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A new method for repair of fiber reinforced concrete corbels using steel threaded rods

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Abstract. The aim of this study is to investigate the efficiency of using threaded rods and steel profiles to produce a steel confining system for rehabilitation of damaged concrete corbels for the first time in literature. Some of the specimens were repaired by crack repair epoxy before being confined for further enhancement. A total of 19 two sided damaged corbels were used in the study with different mechanical properties and parameters but similar dimensions. The differences were in rehabilitation style, shear span, fiber percentage, reinforcement steel diameter, and concrete strength. The rehabilitated specimens were loaded with vertical load until failure. Four different configurations were used in the investigation. Test results show that the proposed rehabilitation technique is effective to enhance the load capacity of the corbels and to improve their ductility. Moreover, new formulations were proposed to calculate the load capacity of the rehabilitated corbels. A good fit was observed between numerical and experimental results.

Keywords: corbels; rehabilitation; external steel; epoxy; threaded rods; repair; concrete; load capacity; ductility

1. Introduction

Rehabilitation of the damaged structures has become a focus of interest all over the world. Therefore, if feasible, much amount of funds has been spent for the rehabilitation of damaged reinforced concrete (RC) structures instead of building the new structures. (Ma *et al*. 2017). Especially, rehabilitation of connection regions, such as beam-column connections, corbels etc., is very crucial for safe RC structures (Marthong *et al.* 2016). Different methods are used to repair the damages of concrete structures, like, decreasing the function of the structure and rebuilding the structure completely or using rehabilitation/strengthening techniques (Macdonald 2008). Several studies show that external confinement is an effective technique in order to recover the strength of damaged concrete columns (Wu *et al*. 2014, Zhou *et al*. 2015, Panjehpour *et al*. 2016, Dubey and Kumar 2016, Peled 2007). Moreover, the confinement technique achieves or recovers the ductile behavior in rehabilitated members (Gu *et al.* 2010, Iacobucci *et al.* 2003, Lehman *et al.* 2001, Stoppenhagen *et al.* 1995).

One of the most familiar confinement technique is jacketing. Different materials were used for jacketing of concrete. For instance, Traditionally vibrated concrete was used for jacketing by Yuce *et al.* (2007). Steel was also used for rehabilitation with jacketing (Sarno *et al.* 2006, Bournas and Triantafillou 2009). It has been found that steel jacketing can improve the capacity of a column by at least 20% (Belal *et al.* 2015). Another confinement material is Fiber Reinforced Polymer (FRP) fabrics which are widely used for the same purpose (jacketing) (Bournas and Triantafillou 2009, Bhattacharyya *et al.* 2012, Chalioris 2008, Kakaletsis 2016). Ferrocement is another rehabilitation material which is used for jacketing (Kaish *et al*. 2012). Furthermore, RC jackets have been used for rehabilitation and/or strengthening of structures (Júlio *et al.* 2003, Karayannis *et al.* 2008, Júlio *et al.* 2005).

During the improvement in concrete repairing technologies, repair of cracks has appeared as an effective technique for complete rehabilitation. The purpose of crack repair is to fill the cracks and bond the sides of cracks (ACI Committee E706). Very low viscosity epoxy is preferred for repair of cracks due to its perfect adhesion, long-term resistance to environmental conditions, great bonding strength, easiness of applying, and lower risk of shrinkage throughout curing (Harrison 2013). It has been found that crack repair epoxy decreases the reduction in the compressive strengths of cracked cube specimens from 40.93% to 8.23% of the original strengths on average(Issa and Debs 2007).

Corbels are short emerging parts from faces of columns which support big concentrated loads (Yassin *et al*. 2015). Corbels behave as deep beams in which shear failure is the main failure mode. In general, shear strength of RC corbels is a function of; shear span-to-depth ratio (*a/d*), reinforcement ratio, strength of the concrete (f_c'), and the ratio of the load components –horizontal and vertical- that is applied (Kriz and Raths 1965, Mattock *et al.* 1976).

Due to importance of RC corbels, especially in industrial building, several researches were carried out for the rehabilitation of them (Ahmad *et al.* 2010, Ivanova and Assih 2015, Al-Fadhli 2017, Ivanova *et al.* 2015, Neupane *et al.* 2017, Mohammed and Assi 2013, Ahmad *et al*. 2013,

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El-Maaddawy and Sherif 2013, Elgwady *et al.* 2005, Shadhan and Kadhim 2015, Erfan 2010). However all these investigations are related with rehabilitation of corbels with FRP fabrics. Therefore, rehabilitation of RC corbels with steel confinement system is still issue of corcern for literature and construction sector. Strengthening of corbels via threaded rods were only investigated by Urban and Krawczyk (2016). Current study investigates the rehabilitation of RC and fiber reinforced concrete corbels via a new steel confinement system composed of steel angles and threaded rods.

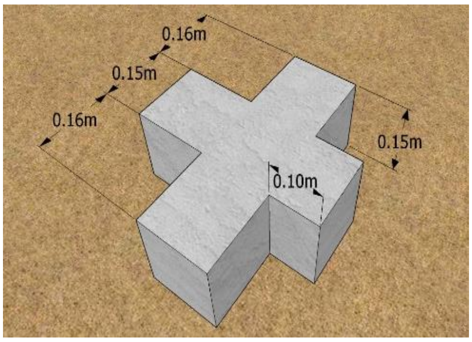


Fig. 1 Dimensions of the specimens

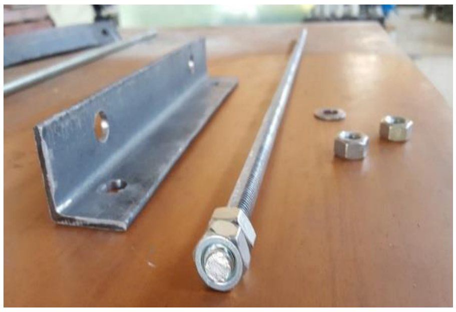


Fig. 2 Steel confining elements

2. Methodology and research objectives

This research shows an experimental study for the rehabilitation of damaged glass fiber reinforced concrete corbels with different characteristics that failed under the effect of diagonal shear previously. The aim of the study is to investigate the results of using the steel confining technique, and injection techniques for the rehabilitation and strengthening of the damaged concrete corbels. The main objectives of the research can be listed through the following points:

1. Investigation of the efficiency of the preferred techniques by studying Load – Deflection curves of the rehabilitated specimen.
2. Studying the efficiency of the injected materials by observing the resultant crack patterns.
3. Investigation of the load transfer mechanism within the new composite members–Steel confined Reinforced Concrete Corbels-.
4. Comparison of the performance of rehabilitated specimens with those of the original ones regarding ductility and load capacity.
5. Prediction of the load capacity of the rehabilitated corbels with the proposed techniques.

3. Experimental program

3.1 Materials

3.1.1 Confining materials

ST37 type steel angles with section of L40×40×4 have been used in the experimental study. Beside the angles, threaded rods with yield strength of 438 MPa and ultimate strength of 475 MPa have been used for the strengthening. Flat steel washers made of A2 stainless steel, and structural hexagon steel nuts made of A2 stainless steel with proof load of 700 MPa were used to achieve confinement of the strengthening configuration.

