STRENGTHENING OF CORBELS USING CFRP AN EXPERIMENTAL PROGRAM

Mohamed A. Elgwady[1], *Mohamed RABIE*[2], *Mohamed T. Mostafa*[3]
1,2,3 Cairo University, Giza, Egypt.

Abstract

Structural engineers are frequently faced with the task of upgrading or strengthening an existing structure. An experimental study was carried out on six corbels strengthened by Carbon Fiber Reinforced Plastic (CFRP) to study the effectiveness of using CFRP as an external strengthening method to increase the load carrying capacity of the corbel. Laminates of CFRP were bonded to the corbels using a two-component epoxy. Different strengthening configurations were used. The test results indicated that the proposed technique has potential in improving the ultimate load carrying capacity of the short cantilever. Using the CFRP enhanced load carrying capacity of the corbels for all specimens, the increase in ultimate load ranges between 8% to 70% compared to the control specimen.

Keywords

Bracket, Carbon Fiber Reinforced Plastic (CFRP), composite materials, corbels, epoxy bonding, external strengthening, short cantilever.

Introduction

The dramatic progress in the use of composite materials in all structural elements and the number of research papers published in the last two decades attest to the fact that there has been a major effort to develop composite material systems, as well as analysis and design methods. One of the major aspects of using composite material is structural strengthening. There are many reasons for upgrading structures such as environmental conditions (e.g. chemical attack and reinforcement corrosion), use considerations (e.g. change in loading requirements), construction and material shortcomings (e.g. incorrect placing of reinforcement, use of wrong size or grade of reinforcement, insufficient lap length at splice or insufficient transversal reinforcement such as hoops, ties, or spirals, and poor construction practices).

Use of advanced composite materials for structural strengthening as stated in many research programs (e.g. Abou-Elez 1997, and Norris 1989) shows great advantages. CFRP compared to steel plates is a non-corrosive material, non-magnetic, non-conductive, highly resistant to chemicals, highly resistant to fatigue and has high strength to weight ratio. While extensive research has been done on corbels, strengthening corbels has received very little attention from researchers. Most of the existing research discussed the behavior of the corbels. This paper presents results of an investigation on the behavior of reinforced concrete corbels strengthened with CFRP from two sides.

Literature Review

Corbels are defined as cantilevers, which have shear depth to span ratio less than or equal to one. Many procedures exist for the design of corbels. Among, one of the pioneer researches in this domain was by (Birkland and Birkland 1966) which discussed the concept of the shear friction method. Many other researchers developed this method and many experimental programs have been conducted to check the validity of this procedure, such as the tests carried out by (Hofbeck et al. 1969). (Mattock et al.1976) enhanced the shear friction theory by taking into considerations these tests results. These extensive efforts resulted in a design procedure based on the “Modified Shear Friction” theory. (Walraven et al. 1981) analyzed the behavior of cracks under static shear and formulated equations to predict the experimental shear friction capacity of corbels. These equations were dependent on both reinforcement ratio and concrete strength. These equations were successfully used to predict the capacity of corbels with different time history loading and with different concrete strengths. Another approach for design was dependent on the truss analogy method proposed by (Leonhardt and Moning 1975).

As stated earlier there are no sufficient experimental or theoretical results for strengthening of short cantilever. There were a series of tests carried out by (Fattuhi 1987, and Abdul-Wahab 1989) to investigate the effect of adding steel fibers to reinforced concrete corbels. From the results it was clear that these steel fibers improved the behavior of corbels but this was not strengthening as it was an improvement of the behavior of a new corbel, which is different from the goal of using CFRP to increase the capacity of existing reinforced concrete elements.

Experimental Program

There are many bridges featuring simply supported beams. These longitudinal beams (main girders) are resting on corbels, which are connected to columns as shown in *figure1*. There are many situations wherein it is necessary to strength corbels without lifting the main girder and this research aims to propose method for strengthening a corbel without lifting the main girder i.e. upgrading by adding the CFRP at both sides of the corbel only (hatched area in figure 1).

