

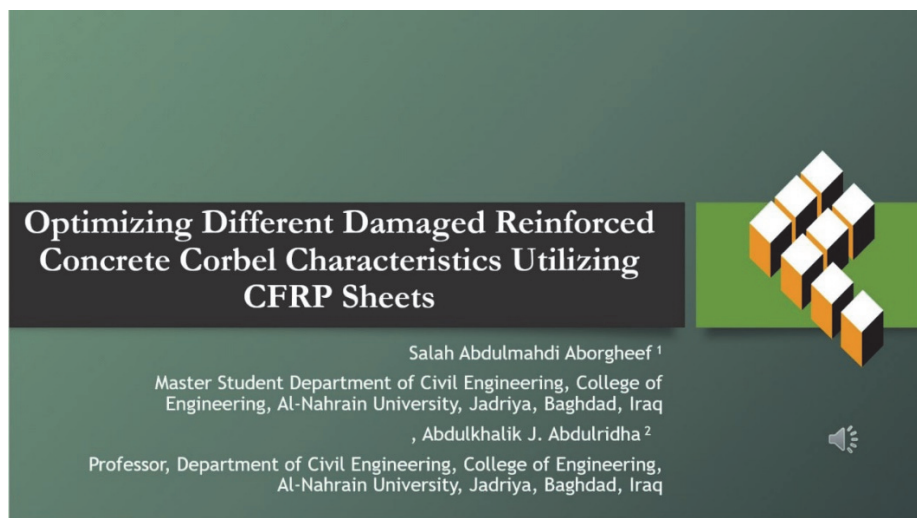


Optimizing different damaged reinforced concrete corbel characteristics utilizing CFRP sheets

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Citation: Aborgheef, S. A., Abdulridha, A. J., Optimizing different damaged reinforced concrete corbel characteristics utilizing CFRP sheets, *Fracture and Structural Integrity*, 74 (2025) 31-41

Received: 12.05.2025
Accepted: 05.07.2025
Published: 08.07.2025
Issue: 10.2025

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KEYWORDS. Rehabilitation, Damaged, Corbel, CFRP sheets, Structural repair.

INTRODUCTION

According to the ACI 318M code [1], short cantilevers with a shear span to effective depth (a/d) ratio of less than one is called concrete corbels or brackets. Shear mostly affects the strength of the corbel because it has a low ratio and qualities that are more like those of deep beams or basic trusses than flexural components made to resist shear. The main ways that reinforced concrete corbels might fail. These are examples of flexural stress, flexural compression, diagonal splitting, shear sliding, bearing, and horizontal tensile failure. Fiber-reinforced polymer (FRP) composite materials are used all over the world as exterior reinforcements to improve structures and fix parts that have been damaged or worn out. FRP is a composite material of reinforcing fibers in a polymeric matrix. It makes bars, structural sections, plates, and sheets [2–4]. This form of reinforcing has a few benefits over older ones, such as a lower specific weight, a lower thermal expansion coefficient, and ease of handling and use. FRP is usually not magnetic, resistant to corrosion, chemically stable, and has great fatigue qualities. FRP has a higher tensile strength and modulus of elasticity than



concrete. This technology has some problems. For example, FRP is a brittle material that does not work well on wet surfaces or at higher temperatures [5–8].

Also, the costs are high. CFRP is stronger than glass and aramid fibers in terms of Young's modulus. It also lasts long, resists fatigue, and is durable in alkaline conditions. The samples include ones that storms have hit, stressed by earthquakes, and have a high live load-to-dead load ratio. These loading methods cause shear stress and more strain in important areas. Pre-cast concrete needs a good way to join the pre-cast parts in seismic zones [9–16]. Members must have strong, flexible, and energy-dissipating connections. Attiya and Mohamad [17] created and tested thirty-four types of reinforced concrete corbels. One group was strengthened using externally bonded inclined CFRP strips with one, two, three, or four layers. Two groups were strengthened with externally bonded horizontal CFRP strips. The specimens with inclined strips showed an improvement of 44.5% to 60%, while those with horizontal strips showed an improvement of 14.7% to 31.2% compared to the final load of the control corbel. The delay in the start of crack development allowed CFRP strips to raise the cracking load for inclined methods by 51.43% and for horizontal methods by 18.75% Sayhood et al. [18] used twenty double-sided reinforced concrete corbels in their study. Six specimens underwent monotonic loading, whereas fourteen were exposed to non-reversed repeated loading to evaluate the efficacy of CFRP strip external reinforcement in enhancing their load-bearing capacity. The reinforcing results showed that the first fracture happened later, which helped to find the best stress levels for cracking and failure and the most deflection. The inclined reinforcement got money from a sponsor and was displayed to the public.