3.1.2 Injection materials

Injection material has been used to repair the cracks. These materials are necessary to bond the sides of the spaces of the cracks.

High viscosity epoxy was used to close exterior cracks and to repair small broken parts of the damaged corbels.

Low viscosity epoxy has been used to repair large cracks (larger than 5 mm). This repair epoxy has a tensile strength of 40 MPa, a compressive strength of 62.5 MPa, and a bond strength larger than 3 MPa (all the strengths are gained after 7 days).

The third type is very low viscosity crack repairing epoxy which was used to close very small cracks (smaller than 5 mm). The compressive, tensile and adhesive strengths of the epoxy is 53 MPa, 25 MPa and larger than 4 MPa, respectively.

3.2 Specimen of the test

3.2.1 Specimen geometry

Nineteen two-sided damaged reinforced concrete corbels have been rehabilitated in the experimental study. These corbels had been failed in the studies carried out by Kamil (2016),d Hussein (2016). All corbels have the same dimensions. Dimensions of cross sections of corbels are 150×150 mm. The column parts have the same cross sections (150×150 mm). The length of the corbels is 160 mm for both sides. The length of the columns is 160 mm and 100 mm above and below the corbels, respectively. The details of the corbel are shown in Fig. 1.

Steel confinement configuration was achieved by 0.2 m and 0.6 m steel threaded rods and 27 cm *L*-shaped steel profiles (L40×40×4) as shown in Fig. 2.

3.2.2 Classification of the specimens

The previously failed specimens had different characteristics which are presented in Tables 1-3.

3.3 Implementation of the injection and confinement

3.3.1 Treatment with epoxy

High viscosity epoxy was used to coat the cracked faces

Table 1 Codes of the specimens

Shear Span	High Strength Concrete			Normal strength concrete		
	Glass Fiber Ratio %			Glass Fiber Ratio %		
	0.0 %	0.2 %	0.4 %	0.0 %	0.2 %	0.4 %
120 mm	S10-120	-	S8-120-0.4%	S10-A120	-	S8-A100-0.4%
	S8-120	-	-	S8-A120	-	S8-A80-0.4%
100 mm	S8-100	S8-100-0.2%	S8-100-0.4%	S10-A100	S8-A100-0.2%	-
80 mm	S10-80	S8-80-0.2%	S8-80-0.4%	S8-A80	S8-A80-0.2%	-
	S8-80	-	-	S10-A80	-	-

*S8: Diameter of reinforcement steel is 8 mm; S10: Diameter of reinforcement steel is 10 mm

Fig. 3 Corbel coated with high viscosity epoxy

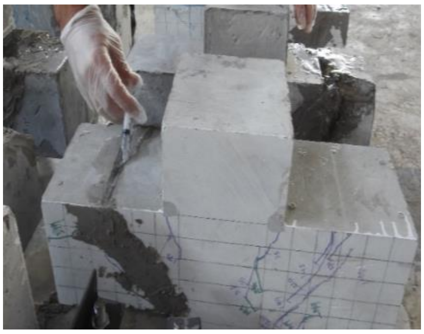


Fig. 4 Filling small cracks with repairing epoxy

Table 2 Properties of the high strength concrete

High Strength Concrete			
Glass Fiber Ratio	Cylindrical Compressive Strength (MPa)	Cubical Compressive Strength (MPa)	Tensile Strength (MPa)
0.0 %	92.79	102.66	4.79
0.2 %	83.76	96.15	4.99
0.4%	88.26	98.69	5.14

externally to prevent leaking of the very low viscosity epoxy, Fig. 3. Very small cracks (smaller than 5 mm) were filled with repairing epoxy using the “Gravity Feed” method to rehabilitate them, Fig. 4. Before injecting the epoxy, cracks were cleaned by compressed air to get rid of loose particles inside that can negatively affect the bonding performance of epoxy.

3.3.2 Procedure of confining with steel

12 mm diameter steel threaded rods were cut into 0.6 m and 0.2 m pieces. Then, *L*-shaped (L40×40×4) steel profiles were cut into 27 cm pieces, and holes were prepared in *L*-shaped pieces by steel drilling machine. All the pieces were

Table 3 Properties of the normal strength concrete

Normal Strength Concrete			
Glass Fiber Ratio	Cylindrical Compressive Strength (MPa)	Cubical Compressive Strength (MPa)	Tensile Strength (MPa)
0.0 %	51.34	64.50	4.60
0.2 %	42.67	63.84	4.78
0.4%	46.39	66.71	4.91

Fig. 5 Installing the steel confinement

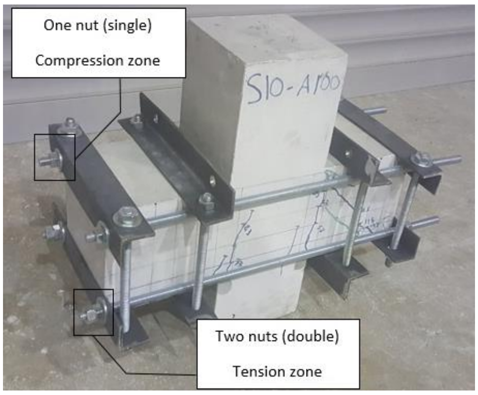


Fig. 6 Doubling nuts

combined and tightened by using nut keys (Fig. 5).

Threaded rods that exist in the tension zones were connected to the steel sections with double nuts because of the expected high tensile stress. Since ductility of the new composite system-the confined concrete- will be very high, the nuts will be under higher strength for a long time. Therefore, the safety of the system was increased by doubling the nuts in the tension zones (Fig. 6).

The inner pieces of vertical threaded rods and the inner steel *L*-shaped profiles were placed in the middle of the

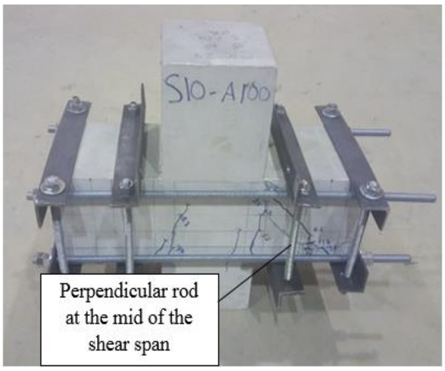


Fig. 7 Place of the middle steel rods

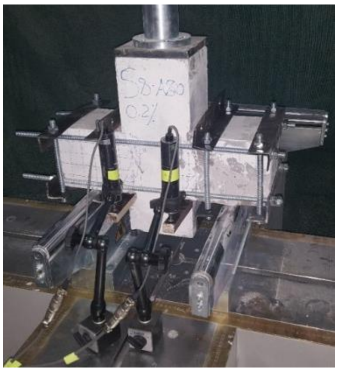
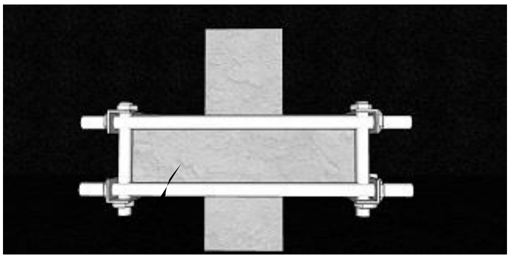
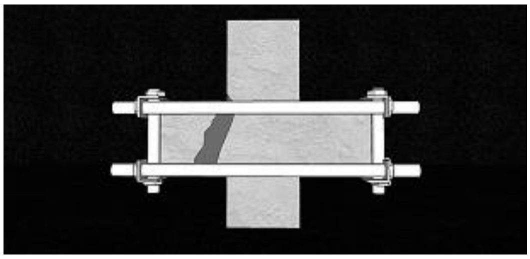


