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CASE STUDY OF SHEAR STRENGTHENING OF RC CORBELS BY STEEL PLATES USING FEA

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The study aimed to explore the possibility of strengthening RC corbels with many strengthening techniques. The research analyzed the RC corbels behavior under a wide range of variables. The theoretical study consisted of twelve models reinforced with GFRP bars with strengthening by steel plate. Finite element analysis with ANSYS APDL was used to verify five specimens. This research deals with a static nonlinear FE simulation to investigate the behavior of RC Corbels reinforced internally and externally. The verification with experimental work demonstrated a satisfactory agreement in the load-displacement relationship, ultimate load and displacement, and failure mode. The parametric study was implemented which included strengthening the four concrete corbels externally and four corbels internally by a steel plate in many configurations while the remaining three were modeled with varied compressive strength (30, 40, and 50) MPa. The external strengthening included the placing of steel plate externally around the corbel in a U-shaped form and partial strengthening by strips and bottom plate. The models with internal strengthening involved placing the steel plate internally instead of stirrups. The results discovered that the strengthening provided enrichments in the stiffness, ductility, and energy absorption by 37 %, 4 %, and 26 %. In addition, in the case of full external strengthening more than internal retrofitting, there is a maximum improvement in the cracking and ultimate load carrying capacity. The external strengthening was better than internal one due to the confinement effect of the concrete. The stress distribution and crack pattern were affected by the strengthening techniques and more cracks appeared in the corbels with external steel plates

Keywords: Nonlinear finite element, RC Corbel, steel plate, deflection, energy absorption, cracking, shear strength, parametric study

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1. Introduction

Recently earthquake has caused massive spoilage in the monarchy and people life. As a result, it became very urgent to improve structural-resistant building [1]. Corbel is a structural short member fabricated and utilized to transfer the applied force from the beam to the columns and wall. This member can be characterized by the ratio of shear span to depth (a/d). The development of new technologies and improvements in structural engineering have an impact on building construction, enhancing strength. The requirement for connections to complete a structure is one of the most crucial elements of structures, and RC corbel is considered one of the most popular types of connections. The joint strength can be estimated by computing the resistance, stiffness and ductility of each component for the joint [2]. The ductility performance of UHPFRC mostly affected by the reinforcing fiber has the most critical role in determining the ductility behavior of UHPFRC structure till the flexural failure. While, the maximum tensile strain can reach 5×10^{-3} because of the existence of fiber [3]. The use of a concrete corbel to support beams is extremely widespread, and the technical community has long given it special consideration. For many years, researchers have examined how concrete corbels behave structurally. Also, the researchers proved that enhancing the stirrups percentage improves the corbel strength but although of these advantages, the over the ratio of transverse reinforcement causes weakening in the crack control under the applied loads. These techniques proved their efficiency in enhancing the shear strength capacity of the RC corbels beside the control of crack spreads along the member.

Corbels or brackets are short hunched cantilevers that initiate from the face of columns and are usually utilized in precast concrete construction to carry heavy load from girder or beam. Due to the predominance of precast concrete, the design of bracket or corbel becomes very important [4]. Therefore, studies are devoted using of horizontal reinforcement in the corbels leads to increase the cracking and ultimate loads are scientific relevance.

2. Literature review and problem statement

The first significant research was conducted in the middle of the 20^{th} century. Previous studies show that, there is not considerable impact for the horizontal stirrups on cracking and ultimate loads of the RC corbels with

HSC when comparing it with NSC. Besides, due to the direct tension stresses, the existence of horizontal loads increases vertical cracks [5–8]. The first research was regarding the behavior of corbels with a low longitudinal reinforcement ratio which explained that the failure of such members included yielding of the steel reinforcement which led to a ductile failure, while the corbels with a high ratio of steel reinforcement suffered from yielding of the concrete earlier than the steel rebar which led to a brittle failure [9, 10]. Nevertheless, the out-of-plane displacements that can occur in the post-buckling regime have the potential to become quite considerable [11]. Some researchers stated that the addition of more stirrups than required, weaken the strength capacity so the need to find another technique was necessary instead of the traditional method. Many researchers [12, 13] investigated the strengthening of the concrete corbels by use of different techniques such as steel plates, steel fibers, CFRP laminates. etc. The strengthening of the members is divided into two types, external and internal strengthening. Publication [14] devoted the behavior and failure mode of the RC corbels which found that increasing the stirrups enhanced the shear strength but this improvement to a certain limit caused to change the failure mode to brittle behavior concerning the internal strengthening. Study [15] found that the deformational capacity of RC corbels was increased when the amount of the main and transverse reinforcement increased. Work [16] investigated the behavior of the RC corbels strengthened internally by steel fibers. The results showed that the addition of steel fibers enhanced the load carrying capacity besides the control of crack propagation.

Regarding external strengthening, many researchers investigated the wrapping of the RC corbels with fibers reinforced polymers. The paper [17] investigated the external strengthening by use of composite reinforcement, which showed that the external wrapping by FRP improved the shear capacity of D-regions. The paper [18] examined the behavior of repaired RC corbels strengthened with an external steel reinforcement connected with a steel plate. The outcomes revealed that the enhancement increased with the increase of the strengthening bars but these improvements were to a certain limit. The paper [19] explored the strengthening effect on the general behavior of RC corbels which the strengthening included the use of threaded post tension rebar. The outcomes proved the efficiency of such bars in control cracks propagation with little enhancements to the ultimate shear strength of the corbels but these enhancements were little and didn't exceed 5 %. In contrast to [18], the major tie of these corbels was merely threaded bars, rather than threaded bars plus passive reinforcements. The findings demonstrated the effectiveness of prestressing in improving the behavior of corbel. The researcher [20] investigated the behavior of high-strength concrete corbels strengthened with web rolled steel. Ten specimens were evaluated experimentally with two a/d ratios of 0.7 and 1. The results showed that employing the steel in strengthening the RC corbels offered high ductility, stiffness, and toughness besides the upgrade in the cracking and ultimate load. The paper [21] examined the behavior of enclosed corbels made from commercially available steel sections (W-shape rolled steel). Eight specimens were produced and tested under static load with the use of many variables such as two shear slenderness ratios. The analysis indicates that the studied composite corbels behaved better than the traditional ones, with enclosed corbels exhibiting more ductility. Regarding the strengthening by steel plate, only [22] strengthened the RC corbel with steel plates no researchers deal with these techniques, which conducted an experimental examination on 18 damaged RC corbels, subjected to vertical stresses and repaired with external steel plates. The transverse and main steel reinforcements, a/d, and the depth of the corbels were investigated. The test findings revealed that the strength ratio of the repaired member to that previous one ranged from 0.70 to 1.50. The analysis indicated that this restoration procedure might be regarded as an effective and cost-effective method of reinforcing existing buildings. [23] investigated the response of strengthened RC corbels with concrete jackets. The results revealed that the shear strength was improved and the jackets enhanced also the cracking behavior and ductility of the RC corbels.