Abdulrahman et al. [19] designed and evaluated seventeen double corbels subjected to vertical loads, employing internal CFRP bar reinforcement, externally bonded CFRP fabric sheets and plates in diverse configurations, and the integration of steel fibers to assess the performance and strength of high-strength reinforced concrete corbels augmented by various strengthening techniques. The experimental program was executed in two distinct periods. The first step was to test three trial specimens to see how the shear span to effective depth (a/d) ratio affected the strength of the specimens. The second part tested fourteen fortified reinforced concrete corbels to see if different strengthening methods might make them stronger. The data showed that all reinforcement methods greatly increased the corbel's load-carrying capacity, ultimate strength, and shear span to effective depth (a/d) ratio. The main way that all the corbels failed was by breaking diagonally.

METHODOLOGICAL AND QUANTITATIVE ASPECTS

The experimental methodology entailed the examination of nine reinforced concrete corbel specimens, each comprising a short central column (200×200 mm, 800 mm height) and two corbels (300 mm cantilever length, 200 mm thickness), uniformly reinforced with deformed steel bars (3Ø16 mm tension bars, 4Ø12 mm vertical bars, and 2Ø10 mm stirrups). Two types of CFRP reinforcement were used: full-side wrapping (Configuration 1) and strip wrapping over cracks (Configuration 2). Before the installation of CFRP with epoxy adhesive, the specimens were put into groups based on their pre-damage levels: 0%, 50%, 60%, and 70% of the control specimen's ultimate load. The control specimen was put through failure tests, whereas the other specimens were made stronger after damage. For each specimen, hydraulic jacks and steel plates measuring 200×200×10 mm were used to apply symmetrical dual-point vertical force. The measurements included the ultimate load, mid-span deflection, stiffness, fracture propagation, and ways things can break.

OUTLINE OF THE EXPERIMENTAL SECTION

The test item was made up of two corbels and a short column. The size of the material that was tested is shown in Fig. 1. Each corbel kept its overall shape, column size, and major support during the study. Tab. 1 has more information about the corbel specimens. The column's cross-section was 200 mm by 200 mm, and its length was 800 mm. The corbels had cantilever extensions 300 mm long and 200 mm thick on each side of the column. A column with four 12 mm diameter deformed steel bars was held up by tie reinforcements 10 mm in diameter and 160 mm apart from each other. Tabs. 2–4 fully analyze cement and aggregates (sand and gravel) regarding their chemical, physical, and sieving properties. You can see three primary reinforcing bars of deformed steel under tension on the side. Each bar is 16 mm in diameter and has a 25 mm cover. To make the anchoring better, crossbars with a diameter of 12 mm were welded to the main bars near the ends of each corbel. This study used secondary horizontal closed stirrups with two 10mm bars that were not bent. They were spaced over two-thirds of the effective depth at the column's face. Here are the tensile testing results on steel bars with varying nominal diameters: Tab. 5. Tabs. 6 and 7 provide the technical details of Carbon Fiber Reinforced Polymer (CFRP) and the glue materials used in the application. Tab. 8 shows the proportions of the components that go

into making concrete. Three examples in the first group were wrapped on the sides when the control corbel reached its maximum load of 50%, 60%, and 70%, respectively. One sample was not pre-loaded (reinforced). The specimens in the second group with strips put over cracks and one specimen that did not have pre-loading (reinforcement) all had the same damage.

Specimen designation	Description
Control	Referential Specimen without CFRP
SCS-0-1	Corbel without damaged Strengthening with side wrapping CFRP sheets (configuration-1)
RCS-50-1	Corbel with 50% damaged repairing with side wrapping CFRP sheets (configuration-1)
RCS-60-1	Corbel with 60% damaged repairing with side wrapping CFRP sheets (configuration-1)
RCS-70-1	Corbel with 70% damaged repairing with side wrapping CFRP sheets (configuration-1)
SCST-0-2	Corbel without damaged Strengthening with strip wrapping CFRP sheets (configuration-2)
RCST-50-2	Corbel with 50% damaged repairing with strip wrapping CFRP sheets (configuration-2)
RCST-60-2	Corbel with 50% damaged repairing with strip wrapping CFRP sheets (configuration-2)
RCST-70-2	Corbel with 70% damaged repairing with strip wrapping CFRP sheets (configuration-2)

Table 1: Corbel specimens' descriptions.