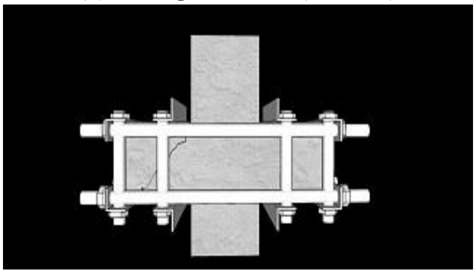
Fig. 8 A prepared specimen to be tested



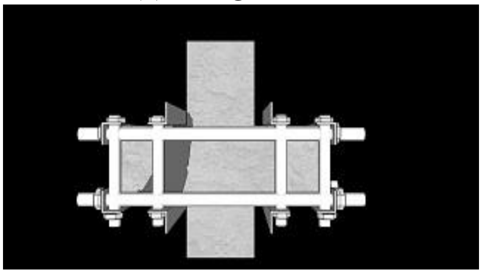
(a) Configuration -1 (Control)



(b) Configuration -2



(c) Configuration -3



(d)) Configuration -4

Fig. 9 Schemes of rehabilitation configurations

corresponding shear spans. The distance of the center of the outer steel profiles is 140 mm from the column face for all corbel specimens. The centers of the perpendicular threaded rods were placed parallel to the middle of the shear span to achieve the most effective performance against shear cracks (Fig. 7).

3.4 Test setup

Loading tests of corbels were carried out via 500 kN capacity displacement controlled loading machine. The load is transferred from the machine to the top of the upper column by a square shaped steel transmission plate in order to distribute the load to the column homogeneously. The loading tests were carried out in a displacement controlled mode with a rate of 0.2 mm/minute. Deflections of corbels were measured via two linear variable displacement transducers (LVDTs). LVDTs were placed at the junction of the bottom of the corbel and column face for each corbel side (Fig. 8), since the highest deflections occur in this region.

4. Experimental results and discussion

Table 4 Details of configurations

Configuration	Steel Profiles	Horizontal Rods	Vertical Rods	Epoxy Details
Configuration -1	4 rods	4	4	No
Configuration -2	4 rods	4	4	Yes
Configuration -3	8 rods	4	8	No
Configuration -4	8 rods	4	8	Yes

4.1 Experimental results

Previously damaged fiber reinforced concrete corbels due to shear failure (Diagonal Tension Failure) were rehabilitated using threaded rods, steel profiles and epoxy according to four configurations. In configuration 1, specimens were confined using 4 pieces of horizontal and vertical threaded rods and 4 pieces of steel profiles, but were not repaired with any type of epoxy. In configuration 2, specimens were confined using 4 pieces of horizontal and vertical threaded rods and 4 pieces of steel profiles as well as repaired with crack repair epoxy. For configuration 3, specimens have been confined using a total of 4 pieces of horizontal and 8 perpendicular threaded rods and 8 pieces of steel profiles, but were not repaired with the epoxy. For configuration 4, specimens were confined using a total of 4

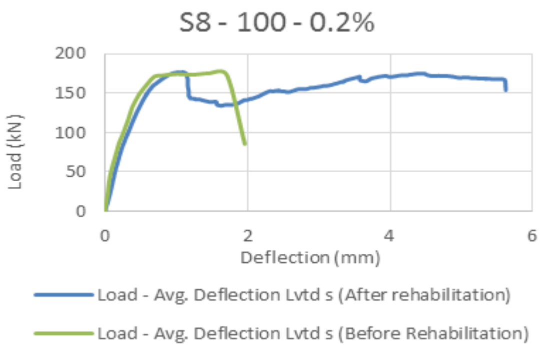


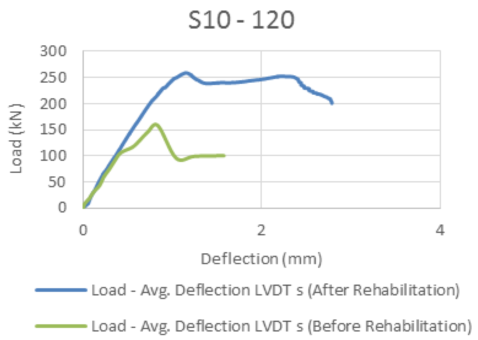
Fig. 10 Configuration -1 result (Control specimen)

pieces of horizontal and 8 pieces of perpendicular threaded rods and 8 pieces of steel profiles in addition to repairing with the epoxy. Details and schemes of the configurations are shown in Table 4, and Fig. 9. The resulting load-deflection graphs of the 19 tested corbels are shown in Figs. 10, 11(a) and (b), 12(a)-(e), and 13(a)-(k).

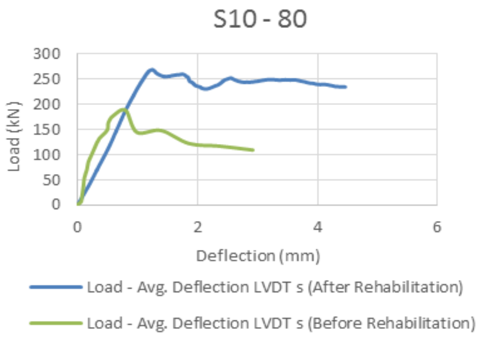
4.2 Discussion of the results

There are several factors that determine the efficiency of each considered rehabilitation configuration. The steel confinement provides both load capacity increase and ductility to the specimens. However, the injection materials (Epoxy) close the cracks and return the specimens to their original strengths. The details of the results are shown in the following graphs and tables.

Results show that the proposed technique is very effective; and can recover the original performance easily. However, the amount of improvement varies due to the original mechanical properties and testing conditions of



(a)



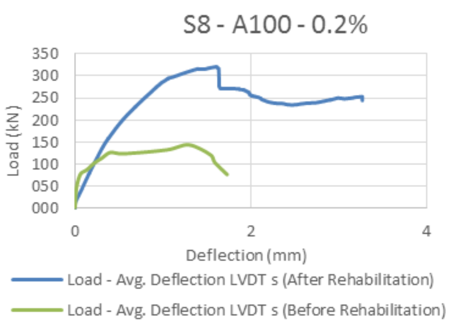
(b)

Fig. 11 Configuration -2 results

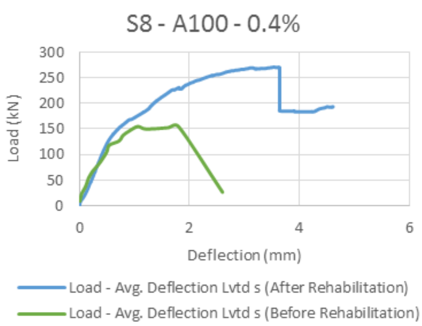
Table 5 Average recovery values

Configuration	Average of Load Capacity Recovery %	Average of Ductility Recovery %
Configuration -1	100	332
Configuration -2	152	286
Configuration -3	192	790
Configuration -4	184	782

