurred to the presstressing bars. The failure of all strengthened slabs was ductile where considerable deflection and wide cracks were observed before failure. The ultimate moments of all slabs was more than twice the cracking moment. Therefore, ACI-318-14 requirements regarding the prevention of brittle failure after cracking were satisfied.

As can be seen from Table 4, the failure load of the two control slabs S-C and S-C* were 10.9 kN and 14 kN. However, the ultimate load of the two strengthened slabs S-0-0 and S-0-0* using externally prestressed bars, without ECC in compression side, increased to 20 kN and 30 kN respectively. The significant differences in slabs's ultimate load were due to variation of concrete strengths of the slabs. Furthermore the strength gain due to external prestressing for case of low trength was 9% while for case of ordinary strength it was 16% as shown in figure 5. The combination of the proposed ECC layer in compression side and the externally prestressed bars in the tension side, used to strengthened slab S-20-0 (fcu=15MPa), was able to increase the load-carrying capacity to 33.5 kN (which is 2 times higher than that of the control unstrengthened slab S-C). Also, the proposed hyprid technique of slab S-20-0 increase the ultimate load of about 67% than the slab strengthened using the external prestressing only. These results indicate that, strengthening the compression side of the slabs using a thin layer of ECC and the corresponding increase in their stiffness significantly reduces the compressive stresses that developed at the substrate concrete extreme compressed fibers compared to slab S-0-0 that was strengthened with external prestressing only. This explains why the ECC-strengthened slabs were able to attain higher load carrying capacity compared to those strengthened using external prestressing only.

The results of testing preloaded slabs S-20-35, S-20-65 and S-20-85 shown in Table 4 showed that, loading the slab prior to the application of the strengthening technique, reduces the achieved strength gain. The recorded reductions in flexural strength gains for the preloaded slabs relative to the gain of slab S-20-0, without preloading, were about 4.4%, 10.4% and 13.4% for the slabs loaded to a preload level of 35%, 65% and 85 %

respectively. This indicates that the hybrid strengthening technique can be effectively used for repairing and strengthening cracked reinforced concrete slabs.

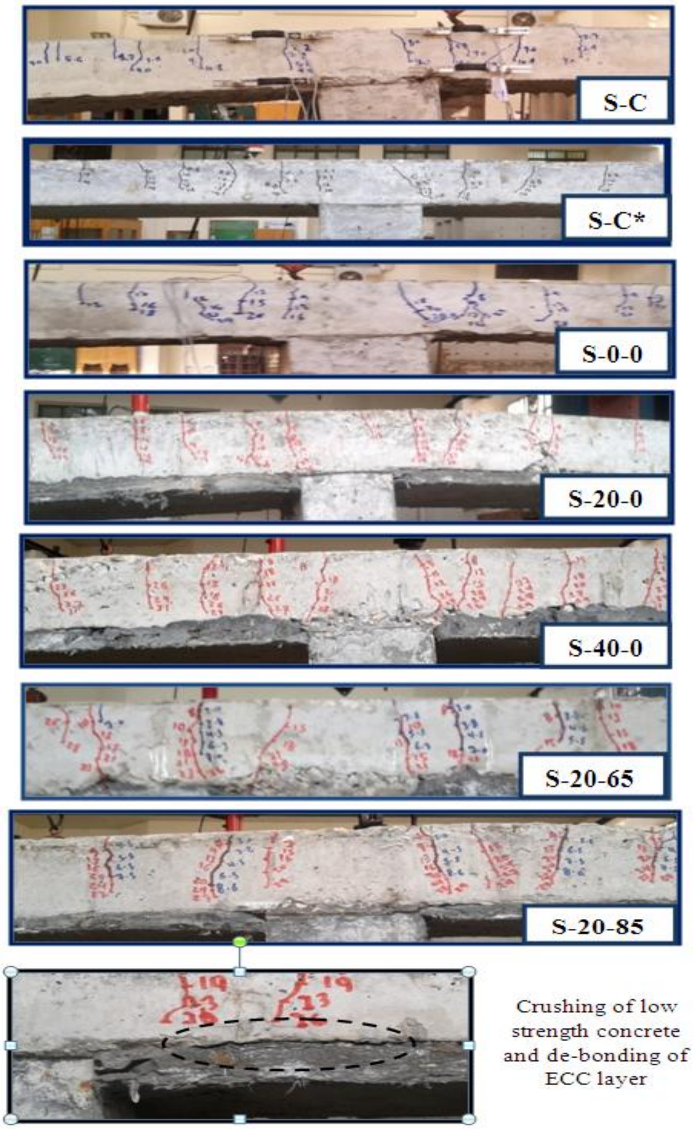

Fig. 5 Crack pattern of the tested slabs.