According to previous studies, few researchers concentrated on the shear behavior of RC strengthened corbels, which did not give a strong foundation for understanding how these brackets withstand shear loads. Notably, researchers didn't resort to the use of steel plates to retrofit these components.

3. The aim and objectives of the study

The aim of this study is to identifying regularities the shear strengthening of RC corbels by steel plates using finite element analysis. This will allow to validate the findings of the experiment method.

To achieve this aim, the following objectives are accomplished:

– to predict cracking and ultimate load behavior of RC corbels;

– to examine the deflection of RC strengthened corbels;

– to investigate the stiffness, ductility, and energy absorption of corbels;

– to analyze cracking pattern, failure mode, and stress distribution.

4. Material and methods

4. 1. Object and hypothesis of the study

The purpose of this study is to use the FEA program ANSYS to model and evaluate the behavior of such members exposed to shear stresses in order to predict cracking and ultimate load behavior of RC corbels. Besides, examine the deflection, stiffness, ductility, and energy absorption of RC strengthened corbels. In addition, analyzing cracking pattern, failure mode, and stress distribution.

Finite element approach is used to modeling the samples by ANSYS program. The material properties and the geometry of investigated samples are taken to verify the modeling approach as specified in previous study [24]. After verify the models that used, models of the materials and the geometric are fixed for each type of element to simplify follow up the parametric study of investigated parameters.

Five specimens modeled to verify the models of the geometry and different material (concrete, steel reinforcement, GFRP bars, bearing steel plate, and strengthening steel plate). Whereas, twelve specimens modeled to study the effect of the studied parameters.

4. 2. Finite element modeling

Employing the FE with nonlinear analysis can be considered one of the newest techniques to simulate concrete structures. To model the beam-column joints as a FE model, the material properties beside the geometry are taken into account before doing the analysis. Preprocessing involved choosing the right components for the materials and entering realistic behavior up to the loading and boundary conditions to recreate an experimental test under identical circumstances. Constitutive models can be used to define the behavior of the material. The concrete damage Plasticity (CDP) is used to characterize concrete nonlinear behavior, smeared and brittle cracking models. Using ANSYS APDL and finite element analysis, five corbels underwent a verification procedure. Through the use of the load-displacement relationships, ultimate maximum loads, and deflections, besides the failure mode, experimental work that was previously carried out by a group of researchers was verified. In this research, the finite element model contains 5966 elements. The refined mesh and input values were subjected to convergence criteria, which revealed that non-convergence occurred below 0.2 of the open and close shear transfer coefficients and that there was excellent matching in the number of elements beyond 5000 elements.

4. 3. Material modeling

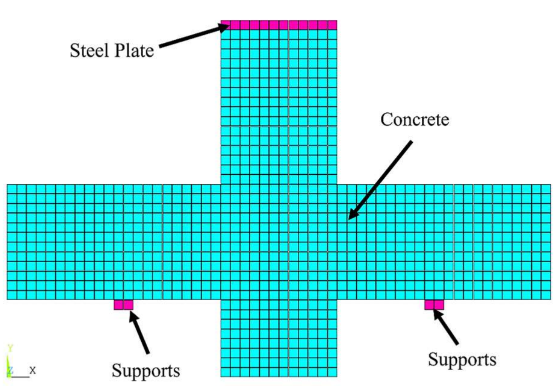
Modeling of the Concrete in ANSYS needs to define the material properties of this material, which is considered as quasi-brittle behavior and has different behavior in compression when compared with tension. Concrete's stress-strain curve exhibits linear behavior (elastic stage) in the compression side up to around 30 % of the material's concrete grade (fcu). After the yielding point, the tension progressively increases until it reaches its maximum level. After reaching the maximum strain, the curve descends into the softening area and fails to reach the ultimate compressive strength. While the tension behavior included increasing the curve linearly up to the maximum tensile strength value which is approximated by many researchers by (8–12 %) from the compressive strength. After the yielding point, the concrete begins to crack and lose its strength gradually reaching failure (crushing of the concrete) [25]. Concrete behavior in ANSYS is defined by the ultimate uniaxial compressive strength, ultimate uniaxial tensile strength elastic modulus (E), (modulus of rupture), Poisson's ratio, and the reduction factor of stiffness [25]. The constitutive model of normal concrete explains the response of uniaxial compression [25].

Damage that is based on plasticity is utilized to simulate concrete behavior. In ANSYS, the element SOLID65 with eight nodes and three degrees of freedom per node simulates concrete and is capable of plastic deformation, cracking, and crushing. Regarding steel reinforcement and GFRP bar, LINK180 elements were used with variation in the stress-strain behavior of both materials. According to the Von Mises failure principle, steel reinforcement was represented by a bilinear isotropic material that exhibited the same behavior in both compression and tension [25]. Table 1 shows a linear constitutive relationship for the SOLID185 that needed to simulate the bearing steel plate. Fig. 1 reveals the model of the RC corbels including the mesh details and the glass fibers reinforced polymers rebar in ANSYS.

