Behavior of Corbels Strengthened with Carbon Fiber Reinforced Polymers (CFRP) – Numerical Study

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ABSTRACT

In this paper, a numerical modeling performed to study the effect of carbon fiber reinforced polymers (CFRP) as a shear strengthening of corbels. In this study a theoretical simulation is achieved with reinforced concrete corbels, several CFRP strengthening positions has been studied with different shear span – effective depth ratio (a/d) of (0.5,0.6&0.7). The numerical model, by using program (ANSYS 12.1) verified by compare its results with the experimental results. It was found that the position and the amount of (CFRP) as well as the vary of (a/d) ratio, have a great effects on the ultimate load capacity of corbels. Where, the ultimate load capacity increase as the amount of (CFRP) increased in certain positions of corbels, with regards the vary in (a/d) ratio.

Keywords: Corbels, Concrete, CFRP, Strengthening, Finite element analysis, ANSYS.

تصرف الدعامات الناتئه المقواة ببوليمرات الياف الكربون – دراسة عددية

الخلاصة :

يتناول هذا البحث انشاء موديل عددي لتمثيل تاثير التقوية ببوليمرات الياف الكربون على الدعامات الناتئه . في هذه الدراسة تم انجاز محاكاة نظرية للدعامات الخرسانية المسلحة الناتئه , وقد تم دراسة التقوية ببوليمرات الياف الكربون في عدة مواضع مختلفة من النموذج مع تغير نسبة امتداد القص-العمق الفعال (a/d) (0.5,0.6&0.7). ان الموديل الرياضي للنموذج وباستخدام برنامج (ANSYS 12.1) قد تم التحقق منه بمقارنة نتائجة مع النتائج العملية. وقد وجد ان لموقع وكمية بوليمرات الياف الكربون المستخدمة مع التغير في نسبة (a/d) لها تاثير كبير ومهم على التحمل الاقصى للدعامات الخرسانية الناتئه حيث يزداد التحمل الاقصى بزيادة كمية الياف الكربون المستخدمة وفي مواضع معينة مع الاخذ بنظر الاعتبار التغيير في نسبة (a/d).

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INTRODUCTION

Reinforced concrete corbels are commonly used to transfer loads from beams to columns. It is widely assumed that reinforced concrete corbels are principally shear transfer device. Stirrups are normally used to improve their shear capacities and reduce the likelihood of sudden failures. However, the contribution of stirrups has been shown to be variable when corbels are subjected to combined vertical and horizontal loads. Furthermore, most corbels containing stirrups as a secondary reinforcement fail in shear in a manner that displays little or no ductility. Also, distress of corbels in the field has been attributed to poor detailing of reinforcement.[1,2&3]

Previous experimentally and analytically studies determined the strength of corbels subjected to vertical and horizontal forces and to highlighting the role of the parameters that influence the performance of corbels including shape and dimension of corbels, type of main and secondary steel reinforcements, presence and type of fibers, and strength of concrete [4-8].

In order to enhance shear and flexural capacity of RC members, carbon fiber reinforced polymer (CFRP) has been used as strengthening wildly in felid and researches. The use of CFRP in suitable positions, such strengthening can enhance corbel capacity. The degree of strengthening afforded by CFRP in corbels depends on the polymer type and anchorage length, as well as reinforced concrete member thickness and tensile strength[9&10] .

Research significance

Recently, the use of carbon fiber (CF) as strengthening or repairing material increased and became a wide procedure in structures.

The aim of this study is to investigate the effect of carbon fiber reinforced polymers (CFRP) as a shear strengthening on the behavior of reinforced concrete corbels by using the software program (ANSYS 12.1).

Finite element analysis

Finite element method (FEM) is a numerical method for solving a differential or integral equations and obtaining approximate solutions to a wide variety of engineering problems. It has been applied to a number of physical problems, where the governing differential equations are available. The method essentially consists of assuming the continuous function for the solution and obtaining the parameters of the functions in a manner that reduces the error in the solution [11&12].

ANSYS is a general purpose software, used to simulate interactions of all disciplines of physics, structural, vibration, fluid dynamics, heat transfer and electromagnetic for engineers.[13]

In this work, a three-dimensional finite element model by using ANSYS software computer program release 12.1has been made. Materials idealization and the elements used to build this model are listed below:

Element type

A Solid65 element is used to model the concrete. This element has eight nodes with three degrees of freedom at each node translations in the nodal x, y, and z directions, and used for 3-D modeling of solids. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing[13&14].

1.2 A Link8 element is used to model steel reinforcement. This element is a 3-D spar element and it has two nodes with three degrees of freedom translations in the nodal x, y, and z directions. This element is capable of plastic deformation. And can be used also to model trusses, sagging cables, links, springs, etc[13&14].

