FINITE ELEMENT STUDIES OF PRE-CRACKED REINFORCED CONCRETE (RC) BEAMS WITH OPENINGS STRENGTHENED BY STEEL PLATE

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مُسْـتَخْلَص

في هذه الورقة، تم دراسة اعادة تاهيل العارضات الخرسانية المسلحة المحملة مسبقا ذات الفتحات في منطقة القص والمقواة بالواح الحديد (steel plate) باستخدام طريقة العناصر المحددة عبر برنامج ANSYS14.5. كما تهدف هذه الورقة الي دراسة تاثير التحميل المسبق للعارضات قبل تقويتها. في البداية تم معايرة برنامج ANSYS14.5 مع نتائج لنماذج تم اختبارها في المعمل للتاكد من صحة النتائج التي سوف يتم التحصل عليها لاحقا. و من خلال مقارنة نتائج التحليل باستخدام طريقة العناصر المحددة مع نتائج الاختبارات المعملية ومع التي تم الحصول عليها باستخدام الكود الامريكي ACI, وجدت ان النتائج كانت متوافقة وبفوارق مقبولة. ايضا تم نمذجة التحميل اللاحق للعارضات باستخدام تقنية birth and death عبر برنامج التحليل والتي يتم فيها تحميل العارضة اولا الي حمل محدد ثم يتم اعتماد تقويتها عند نهاية هذه المرحلة. أظهرت النتائج أن التحميل المسبق للعارضات له اثر واضح غلي قوة تحملها. ايضا استخدام الواح الحديد في التقوية له اثر ايجابي علي قدرة تحمل العارضات الخرسانية. واخيرا تم اقتراح معادلة لحساب قوة تحمل العارضات المعرضة للتحميل المسبق والمقواة بواسطة الالواح الحديدية.

ABSTRACT

In this study, a repairing of preloaded RC beams with openings strengthened with steel plate was studied by using finite element package ANSYS14.5. To ensure that the elements, convergence criteria, and material properties are adequate to model the behavior of the RC beam and to ensure that the simulation process is correct, the FE ANSYS was calibrated with published experimental data. The effect of pre-damage level and loading mechanism were considered as main parameters. Furthermore, birth and death technique was used to model the cracks before strengthening stage. In this technique, loading was first applied till the objective cracking, followed by steel plate application, and then the load was continued to failure. The result showed that pre-damage levels and the steel plate strengthening have a great effect on the failure mode and ultimate load of RC beam. In addition, the results showed good agreement with those obtained from published experimental tests. Based on FE using ANSYS an ACI guideline, an analytical equation for predicting the shear capacity of RC beams with openings strengthened by steel plate under sustained load was then proposed.

***Keywords**: Pre-cracked; Strengthening; RC beam; openings; Steel plate; ANSYS14.5*

1 Introduction

Deep beams are structural elements loaded as beams in which a substantial load is moved to the supports point by compression thrust joining the reaction and the load. Based on ACI 318-05, a reinforced concrete (RC) beam is defined as a deep beam if the span length-to-depth ratio is less than or equal to four [1]. Thus, the strain distribution not considered as linear and the shear deformation becomes remarkable compared with pure flexure. RC deep beams have several applications in civil structures such as foundation pile caps, girders transfer, shear walls, wall footings, and floor diaphragms. Beams of this type often arise in the construction or similar structures, as well as transfer girders and pile caps [2]. Creating an opening in RC beams is a capability that lets a service pass through the structure. This opening leads to the beam cross-section changes, thus, the opening edges receive high stress concentrates, which induce danger cracks in the beam. Steel plate strengthening materials and methods and problems associated with strengthening method to evaluate the structural behavior of RC beams was carried out by many researchers [3-7]. Most of these studies addressed the bonding mechanism and debonding phenomena. Despite the relative complexity of these models, they don't always provide clear or completely sustained predictions. The numerical models for studying the behaviors of steel plate shear strengthened in a simple manner are needed deep investigations. Using steel plates for strengthening RC beams by using adhesive bonding usually lead to debonding or peeling as studied by Sharif, G.J. et al. 1995, Adhikary, B. B., et al. 2000, Barnes, R., et al. 2006 [8-10]. Other studies have carried out to investigate the flexural and shear behavior of bolted side-plated beams and coupling beams as well as the behavior of the connecting bolt groups [11]. A number of studies were carried out in the available literatures on the strengthening techniques and structural behavior of reinforced concrete deep beams with web openings. While, the shear strength of RC shallow beams with openings have been reported in many studies in the available literature [12-18].