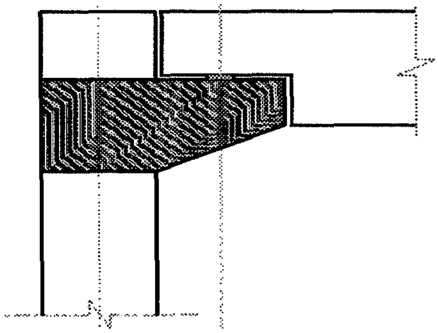
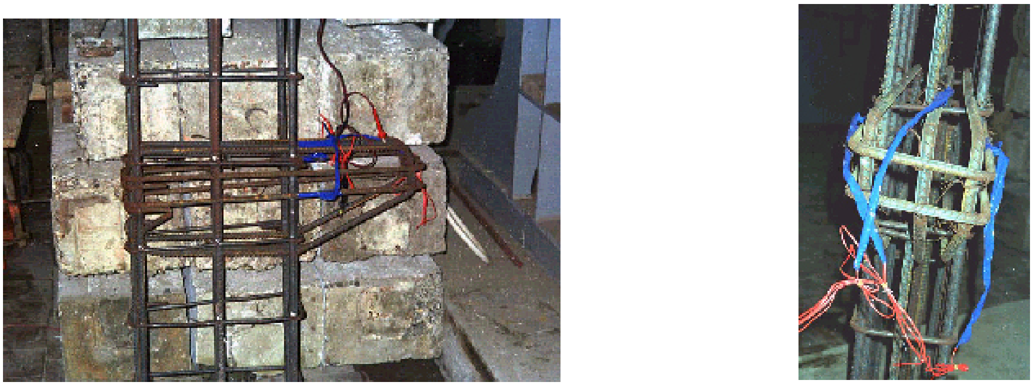


Figure 1. Bridge Longitudinal Beam Resting on Corbel.

Test Specimens Dimensions And Reinforcement

The corbel test specimens had a depth of 250 mm at column face and 150 mm at the end. The corbel was of 200 mm breadth and 250 mm length. The flexural reinforcement consisted of three deformed bars each of diameter 12 mm with two horizontal closed stirrups of diameter 10 mm. All the steel used had ultimate strength of 540 N/mm^2 and yield strength of 360 N/mm^2. The corbels were connected to column with a total height of 1250 mm. The column cross-section dimensions were 400×200 mm. All corbels have the same dimensions and reinforcement detailing as shown in *figures* 2 and *3*.



(a) (b)

Figure 2. (a) Corbel Reinforcement and (b) Electrical Gages.

Concrete Mix

The six corbels were cast in wooden forms in the concrete research laboratory at the Faculty of Engineering, Cairo University. The concrete mix used in this investigation was of 0.5 water cement ratio, 350 kg/m^3 ordinary Portland cement, the fine to coarse aggregate ratio was 1:1.87 by weight, and the maximum aggregate size was 12.5 mm. All specimens and cubes were cured for 28 days prior to testing. All materials were supplied by commercial suppliers to simulate the materials used on site. The cubes were tested at the same time as the main specimen tests. The compressive strength ranges between (27.5 – 32.5) N/mm^2.

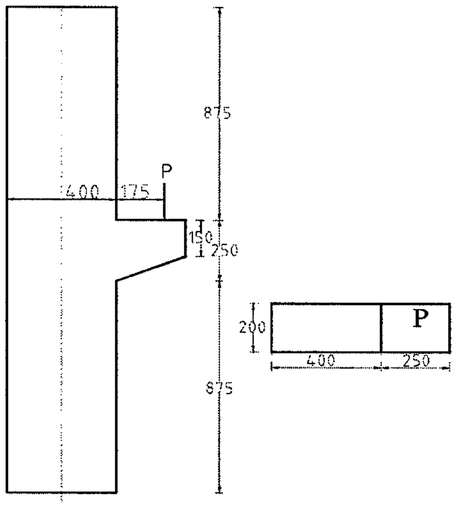


Figure 3. Specimen Ddimensions

Carbon Fiber Reinforced Plastic

Laminates of CFRP with unidirectional fibers embedded in matrix in which the fibers resist the applied load and the matrix is the binding material of the composite. The CFRP of breadth 50 mm and thickness 1.2 mm were supplied in rolls of 23 m. The nominal mechanical properties of the CFRP are as follows:

Fiber volumetric content	>68%
E-Modulus	= 165 kN/mm^2
Elongation	= 1.7%
Tensile strength	> 2800 M Pa

The epoxy resin used to bond the laminates to the concrete is a typical two component mix with an A: B ratio of 3:1 and the following mechanical properties:

Shear strength	= 15 N/mm^2
Tensile bending strength	= 4 N/ mm^2
Modulus of elasticity	= 12.8 kN/mm^2
Brittle temperature	= 62 °C.

Bonding of CFRP to Reinforced Concrete

CFRP strips were applied to all specimens in parallel after 28 days. Prior to bonding CFRP to the corbel, the surface of the concrete was prepared by thoroughly cleaning the surface. Then laitance was removed and aggregates were exposed by using bush hammering. Next, the surface dust was removed using vacuum cleaner. Strips were cut to the desired size using a metal saw and cleaned using a piece of white cotton soaked with solvent. The cleaning was repeated until the white cotton remained white. The two-component epoxy was mixed and then applied to both concrete surface and carbon fiber strips. Finally the coated strips were fixed onto the prepared concrete surface by light finger pressure and the CFRP strips were pressed onto the substrate by means of a hard rubber roller. For specimens 4, 5, and 6 where there are two wythe of CFRP the surface of the first wythe after placing onto the concrete surface was cleaned. Another layer of epoxy with an average thickness of 3 mm was applied to the first wythe surface. The second wythe of the CFRP strips was applied. All strengthening configurations were applied to the two side faces of the corbels only. This was done due to practical considerations which prevent extending the strips around all the sides of the corbel due to the existence of the longitudinal beam (i.e. main girder). A strengthened test specimen has a name consisting of two figures followed by three letters. The first figure is the number of strips, the second figure is the number of wythes, and the letters indicate the strip direction. The test specimens, as shown in *figure 4,* are as following:-

- First specimen (CONT): control specimen without CFRP.
- Second specimen (11HOR): one horizontal strip, one wythe.
- Third specimen (21HOR): two horizontal strips, one wythe.
- Fourth specimen (61DIG): six diagonal strips, one wythe.
- Fifth specimen (32HOR): three horizontal strips. The upper strip was two wythes, while the lower strip was one wythe.
- Sixth specimen (82HAD): first wythe was two horizontal strips and the second wythe was diagonal strips.

These different configurations were chosen as it was expected, from experience of the researchers that failure occurs equally in both flexural reinforcement and stirrups. Hence it was decided to observe the effects of strengthening the flexural reinforcement in some specimens and strengthening the stirrups in the other specimens, with some specimens strengthening both the flexural reinforcement and stirrups of the corbels.

