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Experimental and Numerical Study of Eco-Friendly Corbels Under Static Loading

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Abstract: Corbels are structural members that are often used to support and carry main beams. Failure of such members causes disaster failure and a complete collapse structure. Therefore, attention should be given to such members in terms of design, contention and maintenance to ensure their satisfaction with strength and serviceability requirements. This study put forward practical and programmatically investigation on response and failure mode of recycled concrete aggregate (RA) reinforced concrete (RC) corbels. Four samples test and cast using four replacement ratios of recycled concrete aggregate which are 0%, 35%, 65%, and 100%. All RC corbels are designed using the STM suggested by ACI 318-19 code and loaded using (a/d) = 0.6 up to failure. Failure modes, crack patterns recorded and monitored thoroughly during the tests. Experimental results have shown that for all RC samples increasing the percentage RA reduces the maximum bearing and corresponding displacement of corbels significantly with accelerating the shear cracking. However, all corbels experienced same shear crack patterns which started from the supports towards to the column. The results showed that the maximum reductions in maximum load when the replacement ratio changes from 0% to 100% are 24.03%. Also, the maximum reductions in corresponding displacement are (39.61%). On the other hand, the study showed the possibility of using the ABAQUS/standard 2019 program in modeling corbels cast with recycle concrete aggregate with maximum difference in the maximum shear capacity between the numerical simulation and experimental results in 2.92%.

Keywords: Recycled aggregate, Strut and tie method, Shear Spain to depth

Introduction

Corbel are a very important structural member that is often used to support the main beams that are placed above the corbel. Any error in the implementation or design of the corbel ultimately leads to the failure of the entire structure. The corbel is often connected to columns and walls where it is intended to transfer loads. Recently, many studies and theories have been developed about recycling and reusing construction waste materials as a result of the great expansion of construction and the danger it may cause to the environment. In addition, the alarming increase on the construction in the last decades combined with the limited natural construction material resources have motivated the engineering community to seek a sustainable alternative for these materials. Recycled aggregate concrete, resulting from the demolished concrete buildings, is one of those options. Research studies have shown that it is possible to reuse damaged construction materials thus reducing the risk to the environment by also reducing economic costs resulting from reconstruction. In order to conduct studies of additional variables not used in the experimental program, the non-linear analysis program (ABAQUS) was used. This program identifies the properties of the material in the plastic strain phase.

Sulaiman and Khudair (2019) presented study to shear failure to self-compacting RC corbels containing different proportions of recycled gravel. The study has shown the reliability of using recycled gravel in RC

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corbels. It has also shown that the strength of corbels decreases as the percentage of replacement of recycled gravel increases. Hamoodi et al. (2021) presented a study to demonstrate the behavior and resistance of RC corbels with different percentages of recycled gravel percentages at different percentages of shear distance to depth. Resulting that demonstrated that the shear endurance is constantly decreasing with the use of recycled gravel. Also, Dawood et al. (2018) presented an analytical study using sheer fraction method and the stm to understand factors affecting the response of corbel with the effects of (a /d) ratio, concrete types, yield stress (f y) of reinforcement steel bars and the corbel width. It was noted that the stm was the most accurate and gave reasonable results compared to other available analytical methods. Another experimental study conducted by (Salman et.al**)**, study effect of concrete type used in self-compacting concrete (i.e. normal or high-strength concrete with steel fiber) and shear distance to depth ratio on behavior also failure of corbel. The study detects that when the percentage of steel fiber in concrete was increased, an increase in the strength of the corbel was observed compared to normal concrete. It was also shown that when the shear distance to the depth ratio of the corbel increases, the resistance to shear of the corbel decreases. Batista et al. (2024) used the SAP2000 program to conduct modeling of a corbel previously examined in 1994, where the results indicated the accuracy of FEM programs in analyzing the corbels. Hong and Boon; these two researchers used the (ABAQUS) nonlinear analysis program in realistic modelling of the deep corbel and the regular corbel. Their study demonstrated the accuracy of using the (ABAQUS) program regarding the generated stresses and the maximum endurance strength of the corbel. The object is to share behavior of four models of reinforced concrete corbels and create a numerical model using the (ABAQUS) program and compare the experimental load with the numerical load.

Experimental Study

This section displays experimental programs adopted in study to search for the shear behavior of RC Corbel. Starts with presenting and discussing the method used to obtain recycled gravel with the material properties used in the recycled concrete mix and the trial mix considered to determine the optimum concrete mixture. Also presents the casting of acceptable concrete mixture cubes and cylinders with replacement ratios (0, 35, 65, 100) % from which the corbel model concrete was used. Also, it displays the dimensions and reinforcing details of the RC corbel specimens with their classification and designations according to the parameters investigated in the study which are the recycled concrete aggregate replacement ration. Further, preparation, casting, and curing corbels. This section also explains details of the devices used in the test including the test rig and measuring devices along with, the method of testing samples.

Materials Properties

Different materials used include salt-resistant cement, sand; recycled gravel and natural gravel with maximum size and same Sieve analysis; reinforcing steel; concrete admixture.

Cement

Salt-resistant Portland cement Al-Jesr type (I) was used which is a cement available in the market. Salt-resistant cement was used to get rid of the salts present in the recycled gravel. The physical and chemical tests showed that the cement used conforms to and passed the Iraqi specifications (IQS NO. 5, 2019).

Fine Aggregate

In this study sand was used which conforms to the Iraqi standard (I.O.S NO. 45, 1984) according to laboratory tests

Gravel

Used two types of gravel in the study which are natural crushed gravel and recycled crushed gravel resulting from old and abandoned construction elements.

Natural Gravel

Coarse aggregate (crushed gravel) was used in a saturated and dry surface with a maximum size of 20 mm. According to sieve analysis and physical test. The natural aggregate used conforms to Iraqi specifications (IQS 45/1984, 1984)

Recycled Aggregate

The (recycled gravel) obtained by smash old concrete in the laboratory of the College of Engineering with the number of cubes exceeding 200 cubes. The process of extracting recycled gravel was conducted through the following stages:

- Concrete cube preparation stage: numbers of old cubes are collected and stored at the laboratories of the College of Engineering were selected with more than 200 cubes Figure 1A represents this stage.
- Using manual methods using a hammer, the cubes were crushed to obtain moderately size recycled gravel as shown in Figure 1B.
- Using mechanical machines, the recycled gravel was gradated and distributed on the standard sieve's sizes with maximum size 20 mm similar to that of natural gravel as shown in Figure 1C. Noting that the speed of the mechanical device is lowered to ensure the presence of mortar in the recycled gravel so that the maximum size of recycled aggregates retained in cement mortar.
- After completing the extraction process of the recycled gravel with a maximum size (20 mm), the grain size distribution of the recycled gravel was also examined to ensure obtaining gradation similar to that of natural gravel as shown in Table 1. This table shows that the recycled and natural gravel conform to IQS No. 45/1984(IQS 45/1984, 1984)**.**

(A): Preparing old concrete cubes used to obtain recycled gravel (RA)

(B): Manual method (hammer) used to obtain recycled gravel

(C): Mechanical method used for obtaining recycled aggregates with sieve grades similar to conventional normal aggregates using mechanical device

Figure 1. A, B and C methods used to obtain recycled gravel RA

Table 1. Displays sieve analysis for NA and RA

Size (mm)	%Passing (NA)	%Passing (RA)	Size (5-20)
75	100	100	-
63	100	100	-
37.5	100	100	100
19	97.3	95	95-100
13.2	66.2	59.3	-
9.5	39.24	30.5	30-60
4.75	1.7	0.63	0-10
2.36	0	0	-

Concrete Admixtures

Superplasticizers used in this research to disperse and remove active cement particles which require more water and results in a highly fluid workable concrete mixture that can be formed without the need for excess water in the mixture thus obtaining stronger compressive strength and better durability. GLENIUM 54 Superplasticizer was used in this research and meets ASTM C-494 Type F specification.

Reinforcement of Steel Bars

According to (ACI Committee 318, 2019) RC corbels was designed using the stm. Used, Ø10 mm diameter was used as the main tension reinforcement of the corbel. In addition, the column was reinforced by longitudinal bars and stirrups using Ø10 and Ø8 mm diameter steel bars respectively. Iraqi F-F type steel reinforced was used and the uniaxial direct tensile test was conducted on three specimens with two diameters of bars (i.e. Ø10 and Ø8) mm. Accordance to ASTM specification (ASTM A615M-09b). Table 2 shows the test results in terms of yield and ultimate in stress.

Table 2. Comparison between the experimental results with ASTM A615 specification

Ø (mm)	FY (MPa)	Fu (MPa)	FY in ASTM A615	F_U in ASTM A615 Grade 60	δ mm
8mm	448.5	625.5	420	550	8.8
10mm	553.5	668.5	420	550	9

Design Dimensions and Details of Steel Reinforcement Corbel

Four samples have the same design and details. All corbels and the connected column were designed according to stm proposed by ACI318-code (ACI Committee 318, 2019) to fail by shear failure mode at (200 KN). Based on the design, the cross-section dimensions and the height of the column connected to the double corbel are (200x200) mm and 550mm respectively. This column is designed to strength applied loads reach (500 KN) to ensure that the column does not fail before shear failure of the corbel occurs throughout the period of applying loads to the models. While the dimensions of the RC corbels are (920 x 300 x 200) mm (length x height x thickness) as shown in Figure 2 While the reinforcement of the corbel is characterized as 2Ø10mm bars as main corbel reinforcement and 1Ø8mm bars as the stirrups of the corbel was as shown in Figure 2. Further the column was reinforced by 4Ø10mm bars as longitudinal reinforcement and Ø10mm @ 90mm as stirrups over the column height (i.e 550 mm) so that 6Ø10mm column stirrups was used. In addition, the cover is set to be 40 mm for all specimens because the maximum size of the natural gravel and recycled gravel was 20 mm. Figure 2 represents the design details and reinforcement of the corbel and the column connected to the corbel. Table 3 ddisplays the models used in the study.

