Three-dimensional finite element analysis of reinforced concrete slabs strengthened with epoxy-bonded steel plates

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Abstract. This paper presents a nonlinear finite element analysis (FEA) in order to investigate the flexural performance of one-way slabs strengthened by epoxy-bonded steel plates. Four point loading scheme is selectively chosen. A model is developed to implement the material constitutive relationships and non-linearity. Five Slabs were modeled in FEM software using ABAQUS. One slab was un-strengthened control slab and the others were strengthened with steel plates with varying the plate thickness and configuration. In order to verify the accuracy of the numerical model, a comparison was done between the experimental results available in the literature and the proposed equations by ACI 318-11 for the calculation of ultimate load capacities of strengthened slabs, the agreement has proven to be good and FEA attained accurate results compared with ACI code. A parametric study was also carried out to investigate the influence of thickness of steel plate, strength of epoxy layer and type of strengthening plate on the performance of plated slabs. Also, the practical and technical feasibility of splitting the steel plate in strengthening process has been taken into account. For practical use, the author recommended to use bonded steel plate as one unit rather than splitting it to parts, because this saves more effort and reduces the risk of execution errors as in the case of multiple bonded parts. Both techniques have nearly the same effect upon the performance of strengthened slabs.

Keywords: finite element analysis; concrete slabs; steel plates; ABAQUS

1. Introduction

Changes in the building use, the need of installing new services and construction or design errors might require strengthening of existing slabs. Therefore, a simple and effective method for subsequent installation of flexural reinforcement was developed. The easiest and fastest way for strengthening of concrete slabs is epoxy-bonded steel plates in flexural zone. Strengthening by steel plate is a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. Generally the use of steel plate is preferred in this field due to their advantages such as easy construction work, minimum change in the overall size of the structure after plate bonding and less disruption to traffic while strengthening is being carried out. With the development of structurally effective adhesives now a day, these has been a marked increases in strengthening using steel plates. Strengthening of

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existing structures is an accepted and guaranteed means of improving both load-carrying capacity and serviceability performance of such structures. In the literature, plenty of research efforts have been made to investigate different strengthening techniques of structural elements using different materials. Most of the strengthening projects and research works have been conducted on beams (Osman *et al*. (2000), Sena-Cruz *et al*. (2012), Gholami *et al*. (2013)). Very few research works have been carried out to address the strengthening of one-way slabs in a treatment similar to that of beams. To the best of the authors' knowledge, limited research or nearly no study has been done on the finite element analysis of strengthening of one way concrete slabs by bonded steel plates. In order to ensure the serviceability and strength requirements of such slabs, it is necessary to accurately predict their overall deformational characteristics throughout the range of their elastic and inelastic response as well as their strength at ultimate collapse. Although the need for experimental research to provide the basis for design equations continues, the development of powerful and reliable analytical techniques, such as finite element method, can, however, reduce the time and cost of otherwise expensive experimental tests, and may better simulate the loading and support conditions of the actual structure. Accurate results of finite element analysis, however, require adequate modeling of the actual behavior of reinforced concrete materials including nonlinearity. Reinforced concrete exhibits nonlinearity because of cracking, inelastic material behavior, stiffening and softening phenomena, complexity of bond between reinforcement and concrete and other factors as reported by Chen and Raleeb (1982).

The present work is a numerical study which is conducted to predict the behavior up to ultimate conditions of one-way RC slabs strengthened with steel plates under two line loading. The performance of slabs is evaluated in terms of load-deflection characteristics. The validity and calibration of the theoretical formulations and the program used is judged through comparison of analytical results with available experimental data.

Until now only little has been published on finite element calculations in the field of strengthening with externally bonded steel plates. Therefore, a three dimensional analytical model was developed based on non-linear FE technique (using ABAQUS (2013)) for strengthened concrete slab to identify the important parameters governing load-deformation characteristics of the slabs with and without strengthening. The accuracy of this model is checked by comparing the results obtained from FEA with experiments conducted by Rasheed and Al-Azawi (2013) and the proposed equation from ACI 318-11(2011).

2. Experimental technique

The results of the laboratory test RC slab specimens were used as comparison with the results from the finite element analysis. Hence, the finite element model was implemented based on the parameters and conditions in the laboratory tests made by Rasheed and Al-Azawi (2013). Five reinforced concrete slabs were constructed, one was control and the other four were strengthened by epoxy- bonded steel plates. All slabs have the same geometry. The details of the tested specimens are shown in Table 1. All slabs have been tested using the 5000 kN capacity universal testing machine. The simply supported slabs were loaded under a monotonically increasing vertical load until their collapse. The loading and the vertical deflection readings were recorded after every increment of 20 kN load. Test setup and configuration of steel plates are shown in Fig. 1.