2 Research program

The study program contains two parts; the first part was the validation of the finite element (FE) method by using ANSYS with the results from published experimental tests [13], and the second part was focused on the parametric study. This paper studied the effects of sustained load on load carrying capacity, deflection, stiffness, and shear strength of reinforced concrete beams with web openings strengthened with steel plate. Furthermore, the results obtained from FE method were compared with those from published experimental results, to ensure that the modeled materials is correct and more confidence for RC beams with web openings by using ANSYS software. The achievement of this paper will also can help for further studies in the field. Materials properties which published in Bashir et al 2017 [13] was used to model the beam in ANSYS finite element program.

2.1 Details of studied beams

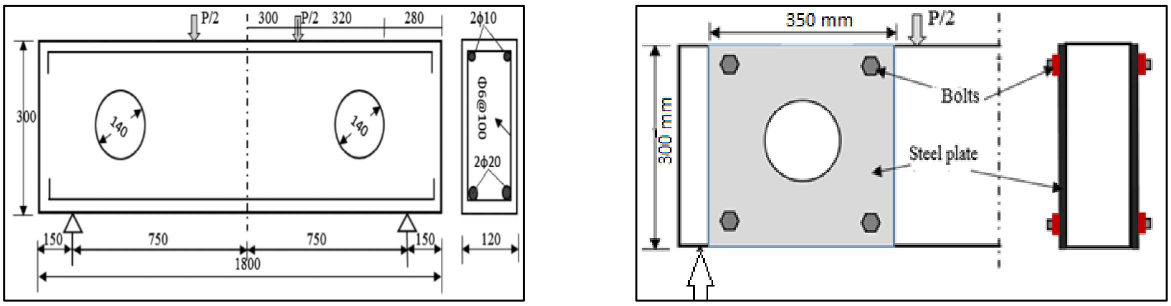
Specimens dimensions, vertical and horizontal reinforcement as well as the steel plate arrangement used here as in Bashir et al 2017 [13]. Figure 1 shows typical geometry of studied beams and steel plate.

2.2 Materials and Methods

This paper provides the results of finite element (FE) program on using steel plate to prevent local cracks around openings in reinforced concrete beams. Effect of different pre-damage loads and with configuration of the applied steel plate is studied. A simplified method to design beams with openings strengthened with steel plate using code of practice is presented.

3 Finite Element Modelling (FEM)

Due to the symmetry of the geometry, loading, boundary conditions, and material properties, a quarter FE model was built and analyzed. Figure 3 shows a typical FE model with the boundary conditions, element types, supports and loading. The developed FE model had two planes of symmetries in the two principal axes. The use of a quarter models significantly reduces the computational time.



(a) (b)

Figure 1: (a) Geometry of studied beams (b) Steel plate details [13]

