Experimental and numerical investigations of RC corbels strengthened by CFRP under cyclic loading.

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ABSTRACT

Reinforced concrete (RC) corbels have a significant function in distributing loads and guaranteeing structural stability. The durability and resilience of RC corbels are crucial due to various environmental phenomena, including corrosion, seismic occurrences, and cyclic loads. The use of carbon fiber reinforced polymer (CFRP) to strengthen corbels has garnered significant interest as an effective way to improve the structural performance of these elements. Even though, the literature has discussed the efficacy of CFRP, there is a knowledge deficit on the behavior of RC corbels strengthened with CFRP under cyclic loading. The study involves both experimental and numerical analysis. The accuracy of the FE model was confirmed by the comparison with the experimental data. After validation, a parametric study was conducted on the finite elements (FE) model to examine the impact of various configurations of CFRP (C1: vertical CFRP strips, C2: inclined configuration, C3: wrapped configuration). The results demonstrated a significant agreement between the experimental findings and the numerical simulation for the load-strain response and crack patterns. Utilizing CFRP in reinforced concrete corbels significantly enhances their load-bearing capacity (configurations C2 and C3, give an increase of 44%) and stiffness while reducing deformation.

Key words Reinforced concrete corbels, CFRP, cyclic loading, numerical simulation, dynamic analysis.

I. INTRODUCTION

Increased use of precast reinforced concrete components in building and bridge construction has been seen in recent decades. Corbel connections are the most typical of the many possible forms of connections between precast beams and columns(ARAÚJO *et al.*, 2017).

A corbel is a small cantilever that projects from a wall or column and is often used to support another component, such a dapped-end beam. Typically, the features that may define the corbels are the complicated flow of internal stresses and a shear span-to-depth ratio lower than one(El-Maaddawy and Sherif, 2014; ACI Committee 318, 2019). Several factors, including the loading type, the ratio of shear span to effective depth, the concrete strength, the reinforcing type, quantity, and orientation, and the geometry of the corbel, determine how reinforced concrete corbels behave. These different characteristics of the corbels result to collapse in various manners (Ozden and Atalay, 2011). Corbel damage can stem from various factors, such as excessive loads, fractures due to severe vibrations, structural fatigue, construction or design errors or code modifications. The presence of high deflection or structural instability may also be attributed to steel corrosion. Symptoms of this condition often include a reduction in corbel shear strength and brittle failure, leading to noticeable issues like excessive deflections or cracking (Assih *et al.*, 2015; Zaioune and Mezhoud, 2023). Strengthening is a technique used to compensate the loss of stiffness and the risk of cracking. The use of this approach significantly enhances the efficiency and sustainability of the building due to its advantageous characteristics, such as being lightweight, having a high tensile capacity, being easy to install, being resistant to corrosion, and having a long lifespan. Therefore, many more experimental and computational investigations have examined the potential effects of CFRP strips on the performance of reinforced concrete corbels under monotonic loading. The use of CFRP as an external reinforcement was found to exhibit a gradual and regulated response, demonstrating the efficacy of this reinforcing technique in enhancing the corbel's performance, longevity, and resistance to shear forces while preserving its structural integrity (El-Maaddawy and Sherif, 2014; Ivanova *et al.*, 2015; Sayhood, Hassan and Gh.Yassin, 2016; Al-Kamaki, Hassan and Alsofi, 2018; Abu-Obaida, El-Maaddawy and El-Ariss, 2020; Zaioune and Mezhoud, 2023). The aim of this study is to further our knowledge of the nonlinear structural response of RC corbels reinforced with CFRP under monotone and cyclic loads by conducting specific investigations. The experimental program involves subjecting reinforced concrete corbels strengthened with inclined CFRP strips to cyclic loading, beginning with a 20KN loading and continuing to unload until the failure load is reached. Subsequently, a numerical simulation was performed to examine the behavior of the RC corbel under cyclic loading with different configurations of CFRP. After validating the suggested FE model with experimental data in terms of strain vs. load, a parametric investigation was conducted. The findings are shown using load-strain, load-defection, and modes of failure curves.

