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Civil Engineering Journal

Vol. 4, No. 5, May, 2018

Experimental Study of Behaviour of Reactive Powder Concrete Strengthening by NSM-CFRP Corbels

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Received 26 March 2018; Accepted 25 May 2018

Abstract

The research contain an experimental examination for the behaviour of reactive powder concrete corbels, strengthened with varying orientation of Near Surface Mounted Carbon Fiber Reinforcement Polymers (CFRP) strips. Six reactive powder concrete corbels were tested. Divided into two groups, each group contain three specimens, one of them without strengthening takes as control corbel specimen, two corbels in each group strengthened by inclined and horizontal near surface mounted carbon fiber reinforced polymer (NSM-CFRP) stripes, other variable was the shear span to the effective depth ratio (a/d) to study the influences of those variables on the ultimate strength carrying capacity, cracking pattern, cracking load, vertical deflection, failure modes. The results showed an important improvement in the behaviour and load capacity of strengthened reinforced RPC corbels in addition to enhancing the stiffness of corbels. For group A where a/d =0.65, the percentages of increase in load failure were about (10.3% - 15.45%) for inclined and horizontal strengthening respectively, and for group B where a/d =0.4, the percentages of increase in load failure were about (7.1% - 14.6%) for inclined and horizontal strengthening respectively.

Keywords: Corbels; Reactive Powder Concrete; Near Surface Mounted; Carbon Fibers Reinforcement Polymer (CFRP); Shear Strength.

1. Introduction

It was found from the last earthquake in the world that most collapse of precast buildings was caused by failure of connections. Therefore, an extensive researches should be carried out to improve precast concrete connections. A common simple precast concrete connection is corbel. Reinforced concrete corbels are structural elements widely used in practice. These corbels, by asset of their locations, are possessed as small as possible and are heavily and seriously loaded. Very often their dimensions are imposed by architectural requirements rather than by considerations of engineering facilities. However, when high strength concrete is engaged with these corbels the tendency is to decrease the dimensions the section gets smaller even though the design engineer still has to comply with the design requirements such as concrete cover, bar spacing and the amount of flexural and stirrup reinforcement. Corbels mainly used to carry beams and girders, and to transfer loads to the other structures in bridges and precast concrete constructions, as show in Figure 1.

Corbels or brackets are extensively used in precast constructions for supporting precast girders or beams on the columns. When they cast with a wall, properly they are called brackets [1].

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http://dx.doi.org/10.28991/cej-0309150

Figure 1. Precast concrete column corbels [2]

Kassem (2015) [3] Studied analytically 455 specimens of corbels to obtain the ultimate load for reinforced concrete corbel by using strut and tie model (STM). The proposed model depend on constitutive laws of cracked reinforced concrete adding to, the normal strut-and-ties force equilibrium requirements, and based on strain compatibility. The suggested approach evaluates the failure load with respect to the mode of failure such as splitting or crushing the diagonal concrete, nodal crushing and steel reinforcement yielding. Anticipations of results that obtained by numerical analysis models were in a well agreement with pervious collected data of similar experimental work. In reinforced concrete constructions, lateral loads, such as wind and earthquake loads are mainly resisted by shear walls and connections. Failure of precast constructions is mostly caused by connections, in which a corbel could be used.

Young et al. [4] in 1985 tested eight high strength reinforced concrete corbels subjected to vertical load. They investigated the effect of the main steel reinforcement to the failure load with constant shear span over depth (a/d) ratio. According to test results they determined that ACI Code: 318-77 [27] is conservative for high strength reinforced concrete corbel. This shows that the increase in concrete strength and the following increase in the shear strength of high strength concrete is not completely employed by the ACI Code.

DeLorenzis and Nanni, 2002 If the existing steel reinforcement is reduced in capacity due to: corrosion or increase in traffic loads (e.g. permissible axle weights), as shown in Figure 2, then we should improve the structural design or seismic resistance. In addition to that, attempts needs to be made to use other forms of FRP strengthening in practice researches. Near surface mounted stripes or bars is a promising technique for improvement shear and flexure strength of reinforced concrete members [5].

Figure 2. Destroyed corbel in local building under construction

1.1. Corbel Strengthening Technique

It may have to carry heavier loads or need change in building usage. Or it may also suffer steel deterioration. Or may have errors made during the design or construction stages. The structure may need to be strengthened or repaired before it can be used. The most common way to strengthen structures is to locate Fibre-Reinforced Polymer (FRP) stripes or sheets on the surface of the structure or inside the structural members.

FRP materials are developed in recent years and takes many types of material, it comprise glass fibers (GFRP), aramid fibers (AFRP) and carbon fibers (CFRP), and takes several forms, for example, fabric, plates, bars, 2D grid and 3D grid as shown in Figure 3 [6].

Figure 3. Available materials of FRP products [7]

Abed Attiya (2012) [8] examined the influence of CFRP stripes on the ultimate load capacity of repaired and strengthened concrete corbels. The strengthened corbels with external bonded of CFRP, as shown in Figure 4 had variables for investigation comprised number of CFRP strips, angle of inclination, bonding type of stripes and ratio of shear span s to effective depth (a/d).