Table 1

Properties of materials

Concrete type	*f'c*, MPa	*E*, MPa	Tensile Strength, MPa	Adopted stress-strain curve
Concrete	24	23,172	3.0	Multilinear stress-strain curve
Steel reinforcement	–	200,000	350	Bilinear stress-strain curve
GFRP bar	–	55,000	1156	Elastic linear stress-strain curve
Bearing steel plate	–	200,000	350	Elastic linear stress-strain curve
Str. steel plate	–	200,000	350	Bilinear stress-strain curve



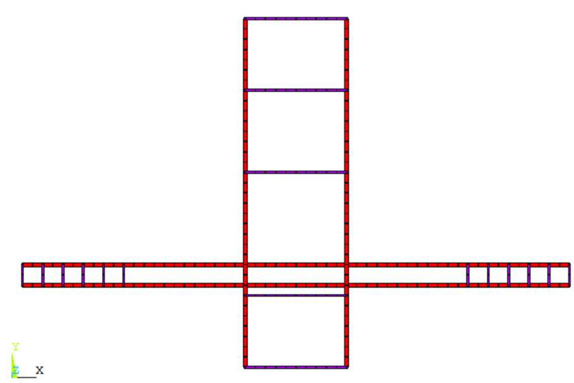


Fig. 1. The model of the RC corbels: *a* – finite element model shows the mesh of concrete; *b* – glass fibers reinforced polymers rebar in ANSYS

4. 4. Verification of finite element modeling

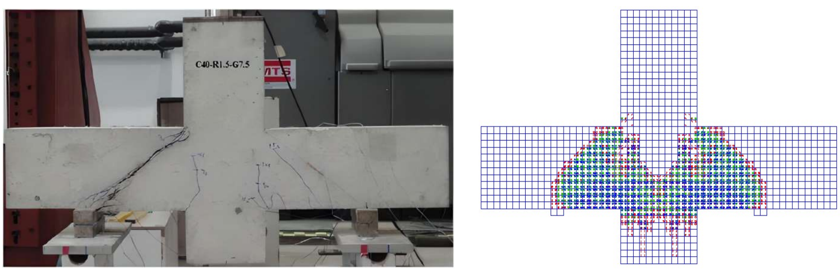
Five models presented by the experimental study of [24] were selected for the verification process. The computational model utilized in this investigation has the same size, material characteristics, and boundary conditions as the experimental study [24]. The verification demonstrated extremely high agreement between the experimental and numerical findings for the load-deflection, test outcomes, and cracking pattern, as shown in Table 2 and Fig. 2. Table 2 shows the shear results and the deflection for both the ANSYS software and experimental results.

The agreement of validation was excellent, but this should be noted that certain curves of the numerical analysis reached the maximum load and then stopped because the concrete element used in the analysis (SOLID65) had a feature where a failure of any element in the model was considered a failure of the entire member.

Table 2

Results of the validation between the experimental and numerical study

ID	V_{Ansys}, KN	$V_{Exp.}$, KN	$V_{Ansys}/V_{Exp.}$	Δ_{Ansys}, mm	$\Delta_{Exp.}$, mm	$\Delta_{ans./\Delta exp.}$
C20-R1-G3.5.0	170	173	98.27 %	1.59	1.63	97.55 %
C20-R1-G5.0	183	185	98.92 %	2.34	2.48	94.35 %
C20-R1-G7.5.0	330	310	106.45 %	3.05	3.15	96.83 %
C20-R1.5-G3.5.0	177	184	96.20 %	5.44	5.64	96.45 %
C20-R1.5-G5.0	229	220	104.09 %	5.94	6.97	85.22 %



a *b*

Fig. 2. Experimental and numerical results: *a* — cracking pattern of experimental concrete corbels; *b* — cracking pattern of concrete corbels in ANSYS

4. 5. Parametric study

Twelve specimens were tested using various parameters to examine the impact of various factors on the performance of reinforced concrete corbels. As illustrated in Fig. 3, test specimens were made up of a beam segment merged with a brief vertical column at the midspan. The analyzed corbels in this study are similar in geometry and boundary conditions to the research of [24]. The specimen's column and beam segments had a cross-section of 150×300 mm as revealed in Table 3. Longitudinal GFRP bars were used to internally reinforce each specimen. To acquire confining and avoid the GFRP bars from slipping during testing, six 6-mm-diameter closed steel stirrups were also put along the length of the GFRP bars outside the test zone. Four longitudinal GFRP bars with a 12-mm diameter were placed in the column segment to strengthen it. The GFRP bars were held together by steel ties that were placed within the column portion. The current study divided the specimens into three sides, the first and second sides include the use of external and internal strengthening by steel plate respectively while the third one included an investigation of model behavior with varied compressive strain. The used parameters included full and partial strengthening (strips, bottom plate) while the internal one included the use of steel plates internally instead of steel transverse reinforcement in many configurations. The external strengthening included the placing of steel plate externally around the corbel by (800 mm) in U-shaped form and partial strengthening by strips and bottom plate. The models with internal strengthening involved placing the steel plate internally instead of stirrups. All FE models were loaded to failure with specified displacements at the midway of the top surface of the bearing plate, which was positioned on the top surface of the corbel's column component. The specimens were supported by two steel pedestals. The deflection was measured at the bottom midway of the corbel specimen's column component. Regarding the support conditions, line support positioned in the center of the bottom surface of each plate on the left side prevented movement in the longitudinal and vertical dimensions (x and y directions, respectively) of the support steel plate on the left side of each corbel specimen. Whereas the support plate on the right side included restraining in (y and z directions).

Table 3

Details of specimens

ID	Compressive strength, MPa	GFRP Ratio	Shear reinforcement	Parameter
C20-R1-G3.5	24	$3.5\rho_b$	–	–
ECP-800	24	$3.5\rho_b$	–	External strengthening
ECP-S500	24	$3.5\rho_b$	–	External strengthening
ECP-P250	24	$3.5\rho_b$	–	Internal strengthening
ECP-UP550	24	$3.5\rho_b$	–	External strengthening
ICPRS	24	$3.5\rho_b$	Ø10@5	Internal strengthening
ICP-V50	24	$3.5\rho_b$	Thin plate @5 cm	Internal strengthening
ICP-250	24	$3.5\rho_b$	Thin plate @5 cm	Internal strengthening
ICP-125	24	$3.5\rho_b$	Thin plate @10 cm	Internal strengthening
C20-30	30	$3.5\rho_b$	–	Compressive strength
C20-40	40	$3.5\rho_b$	–	Compressive strength
C20-50	50	$3.5\rho_b$	–	Compressive strength

The load was applied directly in the vertical direction on the column segment distributed on the column area. The loading was applied gradually in the same method of the experimental tests in the laboratories.