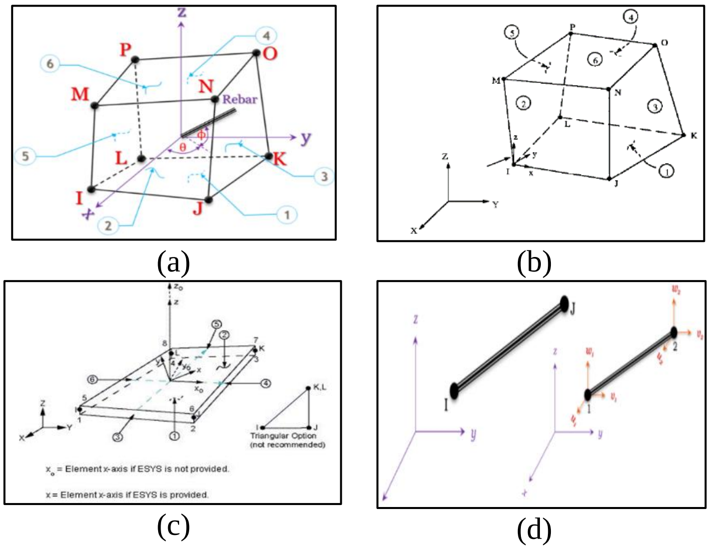


Figure 2: ANSYS elements (a) Solid65. (b): Solid45 (c) Shell 181 (d) LINK8

Using of a quarter model is reduces the computational time significantly. From the available element library in ANSYS, the elements used in this work, SOLID65, SOLID45, shell 181 and LINK8 elements are used to model Concrete, Steel plates at the supports, steel plate composite and for Steel reinforcement, respectively, which has properties as in Figure 2

3.1 Strengthening Model Technique

3.1.1 CONTA175 and TARGE170 Elements

ARGE170 is used to represent various 3D target surfaces for the associated contact elements (CONTA175). CONTA175 may be used to represent contact and sliding between a line and a surface or between a node and a surface. In this paper, steel plate considered as target element and the concrete is contact.

3.1.2 Defining Element's Real Constant and Material Properties

The materials properties steel reinforcement, Concrete, and steel plate used in this paper were based on Bashir H. et al (2017) [13]. For the concrete, ANSYS computer program requires input data for material properties, as follows [19]: ANSYS computer program requires the uniaxial stress-strain relationship for concrete in compression. in this research program, for numerical expressions [20], the subsequent Equations were used along with Equations conducted by Gere and Timosshenko 2004 [21] to construct the uniaxial compressive stress-strain curve for concrete.

$$f = \frac{E_c \varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_o}\right)^2} \quad (1)$$

$$\varepsilon_o = \frac{2f'_c}{E_c} \quad (2)$$

$$E_c = \frac{\sigma}{\varepsilon} \quad (3)$$

Where: σ is stress at any strain ε, N/mm^2, ε is strain at stress f, ε_o is strain at the ultimate compressive strength f'_c, Elastic modulus (E_c), Shear transfer coefficient for opened cracks (β_o) and closed cracks (β_c).The value of β used in many studies of reinforced concrete and composite steel-concrete structures varied between 0.05 and 0.25. In this research program, the shear transfer coefficients for open and closed cracks were ranged from 0.18- 0.25 and 0.50- 0.80, respectively. Eq 3 was used to calculate ultimate uniaxial compressive strength (f_c'), and the elastic modulus of concrete (E_c) of the concrete, while 0.2 considered as Poisson's ratio for concrete.

3.1.3 Modeling and Meshing

A Link8 element was used to represent the steel stirrups and steel reinforcements as shown in Figure 3a. This figure shows a typical steel reinforcement in a quarter of the beam model. the steel reinforcements was connected to concrete nodes by perfect bond technique, so, the steel and concrete shared the same nodes [19]. A shell181 element was used to represent the steel plate. The nodes of this element were attached to the nodes of the concrete element by using CONTACT and TARGET elements. Mapped mesh command was used to generate model mesh, so the shape of the meshed elements is either rectangular or square shape. Figure 3b showed the generally mesh of the specimen.