Figure 4. Detail and Geometry of Strengthened Specimens [8]

The results of this research included:

- Strengthening of RC corbels by Using CFRP strips can improve the shear strength of corbel in percent ranged between (45% - 60%) for inclined strengthening method and between (15% - 31%) for horizontal strengthening compared to reference corbel.
- Strengthening by CFRP stripes can be delayed the initiation of first cracks.
- The loads deflection response curve of strengthened specimens seems stiffer than the unstrengthening ones.

Paul Ciobanu (2012) [9] stated the most familiar technique was the external bonding reinforced fibers (EBR). In this method the carbon fibers stripes bonded directly on the face of concrete members by using epoxy adhesive, until now did not employ the full tensile strength of FRP materials, mostly due to their premature debonding. In near surface mounted method the most of tensile strength can be employed.

El-Maaddawy and Sherif (2013) [10] examined the behaviour of nine corbels strengthened with EBR-CFRP sheets, the parametric study were the configuration of sheets and the amount of steel reinforcement. Results revealed increasing 40% in ultimate load capacity and they noticed the contribution of the CFRP to the load capacity of corbek decreased with increasing of steel reinforcement.

Ivanova and Assih (2015) [11] examined the locals behavior of concrete corbel reinforced with adhering fabrics of composite carbon fiber polymers CFRP. The variables were studied that’s have an effect on mechanical behavior of corbels in this research were: type and nature of strengthening either by warping or bonding directly and method of applying fabric either unidirectional or bidirectional. Results can be showed the modes of failure were: compression failure, shear with fabric debonding failure and flexure failure. They conclude the warping strengthening was best technique than those glued directly in terms of load failure carrying capacities.

Mohammed (2015) [12] examined the effect of CFRP laminates on corbel behavior and mechanical properties of repaired and strengthening corbels. The experimental program test consists of sixteen specimens; they divided into six groups depending on parametric study such as: fully warping strengthening or not fully, number of horizontal CFRP laminates, configuration of laminates and method of bonding. The results showed that the strengthening by CFRP laminates appeared valuable improvement in load carrying capacity. This improvement range about 16-71% in strengthening corbels. The using of CFRP improve the serviceability of corbels by reducing the deflection and delay the first crack load more than 46% comparing with un-strengthening one.

AZADAH (2016) [13] the technique of near surface mounted FRP is capable to achieve higher strains than external bonded reinforcement technique (EBR), resulting in more efficiency by using FRP materials, thus improving shear and flexure capacities for structural members in addition to improving ductility. In lower steel reinforcement ratio of RC members the NSM-FRP strengthening is more efficient. Premature debonding can be avoided by using NSM-FRP in comparison with the EBR-FRP strengthening.

Ammar and Ali (2016) [14] Studied the effect of NSM-CFRP bars on behavior of light-weight reinforced concrete corbel. The experimental program consists of twenty specimens, to study the effects of: shear span to effective depth ratio (a/d), direction of NSM-CFRP bars (horizontal, vertical and inclined), presence of secondary reinforcement, and kind of adhesive (cementitious grout or epoxy) on the structural properties as: crack load, crack pattern, ultimate strength, deflection and ductility. The results showed a significant improvement in the behavior and ultimate load capacity of strengthening and repairing lightweight corbels with an increase about 24.6-72.4 % in the ultimate load with (a/d=0.3 and 0.75) respectively and via the first crack and ultimate loads load increased when the specimen without stirrups. This study showed the deflection decreased with low span /depth ratio in strengthening specimen. Numerical analysis appeared good agreement to predicting the structural behavior of the experimental works with average differences about (4.25%) - (14 %) between the values of ultimate load and deflection at service load, respectively. Using epoxy adhesives achieved higher strengths compared to those specimens strengthened with cementitious grout. It was conclude that the increase in ductility attributed with the strength increasing.

1.2. Fiber Reinforced Polymer (FRP) Strengthening

FRP material is anisotropic and very high strength in one direction of reinforcing fibers. The anisotropic behavior influences the shear strength, and good bond performance by dowel action of FRP. Designers take in account the lack of ductility in concrete reinforced by FRP to check serviceability (e.g. deflection, cracks, creep and fatigue) [15].

Figure 5. CFRP plates (www.sikaproducts.com)

2. Details of Corbels Geometry and Reinforcement

As it is shown in Figure 3, the column supporting the corbel have dimensions 300 by 200 mm supporting by the sides 200 mm two corbels have long 250 mm and the depth near column is 300 mm. Column was reinforced with over design to avoid any failure by column features. The corbels group A and group B are reinforced with by (4-Ø10 mm) as the main tension reinforcement and (2-Ø8 mm + 2-Ø6 mm) horizontal steel stirrups, group A with a/d=0.65, but the group B of corbels are with a/d=0.4 as shown in Figure 6.