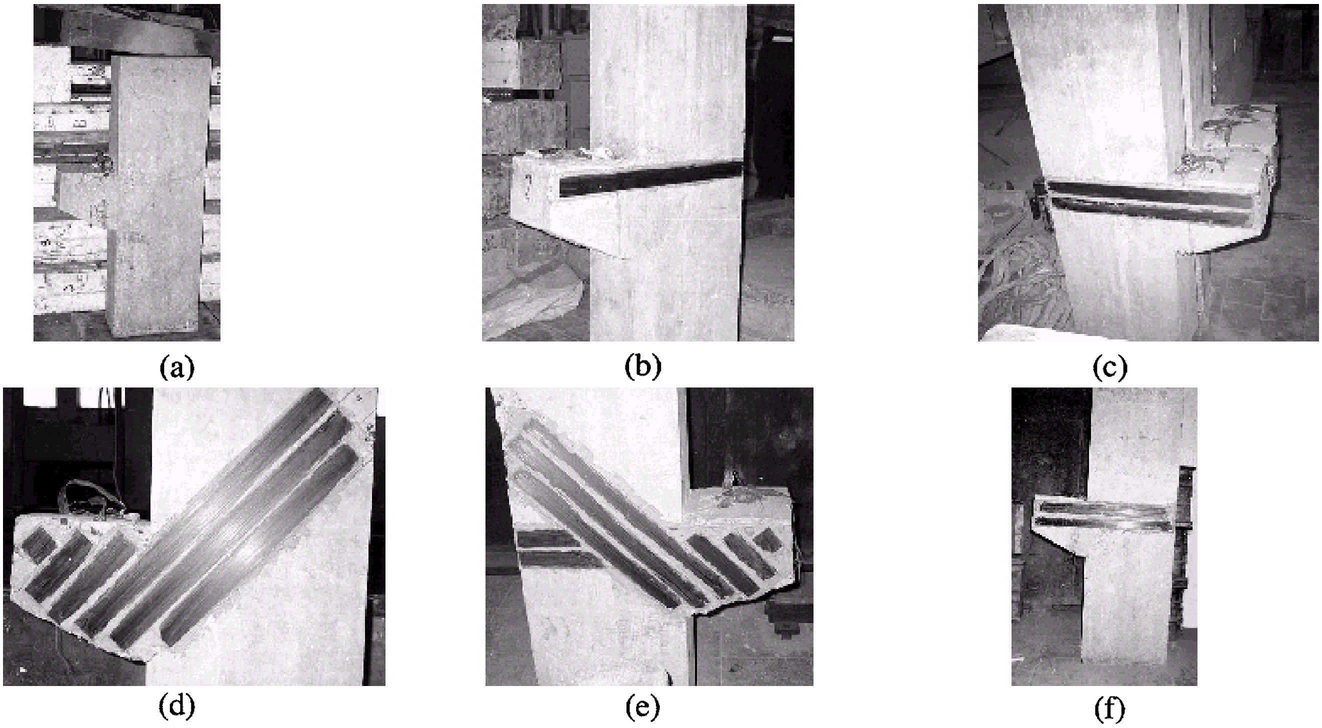


Figure 4. Test Specimens (a) CONT, (b) 11HOR, (c) 21HOR, (d) 61DIG, (e) 32HOR, (f) 82 HAD.

Testing

The 5000-kN test machine used to fix the column is shown in *figure 5*. This machine consists of a piston moving on a spherical head and a top plate moving on rollers to allow adjustment of the top plate to a perpendicular position to the column axis. The machine had been used to fix the column. The column was prevented from rotating by applying a high normal force. Please note that previous research carried out by (Fattuhi 1990) showed no effect for the column load on the corbel behavior. The vertical load on the corbel was applied by hydraulic jack of 450-kN maximum capacity. The applied load started at zero and was applied in equal increments of 20 kN until the

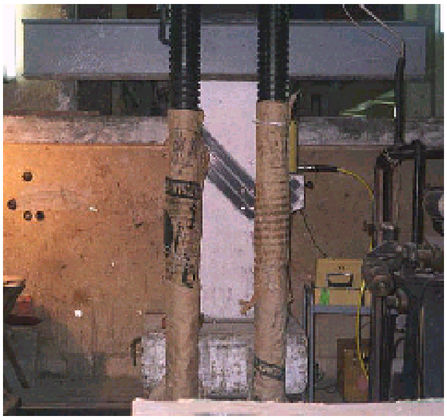


Figure 5. Specimen (61DIG) Ready to Test.

observation of the first crack, then the load increments were decreased to 5 kN. At each increment the strains were measured by

electrical and mechanical gauges. Finally, failure of specimen was defined either by pullout of the CFRP strips or by excessive continuous cracks in the corbel corresponding to a significant decrease in the load carrying capacity of the corbel measured by the hydraulic jack gauge.