II. EXPERIMENTAL PROGRAM

A. Test Specimen

The experimental program was carried out in University of Reims Champagne Ardenne (URCA). RC double-corbel specimens were developed, produced, and tested at the “Halle techologique” of ITheMM laboratory of Reims, France, to assess the structural performance of corbels under cyclic stress. The experimental model is already the subject of reference for the work of Ivanova (2013) on the mechanical behavior of short reinforced concrete corbels strengthened with CFRP. The cross section of the supporting column was 150 mm by 300 mm, and its length was 1000 mm. The depth of the corbel test specimens was 200 mm at the end and 360 mm at the face of the column. The dimensions of the corbel were 150 mm in width and 250 mm in length. The column was reinforced with four deformed bars of 14 mm diameter and supported with 11 stirrups of 6 mm diameter and a spacing of 125 mm. The corbel part was reinforced with two deformed longitudinal bars of 10 mm diameter, as the main reinforcement is located at the bottom with an effective cover of 25 mm. The horizontal closed stirrup has a diameter 6mm of steel bars.

B. Materials properties

Concrete, steel and CFRP characteristics are shown in tables 1, 2, and 3:

C. Test procedure

The hydraulic universal testing machine, of ITheMM laboratory (Fig. 1a), in maximum capacity loading of 1000 kN, was used to test the corbel specimen (Fig. 1b). The average loading speed value was 0.02 kN/s. As shown in Fig. 1c, the strain was measured at the main tie rod of the corbel using strain gauge G1.

TABLE 1. Material properties for concrete damaged plasticity model (CDP model)

Concrete class B30			
Elasticity parameters		**Plasticity parameters**	
Young's modulus (GPa)	31,22	Dilation angle	31
		Eccentricity	0,1
Poisson's ratio	0,2	fb0/fc0	1,16
		K	0,66
		Viscosity parameter	0

TABLE 2. Material properties for steel

Mass density(kg/m³)	Young's modulus (GPa)	Poisson's ratio	Yield Stress (MPa)
7850	210	0.3	520

TABLE 3. Material properties of CFRP and Adhesive

Material	Design thickness (mm)	Young's modulus (GPa)	Ultimate Elongation %	Tensile strength (MPa)
CFRP	0.129	220	1.7	3200
Adhesive	-	4.1	-	

a) b) c)

FIGURE 1. a) Test setup of reinforced corbel b) Configuration of CFRP c) Location of strain gauge on steel bars (main reinforcement)

All corbel specimens were tested under three-point bending loading, with the vertical force, applied to each specimen at the top of the column (Fig. 1a). The shear span-to-effective depth ratio, a/d = 0.45, determined the support's location relative to the column faces. The tested specimen was reinforced by applying two inclined layers of CFRP (Fig. 1b).

D. Loading sequence

The tested specimen followed a loading-unloading cycle. The cycle initiated with a 20 kN load and progressed until reaching the failure load of 385 kN. Fig. 2 shows the testing loading protocol.

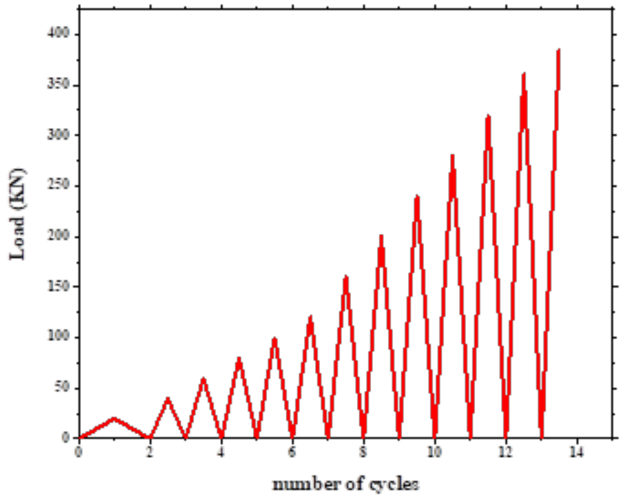

FIGURE 2. Loading protocol

III. NUMERICAL SIMULATION

The aim of this part was to assess the efficiency of ABAQUS CAE 2018 in accurately predicting the static and dynamic responses of the tested corbel specimens. That software program is highly reliable and is based on the finite element method to analyze the responses of structures and solids.