Table 1- Test specimens and strengthening plate dimensions

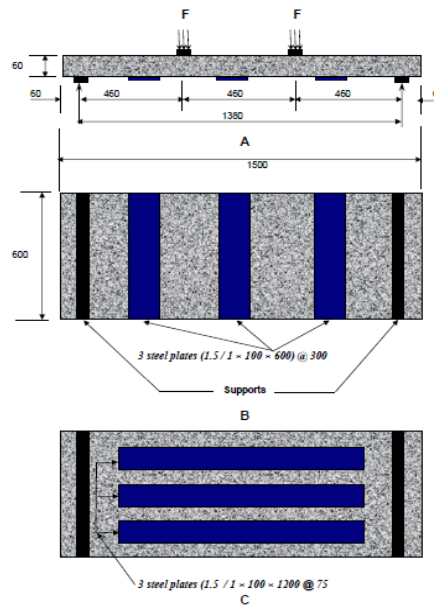| Slab Symbols	Slab dimensions, mm/ Rfts	Strengthening plate				
		No. of plates	Length, (l), mm	Width, (b), mm	Thickness , (t), mm	Configuration type of strengthening
S1(Ref)	60 × 600 × 1500/ 4 Ø 6 bot. mesh	--	--	--	--	--
S2	60 × 600 × 1500/ 4 Ø 6 bot. mesh	3	600	100	1.5	Config. I
S3	60 × 600 × 1500/ 4 Ø 6 bot. mesh	3	1200	100	1.5	Config. II
S4	60 × 600 × 1500/ 4 Ø 6 bot. mesh	3	600	100	1	Config. I
S5	60 × 600 × 1500/ 4 Ø 6 bot. mesh	3	1200	100	1	Config. II

Fig. 1- A: Test setup and layout

B: Configuration I of strengthening steel plates
C: Configuration II of strengthening steel plates

3. Code evaluation of flexural capacity of strengthened slab

The design flexural capacity must equal or exceeds the flexural demand ($\phi M_n \geq M_{ult}$). The flexural demand should be computed with the load factors according to ACI Committee 318 (2011).

The nominal moment capacity for strengthened RC slab with steel plate is given by Eq. (1), where the moments of the internal beam forces are summed about the neutral axis. From the
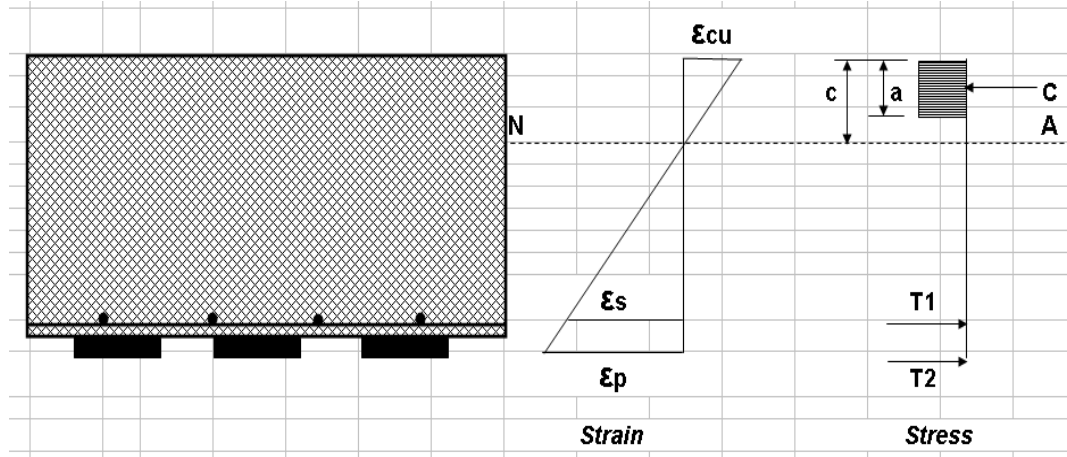
Fig. 2 Stress and strain distribution at ultimate load for config. II

Table 1- Comparison between test results and predicted ones by ACI Committee 318

Slab symbols	Exp. ultimate load	ACI 318 predictions	Pred / Exp
S1(control)	16.2	15.3	0.94
S2	18.1	26	1.44
S3	38.1	39.49	1.04
S4	16.5	22.23	1.35
S5	29.1	31.78	1.09
Av.			1.17
St. dev.			0.21

equilibrium of internal and external moments is shown in Fig. 2.

The nominal moment capacity M_n of a one way slab is calculated according to American code ACI 318-11 as follows:

$$M_n = A_s f_y \left[d - \left(\frac{0.59 A_s f_y}{f_c' b} \right) \right] \quad \text{(N.mm)}$$

for one way slabs strengthened with steel plate , the depth of the equivalent compressive stress block (a) is obtained as follows:

Apply equilibrium equation; $C = T1 + T2$ (see Fig. 2)

Assume that both the steel plate and steel bars yield

Find the value of a from   the following equation :

$$0.85 f_c' a b = A_s f_y + A_p f_{py}$$

The nominal moment capacity M_n of one way slab strengthened with steel plate is calculated by taking the moment about the concrete force C

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) + A_p f_{yp} \left(d_p - \frac{a}{2} \right) \quad \text{(N.mm)} \quad (1)$$

The maximum applied load F for the case of loading shown in Fig.1-A   is obtained by the following equation:

$$F = \frac{3M_n}{L_e} \qquad \text{(N)}$$

where:

A_s = Area of steel bars

A_p = area of steel plate = 3×b_p×t_p (b_p and t_p are dimensions of cross section of plate)

a = depth of the equivalent compressive stress block

C = compression force

c = neutral axis depth

d = depth of concrete section

d_p = depth of plate

f_y = yield strength of bars

f_{yp} = yield strength of steel plate

L_e = effective span of slab

T_1 = tension force in steel bars

T_2 = tension force in steel plate

ε_{cu} = ultimate compressive strain in upper side for concrete

ε_s =   ultimate tensile strain in tension steel bars

ε_p = ultimate tensile strain in strengthening plate

4. Finite element analysis

4.1 Finite element modeling

The general-purpose finite element program ABAQUS (ABAQUS(2013)) is used in the present study to investigate the flexural behavior of strengthened RC slabs previously studied experimentally by Rasheed and Al-Azawi (2013). ABAQUS was selected to perform the numerical analysis owing to its powerful and comprehensive functions and precision, especially in nonlinear analysis including nonlinear material property, nonlinear geometry and nonlinear response. Therefore, a three-dimensional finite element model has been developed to account for geometric and material nonlinear behavior of concrete, steel and epoxy. A nonlinear load–displacement analysis approach was adopted in performing the presented finite element simulations. The ultimate loads, deflections, failure modes, stiffness, and ductility. As well as any other required data are determined from this analysis. Eight-node brick element (C3D8) was employed to model the concrete slab, and steel plates, (which had three degrees of transitional freedom in each node) as recommended previously by Zhao and Alex (2008). Two nodded truss element (T3D2) was used for reinforcing bars model that embedded within the concrete. Perfect bond was assumed between the reinforcement and the surrounding concrete. Adhesive layer was modeled by the eight-node three-dimensional cohesive elements (COH3D8). The connectivity of a cohesive element is similar to a continuum element such as C3D8. Different mesh sizes were used to test the convergence and the final mesh, shown in Fig. 3, has been adopted in order to get the good accuracy of numerical solution.
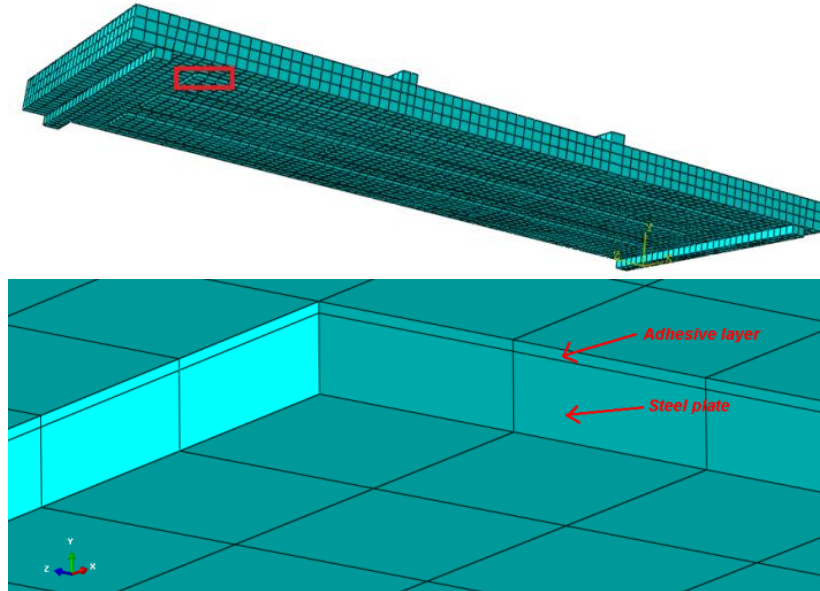
Fig. 3 Finite element mesh for strengthened slab

4.2 Boundary conditions and load application

All modeled slabs were simply supported with roller support at one side and hinged support at the other side. Two steel plates were attached to the bottom of concrete slabs to avoid stress concentration. One of the two plates was supported as a hinge and the other was supported as a roller by applying the constraints along the center line of these plates. The load was applied on other two steel plates attached to the top of the tested slabs. The load was applied in increments as static load following the automatic load control scheme. The modified standard/static general method was used.

4.3 Interaction modeling

4.3.1 Contact between concrete and interior steel bar reinforcement

The interaction between steel bars and concrete was simulated using the embedded element constraint available in ABAQUS program. The embedded elements were specified as the truss elements simulating the reinforcement bar while the host region was specified as the continuum solid elements simulating the concrete.

4.3.2 Contact between concrete, adhesive layer and steel plates

It was noticed during experimental testing, there was nearly no de-bonding has occurred till ultimate loads as reported previously by Rasheed and Al-Azawi (2013). Therefore, tied contact for contact pair (was available in ABAQUS constraint module) was used with no separation interaction behavior between bottom surface of concrete slab and top surface of adhesive layer and between bottom surface of adhesive layer and top surface of steel plate.

Table 3- Properties of steel plates & reinforcement (Rasheed and Al-Azawi (2013))

Strengthening Steel Plates				
Thickness, mm	Yield strength, MPa	Elongation, %	Tensile strength, MPa	Poisson's Ratio
1	279.4	15	353.7	0.3
1.5	279.4	15	365.6	0.3
Steel bar reinforcement				
Bar diameter, mm	Yield strength, MPa	Elongation, %	Tensile strength, MPa	Poisson's Ratio
6 (deformed)	736	5	850	0.3
Loading and supporting steel plates				
Thickness, mm	Yield strength, MPa	Elongation, %	Tensile strength, MPa	Poisson's Ratio
20	850	4	970	0.3

5.1 Materials modeling

5.1.1 Concrete

5.1.1.1 Concrete smeared cracking model

Material properties of the concrete used for the model are modeled using the concrete smeared cracking model available in ABAQUS V. 6.13-1 program (ABAQUS (2013)). For good correlation with experimental results, the plastic material properties of the concrete were assigned according to the results from the experimental test. as shown in Table2.