Instrumentation

Strains were measured by mechanical gauges and electrical resistance gauges of 120-ohm and gauge factor 2.04, the demic points were 50-mm mesh at both corbel side faces, while the electrical gauges were three per specimen, one on the middle flexural reinforcement bar and the other two gauges at the upper horizontal closed stirrups at corbel face from column side as shown in *figure 2.*

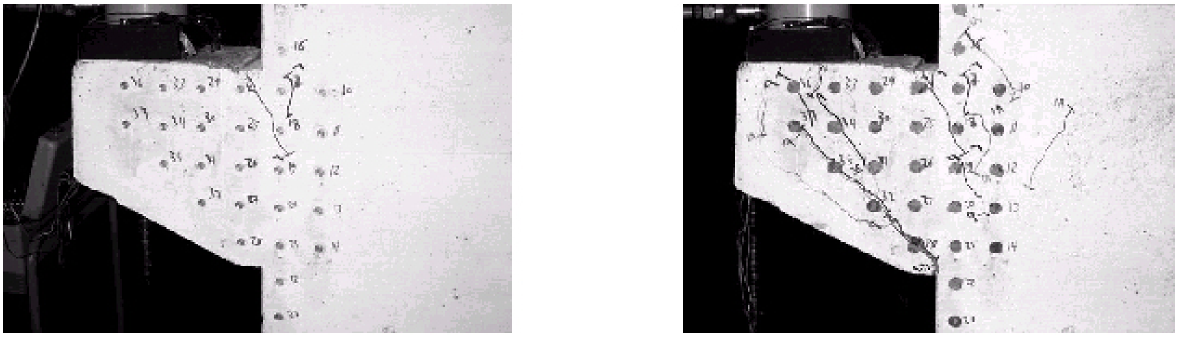
Experimental Result

In this section the observed behavior and modes of failure for each specimen will be described. The crack patterns were changed according to the configuration of the CFRP strips. To determine the best configuration it was important to examine each failure load and each crack pattern. A detailed description of the behavior of the first specimen is given followed by a brief description of the mode of failure of each of the other specimens. For all corbel the first crack occurred in either the horizontal or diagonal direction, then diagonal cracks propagated rapidly. Finally, compression failure or brittle failure happened due to either spall out of lower triangular compression zone or pull out of CFRP strips carrying concrete cover.

Crack Patterns and Failure Mode

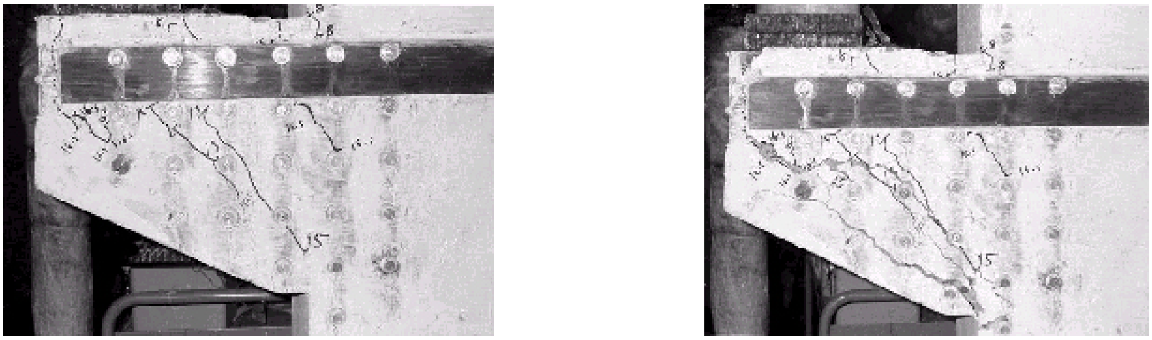
Specimen (CONT): To determine the load-carrying capacity of the short cantilever this specimen was tested as control specimen. The ultimate load failure of this specimen was 180 kN. In this specimen the first major crack appeared at 60 kN as depicted in *figure 6a,* in fact there were two major cracks; the first was a vertical crack appearing approximately at the corbel face from the column side. The other one crack was a diagonal crack almost at an angel of 45 degrees (i.e. shear crack), this was at 33% of the ultimate failure load (i.e. there was a high level of ductility). Increasing the load led to the creation of new diagonal cracks and the diagonal cracks propagated rapidly until failure. The failure of this specimen happened when a large crack initiated at the intersection point of the corbel inclined surface and column face going to the point of applied load as shown in *figure 6b.* Then the lower triangle reinforced concrete was separated. From this crack pattern it is obvious that this is shear failure "beam type".