1.3 A Shell-63 element is used to model the carbon fiber Reinforced polymer (CFRP). This element has both bending and membrane capacities. Both in-plane and normal loads are permitted. The element is defined by four nodes, the thickness, elastic stiffness, and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element has six degrees of freedom at each node: translations in the x, y, and z directions and rotations about the x, y, and z-axes [13]

Material Properties

Responses of concrete under loading without and with confinement are characterized by distinctly nonlinear behaviors, which can be modeled in the SOLID65 element(14). In this work the average concrete compressive strength was 42.8 MPa (10). Poisson's ratio for concrete in all corbels is assumed to be 0.2. The shear transfer coefficient represents a shear strength reduction factor for subsequent loads that induce sliding (shear) across the crack face. The shear transfer coefficient ranges from 0.0 to 1.0 with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 a rough crack (no loss of shear transfer). For an open crack, the shear transfer coefficient varied between 0.05 and 0.50 in many studies of reinforced concrete structures. Coefficient values selected (between 0 and 1) do not appear to be critical; however, a value greater than 0 is necessary to prevent numerical difficulties [14].

In order to model the steel reinforcement, Link 8 element is used .Where Ansys define the steel reinforcement by two parts, the first one is linear elastic material model which defined by Elastic modulus (E_s) and Poisson's ratio (ν). And the second part is bilinear inelastic to represent the stress-strain behavior of material which defined by two values the Yield stress (f_y) and the Tangent modulus (E_{tan}).

In this work, steel deformed bars of 10 mm & 12.5mm diameter were used as reinforcement with nominal properties fy= 455 MPa, Es= 200 GPa, and ν = 0.3[10].

CFRP is a composite material made of a polymer matrix reinforced with cabon fibers[15] defined by ANSYS with Elastic modulus (E_s) and Poisson's ratio (ν) . The CFRP system used in the experimental study was Sika-530C fabric[10]. In this work, one layer of CFRP with thickness of 0.293 mm were used and its Elastic modulus (E_s=231GPa) and Poisson's ratio (ν=0.38)[10]. The high strength of the epoxy used to attach CFRP laminates to the experimental corbels supported the perfect bound assumption[16&17].

Case study

ANSYS 12.1 software program are used to analysis the reinforced concrete corbels of the experimental program. [10] The corbels flange dimensions was685.8mm (27 in.) in width with a cross section of 228.6mm (9in.)x228.6mm (9in.) and with main reinforcement of 3 deformed bars each diameter 12.5 mm. The height of corbels web was 279.4mm (11 in.) with a cross section of 228.6mm (9in.)x228.6mm (9in.) and with main reinforcement of 12.5 mm deformed bars . Transverse reinforcement was provided of 10 mm in diameter deformed bars. Corbels geometry and the reinforcement layout are shown in Fig.(1).

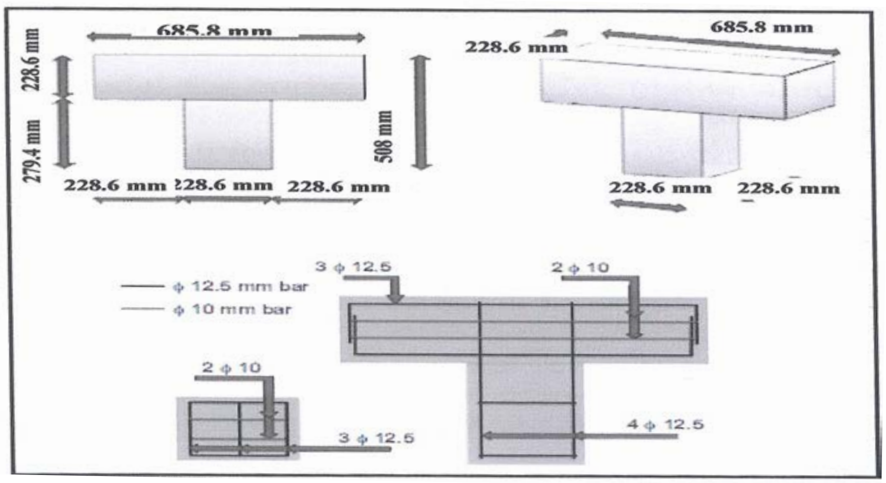


Figure.(1) Details of corbel geometry and steel reinforcement. [10]

Three reinforced concrete corbels with shear span-to-effective depth ratio (a/d) equal to 0.7 [(10)] are analyzed by ANSYS 12.1. Each one was defined, where CBR-01 refer to the control corbel without CFRP strengthening , CBR-04 for corbel strengthening at Side-only (bonded to front and rear) and CBR-09 for Fully wrapped corbel CFRP strengthening (bonded to front, rear, top and bottom).Figs.(2,3&4) show the numerical models for corbels CBR-01, CBR-04& CBR-09 respectively[10].