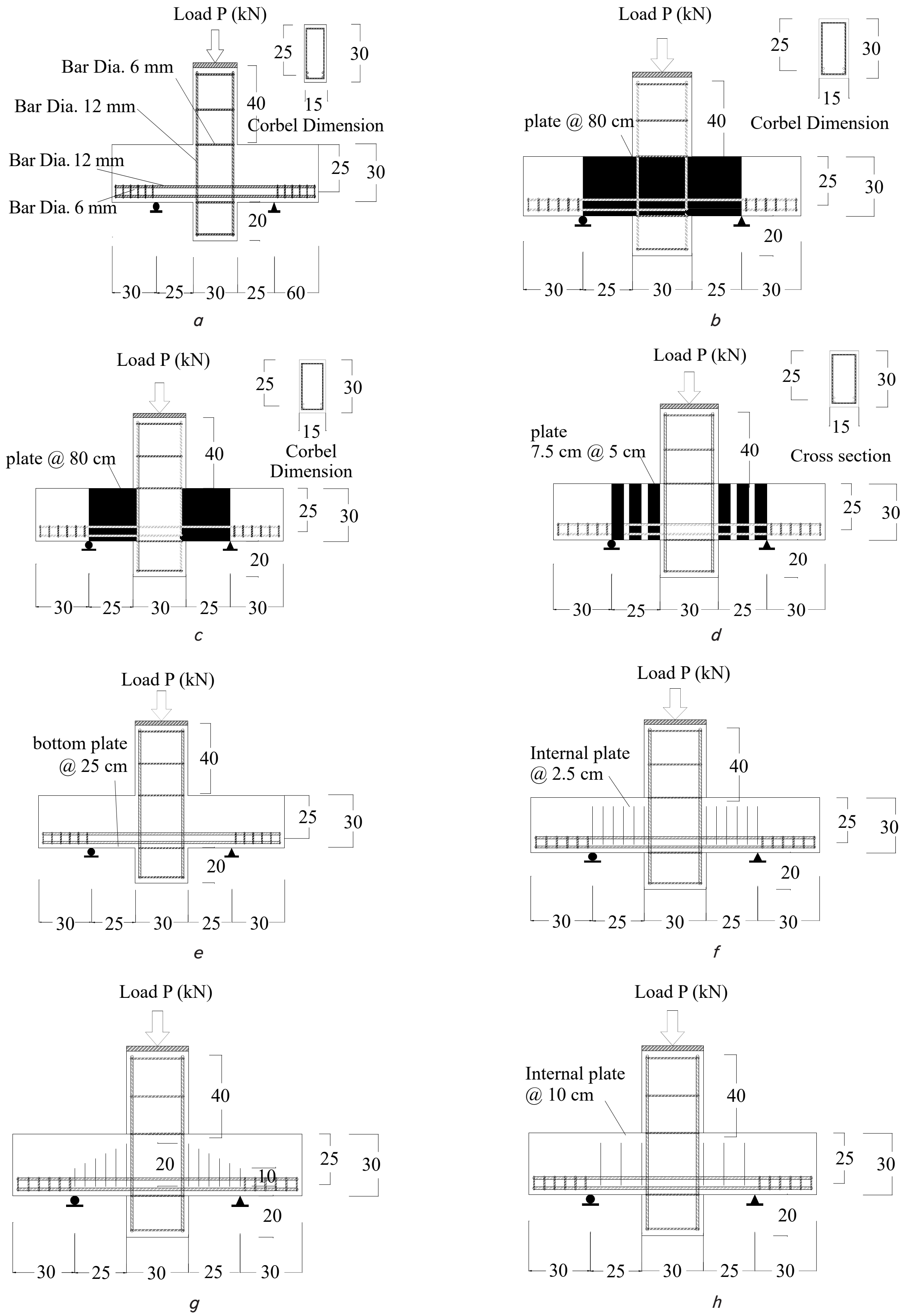


Fig. 3. Geometrical details of reinforced corbels: *a* – C20-R1-G3.5; *b* – ECP-800; *c* – ECP-S500; *d* – ECP-P250; *e* – ECP-UP550; *f* – ICPRS & ICP-250; *g* – ICP-V50; *h* – ICP-125

5. Finite element results of RC corbels

5. 1. Cracking and ultimate load

In comparison with the control corbel (C20-R1-G3.5), strengthening of the RC corbels by steel plate in form of the surrounded plate (80 cm) (ECP-800) enhanced the cracking load by 156.5 % and the ultimate load by 112.2 % as revealed in Fig. 4, *a*. While the model (ECP-S500) which involved strengthening by steel strips 7.5 cm@5 cm enhanced the cracking and ultimate load by 81.4 % and 60.8 % respectively as revealed in Fig. 4, *a*, *b*. The model with a bottom strengthening plate (ECP-UP550), enhanced the cracking and ultimate load by 22 % and 18 % respectively as revealed in Fig. 4, *a*, *b*. Model (ECP-P250) that involved strengthening by sided plates exhibited an enhancement of 117 % and 88.3 % in the cracking and ultimate load carrying capacity as revealed in Fig. 4, *a*, *b*.