A. Concrete Constitutive Model

The concrete damaged plasticity (CDP) model is a constitutive model employed in finite element analysis to simulate the response of concrete under different loading conditions, including both static and dynamic loading. The assumption is made that the main causes of failure are tensile cracking and compressive crushing. The CDPM utilizes the equations developed by (Lubliner *et al.*, 1989), incorporating the adjustments suggested by (Lee and Fenves, 1998).This model integrates principles from plasticity theory and damage mechanics, making it highly efficient in capturing the complete inelastic response of concrete under both tension and compression, including various damage characteristics. The nonlinear behavior of concrete was represented by the damage plasticity input parameters, which included inelastic strain, cracking strain, compression damage, tension damage, and other parameters that are indicated in Table 1. Whereas these parameters collectively define the behavior of concrete in the CDP model within Abaqus, allowing for accurate simulation of its nonlinear response under various loading conditions, and were calculated using a simplified concrete damage plasticity model based on the equations proposed by(Hafezolghorani *et al.*, 2017).

B. Modelling

The concrete part was simulated using a C3D8R continuum (solid) element, which is an 8-node linear brick with reduced integration and hourglass control. The steel reinforcement in concrete was simulated using two nodes. The steel bars reinforcement was modeled using a truss element

T3D2, which consists of two end nodes. Each node has three translation degrees of freedom. The Carbon fiber reinforced polymer (CFRP) was modeled using the S4R shell element, which consists of four nodes and six degrees of freedom in each node. Every node has three degrees of freedom for both translation and rotation. The interaction between concrete and steel is modelled using embedded constraint option. This interaction restricts the translational degree of freedom of the nodes of the embedded components for the response of the host elements (C3D8R, hexagonal eight-node brick elements). The tie is used to define the interaction between concrete and CFRP strips. Fig. 3 depicts the element types of concrete, steel, and CFRP respectively. (Banu, Jaya and Vidjeapriya, 2023; Zaioune and Mezhoud, 2023).

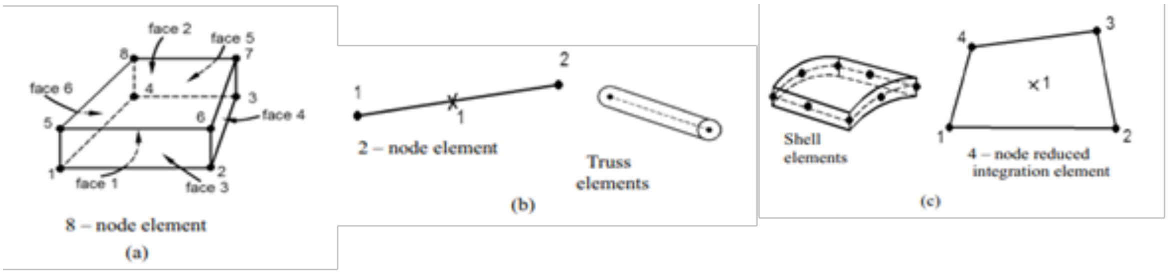

FIGURE 3. **The element types of a) concrete, b) steel, and c) CFRP**

C. The finite element Mesh

To get accurate results, the mesh size of every element in the finite element model was intentionally standardized to guarantee that no two materials are assigned the same node. Furthermore, to achieve an optimal balance between computational efficiency and precision while minimizing the occurrence of errors. The concrete C3D8R mesh element has dimensions of 20 x 20 mm. The T3D2 reinforcing steel has a mesh size of 20 x 20 mm, which was also used for the CFRP strips. Fig. 4 depicts the meshing of concrete elements, steel reinforcement, and CFRP strips.