In addition to the three experimental corbels[10], a new group of corbels models is proposed in this work and analysis by ANSYS, where the CFRP position are changed . Fig.(5) represent the model of corbel strengthening with CFRP at the top between the loads(corbel CBR-A). Fig.(6) show another position of strengthen , as CFRP laminates make an upside down U-shape(corbel CBR-B) . Fig.(7) illustrate the CFRP strengthening at front and rear sides between the two applied loads (corbel CBR-C).

Finite element analysis results, compression and discussion

The experimental work of Ahmed et. al. [10] done by applying a monotonic load using a universal testing machine. This load was transferred to each end of the corbel by a steel rod fitted to the machine resting on bearing plates positioned at the point of application. When the loads were applied, cracks appeared around the joints and extended upward to the point of application. The most prominent of the many cracks appearing in the corbels tested and the ones that ultimately induced failure were the cracks around the joints (the shear-critical zones), and a strain gauge was embedded along this critical area . Failure occurred along a diagonal plane and the crack failure angles ranged from 50º to 70º [10]. For reference corbel CBR-01 (without CFRP laminates) Shear failure load was 628 kN and occurred along a diagonal plane(10). While the numerical model done by ANSYS give higher failure load of 650 kN Fig.(8a) . In corbel CBR-04 strengthening with CFRP laminates on both sides (front and rear), failure appeared in the form of laminate de-bonding. The failure load for corbel CBR-04 was 676 kN, the crack ruptured the CFRP laminate, causing sudden and brittle corbel failure (10) .ANSYS model for corbel CBR-04 give higher failure load of 760 kN Fig.(8b) . Corbel CBR-09 Full wrap CFRP strengthening have failure load of 788.19 kN in compare with numerical model result of 840 kN Fig.(8c).

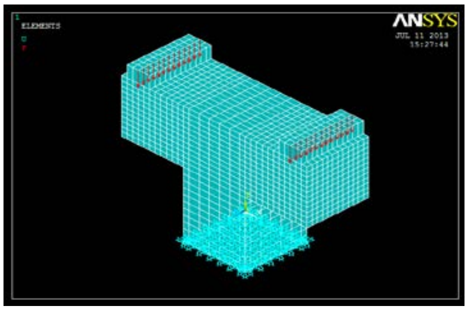


Figure.(2) Numerical model for corbel CBR-01

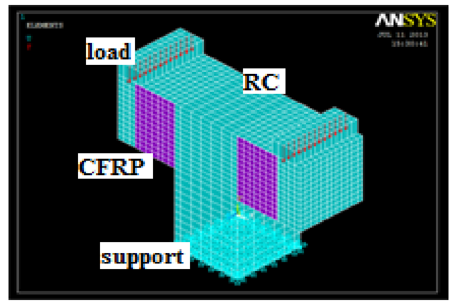


Figure.(3) Numerical model for corbel CBR-04

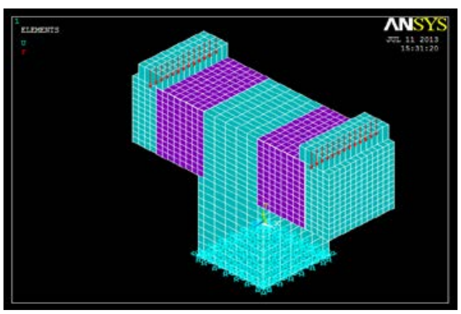


Figure.(4) Numerical model for corbel CBR-09

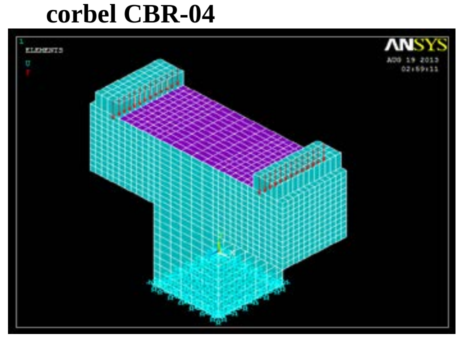


Figure.(5) CBR-A: Numerical model for corbel with CFRP at the top

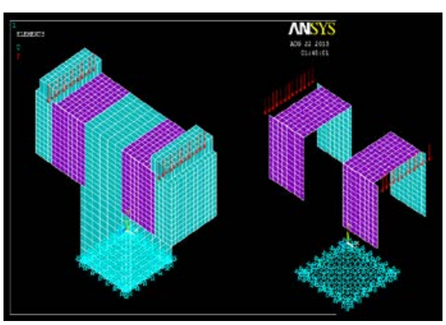


Figure.(6) CBR-B: Numerical model for corbel with upside down U-shape CFRP

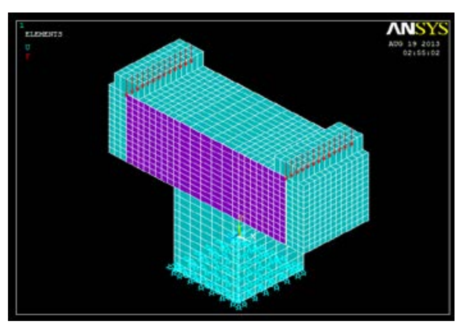


Figure.(7) CBR-C: Numerical model for corbel with CFRP at the front and rear sides