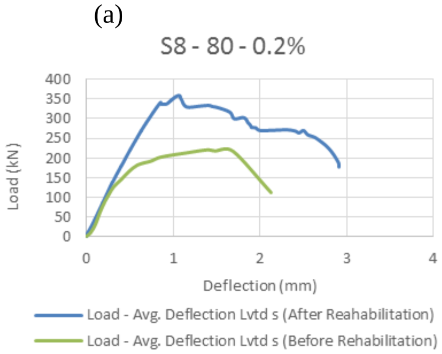
(a)



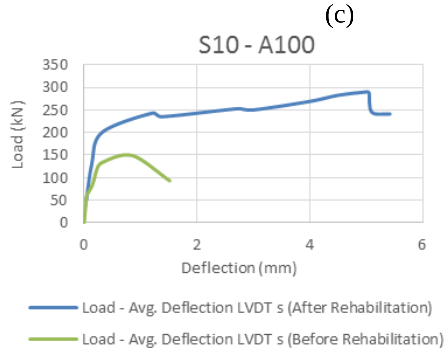
(b)



(c)



(d)



(e)

Fig. 12 Configuration -3 results

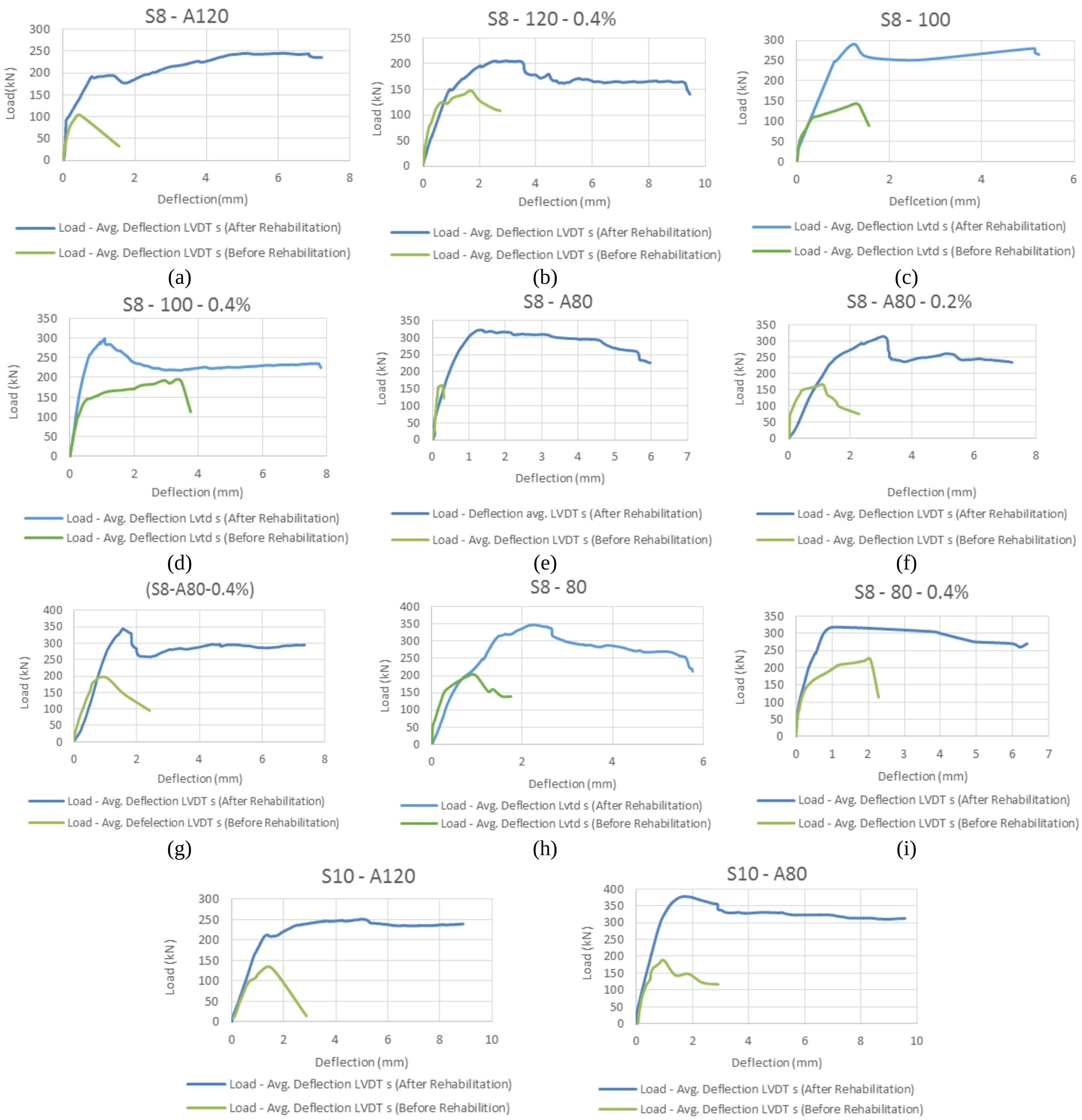


Fig. 13 Configuration -4 results

corbels. The average values of improvement are listed in Table 5.

When the results are examined, it is observed that shear span affects the rehabilitation efficiency, Fig. 14. Specimens with larger shear span were recovered better than those with smaller shear spans. This remark was obvious especially in configurations 2, and 3. This is mostly for two reasons. The first reason, the activity of the steel confinement system starts earlier, since the epoxies have no serious effect in large spans and fail early. The second reason, the old performances were different, while the new performances are more similar because the rehabilitation system forms a new composite material instead of the concrete.

In configuration-2 the concrete failed earlier as compared to configuration 4 because of the lower number of perpendicular pieces of threaded rods. These pieces let the repaired concrete resist the load. So, the steel system did not work directly till the repaired concrete failed. Therefore, the high amount of ductility was achieved after the concrete failed. It was noticed that once the epoxy failed, it caused a semi-sudden loading of the steel system, and this load affected the performance of the steel slightly. However, the