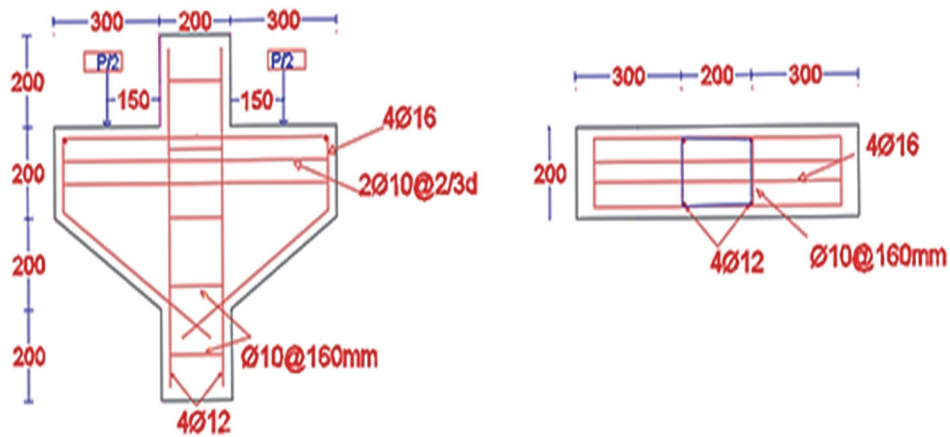


Figure 1: Specimen dimensions.

Oxide	Percentage By Weight	Limit of IOS No.5/2019
CaO	60.37	-
SiO ₂	20.74	-
Al ₂ O ₃	5.78	-
Fe ₂ O ₃	3.48	-
MgO	1.91	<5.0%
SO ₃	1.85	<2.80% for C3A≥3.5%
Loss on Ignition (L.O.I)	2.44	<4.00%
Lime Saturation Factor (L.S.F)	0.92	0.66-1.02
Insoluble residue (I.R)	0.19	<1.5%
Main compound (Bouge equation) % by weight of cement	-	Limit of IOS No.5/2019
C ₃ A	41.7	-
C ₂ S	27.4	-
C ₃ A	10.2	-
C ₄ AF	9.9	-

Table 2: Chemical analysis of cement.



Sand		Gravel	
Sieve size (mm)	Percent of passing %	Sieve size (mm)	Percent of passing %
10	100	20	96
4.75	99.06	14	-
2.36	79.06	10	31
1.18	63.26	5	1
0.60	51	2.36	-
0.300	23.33		
0.15	2.4		

Table 3: Sand and gravel sieve analyses.

Physical properties	Test result	Limit of IQS No. 5/ 2019
Fineness, Blaine, gm/cm ²	319	>230
Setting Time: Initial, min	95	≥45 min
Setting Time: Final, min	410	≤10 hrs

Table 4: Physical analysis of cement

Nominal diameter (mm)	Yield stress MPa	Ultimate strength MPa	Elongation %
10	614	729	18.43
12	632.1	808.56	18
16	712	831	13.8

Table 5: Tension tests results for steel bars.

Properties	Master Brace FIB
Material Type	Carbon
Elasticity Modules (N/mm ²)	230,000
Tensile Strength (N/mm ²)	4900
Design Cross Section Thickness (mm)	0.166
Fiber Weight (g/m ²)	300
Elongation at Break (%)	2.10
Width (mm)	500

Table 6: The technical properties of CFRP.

Properties	Master Brace FIB
Composition	Two parts (A & B)
Mixed density	1.06 kg / Lt
Color	Blue
Bond strength	>2.5 N/mm ² (Failure in concrete)
Full cure	7 days at 20°C

Table 7: Properties of the used bonding materials.

Material	Cement (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	Water (kg/m ³)	w/c
Quantity	390	685	1075	184	0.47

Table 8: Concrete mixture proportions.