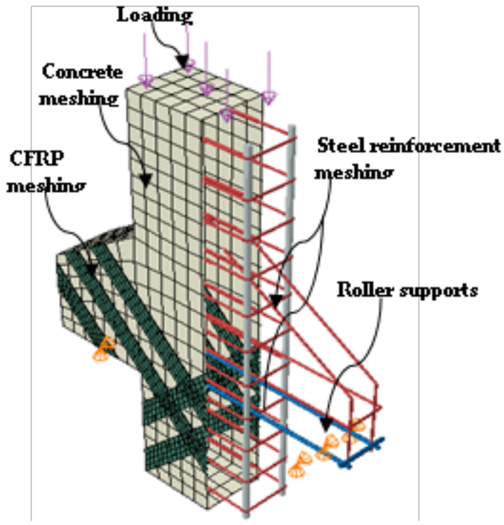

FIGURE 4. **Meshing of concrete element, steel reinforcement, and CFRP strips**

D. Boundary Conditions and Loading

The reinforced concrete corbel model was subjected to loads and boundary conditions in order to simulate the actual experimental test setup. Roller supports were used as supports for the specimens. The upper section of the column area was subjected to cyclic stress in order to investigate the response of reinforced concrete corbels under cyclic loading conditions, as seen in Fig. 4.

E. CFRP Strengthening configurations

Fig. 5 illustrates the development and analysis of four model RC corbels, to comprehend the behavior of an RC corbel and its response to cyclic loading with various configurations. Three additional corbels are examined, each exhibiting a distinct configuration of external strengthening by CFRP whit the same ratio of shear span to effective depth. Corbel specimen C1 uses vertical CFRP strips, Corbel specimen C2 uses an inclined configuration, and Corbel specimen C3 uses a wrapped configuration.

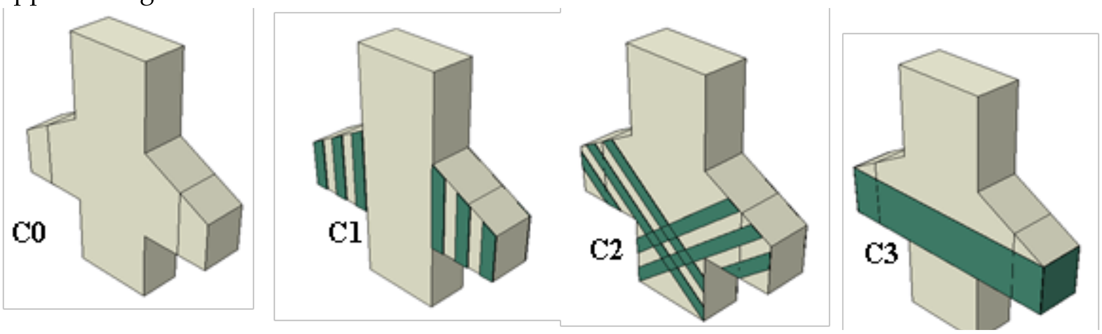

FIGURE 5. CFRP configurations

IV. VALIDATION OF THE PROPOSED NUMERICAL MODEL

The experimental study conducted by Ivanova et al., (2014) was considered to validate the predictions of the computational model under static loads. An experimental test on a RC corbel that was strengthened with CFRP carry out. The dimensions of the tested corbel were kept the same. Additionally, a control corbel without any external strengthening was selected for comparison in this verification. The finite-element prediction is shown in Fig.6 and Fig.7, and it exhibits a high degree of concordance with the published experimental data of Ivanova et al., (2014).

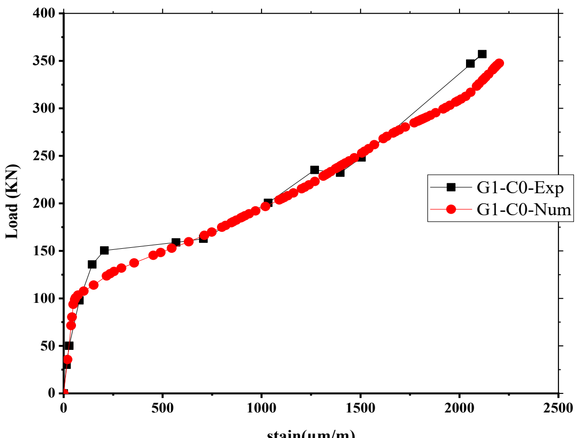

FIGURE 6. Comparison between experimental (Ivanova et al., 2014) and numerical curve of control corbel C0

However, to validate the predictions of the computational model under repeated loading, was considered the experimental work that was accomplished. The reinforced concrete corbel was external strengthened with two layers of CFRP in the form of inclined strips. The corbel was subjected to cyclic loads until it failed. The finite-element predictions of the load vs strain envelope curve and the crack pattern in Fig. 8 and Fig. 9 are compared with the experimental results, which exhibit a high degree of agreement.