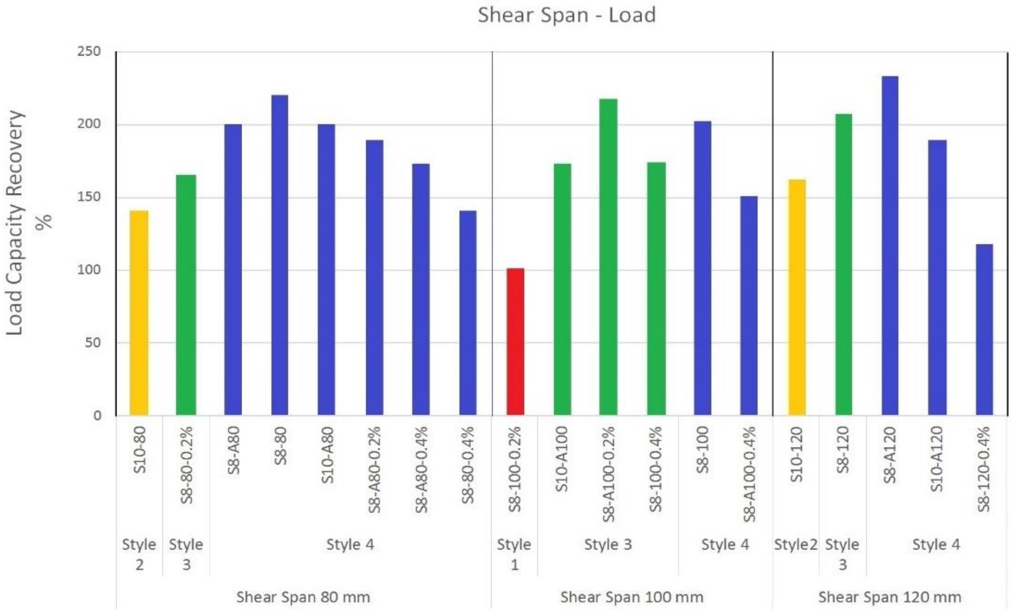


Fig. 14 Load capacity recovery according to shear span

Table 6 Details of improvements

Configuration	Sample***	Old Load Capacity (kN)	New Load Capacity (kN)	Increase in Load Capacity (kN)	Load Capacity Recovery %	Ductility Before Rehabilitation (J)**	Ductility After Rehabilitation (J)**	Ductility Recovery %
Configuration-1	S8-100-0.2%	173	174	1	101	255	847	332
Configuration-2	S10-80	188	265	77	141	371	952	257
	S10-120	158	256	98	162	148	571	286
Configuration-3	S8-80-0.2%	217	359	142	165	353	750	212
	S10-A100	201	347	146	173	175	1306	746
	S8-A100-0.2%	144	314	170	218	180	778	432
	S8-100-0.4%	155	270	115	174	593	1811	305
	S8-120	124	258	134	208	83	1392	1677
Configuration-4	*S8-A80	158	318	160	201	29	1648	5683
	*S8-80	158	347	189	220	34	1530	4500
	S10-A80	188	378	190	201	382	3023	791
	S8-A80-0.2%	166	313	147	189	256	1672	653
	S8-A80-0.4%	197	341	144	173	324	1946	601
	S8-80-0.4%	225	318	93	141	397	3216	810
	S8-100	143	291	148	203	144	1266	879
	S8-A100-0.4%	195	295	100	151	158	924	585
	S8-A120	104	243	139	234	100	1502	1502
	S10-A120	132	250	118	189	273	1970	722
	S8-120-0.4%	174	205	31	118	304	1534	505

* Previously Sudden Failed Specimen.
** Ductility amounts were calculated as area under the load-deflection graphs.
*** Samples which contain “A” in the name designation correspond to normal strength corbels and others refer to high strength corbels.

performance was very good in both situations (Table 6).

It was observed that the improvement of samples containing less glass fibers was higher than those with more glass fibers. In Fig. 13 (e-g), we can see the results of specimens (S8-A80), (S8-A80-0.2%), and (S8-A80-0.4%), which have been rehabilitated by configuration -4. Their load capacities have been increased to 201%, 189% and 173% respectively.

There is an inverse relationship between glass fibers and the rehabilitation efficiency since the glass fibers prevent the epoxy from filling the tiny cracks completely.

The experimental study revealed that the noticeable increase in load capacity was mainly due to the confinement. The strong confinement provided high friction between the sides of the crack, while the epoxy provided an extra strength by bonding the sides of the crack.

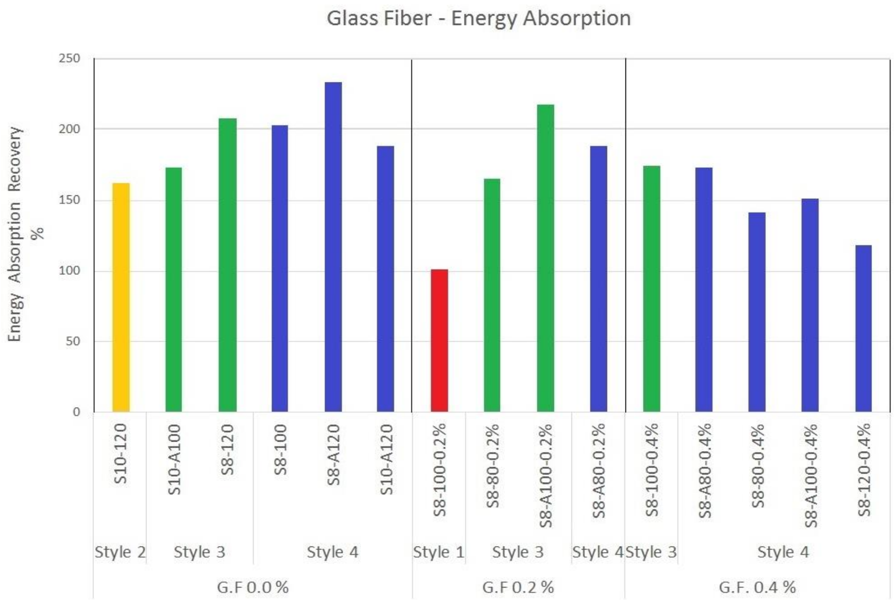


Fig. 15 Ductility recovery according to glass fiber content

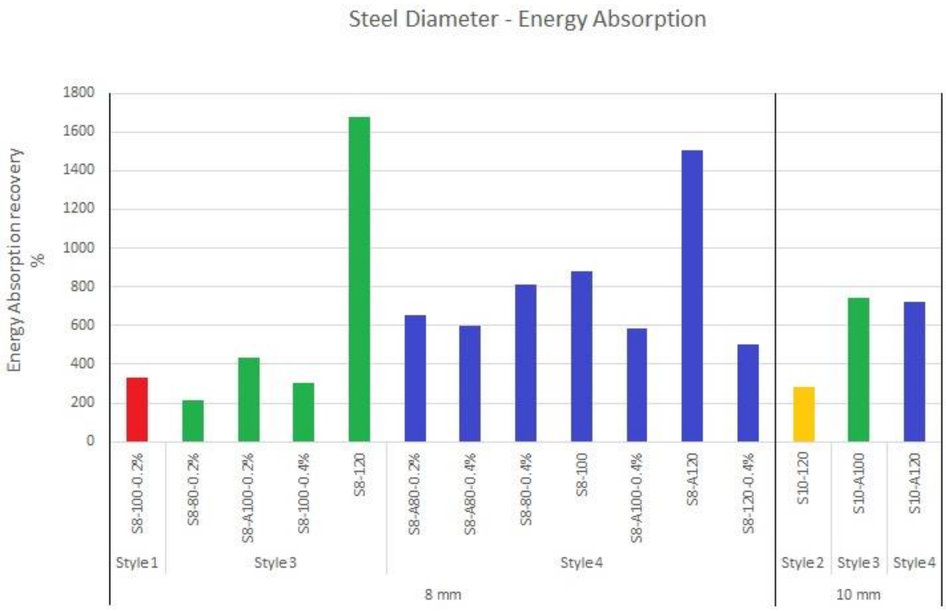


Fig. 16 Ductility recovery according to reinforcement steel diameter

The ductility for specimens (S8-A80-0.2%), and (S8-A80-0.4%) were increased perfectly (Fig. 15). While, the recovery percentage of specimen with span of 80 mm (S8-80) are not shown in Fig. 15, since their failure mode had been sudden before rehabilitation.