Table 4: Test results

	slab	P_{cr} (kN)	P_y (kN)	P_u (kN)	Δ_u (mm)	W_u (mm)	Toughness (kN mm)	Mode of failure
Reference	S-C	2.2	10.9	10.9	89.7	2.8	886	Flexural failure
	S-C*	5	14	14	65	2.5	822	
G-I	S-0-0	7.0	18	20	43.18	2.2	663	Flexural cracking followed by crushing of concrete in the comp. zone
	S-0-0*	10	22	30	33.12	2.0	741	
G-II	S-20-0	8	22	33.5	57.69	1.9	1510	Flexural cracking followed by crushing of conc. in the comp. zone then local de-bonding between conc. and the ECC
	S-40-0	8.5	23.7	36	55.43	1.7	1590	
G-III	S-20-35	7.0	21.3	32	58	2.0	1450	
	S-20-65	7.0	20.9	30	60	2.3	1375	
	S-20-85	7.0	20	29	65	2.48	1300	

P_{cr}=cracking load, P_y=yielding load, P_u=ultimate load, Δ_u=ultimate deflection and W_u=ultimate crack width

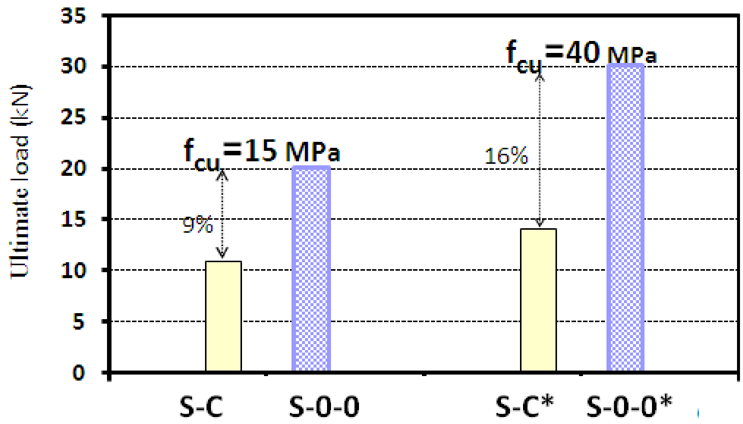

Fig. 5 Comparison among efficiency of external prestressing for low and ordinary strength (G-I).

3.2 Deflection Characteristic and Toughness

Figures 6(a) and 6(b) show the measured load-deflection response for slabs of group I and group II, respectively. The control slab S-C showed the usual elastic and inelastic parts of its deflection behavior. It failed, as expected, due to yielding of the tensile steel reinforcement. For the other strengthened slabs, the response of the load-deflection relationship can be divided into three regions. In the first region, the deflection increased linearly with the applied load till flexural cracks appeared, and the slab stiffness was reduced. In the second region, due to stiffness reduction caused by cracking, the deflection increased rapidly until the internal reinforcement started to yield. Finally, after the section of maximum moment had become sufficiently plasticized, the deflection increased substantially with little increase in load. Figure 6(c) illustrates the load-deflection behavior of group III slabs compared with the behavior of slab S-20-0. It is clear from figure 6(c) that the effect of preloading was to reduce the initial stiffness (slope of load deflection curve) of slabs S-20-35, S-20-65 and S-20-85 by about 25%, 45% and 60 % respectively, compared to slab S-20-0. In addition, the loss of slabs stiffness caused by preloading resulted in increase in deflection compared to slab S-20-0.

Toughness values of the tesed slabs are reported in table 4. It can be observed from figure 7 that the proposed hyprid system (S-20-0) caused an increase in toughness by about 128 % than using external presstressing system only (S-0-0). In addition, using this hyprid system in repair keeps more than 86% of the toughness gain.