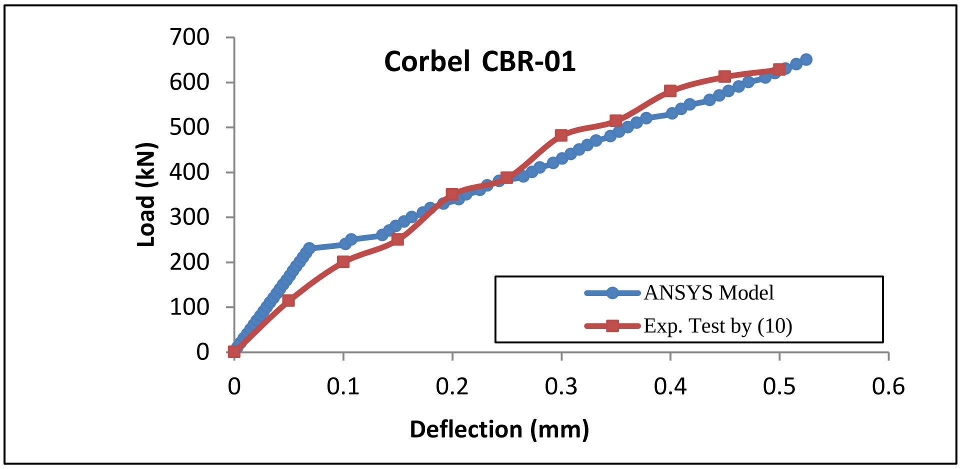


Figure.(8): (a) Corbel CBR-01

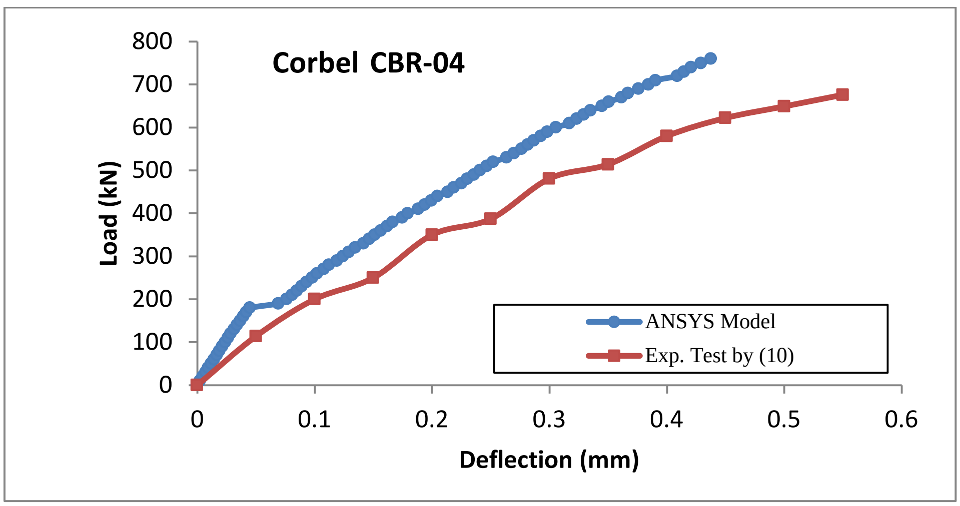


Figure.(8): (b) Corbel CBR-04

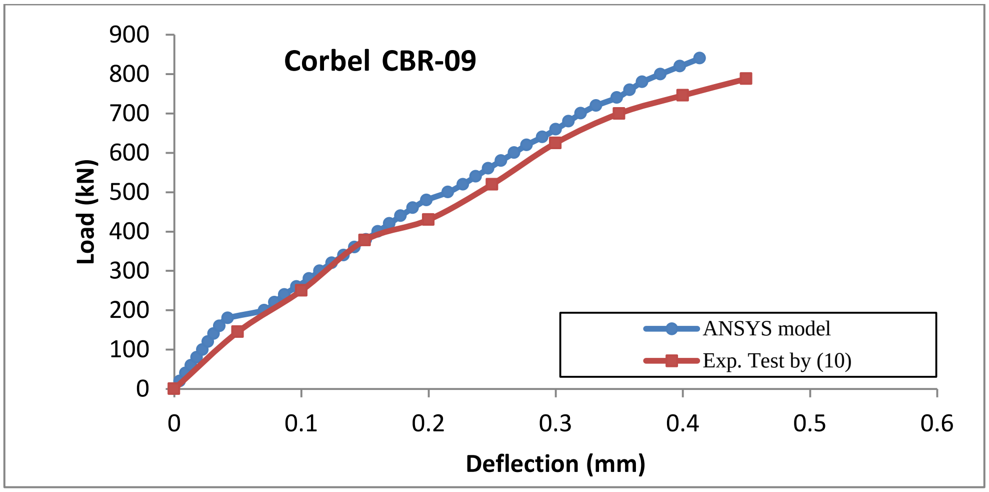


Figure.(8): (c) Corbel CBR-09
Figure.(8) Load-deflection relationship : experimental VS. numerical

Fig.(8) show that the first crack appear in similar manner in both experimental corbels and numerical models. As crack pattern and the load carrying capacity of RC corbels depend on the shear span-to-effective depth ratio (a/d) [(18)]. The ratio (a/d) of 0.6 & 0.5 are studied in this work for all corbels, in addition to the original ratio of 0.7.
The results of load capacity and the deflection of experimental corbels and numerical models with different shear span-to-effective depth ratio (a/d) are summarized in table (1) and table (2) respectively.

Table (1): Load capacity and the deflection of corbels- experimental results [(10)]

No.	Corbel description	Load at failure (kN)	Deflection (mm)	(a/d) ratio
1	CBR-01: Experimental corbel[10]	628	0.5	0.7
2	CBR-04: Experimental corbel[10]	676	0.55	0.7
3	CBR-09: Experimental corbel[10]	788.19	0.45	0.7

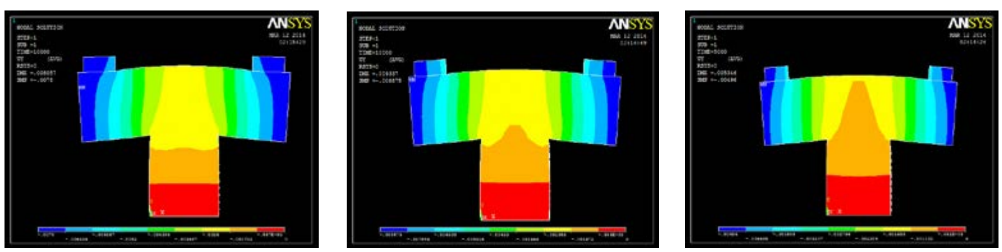