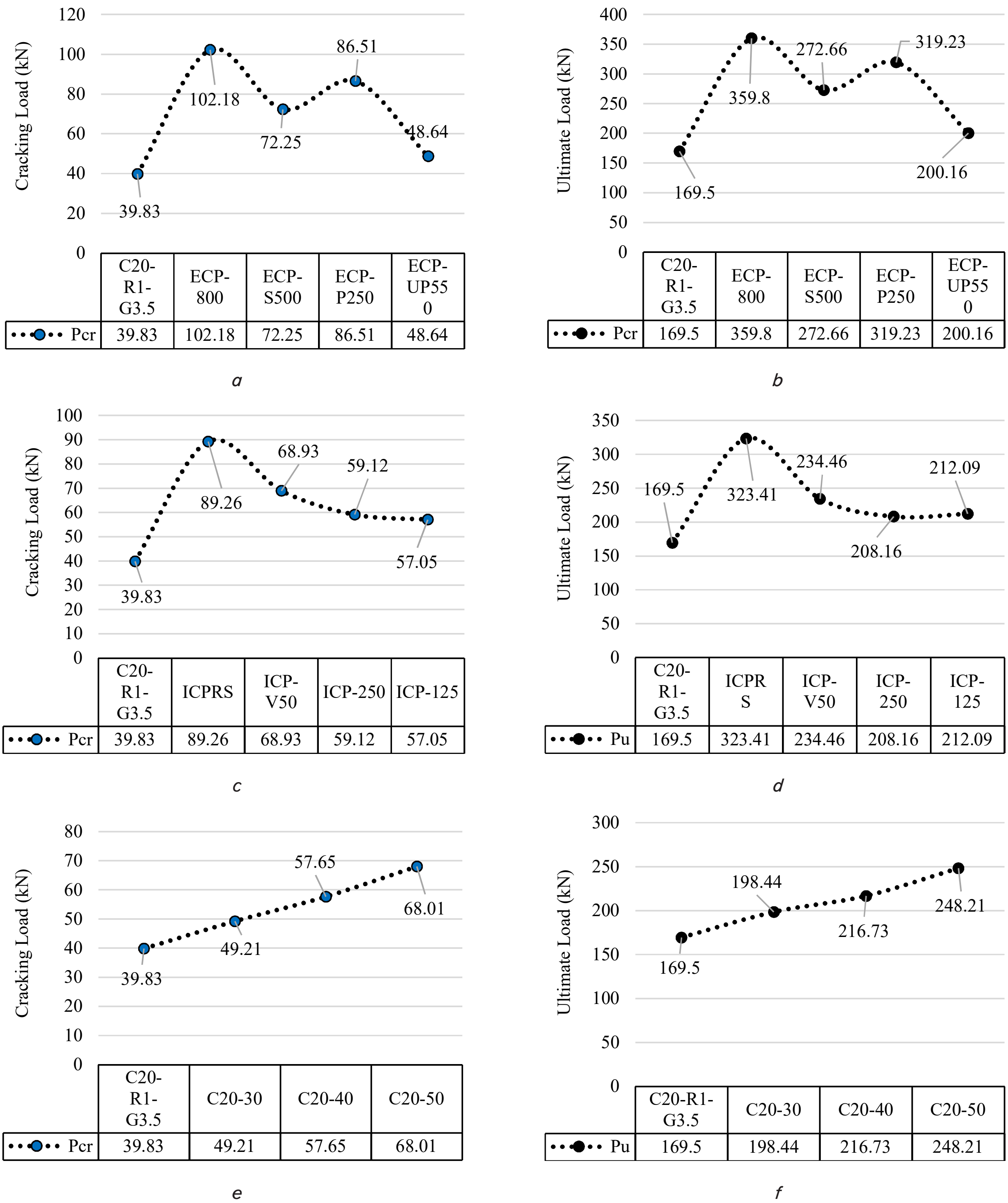


Fig. 4. Analytical results regarding the cracking and ultimate loads: *a* – cracking loads of concrete corbels; *b* – ultimate loads of concrete corbels; *c* – cracking loads of concrete corbels; *d* – ultimate loads of concrete corbels; *e* – cracking loads of concrete corbels; *f* – ultimate loads of concrete corbels

Regarding the internal strengthening, the model (ICP-250) which involved internal strengthening by steel plates located at 5 cm c/c caused an improvement in the cracking and ultimate load by 48.4 and 22.8 % respectively as revealed in Fig. 4, *c*, *d*. Optimizing the dimensions of the plate (model ICP-V50) provided more enhancements in the cracking and ultimate load by 73 % and 38 % respectively as revealed in Fig. 4, *c*, *d*. Reinforcing the RC corbel with steel reinforcement as in model (ICPRS) with Ø10@5 cm provided a high upgrade in the cracking and ultimate load which was by 124.1 % and 90.8 % when compared with the control corbel (C20-R1-G3.5) as revealed in Fig. 4, *e*, *f*.

5. 2. Maximum deflection

Fig. 5, *a–c* depicts the load-deflection curve of the model with external and internal strengthening beside the varied compressive strength models respectively. In comparison with the control corbel (C20-R1-G3.5), model (ECP-800) with an external strengthening plate enhanced the deflection by 53.4 %. While the model (ECP-S500) which involved strengthening by steel strips 7.5 cm@5 cm enhanced the deflection by 27.6 % respectively as revealed in Fig. 5, *b*. The model with a bottom strengthening plate (ECP-UP550), reduced the deflection by 12.7 % as revealed in Fig. 5, *c*. Model (ECP-P250) that involved strengthening by sided plates exhibited an enhancement by 29.4 % in the deflection capacity as revealed in Fig. 5, *a*. Regarding the internal strengthening, the model (ICP-250) which involved internal strengthening by steel plates located at 5 cm c/c caused a decrement in the deflection by 5.5 %. Optimizing the dimensions of the plate (model ICP-V50) provided more enhancements in the deflection by 11.65 %. Reinforcing the RC corbel with steel reinforcement as in the model (ICPRS) reduced the deflection by 20.1 % when compared with the control corbel (C20-R1-G3.5) as revealed in Fig. 5, *b*.

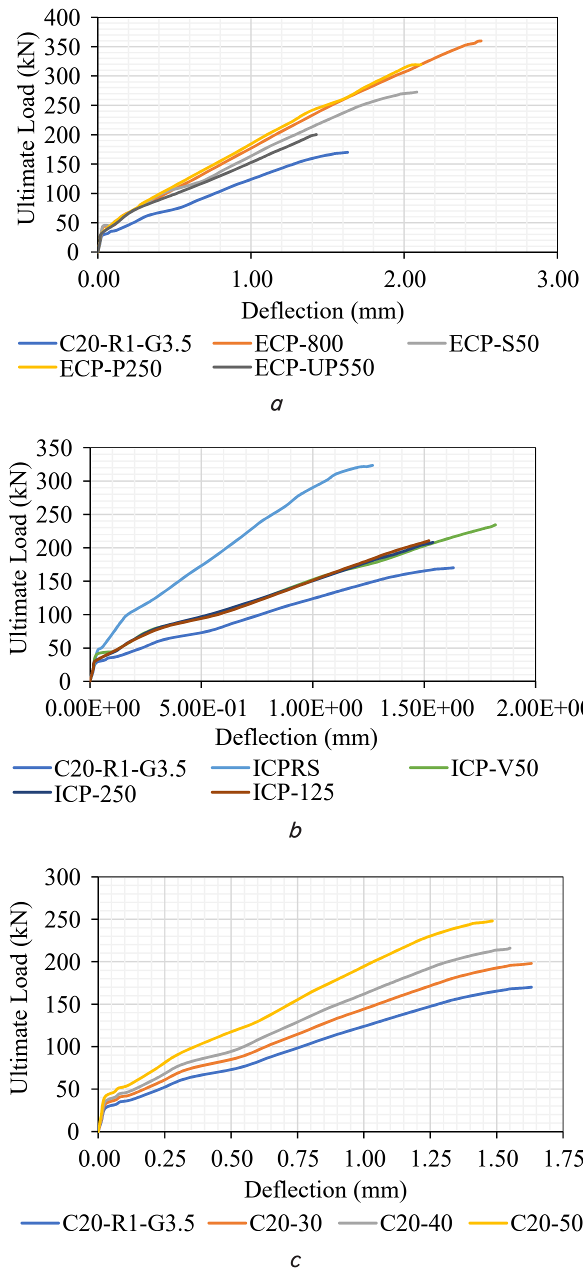


Fig. 5. Analytical results regarding the cracking and ultimate loads showing the maximum displacement of concrete corbels: *a* – external strengthened specimens; *b* – internal strengthened specimens; *c* – strengthened specimens with compressive strength

Increase of the compressive strength decreased the maximum deflection of the RC corbels by slight values for the compressive strengths (30 and 40 MPa) and with a higher percentage for the corbel with compressive strength of 50 MPa as revealed in Fig. 5, *c*.