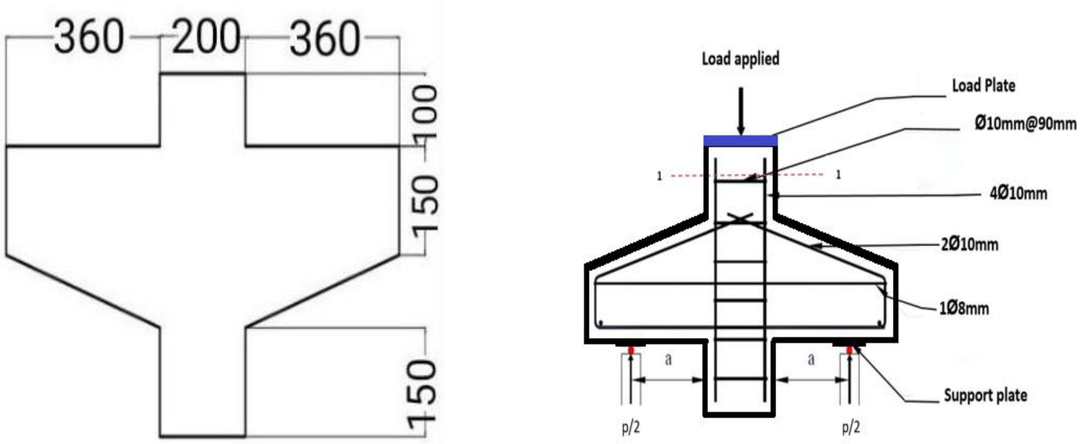


Figure 2. Design details of the corbel model

Table 3. Displays the models used in the study

Designation of the specimen	Means that
CN0%	Corbel it's contains only on natural gravel
CN35%	Corbel it's contains recycled aggregate at a rate 35%
CN65%	Corbel it's contains recycled aggregate at a rate 65%
CN100%	Corbel it's contains recycled aggregate at a rate 100%

Casting and Curing and Testing Corbel Sample

Casting and Curing Corbel Sample

An electronic scale was used to weigh all the materials used in the concrete mixes used to cast all RC corbels (salt-resistant cement; sand, natural gravel; recycled gravel, water and superplasticizer) based on the optimum mix shown in Table 4. Table 5 shows weights of construction materials per single corbel with different replacement ratios. The mechanical mixer was used to mix the mixes ingredients and during casting the mechanical vibrator was used as shown in the Figure 3. The follows steps explain the mixing process:

First, mix the dry materials (recycled aggregate, natural aggregate, sand) in the mixer after checking the weights of the materials. Secondly add cement to the (recycled aggregate, natural aggregate, sand) mixture in the mixer. Thirdly mix these materials with the gradual addition of water in the mixer. Fourthly Gradually add (GLENIUM 54) during the mixing period. It was observed that the higher replacement ratio led to less concrete mix fluidity due to effect of cement mortar on the outer surface of RA causes to reduction in workability of the concrete mix, the need for the mixture to increase the mixture water, but in the study the same W/C ratio was used. After completing the casting process of the corbel concrete with different replacement ratios of gravel, the corbels left about 24 hours before removing the molds for curing process by placing wet burlap on the corbel models for about 28 days before conducting the test. Table 4 shows the weight ratios of a concrete mix with 100% recycled gravel replacement ratio that achieves a f'c of 33Mpa in 28 days these values were obtained through trial and error for concrete cubes and concrete mix design according to (ACI 211.1-91).

Table 4. Required weights quantity concrete mix

Cement (Kg/m3)	Sand (Kg/m3)	Gravel (Kg/m3)	Water (Kg/m3)	(W/c)
421	656	1078	200	0.475

Table 5. Weights of mixed ingredients used to cast RC corbel specimens according to RA replacement ratio

Corbel Designation	Cement (Kg)	Sand (Kg)	Natural gravel (Kg)	Recycled gravel (Kg)	Water (L)	S. P (L)
CN0%	30	50	86	0	9	0.47
CN35%	30	50	56	30	9	0.47
CN65%	30	50	30	56	9	0.47
CN100%	30	50	0	86	9	0.47

Figure 3. Mixing process showing the use of the vibrator

Cubes and Cylinder Casting

Twenty concrete cubes of dimensions (150x150x150) mm were cast by casting Five concrete cubes of dimensions (150x150x150) mm and four concrete cylinders with dimensions of (100x200) mm cast to same mix used in cast the corbels corresponded to each replacement ratio of recycled aggregate (i.e. 0%, 35%, 50% and 100%). These cubes and cylinders are use determine the fc and ft of concrete corbel. Table 6 shows fc and ft strength test results.

Table 6. Compressive strength and tensile strength test results of the RC corbels

Replacament Ratio %	f' c Average MPA	Decrease percentage %	f.st Average MPA	Decrease percentage %
0%	41	---	4	---
35%	37	9.75%	3.8	5%
65%	34.3	16.09%	3.5	12.5%
100%	31	24.39%	3.3	17.5%

Testing Corbel Sample

To simulate the practical load application to the double corbels as close as possible, the corbel was placed in inverted shape as shown in Figure 4 where the load was applied to the column part of the corbel where aces the far ends cantilever part of the corbel (or corbel arms) were simply supported. In this case, the reaction loads at the simply supported ends which are equal to halve of total loads applied to the column would impose a concentrated load or shear force to the end of the cantilever part of the corbel (corbel arms). Therefore, the column was designed to withstand loads of up to (500 KN) to ensure that the column does not fail during testing.

For all tested RC corbels, the load was applied at eccentric (or shear span which is the distance from load to the center of the corbel) to effective depth (d) ratio (a/d) equal to 0.6 so that shear behavior and failure dominate the corbel behavior. According to (ACI18-19 code) the (a/d) ratio should be equal or less that one for the RC corbel so that the shear stress characterizes the behavior of the corbel. However, when a/d=1, the behavior of the corbel would be dominated by combined shear and flexural behavior and flexural failure prevails over shear failure due to the increase in the loading distance (a) which causes an increase and generation of bending moments. Since the corbel is placed inverted (shear force = reactions) the shear span (a) represents the location of the support. Therefore, the shear distance can be calculated as follows: a= 0.6 ($d = 300 - 40 - \frac{10}{2}$) = 153 from the face of the column.

Figure 2,3,4 and 5 show corbel position in the testing device (in the University of Al-Qadisiyah laboratory) A universal hydraulic device with a maximum load capacity of 2000 KN and minimum load increment of 10 KN is utilized to apply the vertical incremental and monotonic static load to the RC corbel specimen up to failure as shown in Figure 5.This machine is used in the laboratories of the College of Engineering and consists of a steel structure in which a hydraulic device is placed to apply vertical loads. The testing device consists of hydraulic motor for generating loads and a load cell and steel support along the space and Iron plate for distributing applied loads (vertical loads).

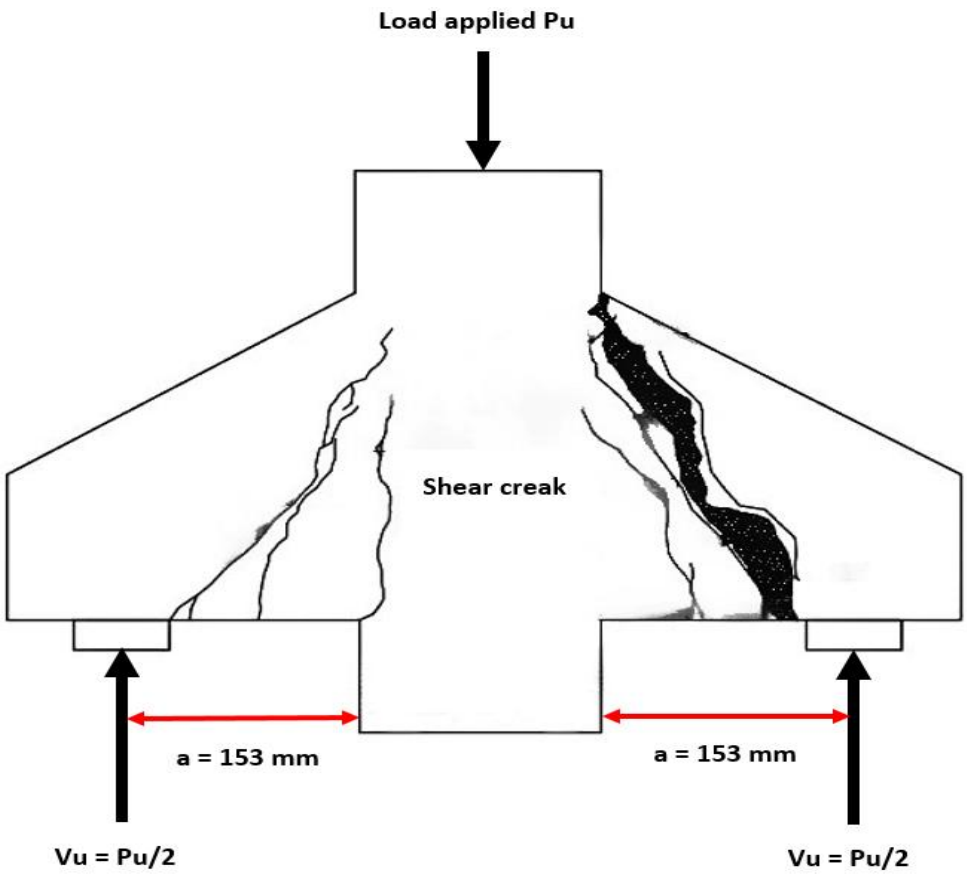


Figure 4. The method of applying loads and placing supports of RC corbels specimens to induce shear behavior