Table (2): Load capacity and the deflection of corbels- numerical models (ANSYS models)

No.	**Corbel description**	**Load at failure (kN)**	**Deflection (mm)**	**(a/d) ratio**
1	CBR-01	650	0.525	0.7
2	CBR-04	760	0.438	0.7
3	CBR-09	840	0.413	0.7
4	CBR-A: CFRP at the top between the loads	1020	0.340	0.7
5	CBR-B: CFRP laminates upside down U-shape	820	0.453	0.7
6	CBR-C: CFRP at front and rear sides between the loads	1640	0.484	0.7
7	CBR-01-0.6	780	0.696	0.6
8	CBR-04-0.6	840	0.657	0.6
9	CBR-09-0.6	860	0.394	0.6
10	CBR-A-0.6: CFRP at the top between the loads	1180	0.378	0.6
11	CBR-B-0.6: CFRP laminates upside down U-shape	840	0.411	0.6
12	CBR-C-0.6: CFRP at front and rear sides between the loads	1720	0.466	0.6
13	CBR-01-0.5	820	0.554	0.5
14	CBR-04-0.5	880	0.642	0.5
15	CBR-09-0.5	940	0.621	0.5
16	CBR-A-0.5: CFRP at the top between the loads	1220	0.397	0.5
17	CBR-B-0.5: CFRP laminates upside down U-shape	920	0.449	0.5
18	CBR-C-0.5: CFRP at front and rear sides between the loads	1780	0.411	0.5

From table (2) results it can be noticed that corbel strengthening with CFRP at front and rear sides has the highest load at failure time of 1640 kN,1720 kN&1780 kN for (a/d) of