5. 3. The general behavior of concrete corbels

The general behavior of the corbel is discussed according to the obtained results, which included stiffness, ductility, and energy absorption as revealed in Table 4.

Table 4

Stiffness, ductility, and energy absorption of the RC corbels

ID	K	K %	DI	DI %	Tn	Tn %
C20-R1-G3.5	24.44	167.45 %	3.16	111.43 %	2724.53	230.01 %
ECP-800	40.86	142.37 %	3.52	119.42 %	6266.60	136.49 %
ECP-S500	34.74	168.04 %	3.77	116.77 %	3718.82	151.48 %
ECP-P250	41.00	139.40 %	3.69	130.23 %	4127.15	123.93 %
ECP-UP550	34.01	288.05 %	4.12	114.66 %	3376.64	200.09 %
ICPRS	70.28	155.22 %	3.62	107.64 %	5451.40	135.92 %
ICP-V50	37.87	157.33 %	3.40	111.43 %	3703.12	129.58 %
ICP-250	38.39	151.83 %	3.52	117.64 %	3530.43	125.20 %
ICP-125	37.05	125.28 %	3.72	127.60 %	3411.06	118.00 %
C20-30	30.57	150.49 %	4.03	118.97 %	3214.95	139.00 %
C20-40	36.72	184.59 %	3.76	115.49 %	3787.09	172.00 %
C20-50	45.04	167.45 %	3.65	111.43 %	4686.19	230.01 %

5. 3. 1. Stiffness of the tested slabs

Comparing the model with external strengthening with the control corbel showed that the retrofitting enhanced the stiffness of such specimens and the external strengthening offered an improvement in the stiffness by 84.5 % approximately as demonstrated in Table 4. Regarding the internal strengthening, the improvement in the stiffness was by 47.4 % approximately. Increase the compressive strength was less than the external strengthening and larger than internal ones which were by 67.5 % approximately as demonstrated in Table 4.

5. 3. 2. Ductility of the tested slabs

Comparing the model with external strengthening with the control corbel showed that the retrofitting enhanced the ductility of such specimens and the external strengthening offered an improvement in the ductility by 20.3 % approximately as demonstrated in Table 4. Regarding the internal strengthening, the improvement in the ductility was by 16.1 % approximately as demonstrated in Table 4. An increase in the compressive strength was less than the external and internal strengthened corbels which were by 15.3 % approximately as demonstrated in Table 4.

5. 3. 3. Energy absorption index

Comparing the model externally strengthened with the control corbel showed that the retrofitting enhanced the ductility of such specimens and the external strengthening offered an improvement in the ductility by 53 % approximately. Regarding the internal strengthening, the improvement in the ductility was by 27.2 % approximately. Increase the compressive strength was higher than the external and internal strengthened corbels which were by 80.34 % approximately as demonstrated in Table 4.

5. 4. Cracking pattern, failure mode, and stress distribution

The results for both exterior and interior strengthening specimens, as shown in Fig. 6–8 are fairly consistent with the experimental results published by [19].

Fig. 8–6 illustrated the failure details at the ultimate loading stage, the deformed area, in addition to the crack pattern and failure mode.

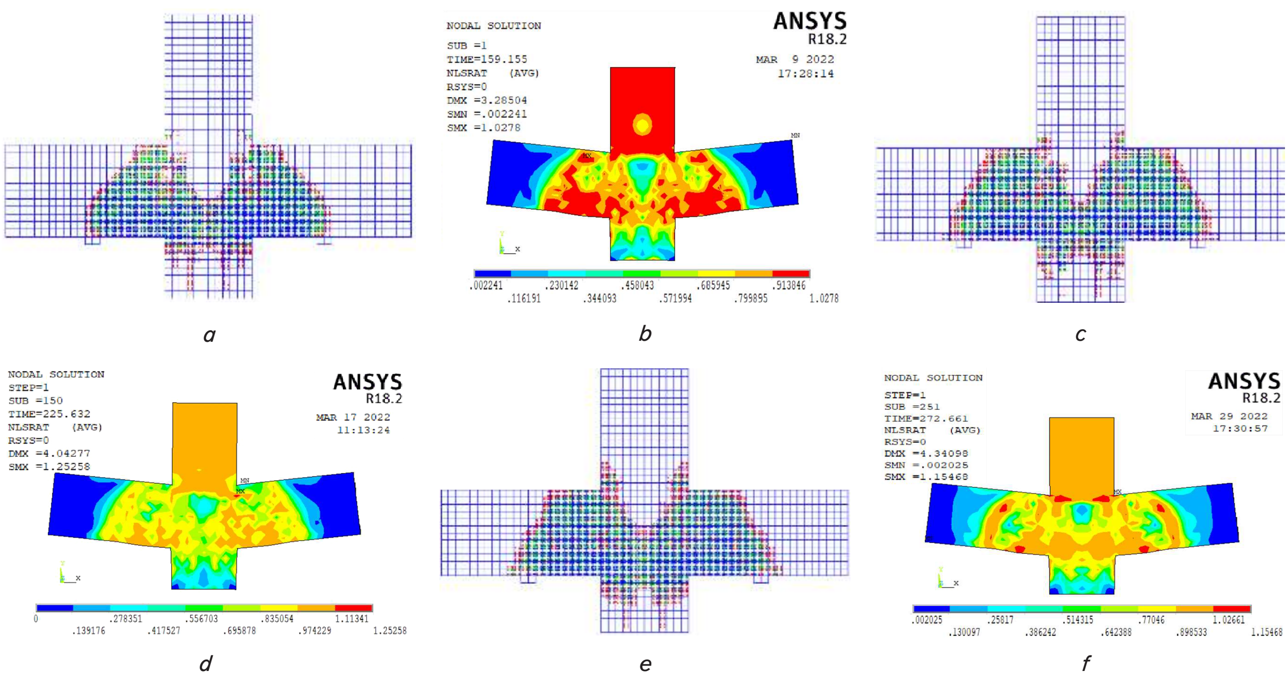


Fig. 6. Analytical results regarding the crack pattern and stress distribution: *a* – crack pattern and stress distribution of C20-R1-G3.5 model; *b* – crack pattern and stress distribution of C20-R1-G3.5 model; *c* – crack pattern and stress distribution of ECP-800 model; *d* – crack pattern and stress distribution of ECP-800 model; *e* – crack pattern and stress distribution of ECP-S500 model; *f* – crack pattern and stress distribution of ECP-S500 model