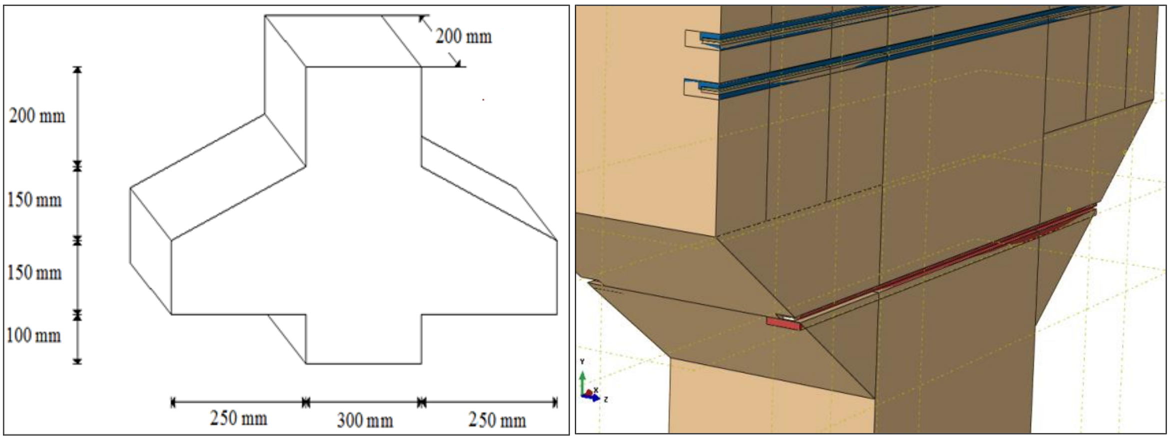

Figure 6. The geometry and CFRP strengthening for the corbels

2.1. Application Procedure

To ensure sufficient bond between the CFRP stripes and concrete, grooves should be done according the standard specification [16] and this method stated by many researchers where the CFRP plate inserted into grooves made on concrete surface by saw then filled the groove by epoxy adhesive to bond CFRP with concrete to improve flexure strength and stiffness by FRP [17]. The steps of stripes applications recommended by codes as follow:

1) Cut grooves in concrete corbels had rectangular cross-section, with size of 18 × 3.6 mm in order to install the CFRP stripes of 12 × 1.2 mm cross section as shown in Figure 7.

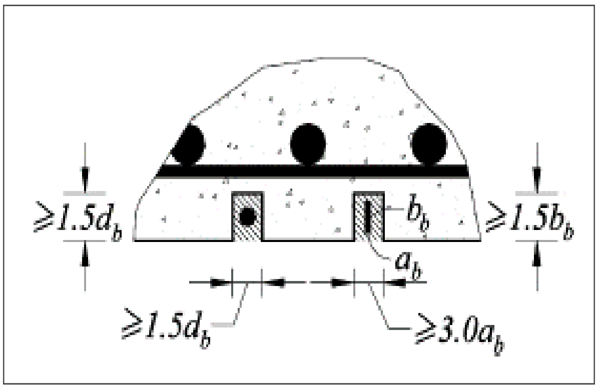

Figure 7. NSM-CFRP grooves dimensions and geometry (ACI 440-2R-17)

2) Clean the groove by air blasted and water jet to remove any remnant dust.
3) Cutting the CFRP stripe to the desired length.
4) Mix the two parts of epoxy (resin and hardener) to prepare the paste.
5) Filled the grooves at half way with epoxy.
6) Putting the CFRP stripe in the grooves and slightly pushed, then filled the groove completely to ensure the paste fill around the sides of stripe.

Figure 8 displays the procedure of NSM stripes installation inside the concrete corbels on two faces. The corbels stay in the laboratory one week before test.

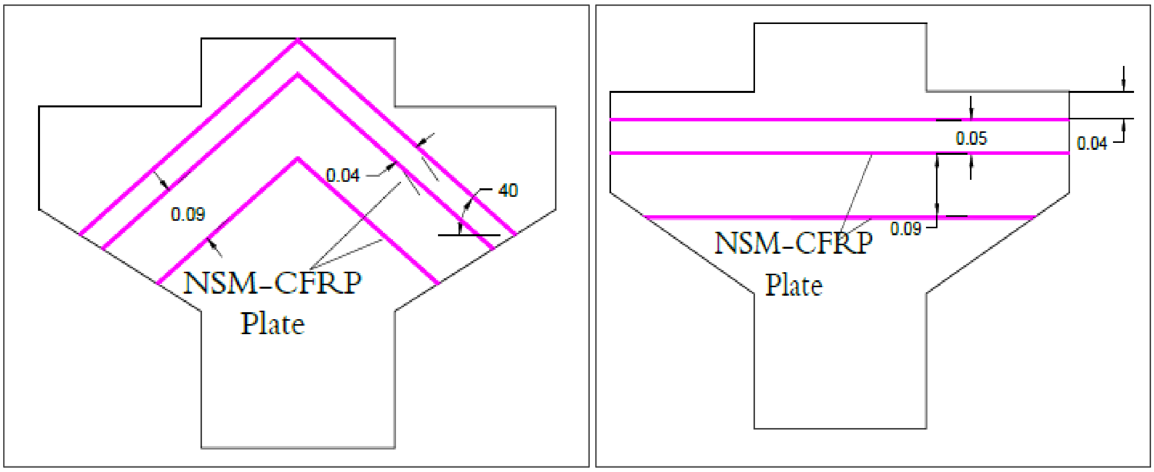

Figure 8. NSM-CFRP position on corbel

2.2. Specimens' Code

The corbel specimens classified depending on two parameters:

1) Near surface mounted (NSM) orientation, either horizontal (0°) or inclined by angle (40°).
2) Shear span over effective depth ratio, either a/d= 0.65 or 0.4.