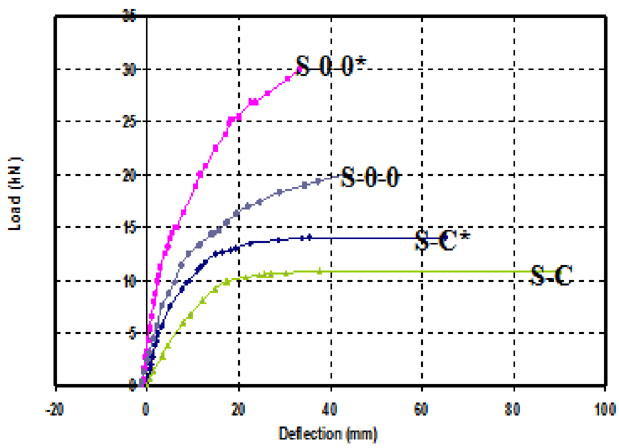

Fig. 6(a) Load- deflection curves for G-I.

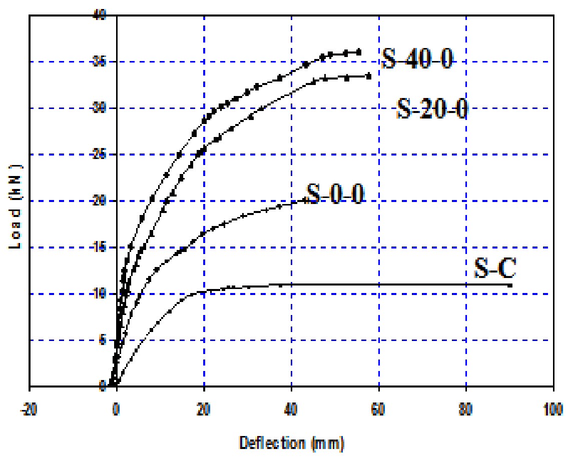

Fig. 6(b) Load- deflection curves for G-II.

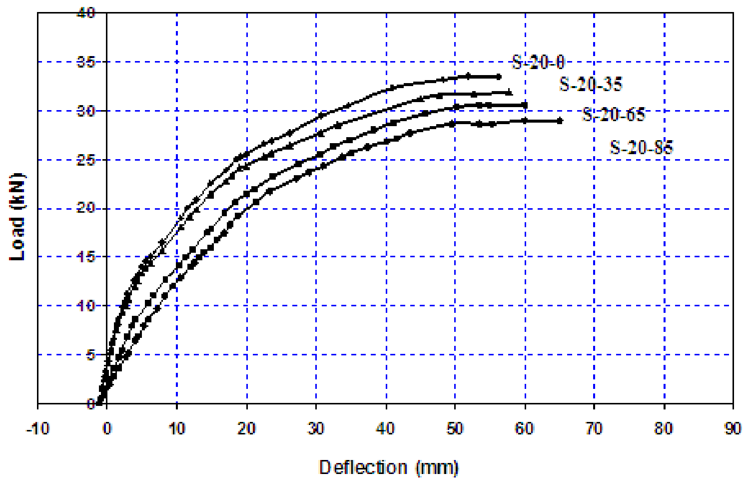

Fig. 6 (c) Load- deflection curves for G-III.

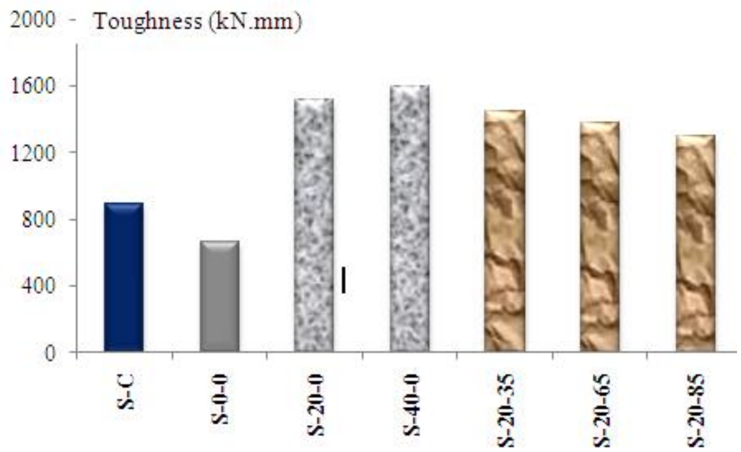

Fig. 7 Comparison among specimens concerning toughness.