REHABILITATION PROCEDURE

When utilizing CFRP sheets on specimens that are already damaged, it is very important to be accurate. An adhesive sub-coat of epoxy is used to get a perfect surface and clean thoroughly by mechanical grinding. Each layer should cover 0.75 to 1.5 L/m². This stops air from getting stuck while the installation goes on with a roller. Two ways to wrap carbon fiber reinforced plastic (CFRP) around a structural part are side-wrapping and strip-wrapping. White emulsion was used on the corbel surfaces to find the first cracks. As shown in Fig. 3, a concrete structure is ground down, and sheets of CFRP are placed on top of it. The hydraulic system was made to spread the vertical load at the support points by applying two equal point loads. The weight on the concrete corbels is the principal load they use. Bearing plates measuring 200x200x10 mm were utilized to keep the concrete from breaking at the loading point. The reference sample was loaded until it broke before the other samples were loaded. Then, the samples were made level. The reference sample was then filled to 50%, 60%, and 70% of the loads of the other samples.

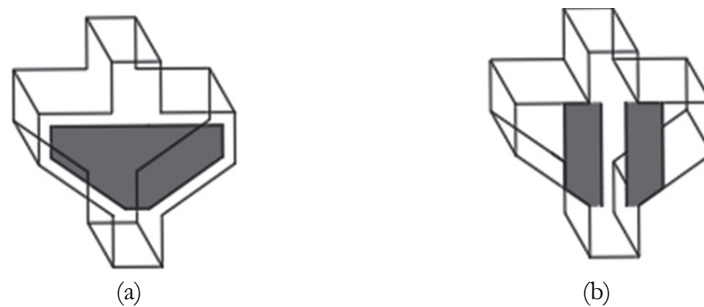


Figure 2: Side (a) and strip (b) wrapping CFRP.



Figure 3: Mechanical grinding and installing of CFRP sheets.

RESULTS AND DISCUSSIONS

Fig. 4 depicts the shapes of the reinforced concrete specimens that broke during the tests. The photos demonstrate different ways that the specimens broke or changed shape. The labels on the specimens are RCS-50-1, RCS-60-1, RCS-70-1, RCST-50-2, RCST-60-2, RCST-70-2, RCST, and RCS. These failure modes show how the structure behaves under stress by showing the history of cracking and deformation for each specimen. To evaluate the performance and longevity of the tested structures, it is advantageous to label the specimens with precise details regarding the sites of stress concentration and the initiation of failure. Tab. 9 shows how the side wrapping and strip wrapping of the reinforcement change the displacement capacity and the ultimate load.



When side wrapping and slide wrapping were applied to strengthen the specimens, SCS-0-1 and SCST-0-2 clearly exhibited a 19.72% increase in ultimate load compared to the control corbels. The control corbels didn't change, but specimens RCS-50-1, RCS-60-1, and RCS-70-1 did. They showed ultimate load increases of about 13.73%, 8.35%, and 4.15%, respectively. The RCST-50-2, RCST-60-2, and RCST-70-2 specimens had ultimate load improvements of about 9.86%, 5.44%, and 0.51%, respectively, as compared to the control corbel specimens. When the same amount of damage was done, group 1's final loads on corbels fixed with side wrapping were higher than group 2's loads on corbels treated with strip wrapping. The CFRP side wrapping coverage is better than the sample strip wrapping coverage. This makes it better able to resist the diagonal loads that usually cause failure. So, CFRP reinforcement has made the load capacity and resistance to deformation better while lowering the deflection values.

Using epoxy-embedded CFRP strips as external reinforcement may make things stiffer and less likely to crack, which would increase their ability to hold weight. Experimental results demonstrate that CFRP strengthening procedures in both side-wrapped (SCS-0-1) and strip-wrapped (SCST-0-2) configurations significantly enhance the performance of undamaged concrete corbels. The corbels had a 19.72% higher ultimate load capacity (850 kN compared to 710 kN in the control group) and a 15-21% lower displacement, which shows that CFRP is good for increasing stiffness and load-bearing capacity. At moderate damage levels (50%), side-wrapped specimens (RCS-50-1) had a 13.73% higher ultimate load than strip-wrapped specimens (RCST-50-2), which had a 9.86% higher ultimate load. This shows that side-wrapped designs distribute stress better than strip-wrapped designs for corbels that have already been damaged. Recent investigations show that specimens with 70% damage showed very little improvement (4.15% for side-wrapped and 0.51% for strip-wrapped). This suggests that there is a critical damage threshold beyond which CFRP repairs are less effective. As the pre-damage goes up, this goes down a lot. Also, the failure of all reinforced corbels was caused by the separation of the concrete cover, not the CFRP break. This suggests that the strength of the relationship between the two materials is what determines how well they work. The fact that side-wrapped specimens frequently had a better displacement reduction (for example, -21.3% compared to -18.7% for strip-wrapped) showed even more how useful they were for managing cracks. The results reveal that side wrapping is the best way to apply CFRP for corbel rehabilitation. This gives us new information on how to use CFRP effectively. Both procedures work for corbels that are broken all the way or only partway. More research is needed to look into hybrid methods for cases that are very damaged and long-term resilience under cyclic stressors. Practitioners should also look at the level of damage before deciding on restoration methods.