As shown in Figure 9 and 10.

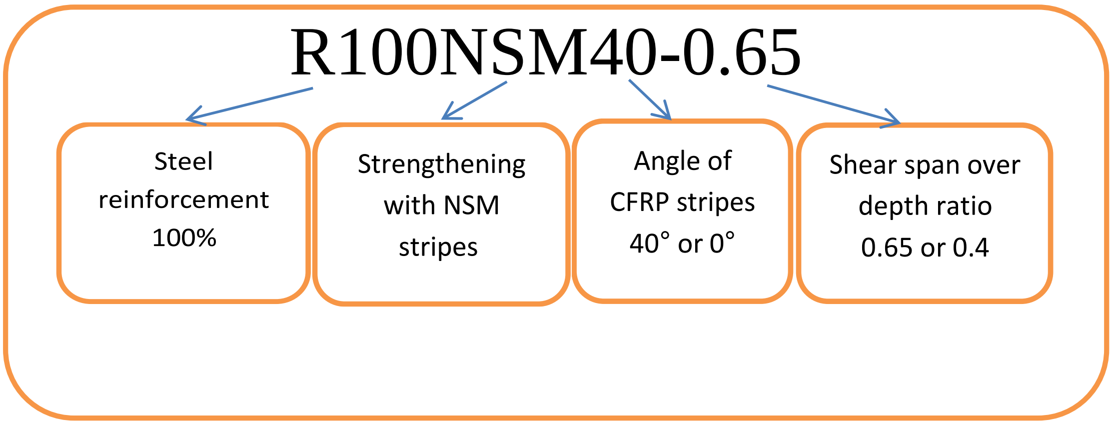

Figure 9. Specimen code

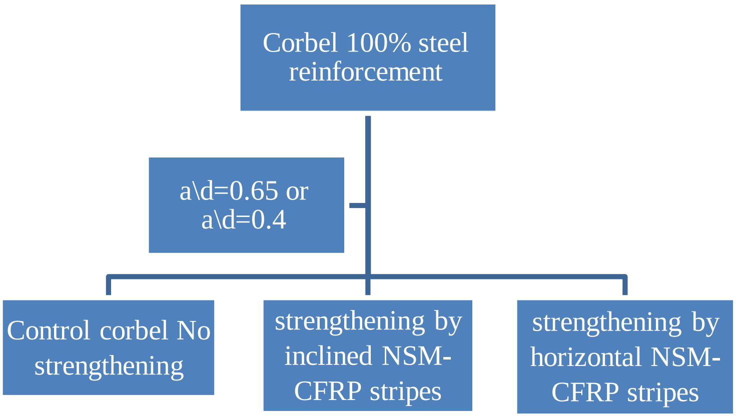

Figure 10. Specimens tree identification

3. Experimental Works Results

The system of loading consists of heavy duty steel column and girders to ensure the load will not dissipated by frame deformations. At the upper side of frame at centre of the hydraulic jack loading electrically and by use the digital load cell as an indicator (200 kN capacity) was supported, suitable height of the machine frame to operate the piston downward movement. Each specimen putted on the testing system, painted and marked. Bearing steel plate putted above the corbel with dimensions (200 × 200×20) mm were used, to assure uniformly distributed load. On the other hand, supporting steel plates with dimensions (200 × 50 × 10) mm were putted under corbel, the dimension of support plat had been selected to ensure the crushing or local failure did not happened at expected testing loads. Many laboratory tests were done to determine the compressive strength, tensile splitting strength and modulus of elasticity. Table 1 shows the mechanical properties of hardened concrete cylinders.

Table 1. Mechanical properties of concrete

Group No.	Cylinder Compressive Strength f_c' (MPa)	Tensile Splitting Strength f_t (MPa)	Modulus of Elasticity Ec (MPa)
R100-0.65	65.8	10.5	36567.29
R100-NS40-0.65	66.1	10.1	37593.29
R100-NS0-0.65	62.4	10.3	36605.54
R100-0.4	63.2	9.9	37560.21
R100-NS40-0.4	62.4	10.3	35998.49
R100-NS0-0.4	62.6	10	36605.54

4. Test Results

Comparison will be done between results to examine the importance of the measured experimental variables. To found the best formation for every case, it was significant to study load carrying capacity, deflection and crack pattern.

A full description of the behaviour of the two groups appoints out; a key finding of this research was that the performance of specimens in provisions of load carrying capacity. The first crack load, failure load, failure modes and deflection at loading periods are recorded in Table 2. The results will be discussed for each group of specimens.