Specimen (11HOR): In this specimen an attempt to enhance the ultimate load capacity was done by applying one horizontal strip one wythe CFRP. The first minor corner crack was at 80 kN (41% of ultimate load) as shown in *figure 7a.* This crack went from the upper edge of the CFRP strip to the upper face of the corbel (i.e. with length about 20 mm) and it was not deep, just penetrating the cover of the concrete. From the next load steps it was clear that this crack was just in the concrete cover because no other cracks were found before 150 kN were applied. The major crack was observed at load 150 kN which was 250% of the reference corbel cracking load. This crack also as in the reference specimen was a diagonal crack. By increasing the applied load by only 10% (i.e. to 165 kN) many other cracks appeared. Failure happened by crushing of the bottom triangle of the compression zone of the corbel (i.e. the same mode as control specimen). Just before failure the crack propagated around the end of CFRP strip with a major crack running from under the applied load and extended around the end of the horizontal strip, it then continued as diagonal crack as shown in *figure 7b.* The ultimate load was 195 kN (i.e. the ultimate load increased by about 8% of control specimen ultimate load).



(a) (b)

Figure 6. Crack propagation for (CONT), (a) initiation of cracks, (b) failure



(a) (b)

Figure 7. Crack Propagation for (11HOR), (a) Initiation of Diagonal Cracks, (b) Failure

Specimen (21HOR): This specimen was strengthened by two horizontal strips one wythe CFRP as an attempt to upgrading the flexural reinforcement and stirrups. The major crack appeared at a load of 180 kN (i.e. 300 % of the reference corbel-cracking load) as shown in *figure 8*. Propagation of cracks was more rapid than for the previous specimens. Before failure the crack went around the end of CFRP strip. The increase in the ultimate load was 20% of the reference corbel ultimate load (i.e. ultimate load was 215 kN). The crack pattern was almost identical to the previous specimen.

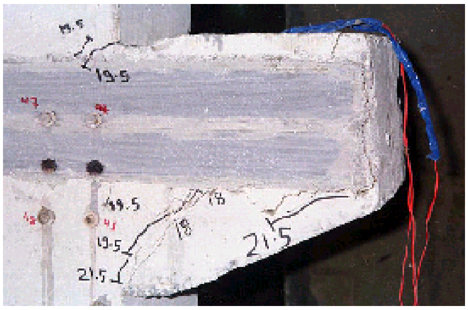
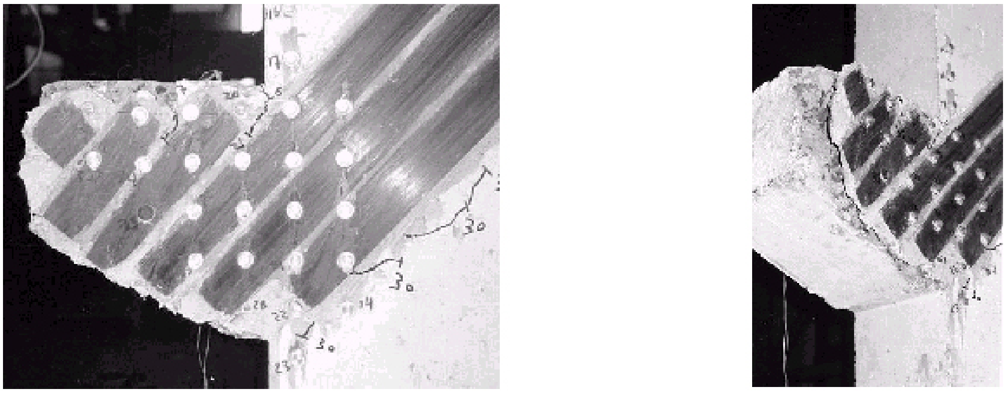