The results of the two specimens (S8-A120) and (S10-A120) are shown in Fig. 13 (a, and i). The two specimens were rehabilitated by configuration-4 and had different diameters of the steel reinforcement (ϕ). Their responses to the rehabilitation were different. Their load capacities were increased to 234% and 189% respectively. Their ductility enhancement are as shown in Fig. 16. These results indicated that the ductility of the corbels with a smaller reinforcement ratio was higher than bigger ones. This result was mostly because of the response of the pre-deformed steel. The larger diameter means stiffer steel, and stiffer steel means less possibility to reach yielding strength. However, configuration-4 was highly effective for both situations and produced satisfactory results.

Specimens (S8-80) and (S8-A80) have been rehabilitated by configuration-4. They did not have any ductility before rehabilitation. However, ductility increased remarkably in these specimens after rehabilitation due to the effect of steel confinement. The improvement of their load capacities was different (Fig. 17), and energy absorption values were 1530 J and 1648 J respectively, as shown in Table 7.

The results stated in Table 7 are close to each other. These results show that the proposed rehabilitation system has a noticeable effect on the load capacity and the ductility of the member, while; the compressive strength of the concrete has no obvious effect.

Table 7 Energy absorption of S8-80 and S8-A80 specimens after rehabilitation

Specimem Code	Ductility after rehabilitation (J)
S8-A80	1648
S8-80	1530

The failure modes of all of the corbel specimens were diagonally shear failure after rehabilitation. In addition, the proposed rehabilitation method prevented the sudden failure in all of the specimens. This result forms a desired earthquake resistance performance.

In a few of the rehabilitated corbels, it is observed that stiffness before the rehabilitation is slightly higher than the stiffness after the rehabilitation. This result is related with the degree of damage before rehabilitation and quality of crack repair during rehabilitation. For instance, damage level of corbels named as, S10-80 and S8-80 was much more (due to low shear span and high compressive strength) as compared to other corbels. As a result, their stiffness after rehabilitation is slightly lower as compared to the stiffness before rehabilitation. The same result is observed in the corbels named as, S8-A80-0.2 and S8-A80-0.4 due to lack of complete crack closure caused by existence of glass fibers.

5. Numerical modelling of load capacity after rehabilitation

New formulations are proposed for corbels rehabilitated with by threaded road technique stated above. It is assumed that the load is directly transferred to the steel confinement with the help of longitudinal threaded loads for the configurations 1 and 3 since there is no epoxy in these configurations.

5.1 The capacity for the configuration 1

As the corbel is loaded, load is transferred to support of corbel and then the load on the support is transferred to the longitudinal threaded rods that are connected to steel L-profiles. Since steel profiles are directed along the width of each corbel, the load on the sections of steel profiles form shear stress. Moreover, each steel section has double shear area since it exists on both sides of each corbel. The capacity of the rehabilitated corbels can be calculated with the following formulation

$$P=2P_1+nP_2 \tag{1}$$

Where P_1 is the load on one corbel when the load reached to shear strength of the steel section, P_2 is the load carried by horizontal threaded rods in tension region and n is the number horizontal threaded rods on corbels in tension region.

P_1 can be calculated by the method stated below;

Firstly, load on the outer section (P_{so}) is calculated when the section reaches its shear capacity

$$P_3 = P_{so} = \frac{2A_{sv} f_y}{\sqrt{3}\gamma_{M0}} \qquad \text{(Eurocode 3)} \tag{2}$$

$$P_1{*}a=P_{so}{*}a_{so} \tag{3}$$

P_1 can be calculated from Eq. (3). In this equation, a is shear span of the corbel and a_{so} is distance of the center of outer steel section from the column face. In Eq. (2), A_{sv} and f_y represent shear area and yield strength of the steel section, respectively. γ_{M0} is factor of safety and can be taken 1 for steel sections.

The load carried by horizontal threaded rods (P_2) can be calculated from the formulations proposed by Paulay *et al*. (1999) for the load carried by bars both in bending and in shear

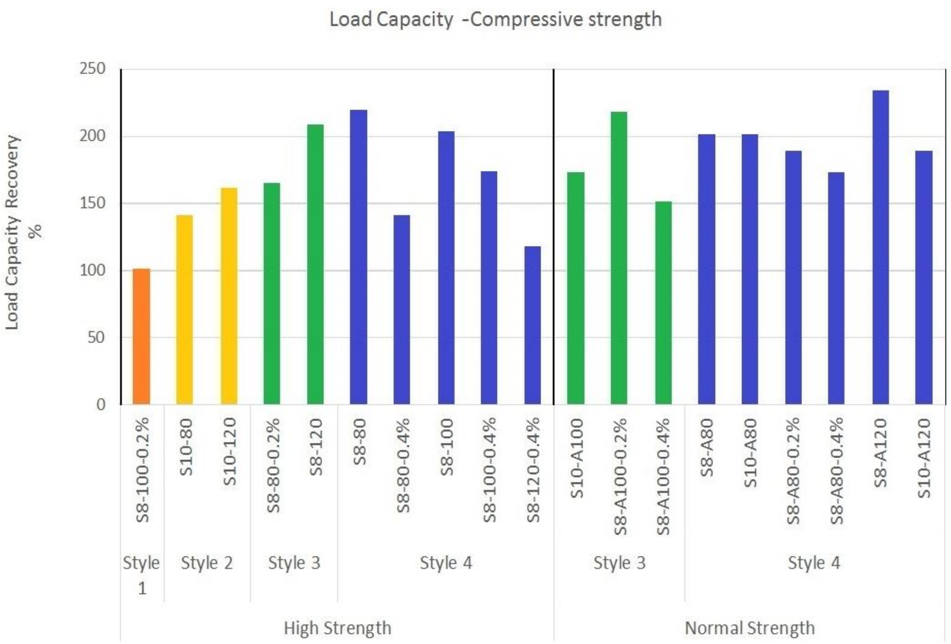


Fig. 17 Load capacity recovery according to compressive strength

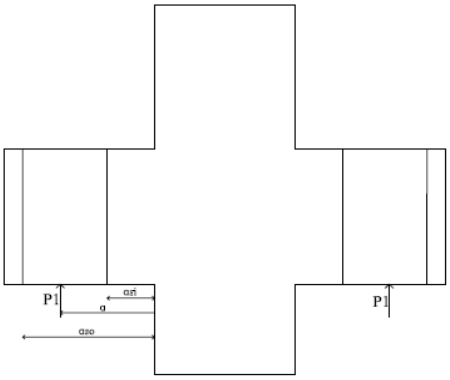


Fig. 18 Representation of P_1, a, a_{si}, a_{so}

$$P_2 = \frac{A_{tr} f_{sy}}{\sqrt{3}} \quad \text{for} \quad a < 120 \text{ mm} \quad \text{and;}$$

$$P_2 = \frac{4\phi A_{tr} f_{sy}}{3\pi a} \quad \text{for} \quad a \geq 120 \text{ mm} \tag{4}$$

In Eq. (4), f_{sy} represents the yield strength of threaded rods, A_{tr} and ϕ are effective sectional area and effective diameter of threaded rods, respectively.