Table Error! No text of specified style in document.**1. Experimental Results of the Tested Corbels**

Corbel Symbol	a/d	First Cracked load (Kn)		Failure load(KN)		Deflection Δ_u (mm)
		Pc	$\frac{P_{cr(i)} - P_{cr(r)}}{P_{cr(r)}} \times 100$	Pu	$\frac{P_{u(i)} - P_{u(r)}}{P_{u(r)}} \times 100$	
R100-0.65	0.65	250	-----	699	-----	3.60
R100-NS40-0.65	0.65	255	2	771	10.3	4.1
R100-NS0-0.65	0.65	260	4	807	15.45	3.3
R100-0.4	0.4	260	-----	1000	-----	1.95
R100-NS40-0.4	0.4	280	8	1071	7.1	1.95
R100-NS0-0.4	0.4	300	15.3	1146	14.6	1.43

4.1. Test Results of Group –A- (a/d=0.65 and Horizontal & Inclined NSM-CFRP Plates)

This group consists of 3 specimens of corbel as:

1. Specimen R100-0.65
2. Specimen R100-NS40-0.65
3. Specimen R100-NS0-0.65

4.1.1. Load Deflection Curve

The response of load–deflection for this group was a linear in almost stages of loading then the curves directed down at high level of load until failure. Control corbel specimen in this group is R100-0.65 was without strengthening and two strengthening specimens have been tested. The results of load-deflection deflection are shown in Figure 4-3. During loading the first flexural crack appeared approximately at load about (250 kN). While the magnitudes of first cracked loads of two strengthening corbels are 255 and 260 kN, it can be noticed the load cracking increased by (2-4)% respectively with respect to the control corbel, as shown in Table 2, it can be notice that no big difference in first crack because it depend on concrete property principally while the ultimate loads of them are 699, 771 and 807 kN, increased by (10.3-15.54) % respectively with respect to control corbel as shown in Figures 11 and 12.