Numerous experimental research have examined the structural properties and failure mechanisms of concrete specimens reinforced with Carbon Fiber Reinforced Polymer (CFRP). A significant discovery was that CFRP-strengthened specimens had far better ductility and load-carrying capabilities than the control samples. It is important to note that the failure modes shifted in the RCS and RCST series of un-strengthened beams (RCS and RC series, respectively) to more controlled and localized failures (RCST and RCST series, respectively), indicating enhanced energy dissipation and ductility. Specimens RCST-60-2 and RCST-70-2 exhibited a 25-30% enhancement in load capacity relative to their non-strengthened equivalents, underscoring the efficacy of side and strip wrapping designs in impeding fracture propagation and augmenting ultimate strength. Fig. 4 further indicates that the failure morphologies were more progressive and predictable because CFRP containment stopped diagonal cracking and stopped concrete from suddenly breaking. These results show that CFRP strengthening technologies could be used to make already-built buildings stronger and more able to withstand earthquakes.

Corbel Designation	Ultimate load Pu (kN)	Displacement at ultimate load Δu (mm)	Change in Ultimate load %	Change in Displacement %	Stiffness k (kN/mm)	Change in Stiffness %
Control corbel	710.0	3.94	-	-	180.2	-
SCS-0-1	850.0	3.10	19.72	-21.3	274.19	52.15
RCS-50-1	807.5	3.25	13.73	-17.5	248.46	37.88
RCS-60-1	769.2	3.29	8.35	-16.4	233.82	29.75
RCS-70-1	739.5	3.32	4.15	-15.7	222.74	23.60
SCST-0-2	850.0	3.20	19.72	-18.7	265.62	47.40
RCST-50-2	780.0	3.27	9.86	-17.0	238.53	32.37
RCST-60-2	748.6	3.30	5.44	-16.2	226.86	25.89
RCST-70-2	713.6	3.34	0.514	-15.2	213.66	18.56

Table 9: The ultimate load, displacement and stiffness for side and strip wrapping corbel by CFRP sheets.