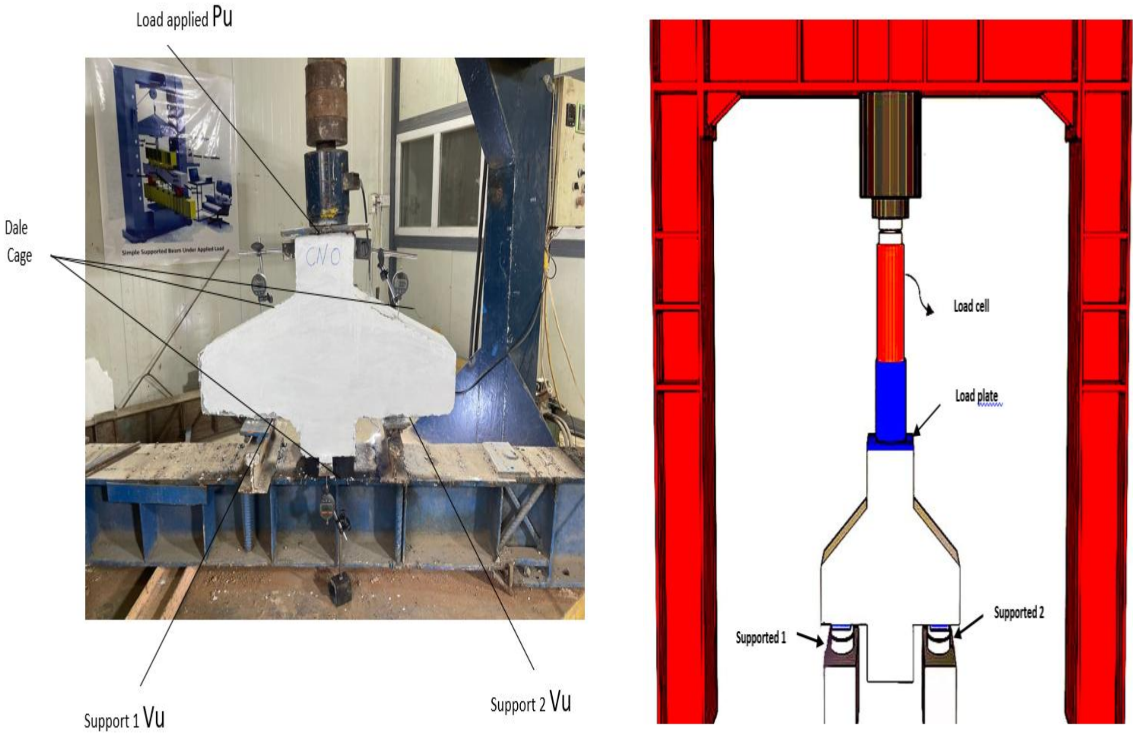


Figure 5. The details of the test mechanics used in the study

Experimental Result

Crack Patterns and Failure Modes

Figure 14 demonstrates crack patterns and failure modes of the four RC corbels at different ratios of replacing natural coarse aggregate with recycled coarse aggregate. As can be seen from Figure 14, the four corbels experienced same crack pattern and similar shear failure mode. When the corbels were exposed to the applied load, cracks are generated near one of the two supports and propagated in an inclined direction toward the column. As the load increases, more inclined shear cracks formed and developed on both sides of the corbels in the same way that the first crack developed. However, one crack propagated faster and wider than the other two cracks causing the shear failure of corbels. Same crack propagation and development scenario were observed in the four corbels. However, the differences are in values of the first crack loads and failure loads.

The first crack of the natural aggregate concrete corbel with 0% recycled aggregate replacement ratio initiated at 200kN, while the initial crack of the corbel with 100% recycled coarse aggregate observed at 100kN, with 50% reduction ratio. This is also the case in the corbels with replacement ratios of 35% and 65%, where it was observed that the initial crack decreased with increasing the RC replacement ratio. However, considering the advantages gained from the environmental and suitability aspect, the reduction in the initial crack load caused by using recycled coarse aggregate is marginal particularly at small replacement ratio. Results have shown that the first shear crack load decreased by 7.5%,25%, and 50% for CN35%, CN65%, and CN100% corbel specimens respectively compared to the corbel with normal (natural) aggregate.

Table 7. Effect of the replacement ratios on maximum load capacity of RC corbels

Corbel Designation	(a/d)	Crack load	Pu (KN)	Maximum displacement (mm)	(%Pu)	% first shear crack load	%Decrease in displacement
CN0%	0.6	200	520	13.58	---	---	---
CN35%	0.6	185	505	11.83	2.884%	7.5%	12.88%
CN65%	0.6	150	475	9.63	8.65%	25%	29.08%
CN100%	0.6	100	395	8.2	19.23%	50%	39.61%

Also, the decrease rate of the total load was 2.88%,8.65%, and 19.23% for CN35%, CN65%, and CN100% corbel specimens respectively. This weakness can be explained by Internal weakness of the concrete structure of the RA in area of interfacial transition zone (ITZ) due to incomplete bonding between the recycled gravel surface and the construction materials. However, for (CN65%) specimens, shear failure occurs in the strut zone with cracks generated at the Tie zone because the recycled gravel in tie zone cause weakness. Table 7 displays the results of experimental tests. Experimental results showed that increasing the replacement ratio causes a decrease in the generated displacement Table 7 displays the percentage decrease in displacements.

Finite-Element Modeling

Use the nonlinear analysis program (ABAQUS/standard 2019) to create a numerical model that approximates reality. This section displays the definition of the numerical model parts, the definition of material properties, connection, load application, and setting of boundary conditions.

Geometric Model

The 3D solid element with eight nodes (C3D8R) in ABAQUS was used to model the corbel and bearing plate in the numerical model. While the steel reinforcement bars were modeled using a 3D truss element with two nodes (wire truss element T3D2). Figure (2-6) and Table 8 show elements used in geometrical modeling of the RC corbels (Sakbana and Mashreib 2020).

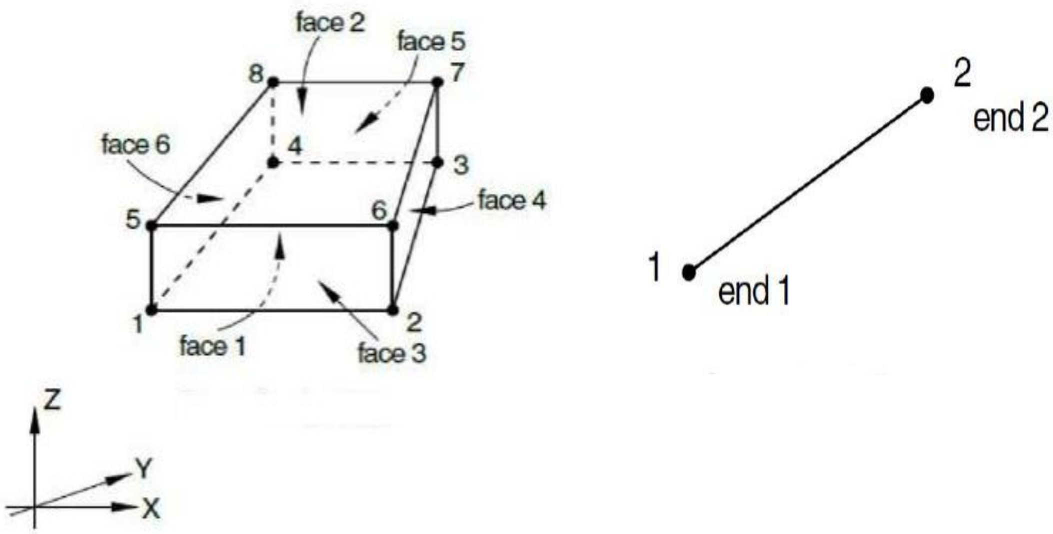


Figure 6. Finite elements used in geometrical modeling of different parts of the RC corbels in this study (Sakbana & Mashreib 2020)

Table 8. Finite elements used in geometrical modeling of different parts of the RC corbels in this study (Sakbana and Mashreib 2020)

Types Martial	Representation in ABAQUS	Means
Corbels	(C 3D 8 R)	(C) ratio stress/displacement, (3D) three dimensions (8) number of nodes (R) reduce integration
Steel plate	(C 3D 8 R)	(C) ratio stress/displacement, (3D) three dimensions (8) number of nodes (R) reduce integration
Steel reinforced	(T 3D 2)	(T) Truss element (3D) Three dimensions (2) number of nodes

Material Model

Concrete Modeling

The concrete damaged plasticity (CDP) model in ABAQUS was used to simulate the behavior of concrete until concrete collapse occurs. This model can reasonably predict behavior of concrete at different loads

(Hafezolghorani et al, 2017). In this model, number of factors should be defined in addition to the plastic properties of concrete in compression and tensile as follows:

(A) Plasticity parameters

The CDP requires the introduction and definition of several damage properties other than the tensile and compressive properties of concrete which are properties in the plastic stage as follows.

Dilation Angle (φ) : which represents the increase in the plastic volume of the concrete beyond the maximum stress and gives an indication of the behavior of the concrete when compressed. An increase in this angle indicates that concrete has ductile behavior, and a decrease in this angle indicates that concrete has a brittle behavior during compressive stresses. The limits of this angle are between 30 to 50 degrees.

The flow potential eccentricity (ϵ): which represents the ratio of uniaxial tensile strength to uniaxial compressive strength. It represents an almost constant value and is entered into the program as (**0.1** $\frac{ft}{f'c}$).