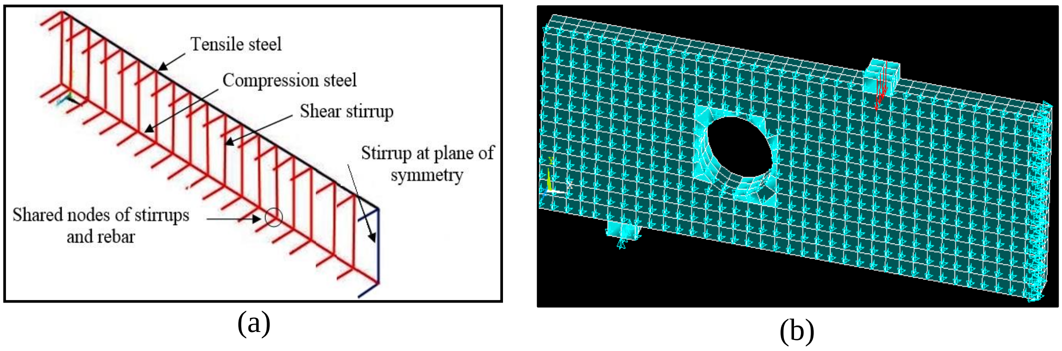


Figure 3: Reinforcement configuration and model meshing

The boundary conditions were applied at symmetry points and at the supports (Figure 3b). The symmetrical boundary conditions were set about two planes. The external force was applied at the entire centerline of the upper steel plate as shown in Figure 3b. To simulate the effect of sustained load on pre-cracked beam with openings before strengthening with steel plate, the element birth and death technique was used in this analysis. The element birth and death feature is useful for many applications in which it can be easily identified killed or born elements by their known positions. For element death effect achievement, the killed elements are not actually removed by ANSYS program, but the identified element must be killed to simulate melting. Instead, it deactivates them by multiplies the stiffness by reduction factor. This factor is taken as 1.0E-6 by default, but can be given other values. When elements are "born," they are not actually added to the model; they are simply reactivated. It must create all elements, including those to be born in later stages of the analysis.

4. Verification study

The FE model was calibrated with the published experimental study [13]. The specimens tested by Bashir H. et al 2017 [13] were modeled in the FE simulation as follow: Specimens B1, B2 were considered as control beams and were tested to failure load without any steel plate strengthening or pre-cracking, and B3 was strengthened with steel plate and tested to failure without pre-cracking. The goal of the comparison between the FE model by using ANSYS14.5 and the experimental results was to ensure that the simulation process is correct. In this paper, the beams which tested in the previous experimental study were simulated for verification study. Figure 4 showed that the numerical load-deflection curves results was in good correlation with that from experimental test at all loading stages. This confirmed the developed FE models validation and reliability of the FE simulation. Table 1 showed the numerical and experimental results for the calibrated beams. As shown from the figure 4, the failure load from FE using ANSYS14.5 was higher than that from the experimental data. This was possibly due to the relative homogeneity of the finite element models when compared to the actual beams which failed early because it has a number of micro-cracks.

5. Results and discussions

5.1 Failure Criteria

Table 1 gives a summary of the load capacity and failure modes of the tested beams. In finite element model using ANSYS, when the load increment of 10 N could not reach a convergence during solution process, beam was reflected to failure. The FE models of the beams typically failed when stirrup reinforcement yielded and propagation of severe cracks were appeared in the concrete. So, the FE solutions lead to terminate due to divergence. Divergence in the FE solution coincided with a considerably large deflection, exceeding the limitation of the displacement which considered in the ANSYS14.5 software. At the end of each load increment, convergence was obtained using the arc length method coupled with Newton Raphson iteration [22] which satisfies a predefined tolerance limit of the convergence criteria. Furthermore, the presented FE simulation adopted time step optimization as automatic time stepping to predict automatically and control load step sizes.

As shown in Table 1, a good agreement between the observed results from experimental tests and those predicted from FE modeling was achieved. This confirms the capability of the FE models using ANSYS for prediction of failure load and deflection of the beams.

5.2 Parametric study

For the parametric study, a rectangular reinforced concrete beams with openings were conducted by using ANSYS14.5 finite element model. All the studied beams had same cross-section as mentioned above.