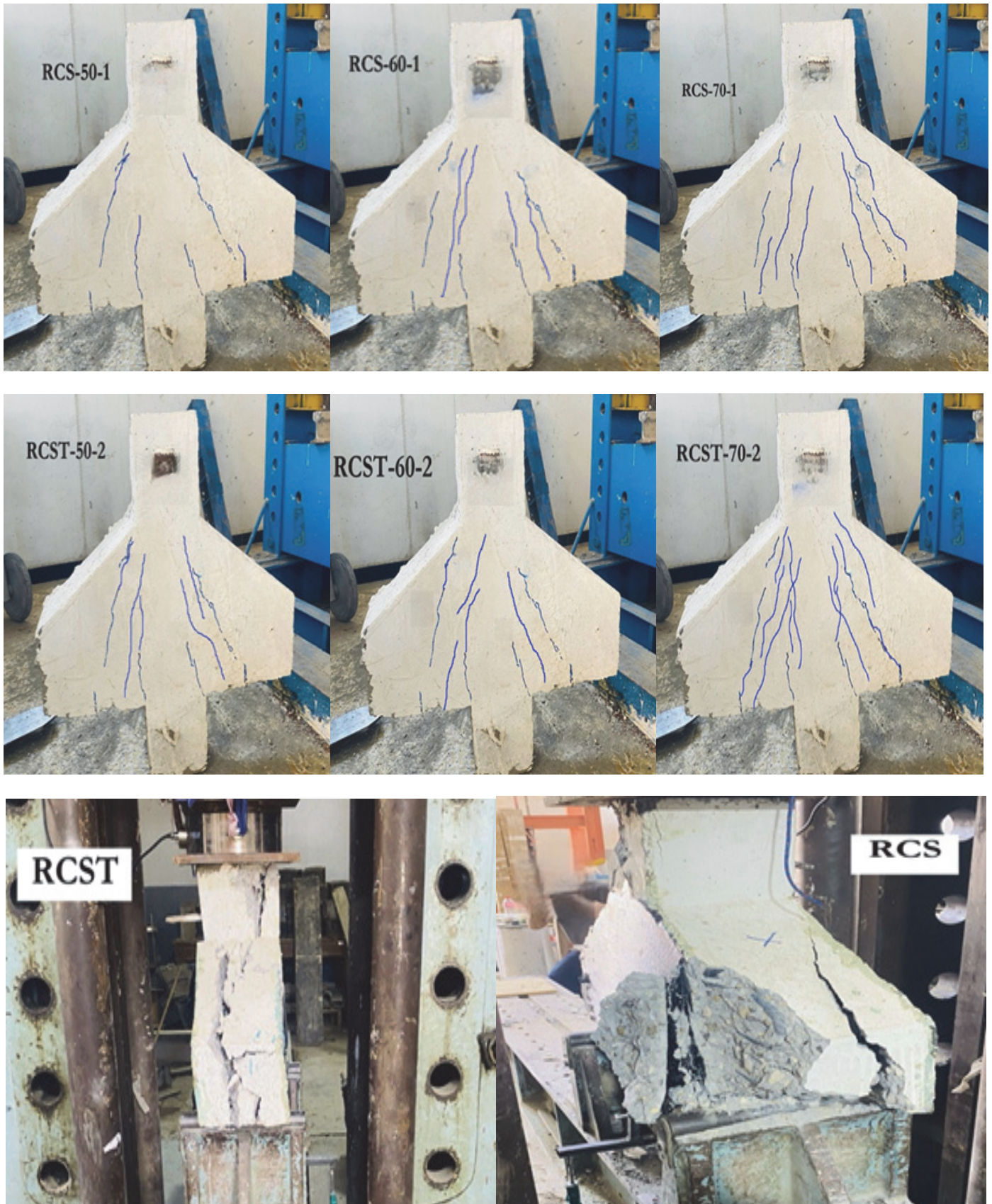


Figure 4: failure shape.

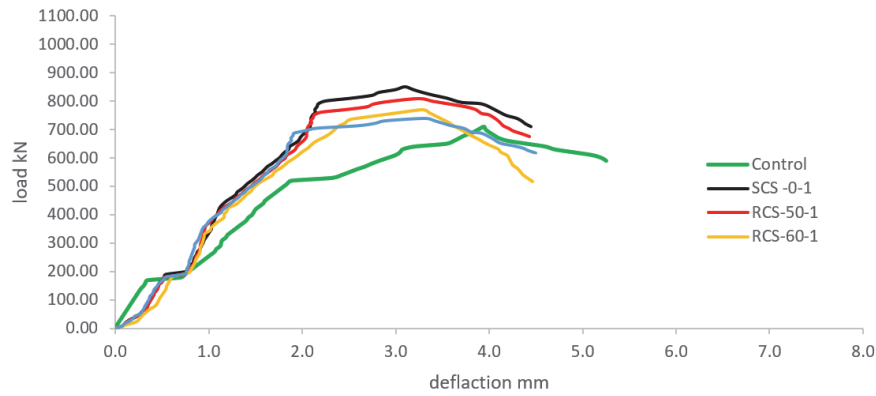


Figure 5: Load deflection response for corbel rehabilitated by side-wrapping CFRP sheet.