3.3 External Prestressing Force

The load versus strain of prestressed bar for the tested slabs is shown in Figures 8(a), (b) and (c). During loading, all the strengthened slabs exhibited similar load-external prestressing strain behavior. Initially, the increase in the external prestressing strain was small till cracking beyond which it started to increase rapidly as the load increased until the internal steel reinforcement yielded. Then the strain of the external prestressing increased dramatically until the crashing of concrete occurred in the compression zone. As known, the external prestressing force, fps at each loading level is proportional to the measured strain values (fps= Eps Aps εps). In this study, the force in all prestressed bars never reached its nominal breaking force and no bar fractured during the tests.

A significant difference in prestressed ultimate strain values was observed for specimens S-0-0 and S-0-0*, and this was attributed to the variation of concrete strength. The achieved ultimate strain for specimen S-0-0* was 3300 με, while The achieved ultimate strain for specimen S-0-0 was 2000 με. Table 4 shows the prestressing force at cracking, yielding as well as ultimate load for all test slabs. It can be seen that, the ultimate bar force (bar force at failure) for slab S-20-0 was about 158 kN, which represents about 80% increase in the ultimate bar force of slab S-0-0. This reveals the effectiveness of the proposed hybrid strengthening technique compared to the externally prestressing technique. The effect of preloading was to reduce the achieved ultimate bar force. Slab S-20-85 preloaded with 85% of the control slab ultimate load exhibited the lowest bar force while specimens S-40-0 exhibited the highest.

Table 5: External prestressing force at different stages of loading.

specimen		Initial force (kN)	External prestressing force (kN)			Relative increase in external prestressing force %		
			at cracking	at yielding	at ultimate	at cracking	at yielding	at ultimate
G-I	S-0-0	44	49.5	76.3	88	12.5	73.4	100
	S-0-0*	44	49.7	66	149	12.9	50	239
	S-20-0	44	48.4	61.8	158	10	40	259
	S-40-0	44	48.4	59.4	175	10	35	297
G-II	S-20-35	44	48.4	63.8	153	10	45	247
	S-20-65	44	49.2	65.56	149	11.8	49	238
	S-20-85	44	50.6	68.2	145	15	55	229

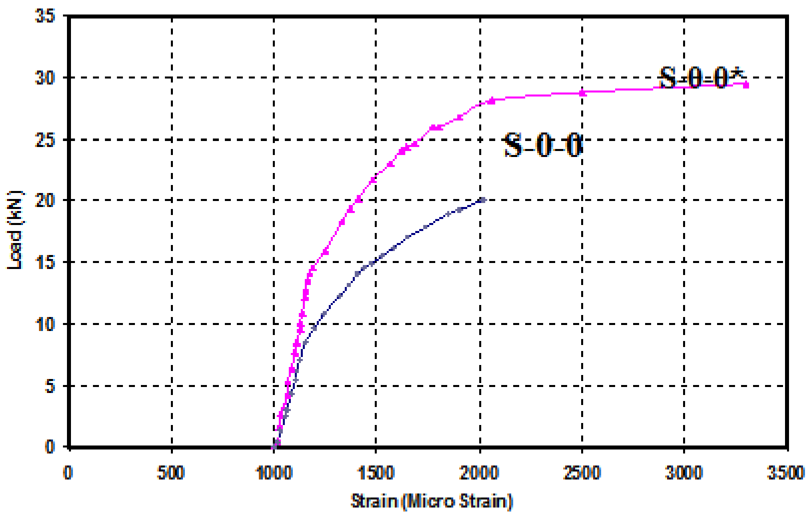

Fig. 8(a) Load vs prestressed bar strain relationship for G-I.

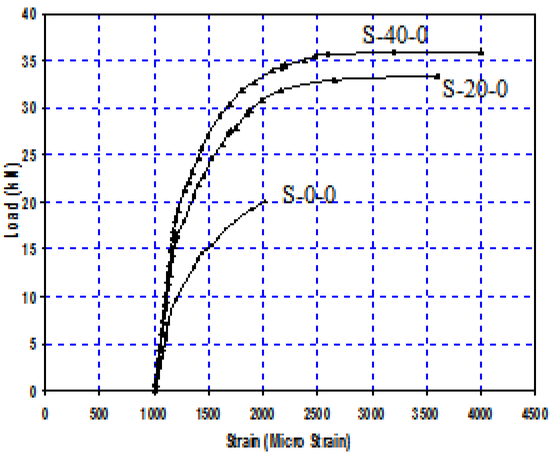

Fig. 8(b) Load vs prestressed bar strain relationship for G-II.