5.1.2 Steel plates, steel bars and steel loading and supporting plates

The constitutive behavior of the steel plate used for strengthening of slabs, bars and loading and supporting steel plates were determined using an elastic-perfect plastic model. The properties used to define this model are the elastic modulus E_s, yield stress f_y, and Poisson's ratio v. these parameters are listed in Table 3.

5.1.3 Adhesive modeling

The Drucker–Prager model was used to simulate the elastic– plastic behavior of the adhesive layer as described by Zhao and Alex (2008). One reason is that the adhesive is expected to be pressure sensitive. Another reason is that the tensile yield strength is significantly smaller than the compressive strength in the adhesive. The measured uniaxial compressive strength and tensile strength are 35 MPa and 19.5 MPa, respectively. The ratio of the uniaxial compressive strength to the tensile strength λ can be used to calculate the parameters, *K* and *β*. These parameters are required in ABAQUS for the linear Drucker–Prager material model. According to Chiang and Chai (1994)

$$K = \frac{2+\lambda}{2\lambda+1} \tag{2}$$

$$\tan\beta = \frac{3(\lambda - 1)}{\lambda + 2} \tag{3}$$

where K is equal to the ratio of yield stress in triaxial tension to yield stress in triaxial compression, which controls the shape of the yield surface. β is the friction angle of the material. In the present case, $\lambda = 1.795$, and Eqs. (2) and (3) give the value of K and β is 0.827 and 32.1°, respectively. Assuming associated flow, the dilation angle (ψ) can be obtained by $\psi = \beta$. In the present research, the epoxy-resin based bond agent is of a trademark of Concresiver ® 2200 supplied by MBT's Dubai, UAE facility (Rasheed and Al-Azawi (2013)). It was selected to bond steel plate to hardened reinforced concrete slabs. Properties of the Concresiver® 2200 are shown in Table 4.

4. Validation of the numerical model

4.1 Load-deflection behavior

In order to validate the finite element model that developed in this paper, the numerical results were compared with the test results in the literature (Rasheed and Al-Azawi (2013)). The experimental and FEA results of the slab specimens are given in Table 5 and figures 4 to 7. It is obvious from the test results and finite element results by ABAQUS that the overall properties of R.C. slabs are enhanced when strengthened with steel plate i.e., increase their first crack loads, ultimate loads, and stiffness after cracking due to the large axial stiffness of plate. It is shown that the first crack began at the zone out of steel plate, and also the failure cracks are found at the same zone as reported by Rasheed and Al-Azawi (2013). This study also showed that, the effect of steel plate dimensions is more effective than the thickness effect.

The effect of steel plate dimensions(plate geometry):
Slab S3 (Config. II of strengthening type see Table 1: steel plate with 1200 mm length and 1.5 mm thickness) attained increase in ultimate capacity equal 135 and 140% compared with reference slab S1 concerning experimental and FEA results respectively. While, S2 (Config. I of strengthening type, steel plate with 600 mm length and 1.5 mm thickness with the same thickness as S3) recorded only 12 and 16% increase in ultimate load compared with reference one concerning experimental and FEA results respectively.

The effect of plate thickness:
Slab S5 (Config. II of strengthening type with 1 mm thickness of steel plate) recorded 80 and 85% increase in ultimate capacity compared with reference slab S1 concerning experimental and FEA results respectively. Comparing S3 with S5, illustrated the little effect of plate thickness than the effect of plate geometry. Therefore Config. II is more feasible than Config. I.

It had been seen clearly that for the R.C. slab strengthened with steel plates, detachment initiates at a zone between the plate end and the load application point at high load level. The increases in ultimate strength are found in slabs S3 and S5 as (135%) and (79.6%), respectively greater than that of the reference slab S1. FEA results by ABAQUS behave the same trend as experimental records, it recorded 140% and 85% increase in ultimate capacity of S3 and S5 respectively compared with S1.

With reference to the test and FEA results, it is possible to observe that the specimen failure is never due to concrete crushing or plate failure. Failure is always driven by a sudden loss of the composite action between the R.C. member and the steel plate. Fig. 8 shows distribution of stress contour in 3-3 direction (Z-direction) for S3 and S2 slabs.
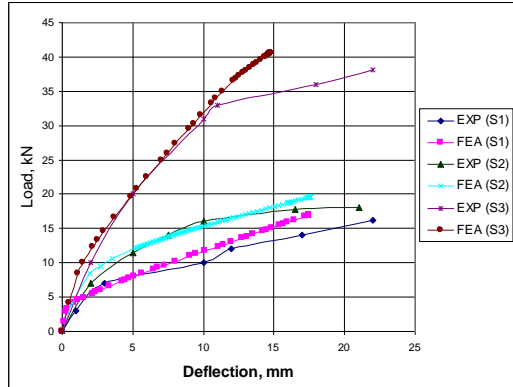

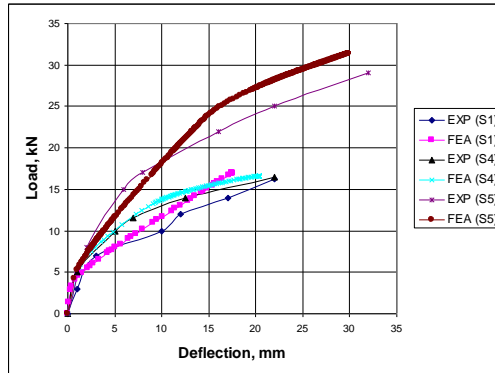Fig. 4 Load-deflection response of strengthened slabs with steel plates (t = 1.5 mm)