(fb / fc): which represents ratio of initial equal biaxial compressive yield stress to initial uniaxial compressive yield stress the ratio determines the point at which the material fails under biaxial compression

(K): which represents the ratio of the constant stress on the tension line to the constant stress on the compression line. It must not be less than 0.5 and not more than 1.0.

(μ): which represents the coefficient of viscosity should not be (0) and should experiment to choose the ideal value. (Demir et al,2018).

All the above-mentioned values are determined by trial and error, and Table 9 shows the values used in this study.

Table 9. The plastic properties used in CDP model concrete in this study

fc	φ	€	fb/fc	K	μ
31	33	0.1	1.15	0.65	0.000001
34.3	38	0.1	1.17	0.68	0.0000000001
37	39	0.1	1.21	0.7	0.000000001
41	40	0.1	1.21	0.7	0.0000000001

(B) Compressive Behaver of Concrete

It is assumed that the compression stress-strain curve of concrete is linear to the point where the concrete reaches ($0.4f_c'$) of the maximum strength after which cracks begin to appear and the concrete enters the non-linear state. The (Hillerborg, 1985) was used through to obtain nonlinear strain in the case of plastic as follows.

$$\sigma_c = f'c\left[2\times\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)-\left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] - - - - - \quad (2.1)$$

σ_c : compressive stress of concrete

ε_c : strain in any point

εco = ($2fc$ / Ec) strain at peak stress (Ec) young's modulus concrete

$$\varepsilon pl = \varepsilon c - (\sigma c / Ec) - - - - - - - (2.2)$$

To obtain stress and strain curve in plastics zone firstly the strain and modulus of concrete should be determined from $\varepsilon_c = 0.4\left(\frac{f_c'}{EC}\right)$ and $Ec = 4700\sqrt{f_c'}$. Secondly the strain at peak stress is determined from εco = ($2fc$ / Ec). Also, the stress σ_c is determined by equation (2.1). Finally strain plastic is calculated from equation (2.2). Figures (2-7) show stress-strain curve of concrete in a state of compression in plastic zone

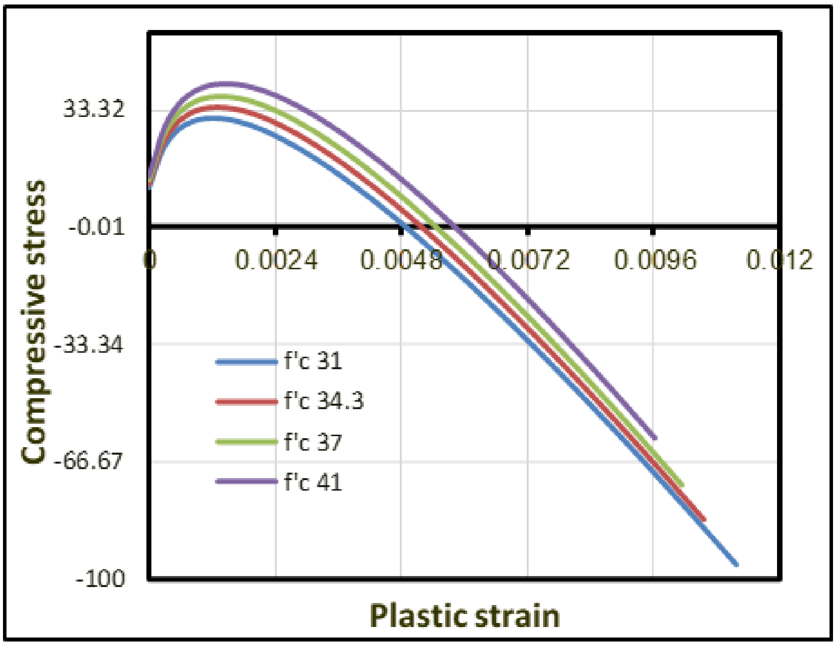


Figure 7. Stress-strain curve of concrete in a state of compression in plastic zone

(C) Tensile Behaver of Concrete

In this study the following tensile stress-strain equations suggested by (Hillerborg, 1985) and developed by Cornelissen (Cornelissen et al., 1986) to account for the tension softening model was used to model the tensile behavior of concrete. Equations depend on the width of the crack and the length of the cylindrical test sample as follows

$$\sigma_t = f_t \left[f_w - \frac{w}{w_c} f w_c \right] - - (2.3)$$

$$f_w = \left[1 + \left(\frac{c1 \times w}{wc}\right)^3 \right] exp\left(- \frac{c2 \times w}{wc}\right)$$

$$f_{wc} = \left[1 + c1^3\right] exp(-c2)$$

Where:

w: is the crack opening displacement

w_c: is the crack opening displacement at which stress can no longer be transferred.

$$wc = 5.14 \frac{Gf}{ft}$$

c1 is a material constant and c1 = 3.0 for normal density concrete.
c2 is a material constant and c2 = 6.93 for normal density concrete
Gf, is the area under the softening curve, according to Beton (1993) estimated as

$$G_f = G_{fo} \left(\frac{f'c}{10}\right)^{0.7}$$

G_{f_o} *this function dapinded on mix size of aggregate and* $f'c$

using a maximum aggregate size of 19 mm and compressive strengths of the cylinder's (41 ,37, 34.3, and 31) MPa for recycled aggregate replacement ratios of 0%, 35%, 65% and 100% respectively Table 10 shows the values of G_{f_o} used in this study

Table 10. Determine amount G_{fo}

	G_{fo} (N/m)							
D_{max} (mm)	C12	C20	C30	C40	C50	C60	C70	C80
8	40	50	65	70	85	95	105	115
16	50	60	75	90	105	115	125	135
32	60	80	95	115	130	145	160	175

$$\varepsilon\, cracking = \frac{w}{L} - - - - - - -(2.4)$$

Also, Equation (2.4) shows the cracking strain due to tensile stress of concrete which depends on the crack width and cylinder length of 200 mm. Figure 8 shows stress - strain curves of concrete under tension and the stress and cracking strain behavior.

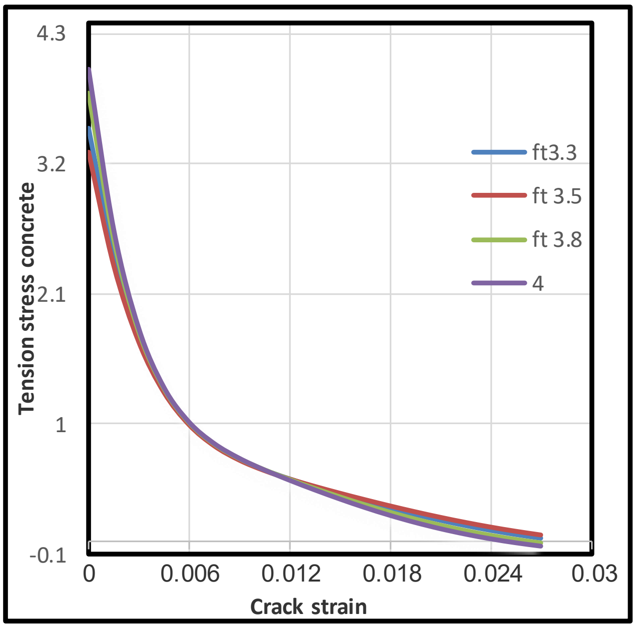


Figure 8. Stress and strain of concrete tension behavior

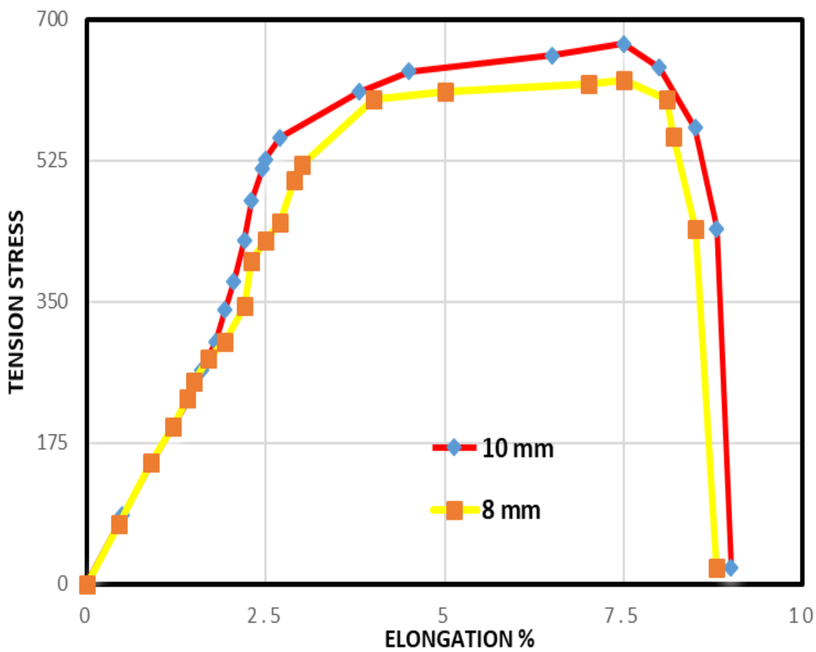


Figure 9. The engineering curve of the steel bars with diameters of 10 mm and 8 mm

Steel Reinforced Modeling in ABAQUS Program

Steel bars are defined in the ABAQUS program through two main parts: the elastic modulus (elastic limit) and the plasticity limits. The elastic modulus of steel E was taken equal to 200000 MPa while Poisson ratio *was assumed* $v = 0.1$. Through the tensile experiment for bars with a diameter of 10 mm and 8 mm, the engineering curve of the stress-strain curve was obtained and from this curve the yield stress and fracture stress was determined. Table 2 shows the yield stress and fractured stress for steel bars with diameters of 10 mm and 8 mm, and Figure 9 illustrates the engineering curve of the steel bars.