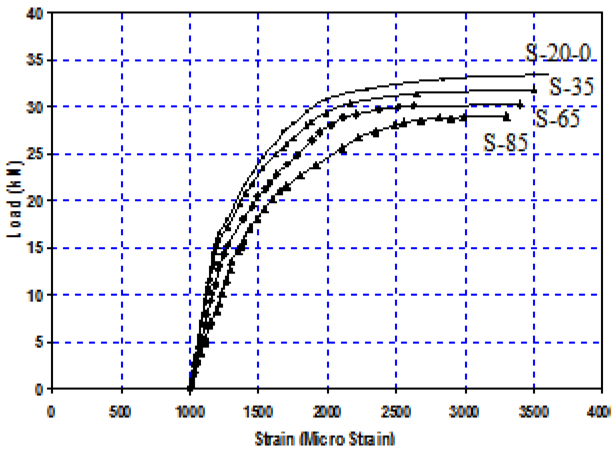

Fig. 8(c) Load vs prestressed bar strain relationship for G-III.

3.4 Cracking Behavior

Figures 9(a), (b) and (c) show the load versus the visual inspection crack width for all slabs during loading. For the two refrences slabs S-C and S-C*, the first crack was observed when the applied load reached about 2.2 kN and 5 kN respectively, and at ultimate load, the maximum crack widths were 2.8 mm and 2.5 mm respectively. Applying the prestressing to specimens S-0-0 and S-0-0*, increased the cracking load to 7 kN and 10 kN respectively, and also decreased the crack width at ultimate to 2.2 mm and 2.0 mm respectively.The first crack was noticed on control slab S-C when the applied load reached about 5 kN. At an ultimate load of

14kN the maximum crack width was 2.5 mm. The application of prestressing to specimen S-0-0, before loading, not only increased its cracking load to 10 kN (which is 2.0 times higher than that of the control specimen) but also decreased the crack width at ultimate load by about 25% compared with that of the control slab S-C. The cracking behavior of the strengthened slabs is shown in Figure 9(b). The figure shows that the greatest increase in cracking load of strengthened slabs was obtained for slab S-40-0, about 8.5 kN , which 2.86 time higher than that of control slab S-C, followed by slab S-20-0, about 8.0 kN, which 2.63 times higher than that of slab S-C. It is clearly revealed that the significant improvement in the cracking behavior was provided by the proposed hybrid strengthening technique. Generally in Figure 9 (c), after the application of the prestressing force, and before reloading, all of the cracks formed during preloading stage completely closed. During reloading the cracks started to appear on the three slabs at an average load of about 7 kN which was 12.5% less than the cracking load of the strengthened slab S-20-0. Then, the cracks width and number increased and the maximum recorded crack widths for slabs S-20-35, S-20-65 and S-20-85 were 2 mm , 2.30 mm and 2.48 mm respectively.

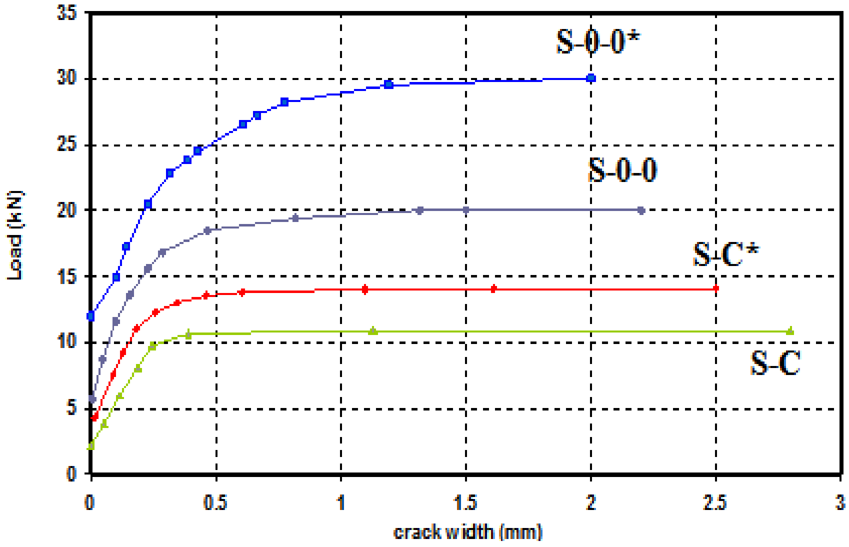

Fig. 9(a) Load- crack width curves for G-I.