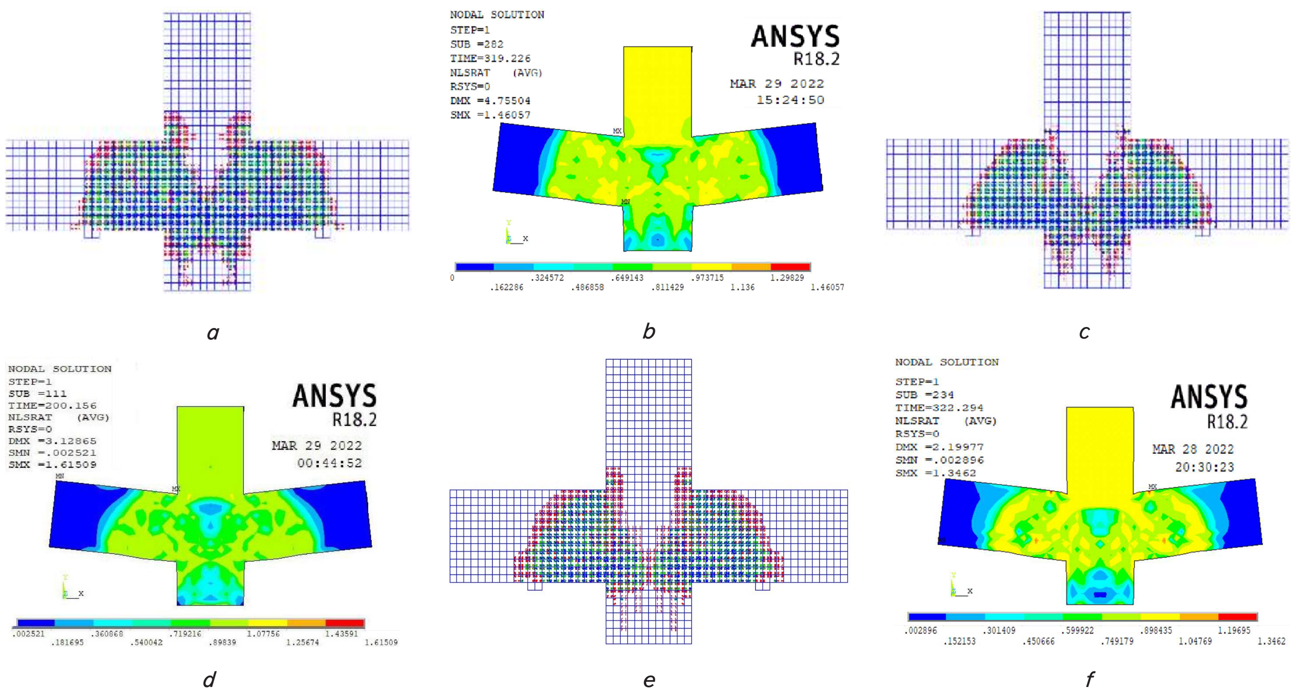


Fig. 7. Analytical results regarding the crack pattern and stress distribution: *a* – crack pattern and stress distribution of ECP-P250 model; *b* – crack pattern and stress distribution of ECP-P250 model; *c* – crack pattern and stress distribution of ECP-UP550 model; *d* – crack pattern and stress distribution of ECP-UP550 model; *e* – crack pattern and stress distribution of ICPRS model; *f* – crack pattern and stress distribution of ICPRS model