The engineering stress-strain curve of the steel reinforcement bars must be corrected because of the decrease in the diameter or (necking) of the section accompanied by the decrease in strain **[14]** as follows.

$$\sigma_{tr} = \sigma\ (1 + \varepsilon) \quad ----- (2.5)$$
$$\varepsilon_{tr} = \ln\ (1 + \varepsilon) \quad ------ (2.6)$$
$$\varepsilon_{pl} = \varepsilon_{tr} - \left(\frac{\sigma}{E}\right) \quad ----- \quad (2.7)$$

Where:

$(\sigma_{tr}, \varepsilon_{tr})$: *True stress and strain* , (ε_{pl}): *Plastic strain*

(σ, ε): *stress and strain in engineering curve*

By using the above equations to the engineering, the tensile stress-strain curve of the reinforcing steel bars the true tensile stress-strain curve was obtained as shown in Figure 10.

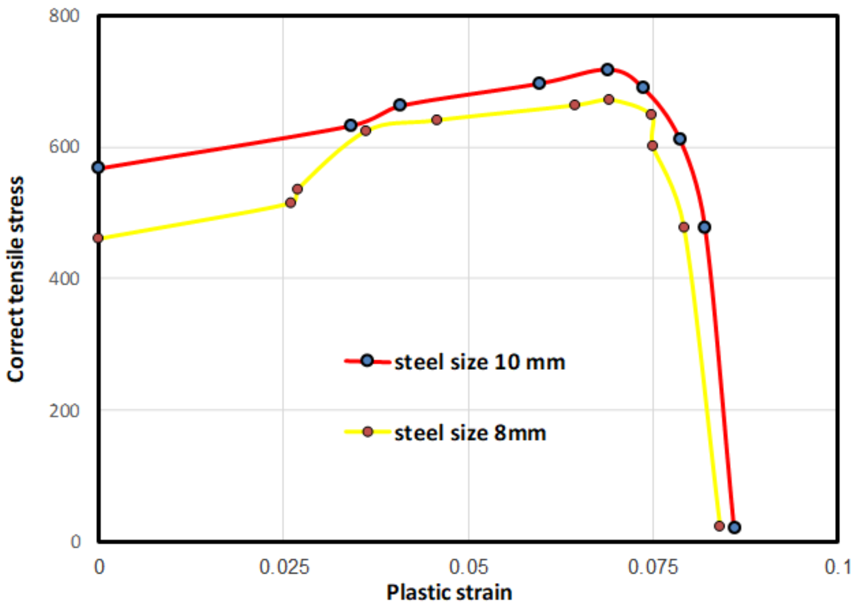


Figure 10. The true stress-strain curve of the reinforcement steel bars used in this study

Definition the Plates Used in ABAQUS Program

The supports and loading plates used in the experimental part also modeled in the ABAQUS using C3D8R element described before with linear elastic behavior with high elastic properties because neither the supports nor the load plates failed during the entire period of load application. These plates are fully bonded to the corbel parts using Tie interaction option in ABAQUS. The dimensions of loading and support plates were taken as (200 x 200 x 10) mm respectively (x. y. z) axis.

Assemblages of the RC Corbel

Embedded interaction option in ABAQUS was used to simulate the bond between steel reinforcement and concrete and the bond between support and loading plate with concrete surface corbel was tie interaction because no failure and de-bonding occurs at support.

Loading and Boundary Condition

The load was applied a static pressure with a constant value on each surface of the bearing plate to approach the experimental test (Inverted corbel test method). Further, pin and roller supports were assumed for corbels. pin support was obtained by constraining the horizontal and vertical move of the support so that no displacement in horizontal and vertical equal us allowed $(U_x \& U_y) = 0$ and the roller support was obtained by constraining the vertical move so that displacement in vertical equal is zero) $(U_y) = 0$. The bearing plates were placed at a horizontal distance of 153mm from the face of the column to achieve the a/h ratio of (0.6). Figure 11 shows that Loading and boundary condition for corbels.

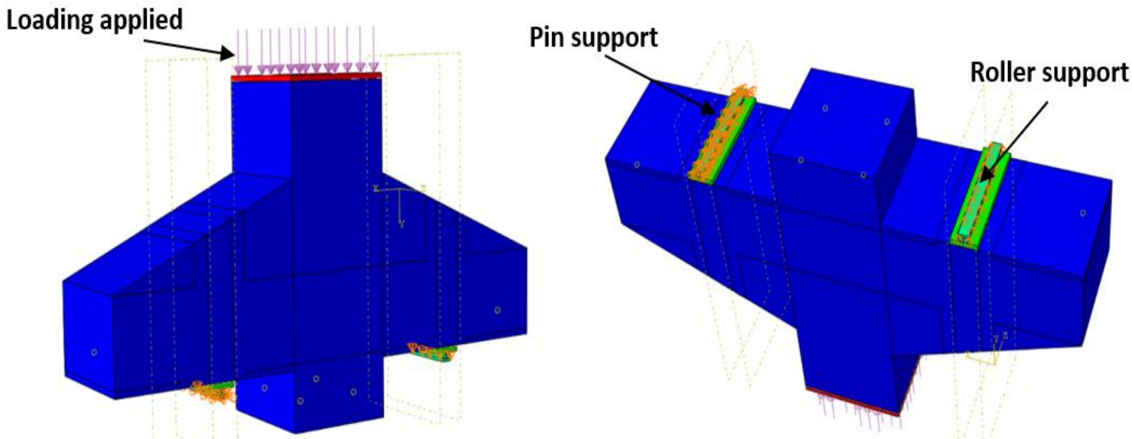
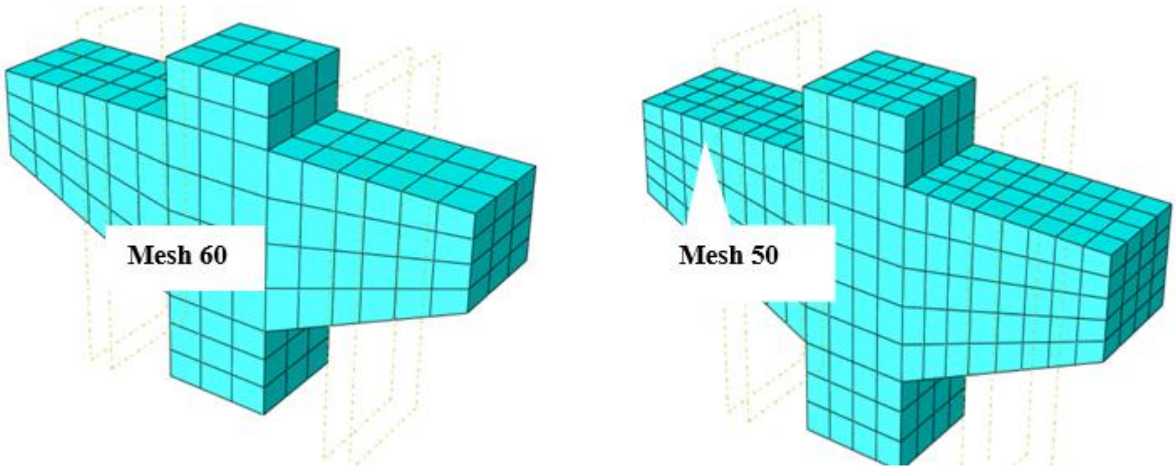


Figure 11. The loading and boundary condition for corbel used in the numerical model

Meshing

Mesh greatly affects the accuracy of the numerical analysis of the model when the number meshes increase numerical results correlated to the experimental work and take more time required to complete the analysis. Use (CN100%) to determine the best mesh size, with numbers mesh (20, 40, 50 ,60) used Figure 12 shows experiments to get the optimal mesh size. Mesh size of 20 was used in the numerical model RC corbel because it gave results close to the practical side. The analysis time took about an hour.