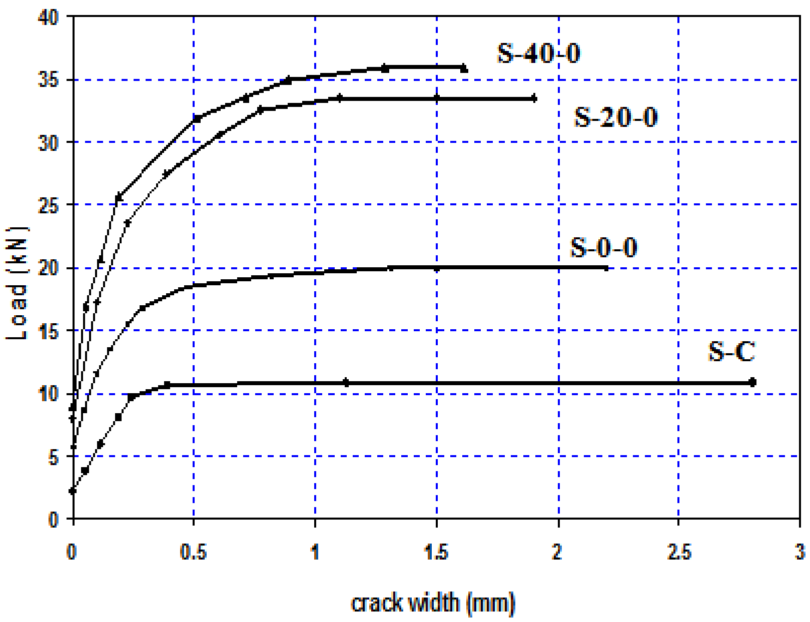

Fig. 9(b) Load- crack width curves for G-II.

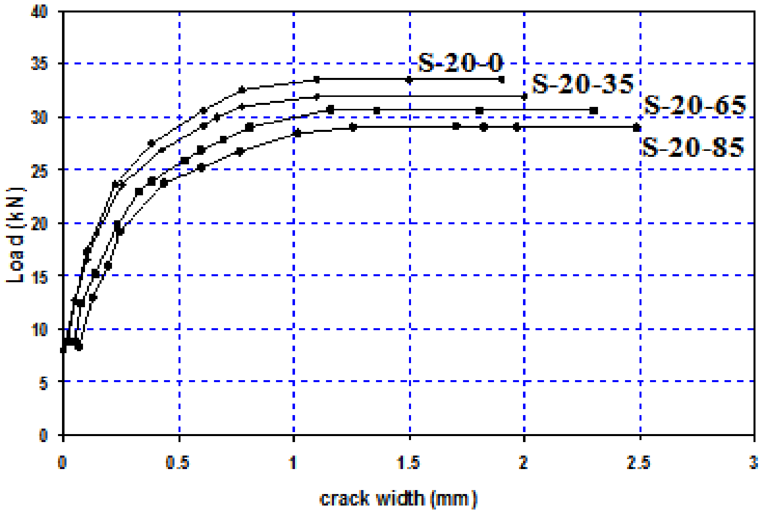

Fig. 9(c) Load- crack width curves for G-III.

IV. Proposed Tendon Stress Prediction Model

The absence of bond between the external tendons and concrete makes the design equations or the analysis methods used in bonded prestressed concrete design unsuitable for the external prestressed concrete. One important factor influencing the analysis of external prestressed concrete is the accurate prediction of the stress in tendon at ultimate load. accordingly, many researchers have attempted to present a mathematical expression describing the relation between the ultimate stress in tendon and the prestressed section properties. The common way to determine the ultimate stress on pre-stressing steel (f_{ps}) at ultimate for externally unbonded tendons is given by the following equation:

$$f_{ps} = f_{pe} + \Delta f_{ps} \qquad (1)$$

Where:

f_{ps} = ultimate stress in the pre-stressing steel;

f_{pe} = effective pre-stress in the pre-stressing steel; and

Δf_{ps} =stress increase due to any additional load leading to ultimate behavior.