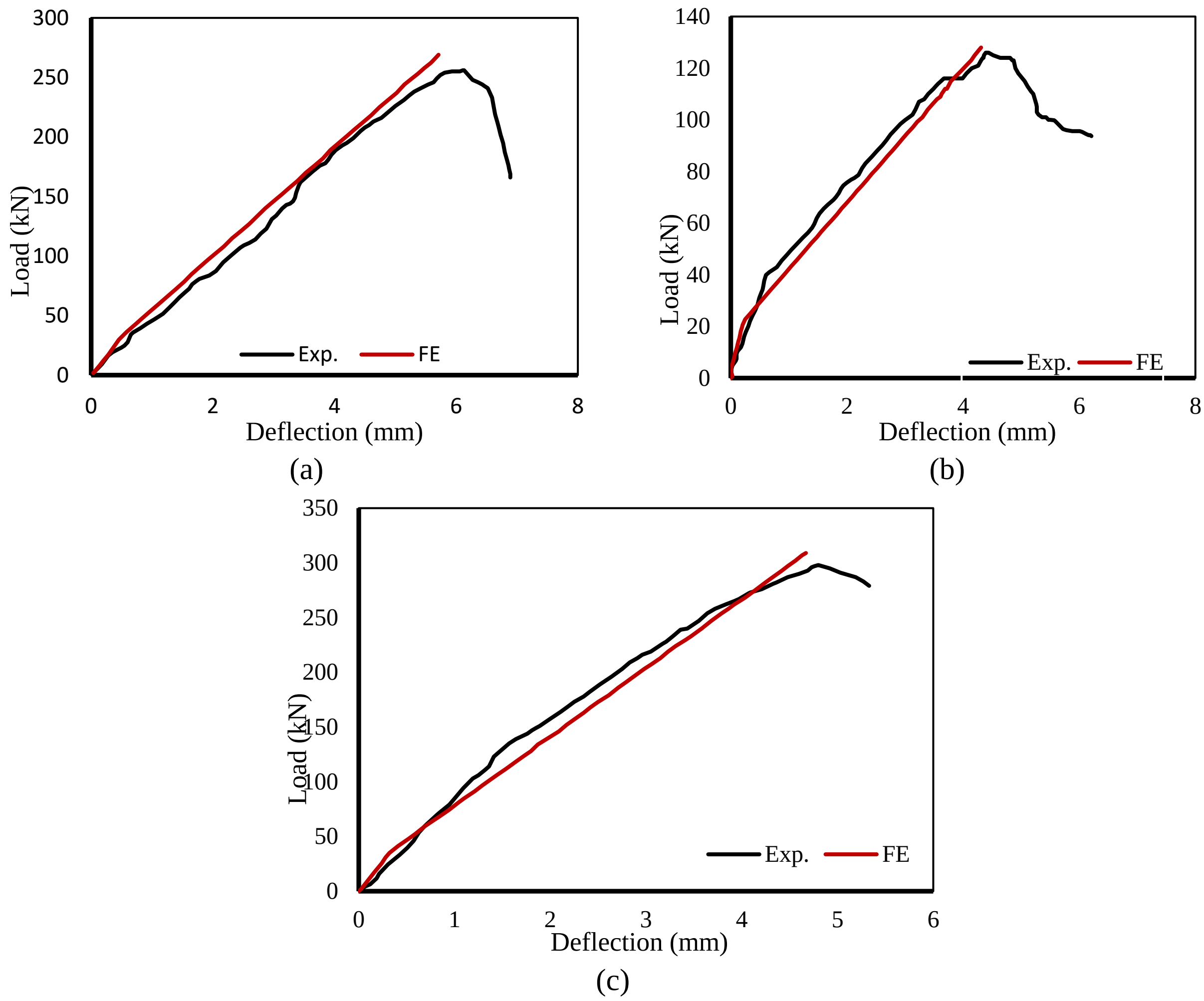


Figure 4: Load deflection curve of FE and experimental test for B1, B2 and B3

Figure 1 showed the studied beam's geometry and dimensions, while Figure 3 showed typical example for the meshing and 3D geometry of a quarter FE model. In this part, in addition to three calibrated beams, other seven beams that were pre-cracked before the application of the steel plate were modeled using ANSYS 14.5 software. Cracking was first induced, and then repair was performed using birth and death technique with steel plate strengthening technique, followed by reloading the beams to failure. To simulate the initial cracks, Beams B4-B10 were initially loaded from 30 to 70% of the failure load of control beam (B2), respectively. At the end of this loading stage, the load was released in these beams by using the technique mentioned above (birth and death). The compressive stresses were a maximum at the opening regions. The concrete failure initiated at the openings regions due to stress concentration as reported in the literature. According to verified model, the shear strength of a strengthened beams using steel plate in shear can be determined by the simplified method of the monolithic coefficients as expressed in the equation 5 [23]. The expression for shear contribution of web-bonded continuous steel plates to the shear strength of beam (V_p) is given by summing up the shear stresses in steel plates over its depth and thickness.

Table 1: Experimental and ANSYS Finite Element Results

Beam	Failure load (kN)		Exp./FE	Max. Deflection (mm)		Exp./FE	Failure Mode
	Exp.	FE		Exp.	FE		
B1	250	269	0.93	6.13	5.71	1.07	Shear failure
B2	126	128	0.98	4.52	4.31	1.05	Shear failure
B3	300	309	0.97	4.80	4.67	1.03	Shear failure

$$V_p = \frac{2}{3} f_{yp} h_p t_p \qquad (5)$$

Where: f_{yp} = Yield strength of steel plate, h_p = Depth of the steel plate, t_p = Thickness of steel plate. As shown in Table 2, the ANSYS proposed model results showed acceptable agreement with the experimental and FE results. These mean that the developed FE models can serve as a numerical platform for performance predictions of pre-loaded RC beams with web openings.