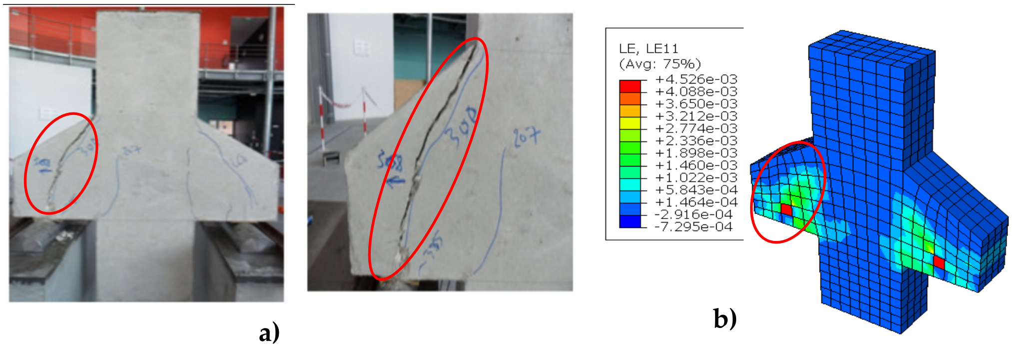

FIGURE 7. **Cracks pattern of a) control specimen C0 (Ivanova *et al.*, 2014) and b) the numerical simulation results of corbel specimen C0**

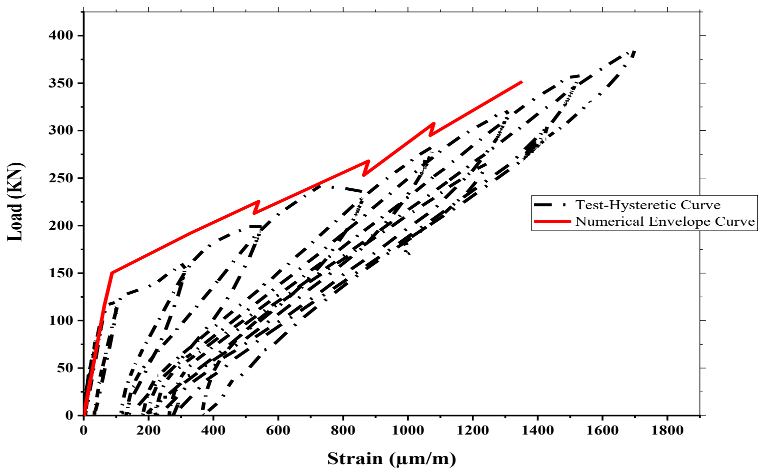

FIGURE 8. **Comparison between experimental hysteretic and numerical envelope curves of corbel C2**

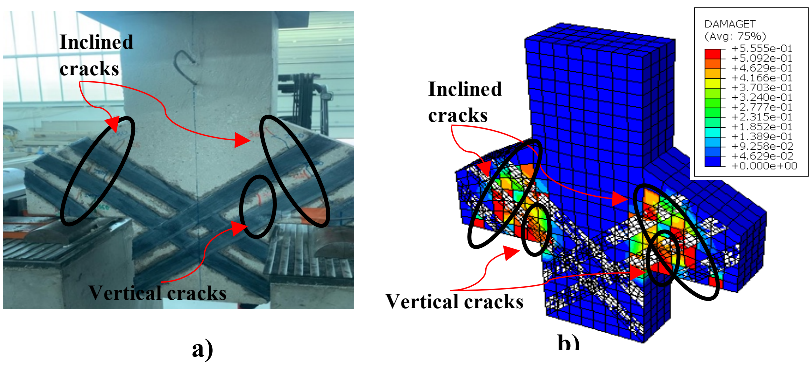

FIGURE 9. **Cracks pattern of a) strengthened corbel C2 and b) numerical results of corbel C2 using the DAMAGET parameter, which represents concrete damage under tension.**