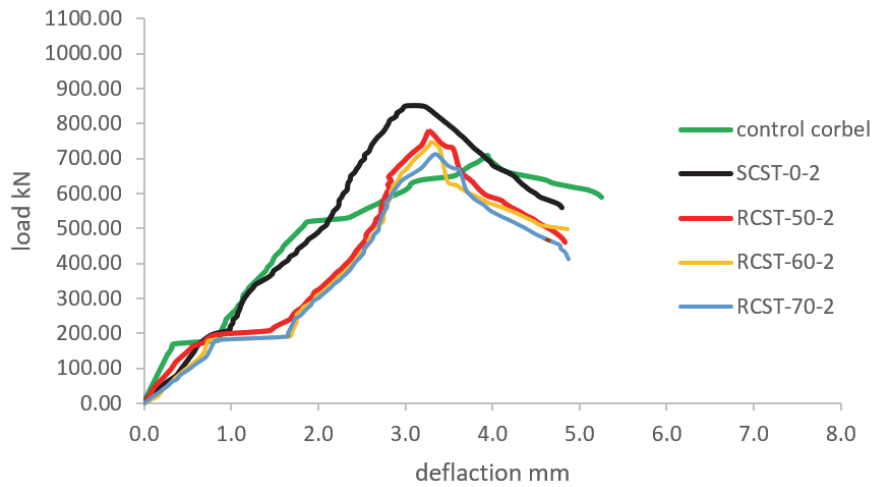


Figure 6: Load deflection response for corbel rehabilitated by strip-wrapping CFRP sheet.

Fig. 5 shows the load deflection response for corbel rehabilitated by side-wrapping CFRP sheet. Also, Fig. 6 shows the Load deflection response for corbel rehabilitated by strip-wrapping CFRP sheet. In the failure mode, especially in tension zones and near rebar, microcracks or microwaves form within the concrete cover when the corbels are preloaded (50%, 60%, and 70% of the maximum load) before applying carbon fiber laminates. Although inconspicuous, these fissures undermine the cohesiveness of the concrete in the cover layer. When reinforcement is applied using lateral sheathing, carbon fiber transmits forces across the concrete surface. Stress concentrations at the adhesive interface occur when the corbels are reloaded after reinforcement. If preloading compromises the concrete cover, failure will occur in the detachment of the lid rather than in the carbon fiber glue or the carbon fiber itself. The accumulation of pre-damage within the concrete and the inadequate cohesiveness of the concrete cover heightens the likelihood of failure with increased preload, even when side packing is present. The loading tests showed that both procedures made the corbels perform better by slowing down the spread of cracks and putting off their onset. Initially, this made the elements stronger when they were being loaded. As expected, the samples eventually broke with abrupt oblique fractures and localized loading zone separation, especially when the load was 70% of the reference load. This indicates that strengthening does not work well when the load is almost at its limit. Side sheathing improved shear resistance and made it less probable that there would be localized separation by delaying the initiation of fractures and spreading stress in the corbel. The slats above the flaws helped slow the growth of visible cracks but did not stop the structure from falling apart under heavy loads. Profile sheathing is the greatest approach to strengthening concrete corbels, especially under medium to high loads. This is because it lets you decide how they break better. The load-deflection curves give us fresh information about corbels reinforced with CFRP. Both strip and side wrapping make them substantially stiffer (15–20% better than control specimens), but side wrapping works better since it supports 5–8% more weight at the same deflection due to superior stress redistribution.

One notable observation is that CFRP tends to preserve its ability to hold weight even after the steel reinforcement gives way (approximately 3mm deflection). It also gently lowers the load after the peak, which is safer because it demonstrates that the system is failing slowly rather than all at once. The curves illustrate a point beyond which harm cannot get much



worse. After cracking, specimens that were 70% pre-damaged (RCST-70-2) lost 30–40% of their stiffness, but undamaged reinforced corbels (SCST-0-2) lost none. This means that CFRP repairs function best when there is not much damage. The ongoing post-yield ductility goes against what most people think about how CFRP-reinforced materials fail when they break. However, all CFRP samples clearly show a "knee" at about 85% of the peak load. This is when debonding starts and shows that better adhesion methods are needed. These results give engineers numbers that help us understand how CFRP makes shear-critical parts less brittle and more ductile. This helps us decide when to mend things (before >50% damage), how to tie things up, and how to create safer buildings that will fail in predictable ways. The nonlinear connection between pre-damage status and repair success can help us determine when to do repairs. This correlation suggests that repairs should preferably occur prior to the buildup of 50% of the damage. CFRP may still hold its shape even when the damage is very bad. This is clear because the displacements always go down (15–21% across all specimens), and the stiffness always goes higher, but the returns go down when the damage is bad enough.