From FE results, according to damage level of 90%, it can be shown that loading the beams to 90% of their failure loads prior to the application of the strengthening steel plate has almost no effect on the repair efficiency. So, the obtained results from experiment (without strengthening), and finite element are almost the same, with values of 126 kN, and 143 kN, respectively with acceptable different. Eq. 4 has underestimated the shear strength of steel plate contribution for RC beams subjected to pre-damage. So, the shear strength values of steel plate is proposed to multiply by reduction factor γ. Therefore, the equation was modified in term of steel plate contribution by coefficient γ as in Eq. 6.

$$V_n = V_c + V_s + \gamma V_p \qquad (6)$$

Where γ = (k_1+ k_2), k_1 = DL/2, k_2 = 1-DL

6 Conclusion

From the finite element simulation using ANSYS 14.5, the following conclusions are drawn.

1- The pre-loaded RC beams with openings strengthened with steel plate under sustained load displayed more load capacity. -Damage level have an effect on the failure load of the RC beam strengthened with steel plate by decreasing in maximum load capacity compared with equivalent beam.

2- All of the strengthened beams displayed higher capacities than did the equivalent un-strengthened control beams, with high capacity. This confirmed the potential efficiency of the steel plate strengthening.

3- The developed FE models and proposed equation can be used as alternatives to experiments, and can serve as theoretical and numerical platform for performance predictions of pre-loaded RC beams with openings strengthened with steel plate

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Table 2: Comparison between the Results from the FE and the modified Equation (Eq. 6)

Beam Model	Damage level % (DL)	γ = (k_1+k_2)	$P_{ex.}$ (kN)	$P_{theo.}$ (kN)	P_{FE} (kN)	$P_{pro.}$ (kN)	$\frac{Exp.}{FE.}$	$\frac{FE.}{Pro.}$
B1	0	-	**250**	**214**	**269**	214	1.07	1.25
B2	0	-	126	108	128	108	1.05	1.18
B3	0	-	300	259.6	309	259.6	1.03	1.19
B4	30% of B2	0.70	-	259.6	270	236.735	-	1.14
B5	40% of B2	0.60	-	259.6	245	229.11	-	1.07
B6	50% of B2	0.50	-	259.6	207	221.48	-	0.93
B7	60% of B2	0.40	-	259.6	183	213.854	-	0.86
B8	70% of B2	0.30	-	259.6	166	206.227	-	0.81
B9	80% of B2	0.20	-	259.6	157	198.6	-	0.79
B10	90% of B2	0.10	-	259.6	143	190.3	-	0.75

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