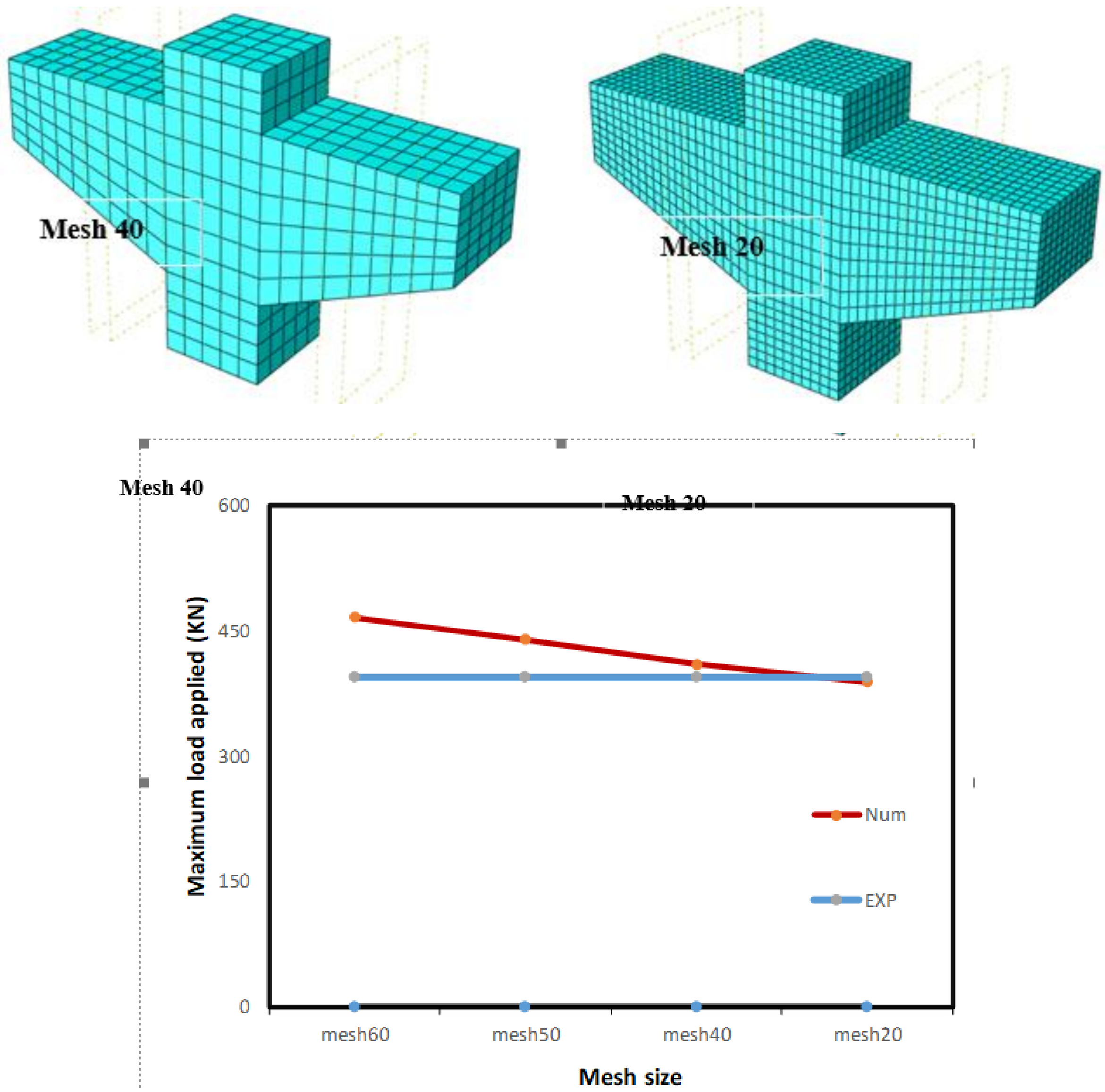


Figure 12. The experiments to get the optimal mesh size

Exprmintal Results and Numerical Simulation

Figure 13-14 and Table 11 displays the results of the numerical analysis with exprmintal results. Table 11 shows very good correlation of the shear failure loads compared to the experimental results. Figure 13 shows comparisons of the failure load between the numerical model and the tested model. The comparison was in the failure loads because the numerical model gave failure loads close to the laboratory failure loads. The displacements were not taken into account in the comparison because of the small displacements in the corbel model when compared to the maximum applied load. Also, Figure 14 shows the failure pattern of the exprmintal and numerical models with the ultimate stresses and strains corresponded to each model along with the stress at the steel reinforced.

Table 11. Comparison of the ultimate load of the control RC corbels between the experimental and numerical results

Sample	Pu EXP (KN)	Pu FEM (KN)	%Diff = (FEM-EXP)/EXP) x 100%
CN0%	520	533.914	2.67%
CN35%	505	501.279	0.73%
CN65%	475	461.12	2.92%
CN100%	395	388.909	1.54%

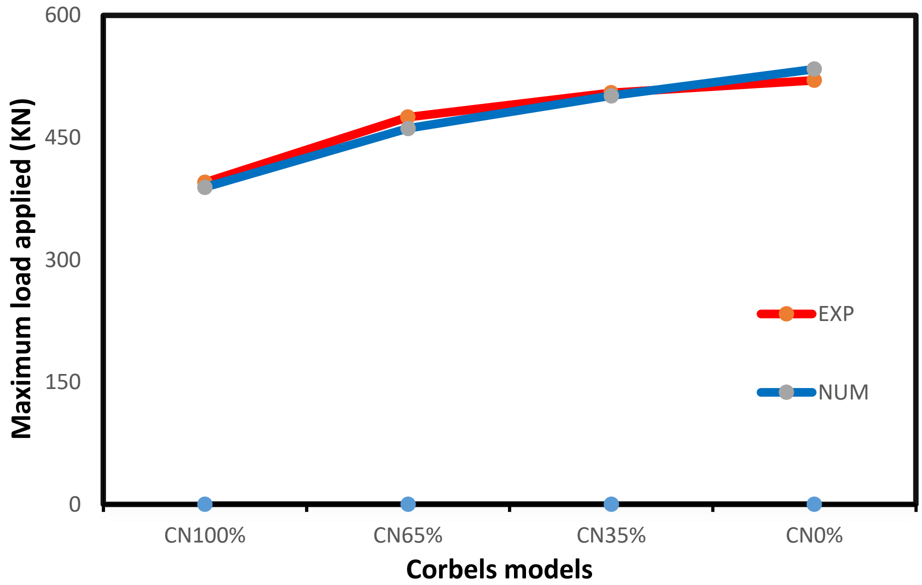
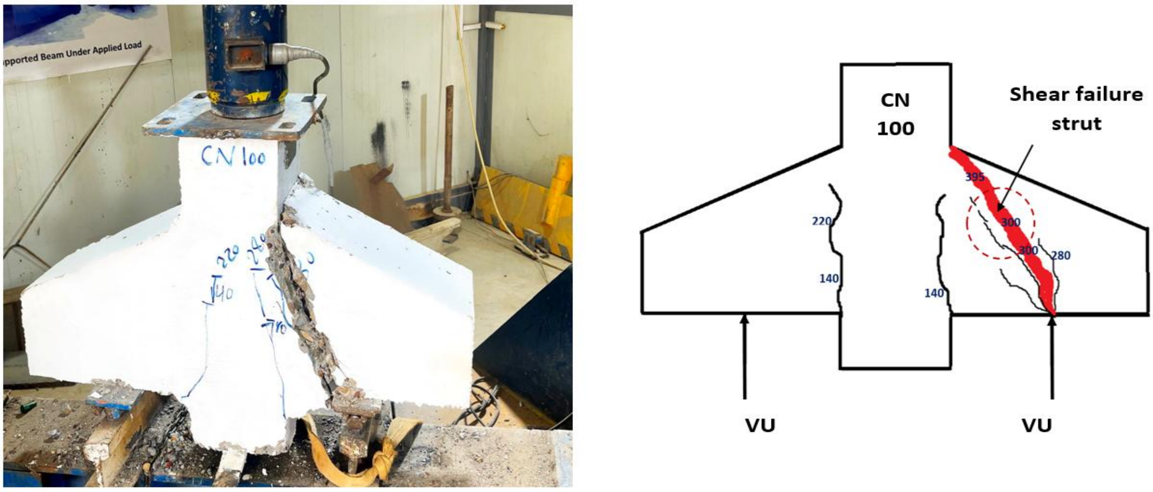
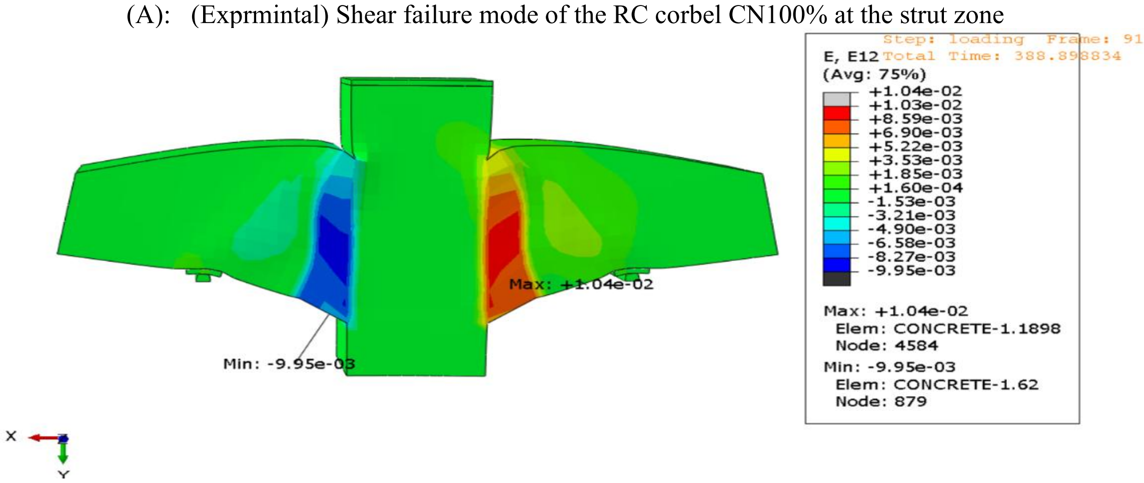


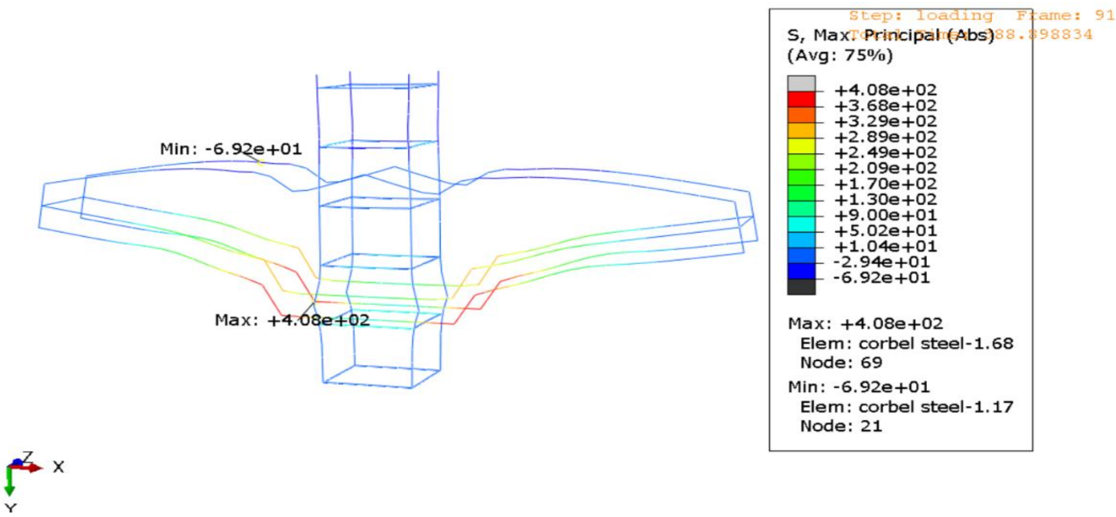
Figure 13. Comparison of the ultimate load of the control RC corbels between the experimental and numerical results