5.2 The load capacity for configuration 3

When 2 steel sections are used on each corbel, the load on inner steel profile (P_{si}) and outer steel profile (P_{so}) are calculated separately and P_1 is calculated according to the smaller one

$$P_{so} = \frac{P_1(a - a_{si})}{(a_{so} - a_{si})} \quad \text{and;} \quad P_{si} = \frac{P_1(a_{so} - a)}{(a_{so} - a_{si})} \tag{5}$$

Where a_{si} is distance of the center of inner steel profile from the column face. P_1 is calculated by taking the smaller value from the Eq. (5) and equating it to P_3 (Eq. (3)). P_1, a, a_{si} and a_{so} are shown in Fig. 18.

After P_1 is calculated, total load capacity can be calculated from Eq. (1).

In the special case of higher shear spans (a≥120 mm), flexural effects are predominant and the difference between the forces existed between outer and inner profiles are much higher. As a result, only load on the section of the outer profile (the higher load) can reach to its shear strength until failure. Therefore, P_{so} is directly equated to P_3 to calculate P_1 for this type of corbels. However, even if the section of inner profile cannot reach the shear strength, it contributes to the total load after the outer section reaches to the shear strength. Therefore, the total load carried by steel sections ($2P_1$) is increased as an amount of 50% and the equation for the corbel with higher span is (a≥120 mm) modified as

$$P=3P_1+nP_2 \tag{6}$$

5.3 The capacity for the configuration 2 and 4

In the case of rehabilitation configurations 2 and 4, corbels are rehabilitated by epoxy in addition to the external steel confinement set-up. Therefore, it can be assumed that this type of corbels can reach to their initial load carrying capacity.

In order to determine the load capacity of the corresponding corbels after rehabilitation process, their original load capacity is calculated according to the formulation proposed by Gulsan (2015) and compared with $2P_1$

$$P_{original} = 2[38.54bh(\frac{d}{a})^{0.8321}(f_{ct})^{0.415}(\frac{A_s}{bh})^{0.6}] \tag{7}$$

This equation is for the prediction of load capacity of fiber reinforced concrete corbels and also it gives good results for reinforced concrete corbels (R^2=0.92). In Eq. (7), f_{ct} is tensile strength of the concrete, A_s is the sectional area of main reinforcement, d is effective depth of main reinforcement, b and h are width and height of the corbel, respectively.

In these type of rehabilitation configurations, since corbels were repaired by crack repair epoxy and so load is transmitted to corbels firstly, a λ factor can be added to the proposed equations. Therefore;

As a result of comparison of $P_{original}$ and $2P_1$;

If: $P_{original}<2P_1$; $P=\lambda 2P_1+nP_2$ (for a<120 mm) ;

$$P = \lambda 3P_1 + nP_2 \quad \text{(for } a \geq 120 \text{ mm)} \tag{8}$$

If: $2P_1 < P_{original}$ < Eq. (1) or Eq. (6);

$$P=P_{original}+nP_2 \tag{9}$$

If $P_{original}$> Eq. (1) or Eq. (6); $P=P_{original}$,

steel confinement only provides ductility (10)

λ can be taken as 1 for high compressive strength corbels, and 0,9 for normal compressive strength corbels.

5.4 Verificaiton of proposed formula for S8-80-0.2 specimen

S8-80-0.2 specimen was rehabilitated with configuration 3 and its properties are;

a=80 mm ; a_{so}=140 mm ; a_{si}=40 mm ; f_y=370 MPa ; f_{sy}=438 MPa

since the rod is threaded, ϕ=10 mm ; A_{tr}=78.54 mm^2

since steel sections are L-shaped, $A_{sv}=\frac{5}{6}*B*t$, where B=40 mm and t=4 mm

From Eq. (5); P_{so} is smaller one and is equal to $2P_1/5$, if this value is equated to P_3;

$$\frac{2P_1}{5} = \frac{2*\frac{5}{6}*40*4*370}{\sqrt{3}*1}$$ from this equation P_1 is found to be 142.4 kN

$$P = 2*142.4 + 4*\frac{78.54*438}{\sqrt{3}*1000} = 364.24 \text{ kN}$$ (Capacity measured from the exp. is 359 kN)

Load capacities resulted from the proposed formulations for all of the corbels considered in the study are listed in Table 8.

5.5 Treatment of some other load capacity equations for rehabilitation techniques 2 and 4

Table 8 Load capacities of the corbels (Calculated and experimental)

Designation	Rehabilitation Configuration	a (mm)	a_{si} (mm)	a_{so} (mm)	P_{cal} (kN)	P_{exp} (kN)	P_{cal}/P_{exp}
S10-80	2				278.8	265	1.05
S8-80	4				364.2	347	1.05
S10-A80	4				335.8	378	0.89
S8-A80	4	80	40		327.8	318	1.03
S8-80-0.2	3				364.2	359	1.01
S8-A80-0.2	4				327.8	313	1.05
S8-80-0.4	4				364.2	318	1.15
S8-A80-0.4	4				327.8	341	0.96
S10-A100	3				335.8	347	0.97
S8-100	4			140	335.8	291	1.15
S8-100-0.2	1	100	50		238.9	174	1.37
S8-A100-0.2	3				335.8	314	1.07
S8-100-0.4	3				335.8	270	1.24
S8-A100-0.4	4				302.2	295	1.02
S10-120	2				204.2	256	0.8
S8-120	3				232.7	258	0.9
S8-A120	4	120	60		209.4	243	0.86
S10-A120	4				209.4	250	0.84
S8-120-0.4	4				232.7	205	1.14
Mean							1.03

Table 9 Results of treatment of several load capacity models from literature as Poriginal in Eq. 7

<table>
<tr><th>Designation</th><th>Rehabilitation Configuration</th><th>P_{cal*} (kN)</th><th>P_{cal**} (kN)</th><th>P_{cal***} (kN)</th><th>$P_{cal****}$ (kN)</th><th>P_{exp} (kN)</th><th>P_{cal*}/P_{exp}</th><th>P_{cal**}/P_{exp}</th><th>P_{cal***}/P_{exp}</th><th>$P_{cal****}/P_{exp}$</th></tr>
<tr><td>S10-80</td><td>2</td><td>337.77</td><td>320.4</td><td>306.77</td><td>288.4</td><td>265</td><td>1.27</td><td>1.21</td><td>1.16</td><td>1.09</td></tr>
<tr><td>S8-80</td><td>4</td><td colspan="4">364.26</td><td>347</td><td colspan="4">1.05</td></tr>
<tr><td>S10-A80</td><td>4</td><td colspan="4">335.78</td><td>378</td><td colspan="4">0.89</td></tr>
<tr><td>S8-A80</td><td>4</td><td colspan="4">335.78</td><td>318</td><td colspan="4">1.06</td></tr>
<tr><td>S8-A80-0.2</td><td>4</td><td colspan="4">335.78</td><td>313</td><td colspan="4">1.07</td></tr>
<tr><td>S8-80-0.4</td><td>4</td><td colspan="4">364.26</td><td>318</td><td colspan="4">1.15</td></tr>
<tr><td>S8-A80-0.4</td><td>4</td><td colspan="4">335.78</td><td>341</td><td colspan="4">0.98</td></tr>
<tr><td>S8-100</td><td>4</td><td colspan="4">335.78</td><td>291</td><td colspan="4">1.15</td></tr>
<tr><td>S8-A100-0.4</td><td>4</td><td colspan="4">310.2</td><td>295</td><td colspan="4">1.05</td></tr>
<tr><td>S10-120</td><td>2</td><td colspan="4">204.3</td><td>256</td><td colspan="4">0.80</td></tr>
<tr><td>S8-A120</td><td>4</td><td colspan="4">209.9</td><td>243</td><td colspan="4">0.86</td></tr>
<tr><td>S10-A120</td><td>4</td><td>184.24</td><td>171.1</td><td>163.17</td><td>209.93</td><td>250</td><td>0.74</td><td>0.68</td><td>0.65</td><td>0.84</td></tr>
<tr><td>S8-120-0.4</td><td>4</td><td colspan="4">232.7</td><td>205</td><td colspan="4">1.14</td></tr>
</table>