The findings improve the understanding of CFRP rehabilitation by quantitatively examining the relationship between damage severity, expected performance recovery, and the choice of wrapping approaches. In practice, this helps engineers make better choices when fixing corbels. The stiffness test on CFRP-strengthened corbels showed that side-wrapped specimens (SCS-0-1) are much stiffer (274.19 kN/mm) than the control (180.2 kN/mm), which is a 52.15 percent increase. Strip-wrapped specimens (SCST-0-2) show a 47.40% improvement at 265.62 kN/mm, slightly less than the last sample but still quite good. For example, the stiffness improvements for side-wrapped corbels went from 37.88% at 50% damage to 23.60% at 70%. This illustrates that the increases in stiffness get worse as the damage level increases. The statistical significance of the relationship between the degree of damage and the effectiveness of rehabilitation is shown by the drop in the percentage of strip-wrapped specimens from 32.37% to 18.56%. The changes in load capacity and the manner stiffness decreased are related. CFRP can assist in restoring some of the structural rigidity in corbels that have been badly damaged, but it does not work as well, and the damage worsens. Its decreased frequency sees this of occurrence. The fact that side-wrapping is always 3–5% stiffer than strip-wrapping illustrates that CFRP can be used well to control deformation. This indicates how crucial it is to choose the right wrapping type for the greatest results in rehabilitation, especially for corbels that have some damage ($\leq 50\%$).

CONCLUSIONS

The following conclusions are drawn from the test results of the evaluated corbels:

- ✓ Side-wrapped specimens consistently showed greater improvements in both ultimate load (up to 13.73%) and stiffness (up to 52.15%) than strip-wrapped specimens, especially in damaged corbels. This shows that side wrapping is better at redistributing stresses and strengthening shear resistance.
- ✓ The effectiveness of CFRP strengthening drops a lot after 50% pre-damage. Specimens with 70% damage showed very little improvement (as little as 0.51% in ultimate load), meaning there is a critical damage threshold beyond which CFRP repair does not work.
- ✓ Both CFRP configurations successfully postponed crack initiation and curtailed crack propagation, with side wrapping providing superior control. This makes the structure more ductile and makes failure modes happen more slowly and predictably.
- ✓ CFRP-wrapped specimens withstood loads beyond the yield point of the internal steel reinforcement and showed a gradual decrease in load after the peak, which shows that they absorbed energy better and failed slowly instead of all at once.
- ✓ the CFRP-strengthened corbels broke because the concrete cover came off, not because the CFRP broke. This shows how important surface preparation and adhesive properties are for ensuring that force transfer works and the structure stays strong.
- ✓ A clear "knee" in the load-deflection curve at about 85% of the peak load shows that CFRP debonding is starting. This is a useful diagnostic tool for checking the condition of CFRP-reinforced structures when they are under load.
- ✓ Side wrapping made things 52.15% stiffer and 15–21% less likely to move. These improvements in stiffness are directly related to better crack control and usability.
- ✓ Strip wrapping is helpful but only strengthens certain areas and is less effective at stopping catastrophic failure when loads are high or severe. This makes it best for minor repairs.
- ✓ CFRP still helps with stiffness and displacement control, even when the benefits are less at higher damage levels. This shows that it is still useful even when things are bad.



- ✓ A nonlinear relationship between damage level and CFRP efficacy highlights the necessity of prompt intervention. The best strengthening results are seen when CFRP is used before 50% damage. This supports proactive structural health monitoring strategies.

FUTURE RESEARCH RECOMMENDATIONS

Based on the findings of this study, future research should focus on exploring hybrid strengthening techniques combining CFRP with other materials (e.g., GFRP or steel plates), as well as developing improved bonding agents to address the observed debonding failures at the CFRP–concrete interface. Investigations into long-term durability under environmental exposure, including temperature variations, moisture, and chemical attack, are essential to assess real-world performance. Further studies should examine the behavior of CFRP-strengthened corbels under cyclic and seismic loads to evaluate fatigue resistance and structural resilience. Alternative wrapping configurations, full-surface coverage, and anchorage systems should be explored to enhance efficiency. Enhanced nonlinear finite element modeling would support accurate prediction of failure mechanisms and optimize design strategies. Additionally, research should address strengthening strategies for severely damaged corbels (beyond 70% degradation) and conduct lifecycle cost-benefit analyses to support practical implementation. Ultimately, the development of standardized design guidelines specific to CFRP strengthening of corbels is necessary to ensure consistent, safe, and effective rehabilitation practices in structural engineering.

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