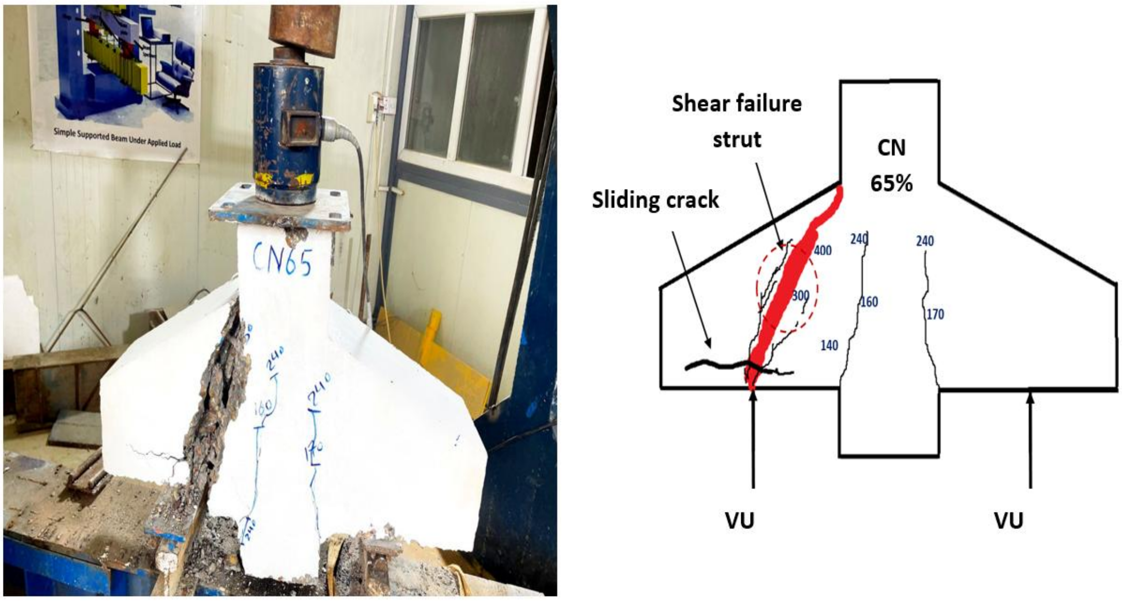
(A): (Exprmintal) Shear failure mode of the RC corbel CN100% at the strut zone



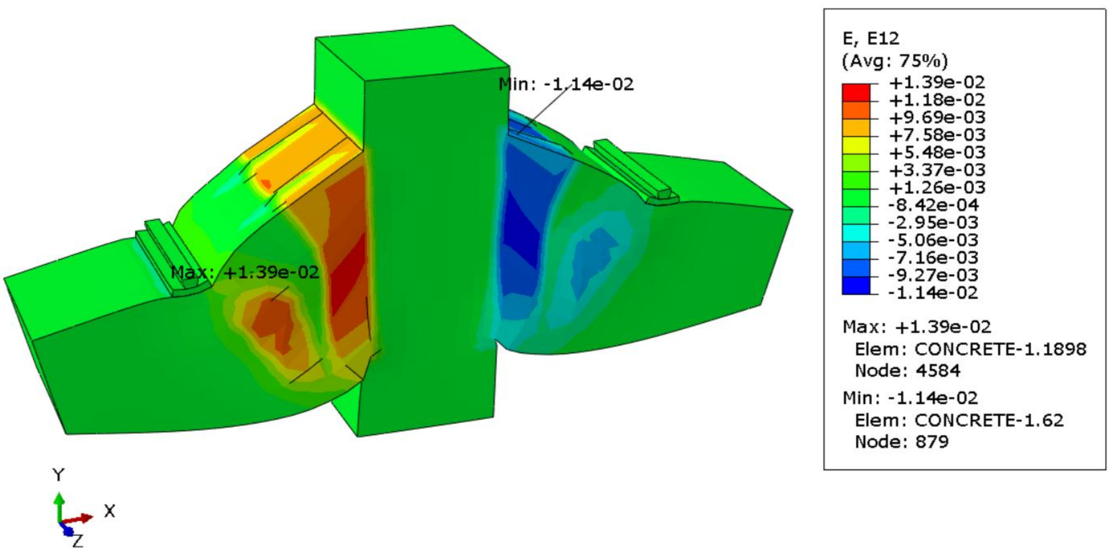
(A): (Numerical) Strain in direction (X, Y) Shear stain of CN100% specimen



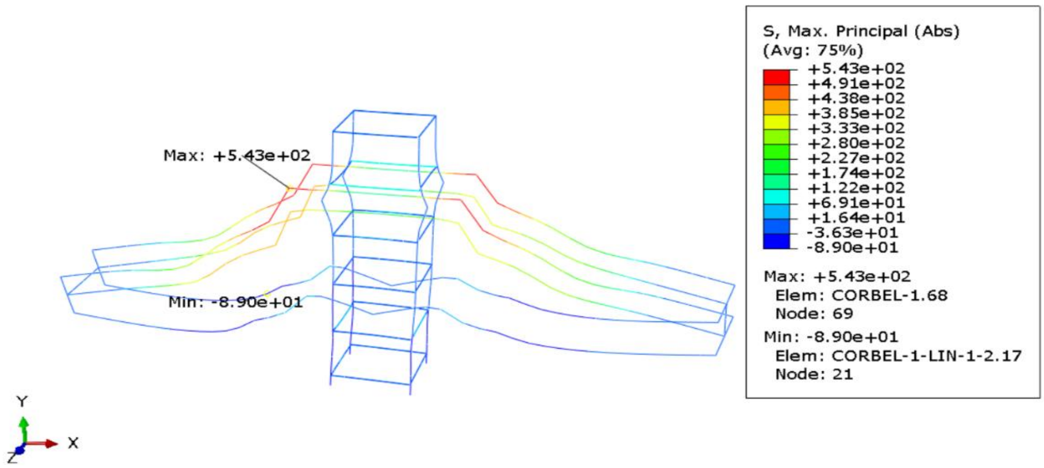
(A): (Numerical) Stress in steel reinforced of CN100% specimens



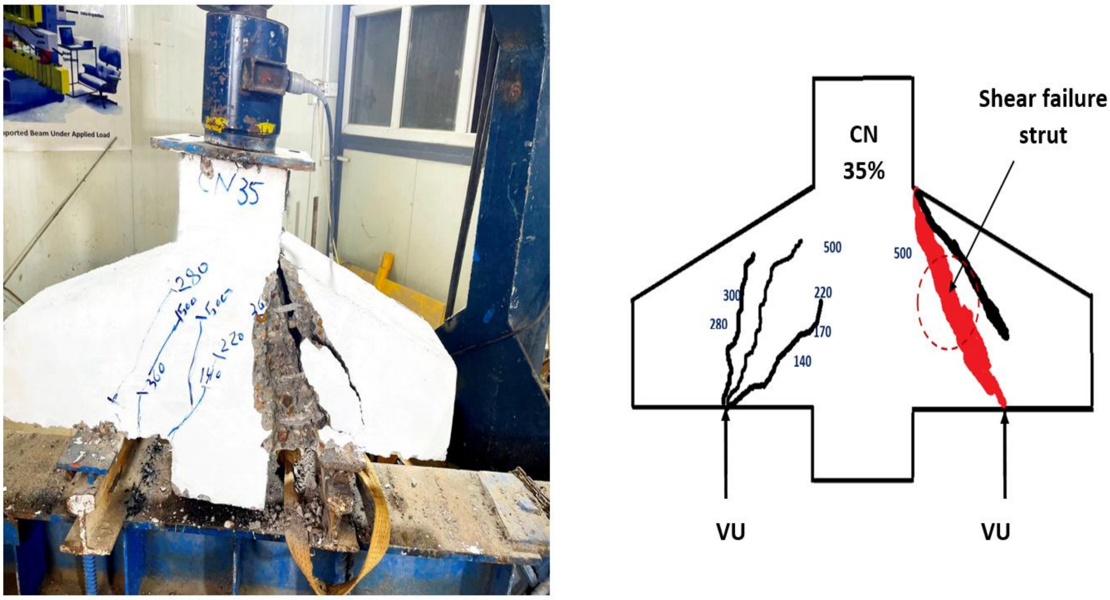
(B): (Exprmintal) Shear failure mode of the RC corbel CN65% at the strut zone