* Calculated according to the model proposed by Fattuhi (1990)
**Calculated according to the flexural model proposed by Fattuhi (1994)
***Calculated according to the truss model proposed by Fattuhi (1994)
****Calculated according to the model proposed by Hagberg (1983)

In this section, some equations from literature for the determination of load capacity of RC corbels were used as $P_{original}$ in Eq. (7) (all details for the equations are given in Appendix part). Load capacities of the corbels after rehabilitation which are rehabilitated by techniques 2 and 4 are recalculated according to proposed formulations in this study.

All results are given in Table 9. Results show that the proposed model can be used effectively, even different load capacity models are used for the calculation of $P_{original}$. Since main load carrying mechanism is external steel confinement and the proposed model are produced by taking mechanical behavior of the steel confinement as basis, a good correlation is obtained between experimental and numerical results even different approaches are preferred for the original load capacity of RC and fiber reinforced corbels.

6. Conclusions

This study is the first experimental investigation which studies rehabilitation of reinforced concrete corbels using threaded rods and steel profiles. The rehabilitated damaged specimens had the same dimensions but different characteristics of shear-span, reinforcement steel diameter, glass fiber content and strength of concrete. They were treated using four different configurations. The following conclusions can be drawn as a result of the study:

- The proposed technique is very effective, and can easily recover the original load capacity and ductility of the corbels significantly.
- Steel confinement highly compresses the corbel, and this compression provides a high friction between the two sides of cracks. This friction resists the diagonal shear force and contributes the transfer of the load to the steel confinement system.
- Members with larger shear spans were improved more than those with smaller shear spans, and this is mostly because the confinement steel systems start to work earlier.
- The failure mode is always diagonal shear because the external steel enhances the flexural strength perfectly.
- The proposed rehabilitation technique prevents the sudden failure for all type of the corbels considered in the study which is a desired earthquake resistance performance.
- The geometry of the corbel stays stable after failure because the confinement system maintains the geometry.
- The compressive strength of the concrete has no clear effect on the rehabilitation. The efficiency of the proposed rehabilitation technique is basically determined by the properties of the epoxy, steel threaded rods and steel profiles preferred for repairing.
- Since the confining perpendicular rods resist sliding caused by diagonal shear forces, the corbels that were rehabilitated with configurations containing perpendicular rods (configurations 3, and 4) showed higher load capacity.
- Enhancement on load capacity and ductility after the proposed rehabilitation technique is higher for corbels which contain less glass fibers as compared to those with more glass fiber. This is mostly because the glass fibers prevent the very low viscosity repairing epoxy from filling cracks completely.
- For epoxy treated members, the presence of the perpendicular steels make the epoxy more effective because they press the center of the diagonal crack zone and protect it from sliding.
- The load capacity of the rehabilitated corbels with the proposed technique can be determined practically by the proposed numerical formulations for them.
- This technique can be applied in the field easily for any two-sided corbels.
- In case of two-sided corbels with a wall separating them, this technique can be applied by drilling four holes to pass the threaded rods of confinement system through them.

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Notations

a: shear span of corbel
b: width of the corbel
d: effective depth of the corbel
h: height of the corbel
f_y: yield strength of the main reinforcement
f_{cu}: cubic compressive strength of the concrete
f_c: cylindrical compressive strength of the concrete
f_{ct}: splitting tensile strength of the concrete
A_s: cross-sectional area of the main reinforcement
ρ: reinforcement ratio of the corbel
β_1: the coefficient taken from ACI 318 design code according to the cylindrical compressive strength of the concrete. Its value between 0.65 and 0.85

Appendix

Models for the calculation of load capacity of reinforced and fiber reinforced concrete corbels:

Model proposed by Fattuhi (1990)

$$V_n = k_1 bh(f_{ct})^{k_2} (\frac{a}{h})^{k_3} (\frac{f_y}{f_{cu}})^{k_4} (\frac{d}{h})^{k_5} (\rho)^{k_6} \quad \text{(A.1)}$$

where, k_1=57.292, k_2=0.315, k_3=-0.812, k_4=-0.049, k_5=0.678, k_6=0.626.

Flexural model proposed by Fattuhi (1994)

$$V_n = \frac{f_y A_s}{a}(d - \frac{a_1}{2}) + \frac{k_o f_{ct} b}{2a}(h - \frac{a_1}{\beta_1})(h + \frac{a_1}{\beta_1} - a_1) \quad \text{(A.2)}$$

$$a_1 = \frac{f_y A_s + k_o f_{ct} hb}{0.85 f_c b + k_o f_{ct} \frac{b}{\beta_1}} \qquad k_o = \frac{9.519}{f_c^{\,0.957}} \quad \text{(A.3)}$$

Truss model proposed by Fattuhi (1994)

$$V_n = \frac{f_y A_s (d - \frac{l \sin \beta}{2})}{a + 0.5(l \sin \beta)\cot \beta} + \frac{0.5 k_o f_{ct} bh(h - l \sin \beta)}{a + 0.5(l \sin \beta)\cot \beta} \quad \text{(A.4)}$$

$$l \sin \beta = \frac{f_y A_s + k_o f_{ct} bh}{0.85 f_c b + k_o f_{ct} b} \quad \text{(A.5)}$$

cotβ is determined from the following equation

$$\begin{aligned} &0.425 f_c b(l \sin \beta)^2 \cot^2 \beta + 0.85 f_c ab(l \sin \beta)\cot \beta \\ &- f_y A_s (d - \frac{l \sin \beta}{2}) - 0.5 k_o f_{ct} bh(h - l \sin \beta) = 0 \end{aligned} \quad \text{(A.6)}$$

Model proposed by Hagberg (1983)

$$V_{n1} = \frac{F_s}{\tan \beta}; \quad F_s = A_s f_y \quad \text{(A.7)}$$

tanβ is calculated from the following equation

$$(1 - \frac{2 f_c bd}{F_s})\tan^2 \beta + \frac{2 f_c ba}{F_s}\tan \beta + 1 = 0 \quad \text{(A.8)}$$

$$V_{n2} = f_c bw\cos^2(\beta_{max}) \quad \text{(A.9)}$$

β_{max} is obtained from the following equation

$$\tan \beta_{max} = \frac{(a + w/2)}{d} \quad \text{(A.10)}$$

Load capacity is the smaller value of V_{n1} and V_{n2}.