Many researchers suggested formulas to calculate the stress in the pre-stressing steel based on experimental results of studying the behavior of the pre-stressed system with un-bonded tendons. Depending on researches made by Pannell and Tam [26], the Britich standard BS8110 [27] suggested the following equations to determine f_{ps}:

$$f_{ps} = f_{pe} + \frac{7000}{\left(\frac{L}{d_{ps}}\right)}\left(1 - \frac{1.7 f_{pu} A_{ps}}{f_c b d_{ps}}\right) < 0.7 f_{pu} \qquad (2)$$

Where:

f_{pu} = ultimate strength of pre-stressing steel;

f_c' = concrete compressive strength;

A_{ps} = area of pre-stressed steel;

d_{ps} = depth from concrete extreme compressive fiber to centroid of prestressed steel reinforcement;

L = tendon length between end anchorages.

Also Due and Tao [28] carried out an experimental research to investigate the effects of the presence of non pre-stressed reinforcement and its influence on the f_{ps} value. Their experimental results led to the following equations:

$$f_{ps} = f_{pe} + 786 - \frac{1920}{bd_{ps} f_c^{'}} (A_s f_y + A_{ps} f_{pe}) \qquad (3)$$

Provided that:

$$\left(\frac{A_s f_y + A_{ps} f_{pe}}{bd_{ps} f_c^{'}} \right) \le 0.3 \qquad (4)$$

Where:
A_S = area of non-prestressed steel;
f_Y = yield stress of the non-prestressing steel.
Moreover, structural and concrete building code (ACI 318-14) [29] stated that, for member with unbonded tendons and with span-to-depth ratio of 35 or less:

$$f_{ps} = f_{se} + 10{,}000 + \frac{f_c^{'}}{100\ \rho_p} \quad \text{(psi)} \qquad (5)$$

Where:
ρ_p = ratio of A_{ps} to bd_p (6)

f_{ps} in the pervious equation shall not be taken greater than the lesser of f_{py} and (f_{se} + 60,000). Also, the Egyptian code, ECP 203-2007 [30] uses the same equation in MPa unit. Table (6) illustrates a comparison between the prestressing forces at ultimate obtained from experimental results of the two control specimens (without ECC layer) S-0-0 (f_{cu}=15MPa), S-0-0* (f_{cu}=40MPa) , and the pervious equations. It was found that the ACI and BS8110 underestimate the ultimate stress in the pre-stressing steel of the tested slabs by more than 20% for low concrete strength and by 48.5%, 37.4% respectively for moderate concrete strength. While the model proposed by Due and Tao provided the nearest value to the experimental results of the current study tested slab. Because of the accuracy and simplicity of Due and Tao equation, it was modified to propose an equation that can be used for the suggested hybrid strengthening technique. The contribution of the ECC layer was presented by the term ($\lambda\ f^{'}_{cECC}$). In addition, the effect of preloading level is considered in the proposed equation hy adding the coefficient **α.** Figure 10 indicates the required dimensions and the free boody diagram of the proposed technique. The following proposed equation (Eqn 7) gives more precise prediction of the ultimate tendon stress for the case of proposed hybrid strengthening technique as illustrated in table (7) which reported the output of the proposed equation is compared with the experimental result.

Table 6: Verification of F_{ps} obtained from the experimental result for specimens S-0-0, and S-0-0*.

Spec.	f_{cu} *(MPa)*	F_{ps} (kN) *Exp.*	*Due &Tao [7]*		*BS8110[4]*		*ACI [1] & ECP[8]*	
			F_{ps} (kN)	*Tolerance*	F_{ps} (kN)	*Tolerance*	F_{ps} *(kN)*	F_{ps} *(kN)*
S-0-0	15	88	84.7	-3.7%	69.9	-20.6%	66.2	-24.8%
S-0-0*	40	149	167.7	12.5%	93.2	-37.4%	76.8	-48.5%

$$f_{ps} = f_{pe} + 786 - \frac{1920\ \alpha}{bd_{ps} \lambda\ f^{'}_{c_{ECC}}} (A_s f_y + A_{ps} f_{pe}) \quad \text{(in MPa)} \qquad (7)$$

Where:
t_{ECC} = thickness of ECC strengthening layer;
$f^{'}_{cECC}$ = 0.8 compressive strength of ECC strengthening layer.