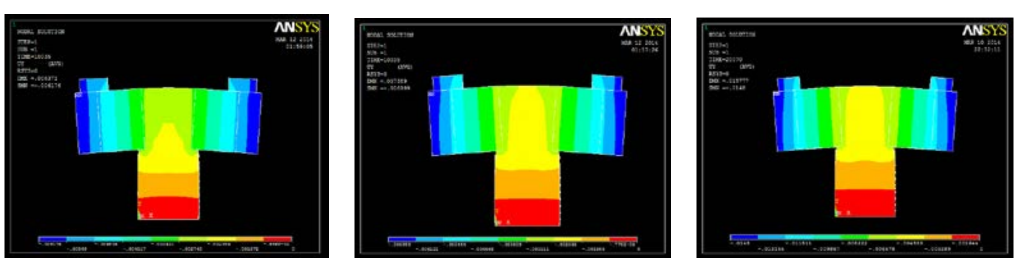
0.7, 0.6 & 0.5 respectively. This occurred due to the position of CFRP, as this corbel strengthened at the front side near the joints in the shear-critical zone where the cracks appeared. In the other hand corbel strengthened at the top has the lowest deflection with high load capacity of 1020 kN, 1180 kN &1220 kN for (a/d) of 0.7, 0.6 & 0.5 respectively. The Finite element analysis results of corbel (CBR-09) and corbels upside down U-shape strengthening with CFRP show a very small difference in failure load, which refer to a neglectable effect of CFRP at the bottom side of corbel. In general, for most corbels models studied in this work, the failure occurred and the crack started to appear in the shear-critical zones around the joints similarly to the experimental test Figs.(9-14) show the stress distribution in the direction of deflection at failure time, these figures refer that the stresses concentrate in corbel web as the corbel flange confined by CFRP especially in case of critical zones confinement at the positions of cracks, corbels CBR-A & CBR-C.

Also, the decrease in (a/d) ratio show a positive effect on corbels load capacity, and stresses concentrate towards the corbel web as (a/d) ratio decreases from 0.5 to 0.7 Figs.(9-14). The increase in load capacity varies as the position and the amount of CFRP changed in corbels. Fig.(15) illustrate the load-deflection relationship for corbels studied in this work. Where in these figures the effect of CFRP and (a/d) is obvious.



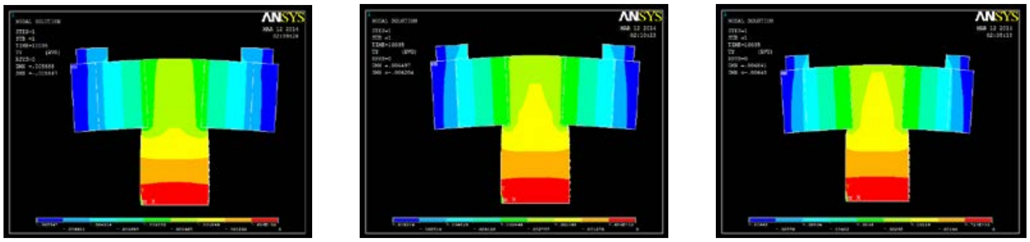
(a) Corbel CBR-01 (a/d=0.5) **(b) Corbel CBR-01 (a/d=0.6)** **(c) Corbel CBR-01 (a/d=0.7)**

Figure.(9) Stress in the direction of deflection: corbel CBR-01 failure



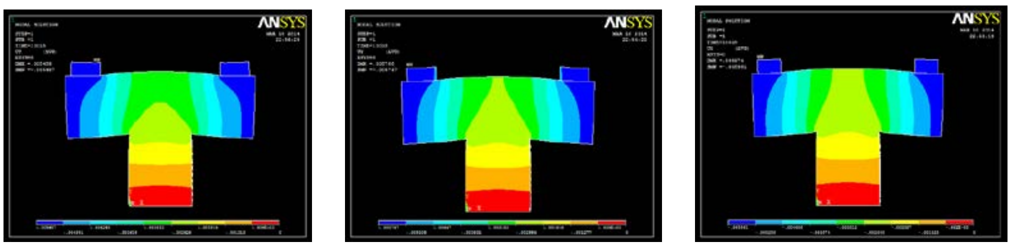
(a) Corbel CBR-04 (a/d=0.5) **(b) Corbel CBR-04 (a/d=0.6)** **(c) Corbel CBR-04 (a/d=0.7)**

Figure.(10) Stress in the direction of deflection: corbel CBR-04 failure



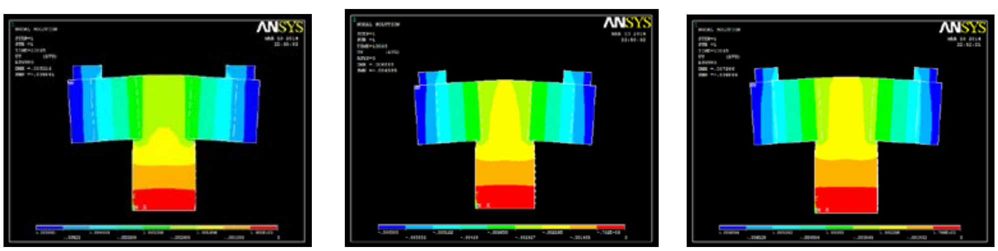
(a) Corbel CBR-09 (a/d=0.5) **(b) Corbel CBR-09 (a/d=0.6)** **(c) Corbel CBR-09 (a/d=0.7)**