It is important to note that in the numerical test using the CDP behavior model, concrete failure is typically indicated by monitoring damage criteria based on stress and strain thresholds. When these thresholds are exceeded in a finite element region, it suggests critical material damage and implies failure. To precisely determine the failure point, the "concrete failure" option is essential. However, in this study, we have not included this option. Therefore, the CDP model remains active, as observed in the envelope curve of Fig. 8, and the initiation of cracking and failure is controlled by default settings. However, the finite element (FE) model accurately predicted the locations of failure characterized by a small vertical crack at the intersection of the corbel and column, and a wide inclined crack extending from the bearing plate to the upper slope of the corbel. These locations are indicated by black circles in Figs. 9a and 9b.

IV. PARAMETRIC STUDY

This section will present the results of numerical work for groups (I) and (II) which consist of four corbel specimens, as shown in Fig. 4b. Specimens in group (I) were subjected to static loading up to failure. Specimens in group (II) were subjected to cyclic loading under load-control as illustrated in the protocol loading that is described in Fig. 2.

A. Numerical results and discussions of Group (I)

Load-strain behavior

The load versus strain curves obtained from the primary reinforcement location of the RC corbel demonstrate the efficacy of CFRP in improving the structural performance of RC corbels. As illustrated in Fig.10 the unreinforced corbel (C0) shows a strain of 2000µm/m, accompanied by a load of 250 kN. On the other hand, the inclined (C2) and wrapping (C3) configurations demonstrate the beneficial impacts of CFRP. The specimen C2, a strain of 1400 µm/m and a load of 400 kN are observed, whereas in C3, a strain of 1000 µm/m and a load of 385 kN are seen. The findings confirm that CFRP can significantly improve the load-carrying capacity of RC corbels when subjected to static loading. The corbel strengthened by inclined strips show a 44% increase in the ultimate load.

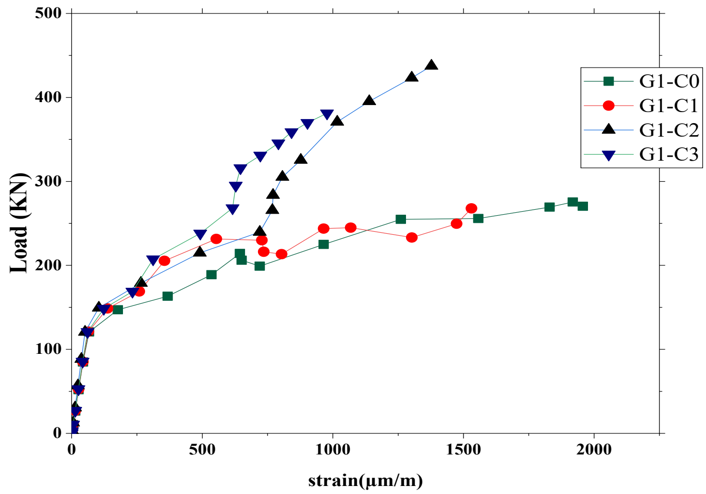

FIGURE 10. Load–strain curves of corbel specimens C0, C1, C2, C3.

B. Numerical results and discussions of Group (II)

The control specimen C0 (Fig. 11), displays consistent and elastic behavior throughout the first cycles, which is indicative of the early loading phases. As the cyclic loading progresses, an obvious change takes place with larger cycles, especially when the load exceeds 250 kN. The following cycles vary between large and narrow configurations, indicating a shift from elastic to inelastic behavior. The last cycle shows a load of 385 kN accompanied by a substantial rise in deflection, signifying the occurrence of cyclic softening. The vertically strengthened corbel C1 (Fig.10), behaves similarly to C0, displaying identical cyclic characteristics but with a notable reduction in deflection by approximately 74%.

The elevated load experienced in the recent cycles correlates with amplified deflections, indicating the influence of cyclic loading on the corbel's performance. On the other hand, both strengthened corbels C2 and C3 exhibit a uniform and consistent cyclic response over the whole loading protocol (Fig. 12). The load capacity of 385 kN was achieved effectively for both configurations, with C2 experiencing a deflection of 40 mm and C3 experiencing a deflection of 29 mm.