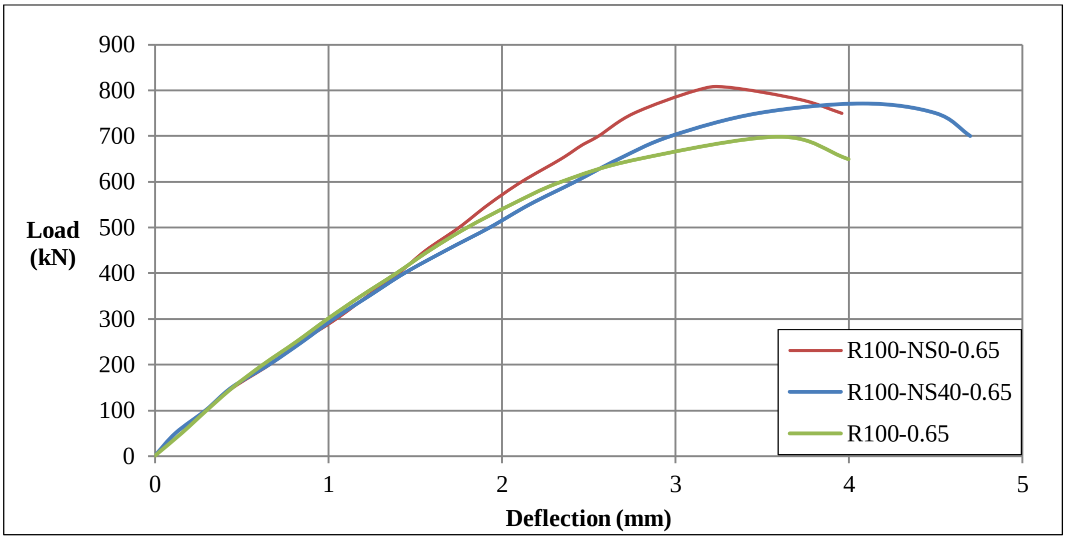

Figure 11. Load-deflection curves of group-B-

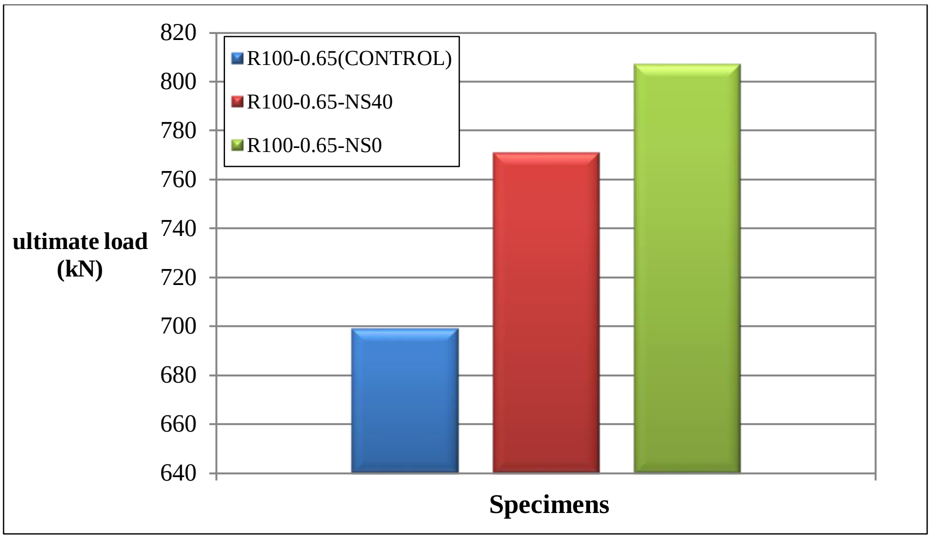

Figure 12. Bar chart of failure load of group –B- corbels

4.1.2. Crack Pattern

The crack patterns at failure for corbel specimens R100-0.65, R100-NS40-0.65, and R100-NS0-0.65, are shown in Figure 4-3, respectively. It was noticed that the crack pattern was identical in the three specimens. For instance, as the corbels were loaded, flexural hair cracks developed initially at the section of the maximum moment (at the column interface). In corbel R100-0.65 the flexural cracks started to develop at loads that ranged between 300 to 400 kN. As the load increased, additional cracks developed diagonally in the shear span zone and progressively deviated into inclined cracks due to the presence of the shear stresses, it can be show the mode of failure was diagonal splitting as shown in plate (4-3a). In case of corbels R100-NS40-0.65 and R100-NS0-0.65 when the cracks arrived to the CFRP plane, they stopped while the loading was continuing at many steps of loading, this case repeated with the CFRP layers, after that the cracks resumed at inclined route toward the edges of loading steel plate. Increasing loading led to new inclined cracks and the cracks propagated rapidly till failure. It was noticed also from the results that strengthening corbels increased their load capacities and shear strengths, so the mode of failure was by shear flexure crushing and compression as shown in Figure 13.

a) R100-0.65 **b) R100-NS40-0.65** **c) R100-NS0-0.65**

Figure 13. Crack pattern and failure mode of group B corbels

4.2. Test Results of Group-B-with Minimum Reinforcement, a/d=0.4 and Horizontal & Inclined NSM-CFRP plates)

1. Specimens R100-0.4.
2. Specimens R100-NSM40°-0.4.
3. Specimens R100-NSM0°-0.4.

4.2.1. Load Deflection Curve

The response of load-deflection was linearly in first stages of loading until 25% of the ultimate load then the rate of deflection increased as nonlinear behavior until failure as shown in Figure 14 and 15. The first crack formed at lower load of (260 kN) for control corbel while in two other corbel happened at (280 and 300 kN) respectively. In comparison with strengthening specimens, it can be noticed that the first and failure cracks formed in loads more than the control corbel by (7.7 - 15.3) %. The results showed that the ultimate load of control corbel R100-0.4 was (1000 kN), and (1071 and 1146 kN) for strengthening corbels R100-NSM40°-0.4 and R100-NSM0°-0.4 respectively. It can be noticed the strengthening appeared (7.1, 14.6) % increasing in load failure with comparison to unstrengthen corbel.