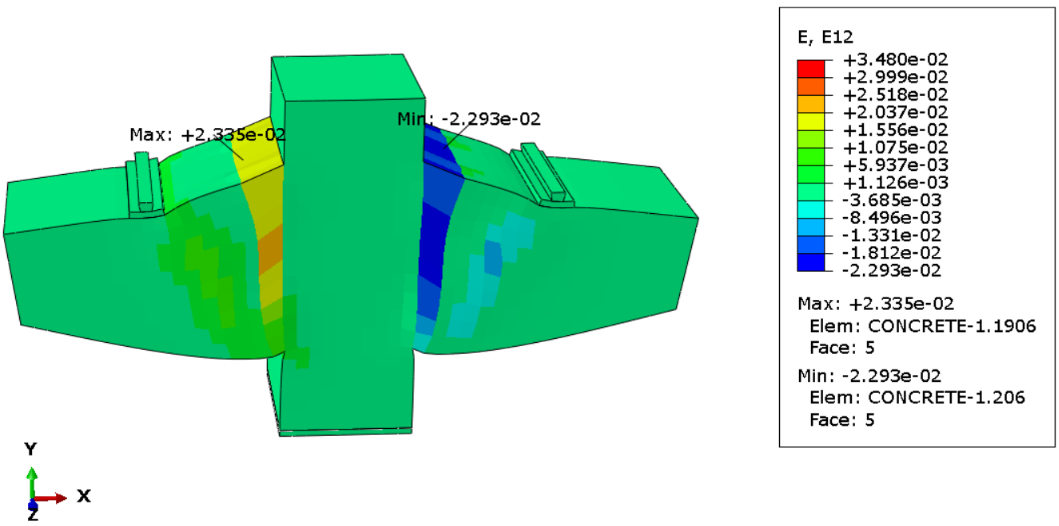
(B): (Numerical) Strain in direction (X, Y) Shear stain of CN65% specimen



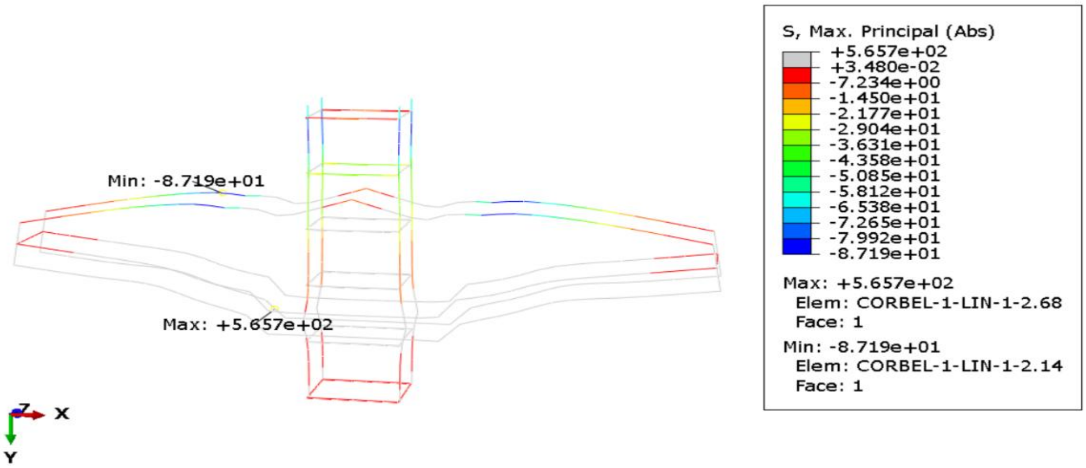
(B): (Numerical) Stress in steel reinforced of CN65% specimens



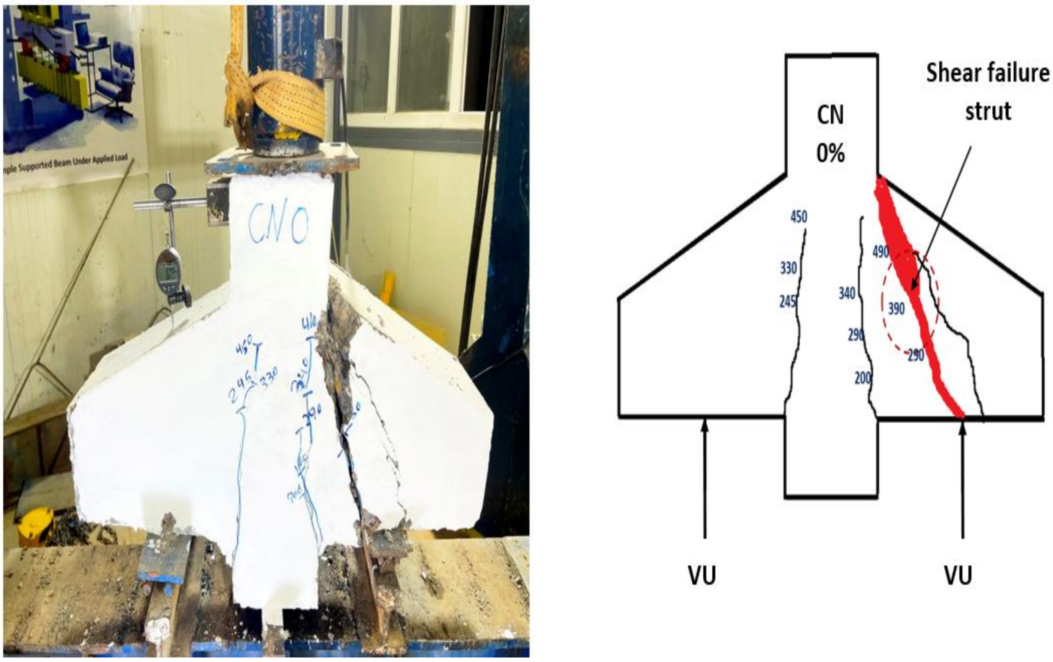
(C):   (Exprmintal) Shear failure mode of the RC corbel CN35% at the strut zone



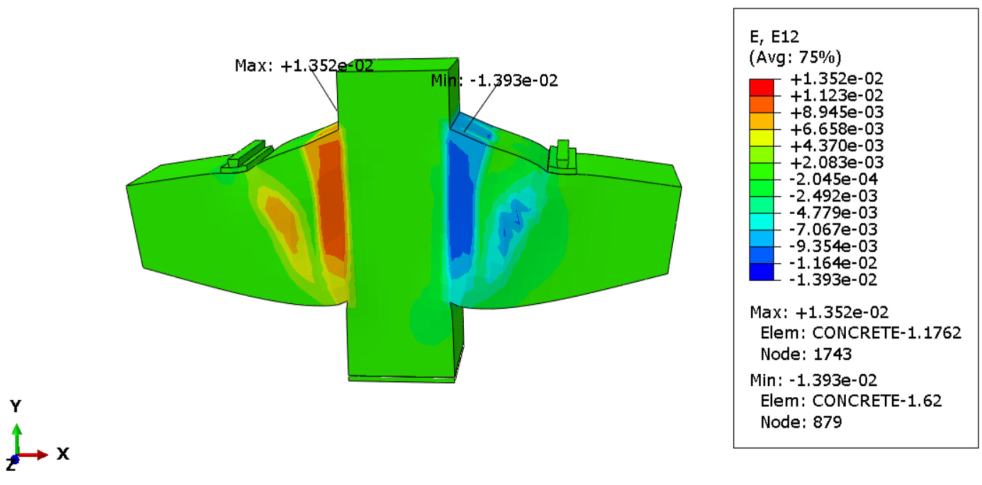
(C): (Numerical) Strain in direction (X, Y) Shear stain of CN35% specimen



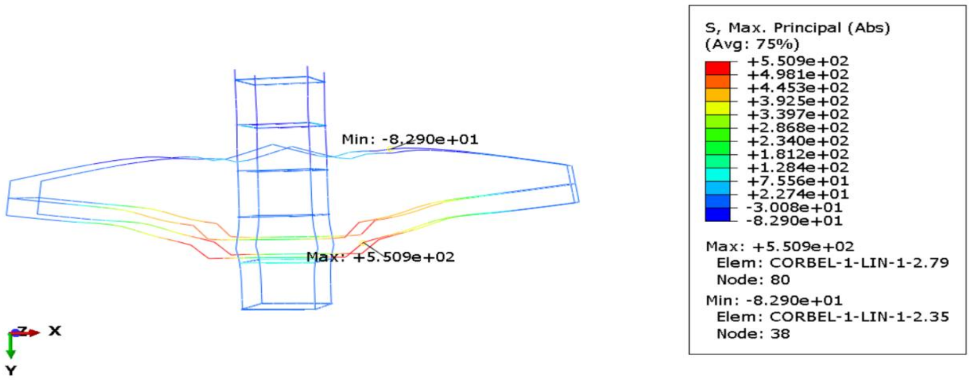
(C): (Numerical) Stress in steel reinforced of CN35% specimens



(D): (Exprmintal) Shear failure mode of the RC corbel CN0% at the strut zone



(D): (Numerical) Strain in direction (X, Y) Shear stain of CN0% specimen



(D): (Numerical) Stress in steel reinforced of CN0% specimens

Figure 14. Shear failure of the RC corbel along with the stress in steel reinforced at different recycled aggregate replacement ratios

Conclusions

From the experimental and numerical results of this study can conclude the following:
The experimental tests have shown that it is feasible to use recycled coarse aggregates obtained from damaged concrete materials in RC corbels with reasonable shear resistance provided that an A good and reliable method, which is the Strut and Tie method design method is. For all samples in this study, it has been found that increasing the percentage of recycled aggregate concrete reduces the value of first shear load of corbels significantly. Therefore, the increasing replacement accelerates shear cracking and makes corbels weaker. However, all corbels experienced same shear crack patterns which started from the supports towards to the column. Results have shown that the maximum reductions in first shear crack load are 50%.

Results have also shown that the maximum reductions in ultimate loads when the replacement rate increases from 0% to 100% are 24.03% also, the maximum reductions in corresponding displacement when the replacement rate increases from 0% to 100% are 39.61%. The study showed the possibility of using the finite element program (Nonlinear analysis program, ABAQUS/standard 2019) in modeling a numerical model that simulates reality, as the maximum difference between the numerical model and the exprmintal model regarding the ultimate load (2.92%) in (CN65%) model.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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