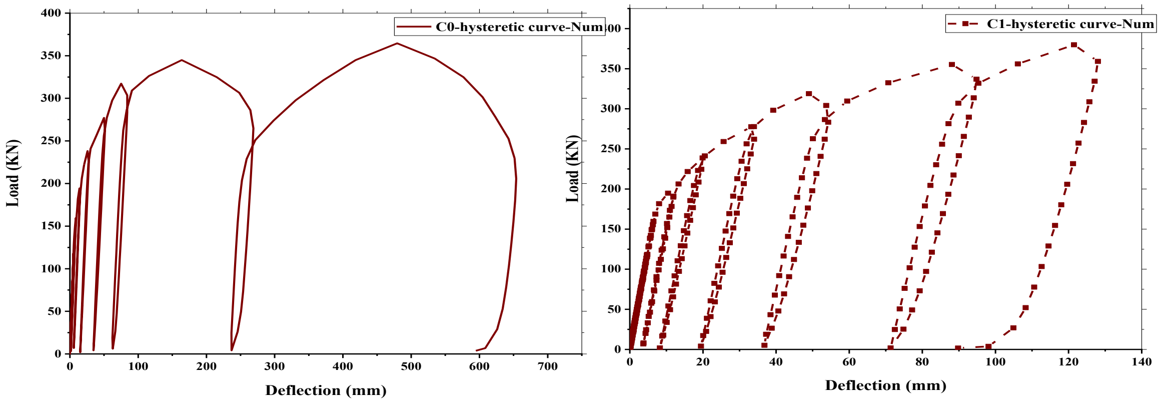

FIGURE 11. **Load–deflection curves of corbel specimens C0 and C1 under cyclic loading.**

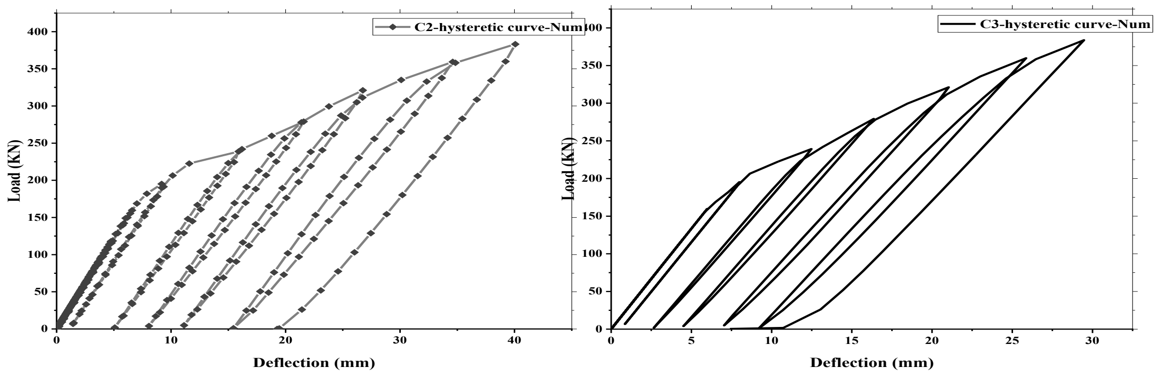

FIGURE 12. **Load–deflection curves of corbel specimens C2 and C3 under cyclic loading.**

V. CONCLUSION

The use of carbon fiber-reinforced polymer (CFRP) in RC corbels has shown a significant and positive effect on their structural response when subjected to different types of loads. The load-bearing capacity of RC corbels C2 and C3 is greatly increased, reaching 44%. This demonstrates the effectiveness of CFRP in enhancing the ability of corbels to withstand applied loads. The RC corbels C2 and C3 exhibit consistent and uniform cyclic behavior, demonstrating enhanced stiffness and stability under both static and cyclic loads, compared to the unreinforced and vertically reinforced corbels (C0 and C1). The cyclic loading effects, which are identified by the widening of cycles and the higher deflection in certain configurations, enhance our comprehension of the dynamic response of corbels. The presence of cyclic softening in C0 and C1 highlights the need to consider durability and fatigue resistance.

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