Figure.(11) Stress in the direction of deflection: corbel CBR-09 failure



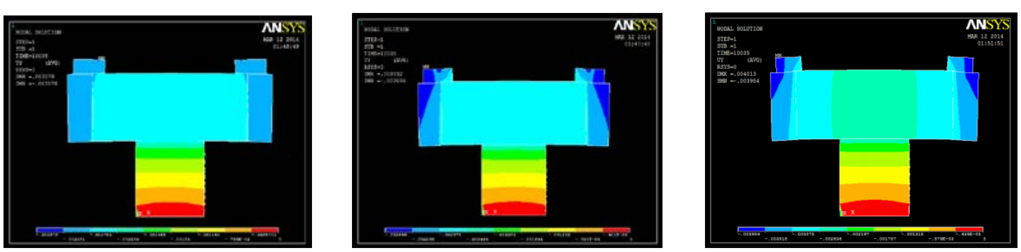
(a) Corbel CBR-A (a/d=0.5) **(b) Corbel CBR-A (a/d=0.6)** **(c) Corbel CBR-A (a/d=0.7)**

Figure.(12) Stress in the direction of deflection: corbel CBR-A failure



(a) Corbel CBR-B (a/d=0.5) **(b) Corbel CBR-B (a/d=0.6)** **(c) Corbel CBR-B (a/d=0.7)**

Figure.(13) Stress in the direction of deflection: corbel CBR-B failure



(a) Corbel CBR-C (a/d=0.5) **(b) Corbel CBR-C (a/d=0.6)** **(c) Corbel CBR-C (a/d=0.7)**