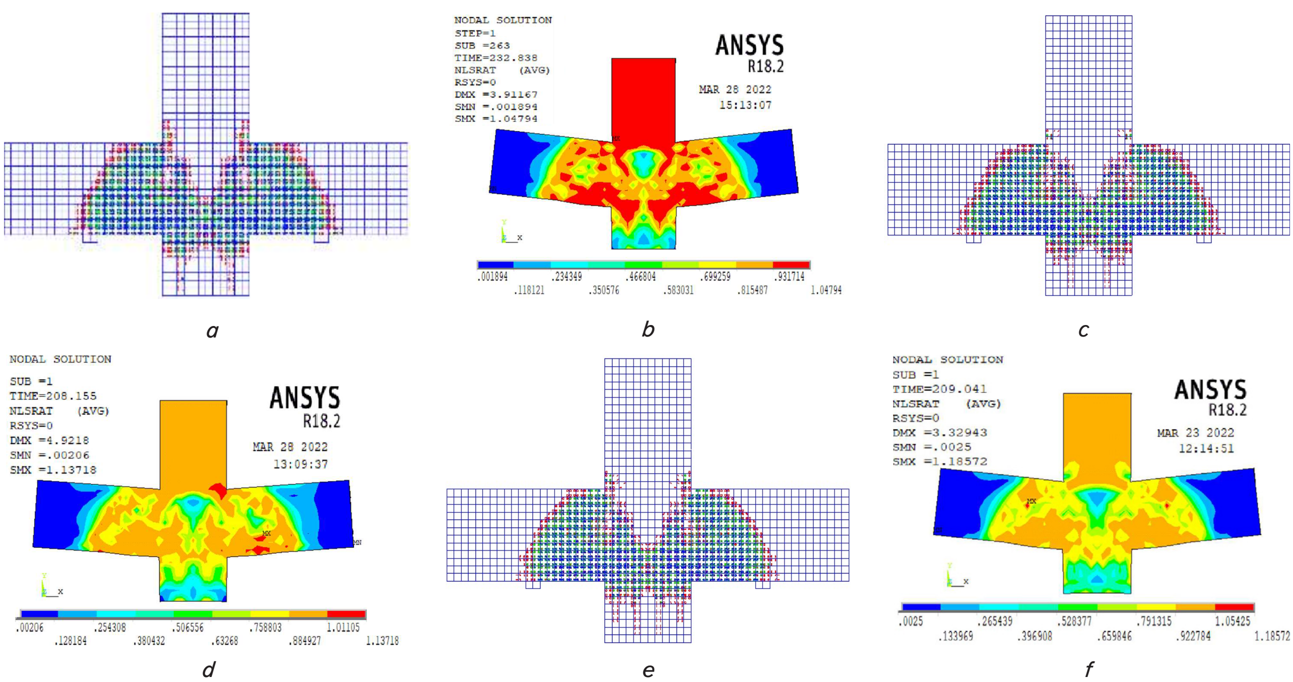


Fig. 8. Analytical results regarding the crack pattern and stress distribution: *a* – crack pattern and stress distribution of ICP-V50 model, *b* – crack pattern and stress distribution of ICP-V50 model; *c* – crack pattern and stress distribution of ICP-250 model; *d* – crack pattern and stress distribution of ICP-250 model; *e* – crack pattern and stress distribution of ICP-125 model; *f* – crack pattern and stress distribution of ICP-125 model

Fig. 8–6 also showed that specimens with external strengthening by steel plates exhibited a diagonal compression (DCF) mode of failure because of happening of crushing in concrete at the struts zone that developed between the diagonal cracks. The FE findings revealed that strengthening the RC corbels internally by steel plates changed the failure mode to (DCF/FLF).

6. Discussion of the numerical results

In order to verify the finite element model results with the experimental results, five models were chosen from an experimental study [24]. The numerical models that have been modeled in this study have same size, boundary condition and material characteristics of the experimental models. According to the verification between the numerical and the experimental, there is a high agreement between the experimental and the numerical analysis results. According to the revealed outcomes, which explained that, the external strengthening was better than internal one due to the confinement effect on the concrete. The confinement effect in case of external strengthening allows the stresses to distribute along the member. When compared to internal strengthening, the external strengthening demonstrated greater improvements in the cracking and ultimate load carrying capacities. The average improvements for the cracking and ultimate load capacities of the corbels with external strengthening, respectively, were 94.3 % and 72.2 %. While for the internal ones, the average improvements for cracking and ultimate load capacity were (69.88 %) and (44.26 %), respectively. On the other hand, for the external strengthening there is a clear enhancement in the deflection of the 53.4 %, 27.6 % and 29.4 % for model (ECP-800), model (ECP-S500), and model (ECP-UP550) as shown Fig. 5, *a*, respectively as shown in Fig. 5, *a*. While, for the internal strengthening the deflection has enhanced by 5.5 %, 11.65 %, and 20.1 % for model (ICP-250), model (ICP-V50), and model (ICPRS) as shown in Fig. 5, *b*. As a good alternative, increasing compressive strength resulted in less ductile behavior compared to the corbels that had been internally and externally reinforced. The compressive strength has increased by 15.3 % which were less than the external and internal strengthening corbels as shown in Table 4. The results concluded that the increase of the compressive strength could gain an additional strength in cracking and ultimate load carrying capacity when compared with the reference model.

In comparison with the existing methods of the strengthening, this method was more efficient that classic methods. The strengthening efficiency was in term of the loading, deflection, stiffness, ductility, energy dissipation, and failure mode. The results showed that the stiffness has been improved by 84.5 % for the external strengthening specimen. However, for the internal strengthening specimen the stiffness has been improved by 67.5 % as shown in Table 4. Moreover, the ductility of the externally strengthening specimen has been improved by 20.3 %. While, the ductility of the internally strengthening has been improved by 16.1 % comparing with the control corbel as illustrated in Table 4.

The limitation of the study was the implementation method of strengthening which need to skilled work staff to implement the strengthening with accurate process. Moreover, the behavior of the tested corbels revealed that the analyzed members were sensitive in term of the shear stresses which affect the stiffness and ductility of these members. According to the finite element analysis, the response of the analyzed corbels was stiffer than the experimental analysis. This could be due to the effects of some assumptions, such as the values of tension and compression in concrete, or due to the conditions of experimental tests, such as the possibility of material deficiencies in loading conditions. It should be noted that all corbel specimens faced a shear failure. For the control model (C20-R1-G3.5), the failure of this corbel was in a brittle manner because of higher degradation in the stiffness. According to the gotten outcomes, Two failure modes were detected during the analysis which were diagonal compression failure (DCF), and a composite of flexural crushing (FLF) and diagonal compression failure (DCF) which is represented by (the DCF-FLF mode). The crushing of concrete in the diagonal strut generated between diagonal fractures that originated within the shear span was the DCF mechanism of failure. While the DCF/FLF mode of failure includes concrete crushing at the beam-column top zone after the appearance of flexural cracks at the maximum moment region beside the appearance of diagonal shear cracks at the shear zone.

One of the disadvantages of this method of strengthening is the cost of implementation, as it requires high costs if implemented for large facilities.

The research can be developed by finding the optimal way to design this type of structural element according to the American and British code.

7. Conclusions

1. The improvement in the cracking and ultimate load carrying capacity occurred in the case of full external strengthening more than internal retrofitting. The cracking and the ultimate load were improved by 94.3 % and 72.2 %, respectively for the external strengthening. While, the cracking and the ultimate load were improved by 69.88 % and 44.26 %, respectively.

2. External strengthening provided improvement in deflection, more than internal one while the increase of compressive strength caused a reduction in the deflection by slight values for the compressive strengths of 30 and 40 MPa and with a higher value for the compressive strength of 50 MPa.

3. External strengthening provided improvement in stiffness, ductility, and energy absorption more than internal one and the variation in the average enhancements for the stiffness, ductility, and energy absorption were 37 %, 4 %, and 26 % respectively. Increasing the compressive strength enhanced the stiffness, ductility, and energy absorption by 15.3 %, 4 %, and 80.34 % respectively when compared with the control specimen.

4. Steel plates reinforced corbels had a deformation capability higher than unstrengthen ones. The presence of the steel plates caused higher deformations which the concrete member semi-fully distorted. Stress distribution of the corbels redistributed when the use of steel plates exposed less concentration than occurred in the bracket without steel plate. The distribution of the maximum stress was noticed in the column section and in the mutual part between the column and the beam.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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