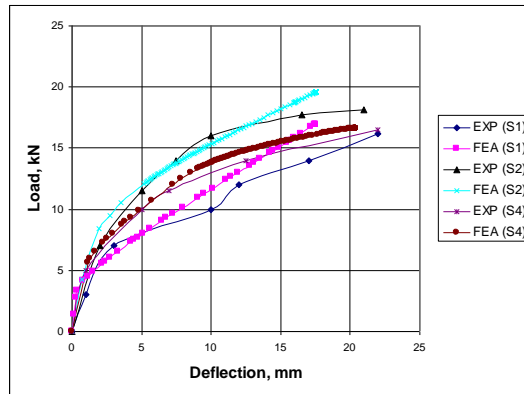Fig. 5 Load-deflection response of strengthened slabs with steel plates (t = 1 mm)

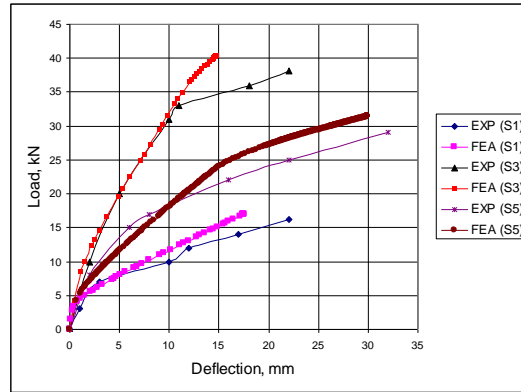Fig. 6 Load-deflection response of strengthened slabs with steel plates (l = 600 mm)

Fig. 7 Load-deflection response of strengthened slabs with steel plates (l = 1200 mm)
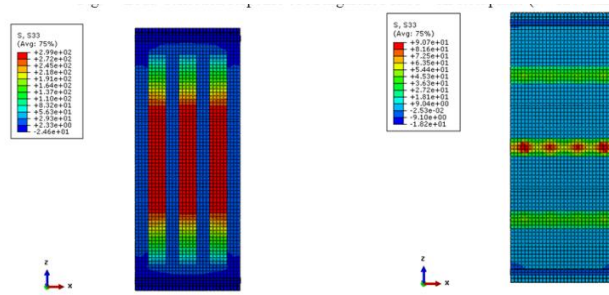

Fig. 8 Distribution of stress in 3-3 direction (Z-direction) for S3 and S2 slabs (Config. II & I)

Table 5- Comparison of the   FEA results from the present study and experimental ones

Slab	First cracking load, kN			De-bonding load, kN		Ultimate load, kN			Ultimate defl. , mm			Stiffness, kN/mm		
	Exp	FEA	FEA/Exp	Exp	FEA	Exp	FEA	FEA/Exp	Exp	FEA	FEA/Exp	Exp	FEA	FEA/Exp
S1	6.2	6.8	1.1	--	--	16.2	16.9	1.04	22	17.5	0.80	0.74	0.97	1.31
S2	9.9	10.5	1.06	**	**	18.1	19.6	1.08	21	17.5	0.83	0.86	1.12	1.30
S3	26.9	29.5	1.1	37.9	40.3	38.1	40.5	1.06	22	14.7	0.67	1.73	2.75	1.59
S4	9.9	10.98	1.11	**	**	16.5	16.5	1	22	21.2	0.96	0.75	0.78	1.04
S5	16.2	12.56	0.77	29.1	31.3	29.1	31.3	1.07	32	29.9	0.93	0.91	1.05	1.15
Av.		1.03						1.05			0.84			1.28

4.2 Stiffness and ductility

   Stiffness of the strengthened RC slabs were computed as the ratio between maximum failure load to corresponding deflection (at the ultimate load) (Osman *et al.* (2000)) as tabulated in Table

5.

From the load-deflection curves (figures from 4 to 7), it can be seen that the slope of S3 slab is very steep. It recorded the maximum value of stiffness with increments of 134% and 183% compared with the reference slab S1 concerning test and finite element results respectively. Stiffness is considered as a measure of the ductility. As the stiffness increases, the slab specimen indicates lower ductility (Osman *et al*. (2000)). From the results in Table 5, all strengthened slabs have shown big values of stiffness than the reference one. This lead to less ductile behavior has occurred due to strengthening by steel plates.

The results of the present nonlinear finite element analysis by ABAQUS of the investigated slabs in terms of initial crack load, de-bonding load, ultimate load, ultimate deflection, and stiffness are compared against the experimental measurements and listed in Table 5. The results in Table 5 indicate that, the predicted ultimate capacities by ABAQUS to experimental ones equal 1.05 with a standard deviation of 0.03. Therefore, it can be observed that the present finite element model performs satisfactorily and it predicts accurately the real behavior of strengthened slabs.

5. Parametric study

The ABAQUS software has been used in the previous section to analyze the performance of strengthened slabs, and the model was validated by the test results in the literature. A new finite element model is developed using the same method in the previous section, and it is used to analyze the strengthened slabs, in order to understand the influence of various parameters on the performance of them. The following parameters are analyzed as steel plate thickness, strength of adhesive layer, and type of strengthening plate. The calculation only changes one parameter while keeping other parameters unchanged.