Figure.(14) Stress in the direction of deflection: corbel CBR-C failure

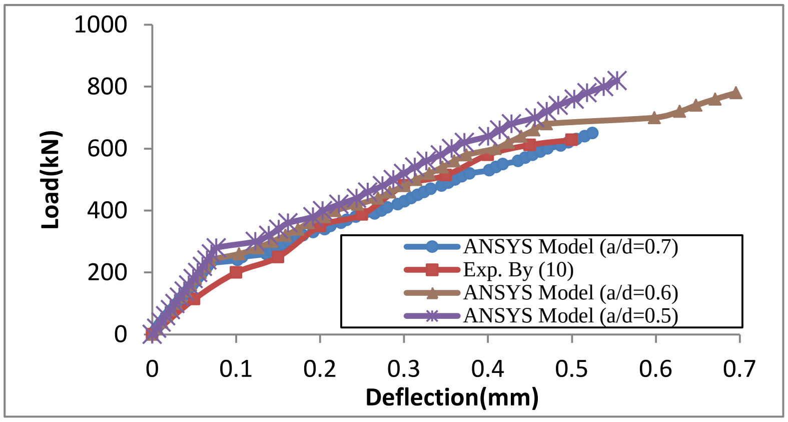


Figure.(15): (a) Corbel CBR-01

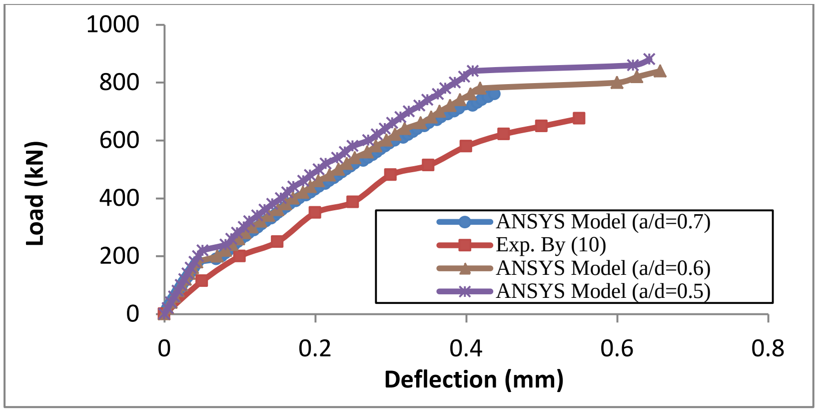


Figure.(15): (b) Corbel CBR-04

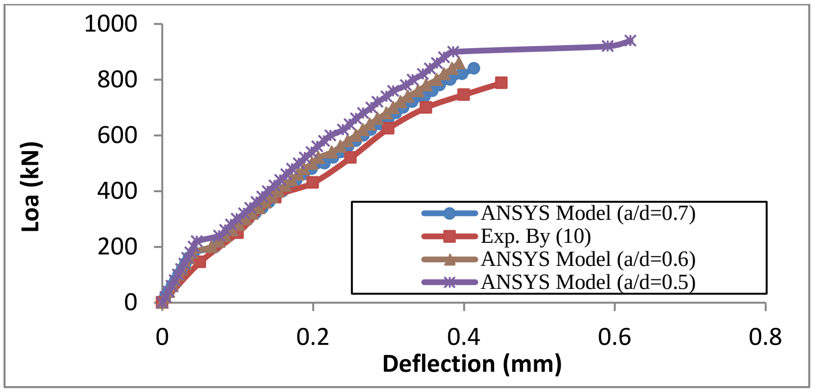


Figure.(15): (c) Corbel CBR-09

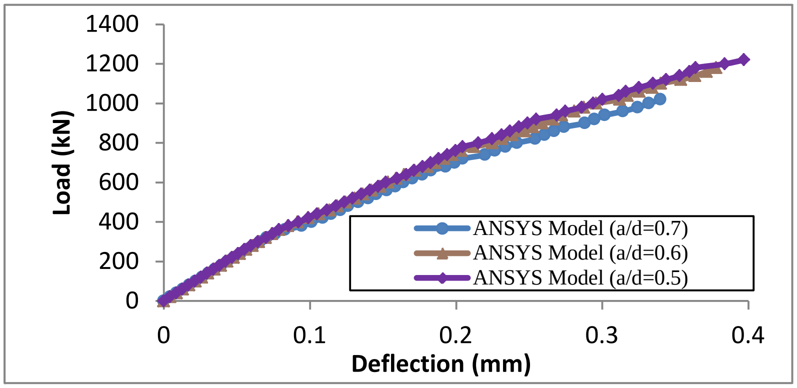


Figure.(15): (d) Corbel CBR-A

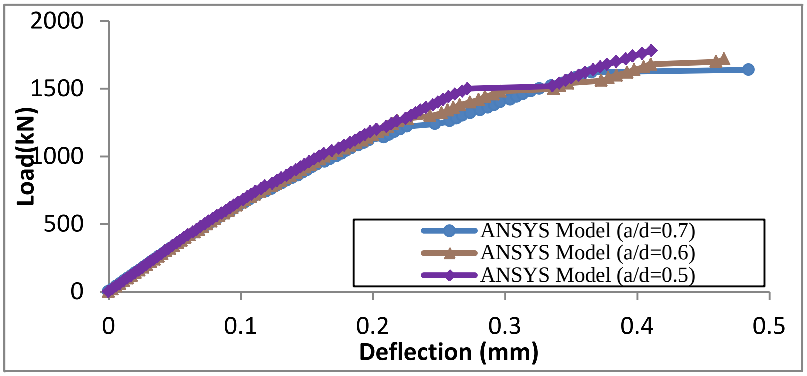


Figure.(15): (e) Corbel CBR-B

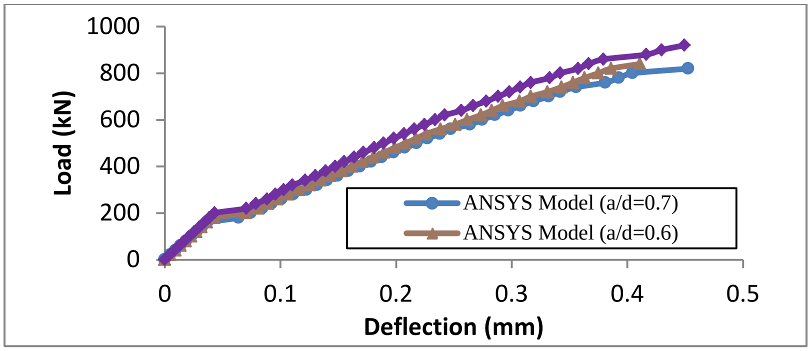


Figure.(15): (f) Corbel CBR-C

Figure.(15) Load-deflection relationship of corbels with various (a/d) ratio

CONCLUSIONS

From finite element analysis results the following facts can be conclude:

1- The use of CFRP as a strengthening increase the load capacity of reinforced concrete corbels. The increasing in load capacity generally depends on the position and the amount

2- of CFRP.

3- The strengthening with CFRP along the front and rear sides have the most positive effect on the load capacity of reinforced concrete corbels. In this case CFRP covered the shear-critical zone in corbel.

4- Corbels strengthened along the top side has a lower deflection in compare with other corbels.

5- Load capacity of corbels increased as shear span-to-effective depth ratio (a/d) decreased.

6- Corbels with CFRP strengthening failed in sudden and brittle manner with less deflection than corbels without strengthening.

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