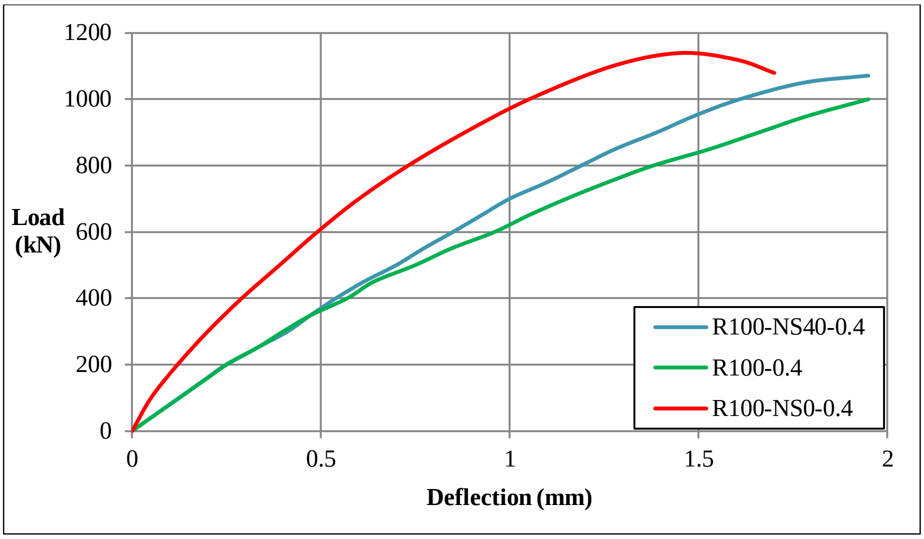

Figure 14. Load- deflection curves of group-B

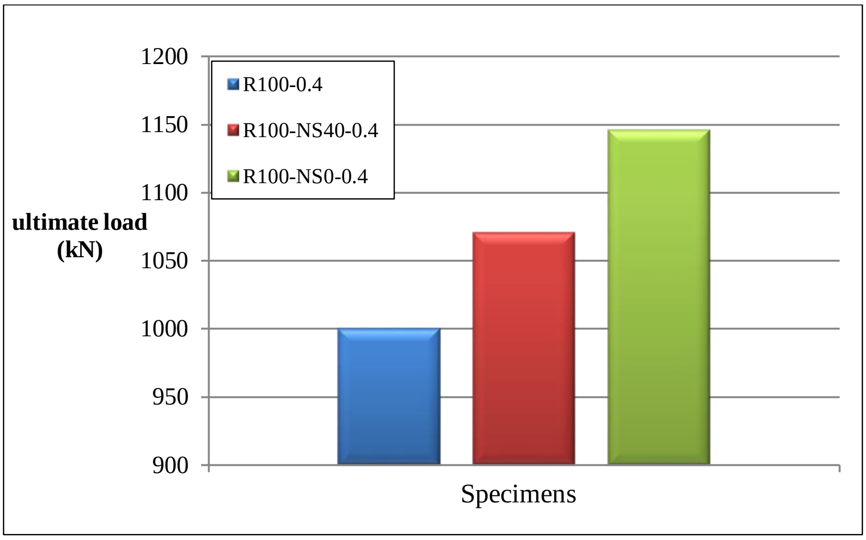

Figure 15. Bar chart of failure loads comparison of group –B- corbels

4.2.2. Crack Pattern

Corbels of this group were failed in a combination of shear and concrete crushing under compression. During loading these corbels the vertical direct shear crack which appeared at horizontal face as evident in Figure 16, and diagonal cracks formed in each case at the inner edge of the bearing plate towards the loading plate and widened with increasing load, ultimately leading to failure with simultaneous shear and crushing of concrete in the compression zone. The crack continued to widen and propagate until it caused failure, at failure, final destruction occurred by crushing of the concrete in compression at the junction of the column and the inclined face of the corbel as shown clearly in Figure 16. It can be noticed that the shear crack remained fine, failure of all specimens occurred only after a primary diagonal crack parallel to the strut developed between the supports and the intersection of the sloping face of the corbel and the column face.

R100-0.65 **R100-NS40-0.65** **R100-NS0-0.65**

Figure 16. Crack Pattern and failure for strengthening corbels of group B

4.3. Studying of Parameters Effect on Corbel Strength

The effect of variables of this research can be studied to obtain the influence of each variable on corbel behaviour. The percentage of increase of failure loads due to strengthening with respect to control in each group that will be a principal aspect of comparison between parameters of this study.

4.3.1. Effect of Shear Span to Effective Depth Ratio (a/d)

The effect of shear span to effective depth ratio (a/d) was examined in this study. Corbels with two various (a/d) ratios (0.65) and (0.4) were used. Table 3 shows the percentage of increase (%). The increasing in strength obtained by NSM-CFRP stripe using same amount of CFRP stripes. Essentially the cracked load and ultimate load of lower (a/d) corbels greater than those have higher (a/d) as shown in Figure 17.

Table Error! No text of specified style in document.**2. Effect of span/depth (a/d) ratio on percentage of increase (%)**

Corbel Symbol	Percentage of increase (%)	
	a/d=0.65	a/d=0.4
R100-NS40	10.3	7.1
R100-NS0	15.45	14.6

It can be notice the increasing of failure load in strengthened corbels of a/d=0.65 more than corbels of a/d=0.4 in all cases of steel reinforcement or CFRP configuration. These results can be expected, that's because of the CFRP strengthening more effective for increasing tension forces for high span/depth ratio corbels, depend on principle properties of FRP in tensile strength.

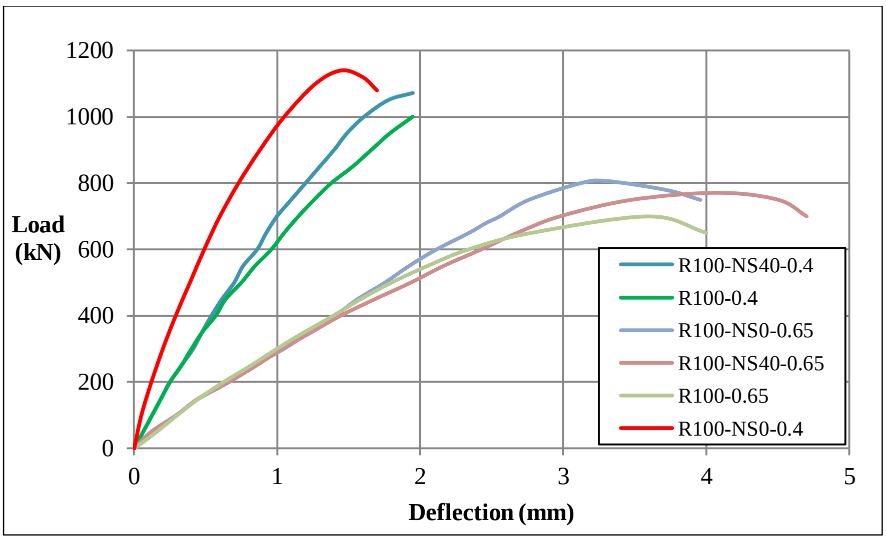

Figure 17. Effect of a/d on strengthening ratio for horizontal and inclined CFRP at As= 100%