5.1 Effect of steel plate thickness

A numerical analysis was carried out on the Config. II with increasing the thickness of strengthening plate to 3,5, and 7 mm as shown in Table 6. The results are shown in Fig. 9. It can be seen that prior to yielding point, increasing of thickness of plates does not influence the load-deflection characteristics. However, after yielding, the load deflection curve becomes quite stiffer specially for slabs strengthened with plates have 3, 5 and 7 mm thickness. Fig. 10 shows the proportional relationship between stiffness of strengthened slab and the plate thickness. The greater thickness, the more stiff of the slab against excessive deflection. The stiffness of slabs bonded with 1, 1.5, 3, 5 and 7 mm thick steel plates increased to 1.05, 1.39, 1.51, 1.7 and 1.83 times that of reference slab (S1), respectively. The load deflection curves in Fig. 9 also show that for a given load, the deflections generally decrease with increasing thickness of steel plate. Also, increasing the plate thickness caused remarkable growth in capacity of slabs till thickness equal 5mm beyond this limit the load decreased (at $t = 7$ mm) as shown in Fig. 11. This refers to higher stiffness of strengthened slabs by steel plate of thickness 7 mm which generated shear stress on adhesive layer led to cracks in this layer before yield of steel plate causing failure of slab. Fig. 12-A shows yield stress generated in adhesive layer caused cracks especially at end of the adhesive layer leading to premature plate end de-bonding failure of steel plate, in the same time the strengthening steel plate not reached to yield point at failure of slabs (Fig. 12-B).

5.2 Effect of strength of adhesive layer

The purpose of the adhesive is to produce a continuous bond between plate and concrete, to ensure full composite action across the thickness of the adhesive layer. Therefore, the adhesive must have high strength, long-term stability and durability, especially with respect to creep.

As shown in Fig. 13, using of epoxy layer with high strength (compressive and tensile strengths equal 80 and 45 MPa respectively and Young's modulus of 13,000 MPa according to the range of

Table 6 - Test specimens and strengthening plate dimensions for parametric study(Confg. II)

Slab symbols	Slab dimensions, mm/ Rfts	Strengthening plate dimensions			
		No. of plate	Length, mm	Width, mm	Thickness, mm
S6 (t = 3mm)	60 × 600 × 1500/4 Ø 6 bot. mesh	3	1200	100	3
S7 (t = 5mm)	60 × 600 × 1500/4 Ø 6 bot. mesh	3	1200	100	5
S8 (t = 7mm)	60 × 600 × 1500/4 Ø 6 bot. mesh	3	1200	100	7

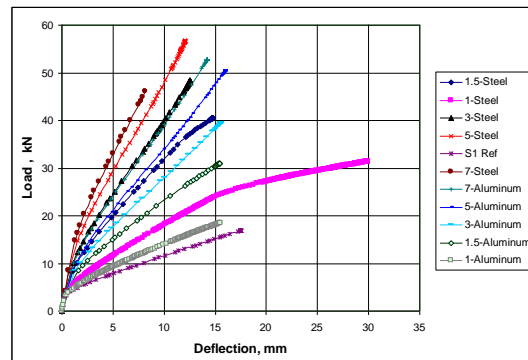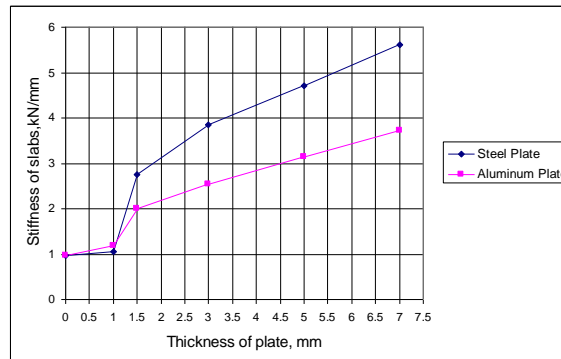Fig. 9 Effect of plate thickness on load-deflection behaviour of strengthened slabs (confg. II) by FEA

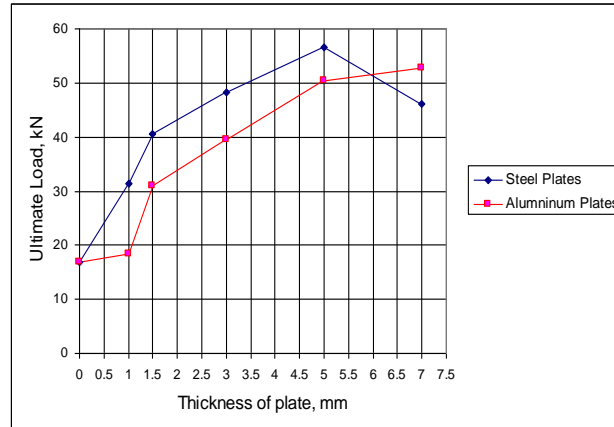Fig. 10 Effect of plate thickness on stiffness of strengthened slabs (confg. II) by FEA

Fig. 11 Effect of plate thickness on load carrying capacity of strengthened slabs (confg. II) by FEA

mechanical properties of available commercial epoxy which specified in ref. FIB(2006) can be overcome to the previous problem of end plate de-bonding failure for Config. II of strengthened slabs by steel plate of thickness 7 mm. It is noticed that the capacity of slab jumped to 60 kN, while the opposite one with normal strength epoxy layer recorded only 46 MPa. This is due to strong epoxy layer with high strength which can resist and confront the generated shear stress from higher stiffness of strengthened slab with 7 mm steel plate.