λ**,** coefficient of thickness effect of ECC layer, $\boldsymbol{\lambda} = \dfrac{t\ f_C + t_{ECC}\ f^{'}_{cECC}}{f^{'}_{cECC}\ (t + t_{ECC})}$ (8)

f_C = 0.8 concrete compressive strength of the member
α, coefficient of preloading level, **α** = 1 + 0.1 P_L (9)
where P_L is the preloading level.

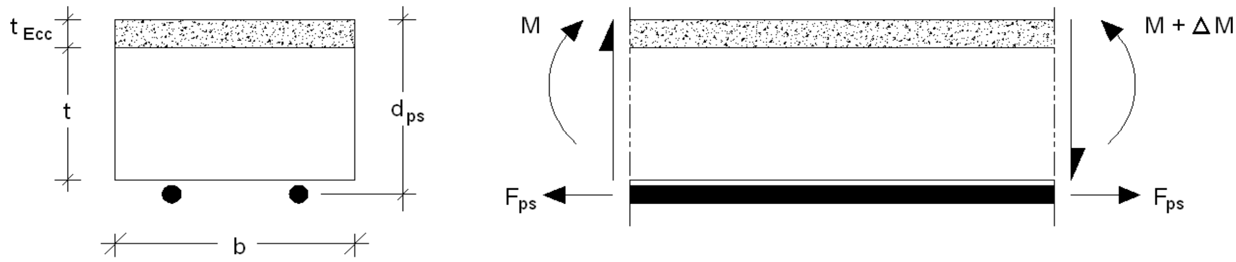

Fig. 10 Dimensions and free boody diagram of the proposed technique

Table 7: Verification of the proposed eq. for the hybrid strengthening technique with the experimental results.

Slab	F_{ps}(kN) Exp.	F_{ps} (kN) Proposed Eqn 7	Tolerance
S-20-0	158	140.2	-11.3%
S-40-0	175	150.8	-13.8%
S-20-35	153	137.5	-10.1%
S-20-65	149	135.2	-9.3%

V. Conclusion

An experimental program was conducted to evaluate the structural performance of an innovated hybrid strengthening technique for low strength RC cantilever slabs. The proposed technique composed of external prestressed stainless steel bars on the tensile surface and ECC strengthening layer overlay on the compressive surface. The experimental program was also carried out to evaluate the efficiency of the proposed technique for repair purposes. Based on the experimental investigation, the following conclusions can be drawn:

1) The tested externally prestressed strengthened slab failed by concrete crushing in the compression zone. In this case, the achieved ultimate load is mainly dependent on the concrete strength, and hence the strength gain increased in case of using the hybrid strengthening technique when compared to external prestressing only.

2) The experimental program carried out demonstrated that the proposed hybrid strengthening technique has a great potential application towards flexural strengthening of low strength concrete cantilever slabs, not only in terms of increasing the slab ultimate load capacity, but also in increasing its stiffness.

3) The combination of the proposed ECC layer in compression side and the externally prestressed bars in tension side, was able to increase the load-carrying capacity to 3 times higher than that of the control unstrengthened slab and to 1.8 times higher than that of the strengthened slab by prestressing only.

4) Applying the hybrid strengthening technique for case of using 20mm thickness of ECC pre-loaded by 35%, 65% and 85% of the control slab ultimate load resulted in not only closing all the formed cracks in these slabs, due to initial prestressing force, but also achieving about 95%, 89%, and 86% respectively of the strengthened slab ultimate load without preloading. This indicates that the proposed strengthening technique can be effectively used for both repair and strengthening of cracked slabs.

5) Based on the experimental results the toughness of all ECC strengthened slabs was higher than the control slab. In other words the use of ECC layer was able to compensate the possible loss of toughness resulted from the use of external prestressing.

6) No slip was observed between the ECC strengthening layer and concrete surface until the failure load and this reflect the enhanced bond characteristics between the ECC and concrete surface.

7) The proposed equation for prediction of the ultimate stress in the pre-stressing steel in case of the suggested hybrid strengthening technique gave good agreement with the experimental results.

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