4.3.2. Effect of NSM-CFRP Stripes Orientation

The orientation of the NSM-FRP stripes was showed to be an effective parameter of strengthening RPC corbels. The test results revealed a high effect of NSM-CFRP plate orientation on cracking pattern, load carrying capacity, and deflection as shown in the Table 4 and Figure 18. In the strengthened specimens with different orientation of NSM-CFRP stripes NSM0° and NSM40° the increasing in the shear cracking and ultimate loads causes decreasing in the deflection as shown in Table 2. It can be concluded that the strengthening specimens by horizontal NSM-CFRP stripes gives no significant difference compared with the inclined strengthened model. The simple increasing between them, it may be due to the continuity of the development length of CFRP plate in experimental works along the width of column and double corbels.

Table Error! No text of specified style in document.. **Effect of configuration of NSM-CFRP stripes**

No.	Corbel Symbol	Percentage of increase %	
		Strengthening orientation (40°) inclined	Strengthening orientation (0°) horizontal
1	R100-0.65	10.3	15.45
2	R100-0.4	7.1	14.6

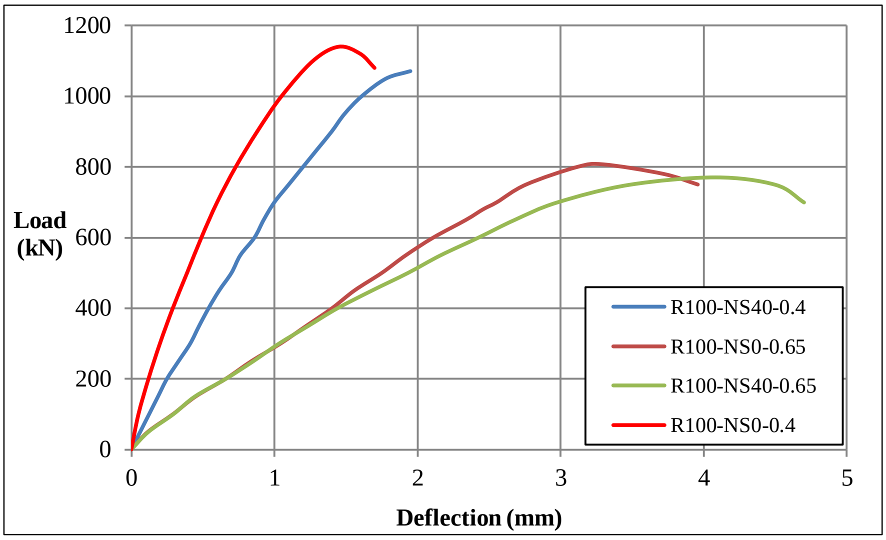

Figure 18. Effect of CFRP orientation on ultimate load for a/d= 0.65 & 0.4

5. Results and Discussions

There are two groups of corbel each group consist from 3 corbels, each group has shear span over depth differ from other, group A have a/d= 0.65, group B have a/d=0.4. The first corbel represent control corbel without strengthening, the two other corbels strengthening by carbon fiber polymer reinforcement (CFRP), on two ways horizontal and inclined at 40 °. From results we notice that the first cracks delay when the corbels strengthening by CFRP, the percentage of increase in load cracks is ranged as (2-4) % for a/d=0.65 and (8-15.33) % for a/d=0.4 that's due the confinement of concrete by CFRP. Also it can can conclude that the group A gives more percentage of increase from group B, where the increasing in load failure is (10.3% - 15.45%) while the increasing in load failure of other group is (7.1% - 14.6%) that's due to using CFRP where its activity was affected at long span, depending on properties of FRP in tensile strength that resist the flexure in beams. And we notice the deflection is reduced when we strength the corbels with respect to unstrengthen corbel. From the experimental tests we can conclude that the CFRP is used more effectively because a bigger portion of its tensile capacity is engaged, and it contributes to the load carrying capacity under both service and ultimate situations. It closes cracks, delays the opening of new ones.

6. Conclusion

- NSM-CFRP stripes strengthening is a good post preparing for reactive powder concrete (RPC) corbels, where the NSM-CFRP stripes strengthening can possibly contribute to the carrying capacity of the corbels.
- The NSM-CFRP stripes strengthening have considerable role in the enhancement the corbel strength, throughout reducing the strains in concrete, decreasing the width of cracks and redistribution the cracks by the confining the

concrete region.

- Shear span to effective depth ratio and CFRP orientation were important variables that influenced on the behavior and resistance of RPC corbels.
- The mode of failure can be changed from a brittle failure to more ductile failure (less sudden failure) after strengthening by NSM-CFRP.
- The effectiveness of the epoxy adhesive was very good in a narrow groove of CFRP stripes, so that, peeling of stripe don't occurred in all tested specimens approximately.
- The percentage of increase is about (10.3 – 15.45) % for a/d= 0.65 for inclined and horizontal strips respectively and (7.1 -14.3) % for a/d= 0.4 for inclined and horizontal strips respectively compared to control corbels.

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