5.3 Effect of strengthening plate type

Use of aluminum plate instead of steel one for strengthening of RC slabs was utilized in this research. The measured stress- strain curves reported by Oehlers and Seracino (2004) for the aluminum plates were used in this FEA analysis. The aluminum plate is assumed to have isotropic hardening behaviour.   The used yield stress = 180 MPa, Young's modulus = 63000 MPa, ultimate tensile stress = 210 MPa, ultimate strain = 0.09 and Poisson 's' ratio = 0.33.

Strengthening of RC slabs with aluminum plate attained a noticed increase in both strength andstiffness. From Figures 9, 10 and 11, using aluminum plate with thickness of 3 mm, attained increase in stiffness and strength equal 161% and 133% respectively compared with reference un-plated slab.

Strengthening of RC slabs with aluminum plate reduced the stiffness and ultimate load capacity of slabs compared with steel plates as shown in Figs. 9, 10 and 11. For example, at thickness of 5 mm, the stiffness and ultimate load capacity of strengthened slab by aluminum plate reduced by 33% and 11% respectively compared with slabs strengthened by steel one.

Fig. 11 shows, after 5 mm thickness of aluminum plate, the ascending curve of strength of plated slab is continues to rise up till at thickness of 7 mm, in contrast for case of use steel plate.

This is due to, reduction of stiffness of strengthened slab with aluminum plate by 34% than slab strengthened with steel one, consequently, the adhesive layer can bear and resist efficiently the low generated shear stress. Reduction of stiffness is generally leads to increase in ductility of plated slabs as reported by Osman *et al*. (2000) and Arslan *et al*. (2008). This refer to that aluminum plate tends to be less stiff than steel and is also ductile, it has a Young's modulus about one-third that of steel, i.e., aluminum is flexible and ductile with a high strain capacity.
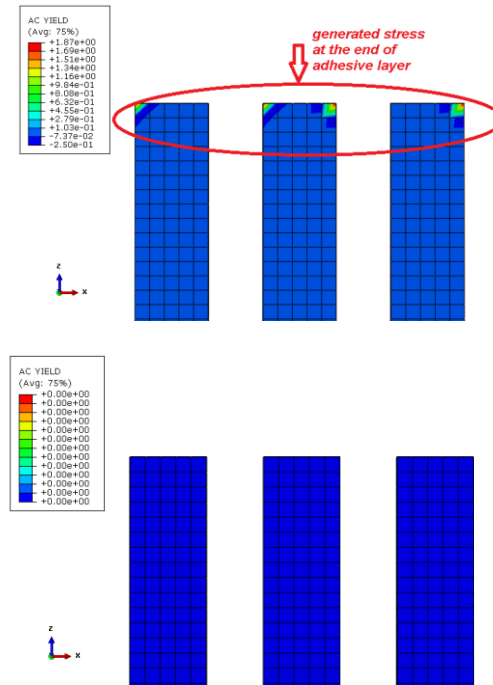
Fig. 12- Generated yield stresses in adhesive and steel plates (A & B) of   strengthened slabs (confg. II, t = 7 mm) by FEA
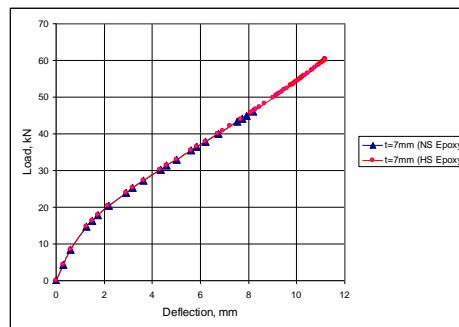

Fig. 13 Effect of epoxy strength on capacity of strengthened slab (confg. II) by FEA

5.4 Practical and technical feasibility of splitting the steel plate in strengthening process

This part concentrates on the practical and technical feasibility of splitting the plate in the strengthening process of RC slabs. In other words, shows the effect of width of the bonded steel plates on behavior of strengthened RC slabs. Jansze (1997), strongly recommended in his thesis that it is very necessary to study this topic in the future. Till now there are not any investigation upon this issue ((Hwang *et al*. (2013), Lesmana *et al*. (2013), Afefy and Fawzy (2013)). So, it is necessary to focus it. Some models were established by ABAQUS with various plate widths
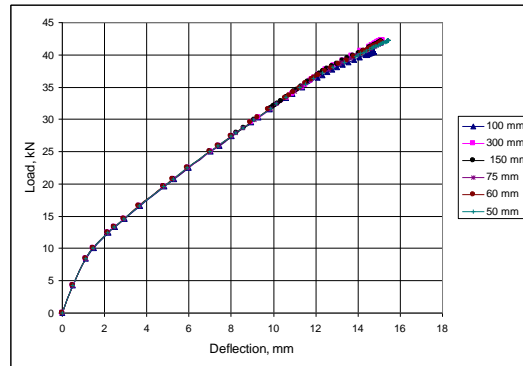
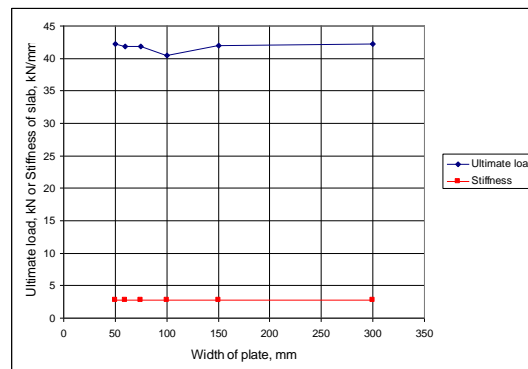Fig. 14 Effect of plate width on behavior of strengthened slabs

Fig. 15 Effect of plate width on ultimate capacity and stiffness of strengthened slabs
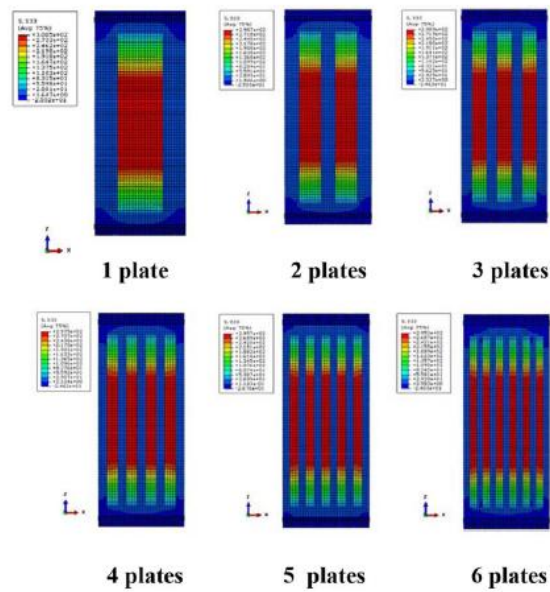

Fig. 16 Effect of plate width on ultimate capacity and stiffness of strengthened slabs

as 300 mm (one plate), 150 mm (two plates), 100 mm (three plates as S3 slab), 75 mm (four plates), 60 mm (five plates), and 50 mm (six plates). The plate length and thickness are constant for all slabs equal 1200 and 1.5 mm respectively. Were taken into account to be the sum of the widths is fixed (300 mm) and the length is also fixed (1200) for all slabs. Fig. 14 shows that the variation of the width (with a fixed value of total plate widths = 300 mm) has not nearly any effect on the ultimate load capacity and stiffness (which it ranges from 40.5 to 42.2 kN for ultimate load capacity and ranges from 2.74 to 2.79 for stiffness, see to Fig. 15) the load- deflection curves are almost identical to each other which means that, the load-deflection behavior of strengthened slabs, stiffness and stress contour distribution in the 3-3 direction are similar as indicated in Figs. 14, 15 and 16. Consequently, use of bonded steel plate as one unit rather than splitting to parts is easily and effectively technique because it save more efforts and reduces the risk of execution errors as in the case of multiple bonded parts.

6. Conclusions

A computer program (ABAQUS) suitable for nonlinear analysis of three dimensional reinforced concrete members under monotonic increasing loads has been used to simulate the behavior of slabs strengthened with epoxy-boded steel plates. The following conclusions may be drawn from the present research:

1.   Nonlinear finite element method based on 3D models created by ABAQUS is a powerful and relatively economical tool which can be effectively used to simulate the real behavior of strengthened reinforced concrete slabs.

2.   The choice of adequate material models for numerical simulation is the most important aspect in finite element modeling of concrete structures. The non-linear material models which are available in the ABAQUS Standard/Explicit material library such as Smeared Cracking model (was used for modeling the reinforced concrete) and Drucker-Prager model (was used for modeling the adhesive layer) give better and realistic results.

3.   This study indicates that the FEA by ABAQUS can predict the flexural capacity of strengthened slabs with an average predicted over experimental capacity ratio of 1.05 with a standard deviation of 0.03, while ACI 318-11 code prediction ratios   have an average of 1.17 and standard deviation of 0.21

4.   Using steel plates to strengthen RC slabs is simple and easy to install, and it effectively improves the overall properties of these members.

5.   All slabs failed without de-bonding of the steel plate except for the slab (S3) for which the steel plate de-bonded at 99% of failure load.

6.   The effects of dimensions of the strengthening steel plate (geometry of plate) are more effective and feasible (concerning strength and stiffness) than the effect of plate thickness for all specimens.

7.   RC slabs strengthened with steel plates exhibited more stiffness and lesser ductility than the non strengthened one. The greater thickness, the more stiff of the slab against excessive deflection.

8.   parametric study showed, increasing the plate thickness (from 0 to 7 mm) caused remarkable growth in both stiffness and ultimate capacity of slabs (for configuration II of strengthening) till a specific thickness (5 mm) beyond this limit the capacity of slab decreased.

This problem can be overcome by using epoxy layer with higher strength.

9. Use of aluminum plate instead of steel one for strengthening of RC slabs attained a noticeable increase in both strength and stiffness compared with un-plated slab.

10. Aluminum-plated RC slabs have less stiffness and strength and consequently high ductility compared with those strengthened with steel ones.

11. Regarding to practical application, use of bonded steel plate as one unit rather than splitting to parts is easy and effective technique and is the recommended method because it saves more efforts and reduces the risk of execution errors as in the case of multiple bonded parts. Both techniques have nearly the same affect upon the performance of strengthening slabs.

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APPENDIX

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) + A_p f_{yp} \left(d_p - \frac{a}{2} \right) \qquad \text{(SI Units)} \qquad (1)$$

$$K = \frac{2 + \lambda}{2\lambda + 1} \qquad \text{(SI Units)} \qquad (2)$$

$$\tan \beta = \frac{3(\lambda - 1)}{\lambda + 2} \qquad \text{(SI Units)} \qquad (3)$$