Figure 8. Propagation of Cracks Around CFRP Ends for Specimen (21HOR)

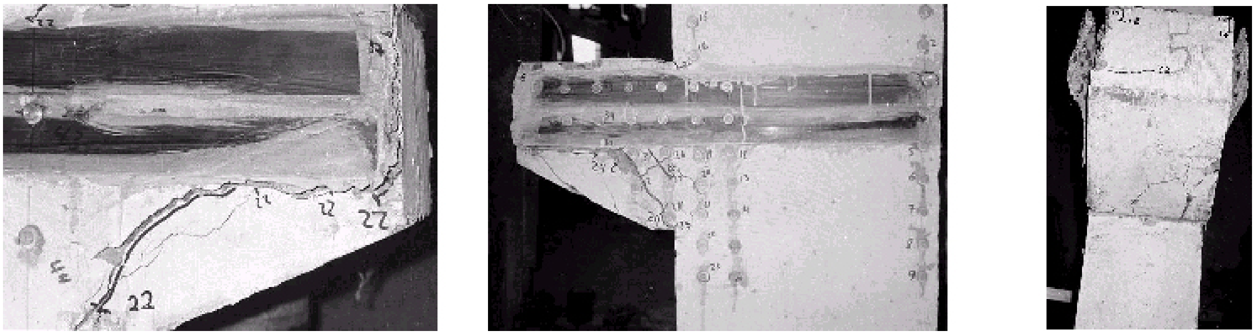
Specimen (61DIG): From the crack pattern seen in the previous results, it was clear that for these specimens shear cracks were controlling the failure modes. So the use of diagonal CFRP strips was assumed the more effective strengthening configuration. Here, one wythe of diagonal strips was used. These diagonal strips started from just the point below the applied load and continued across the corbel face with an inclination angel of 45 degrees. According to supplier instructions a minimum of 50 mm tolerance distance must be allowed between any two adjacent strips to help the worker squeeze out excess adhesive and removed by steel spatula. This tolerance distance was the weakest point and thus the first crack appeared between the adjacent strips, it was a diagonal crack initiating at 210kN (i.e. 350% of the reference corbel cracking load) as shown in *figure 9a*. The crack inclination was different from the other specimens. It was almost perpendicular to the crack inclination of the other specimens. The propagation of cracks was different and slower. The ultimate load was 310 kN (i.e. 172% of the reference corbel ultimate load). At failure all the CFRP strips in the corbel face were pull out at the same time as shown in *figure 9b*. The test was stopped just after pull-out of CFRP strips, and at this stage there was no deterioration in the concrete itself as had occurred in the other specimens.

Specimen (32HOR): This specimen was strengthened with three strips of CFRP; two horizontal strips i.e. similar to specimen (21HOR) but the first horizontal strip consisted of two wythe of CFRP. The main objective of this specimen was to investigate the influence of the number of wythe of CFRP on the corbel ultimate load caring capacity. Local cracking under the load bearing plate was observed. Then the similar behavior as in specimen (11HOR) and (21 HOR) was observed. Diagonal cracks were formed and propagated rapidly with increasing applied load. The first major crack appeared at a load of 170 kN (i.e. 280% of the cracking load for the reference corbel). Cracks at failure went through the end of the CFRP strips and propagated around the end of strips as shown in *figure 10a.* The ultimate load increased to 240 kN (i.e. 130% of the ultimate load for reference corbel). At failure pull out of concrete cover which extended through corbel reinforcement was observed as shown in *figure 10 b,c.*



(a) (b)

Figure 9. Crack Propagation for (61DIG), (a) Diagonal Cracks between CFRP Strips, (b) Pull Out of CFRP at Failure.



(a) (b) (c)

Figure 10. Failure of Specimen (32HOR), (a) Cracks Around CFRP Ends, (b) Diagonal Cracks at Failure, (c) Compression Failure

Specimen (82HAD): In this specimen the main objective was studying the effect of using two different strip orientations. First there were two horizontal strip as first wythe and then the second wythe was diagonal strips. It was found that the first minor crack was horizontal and initiated at a load of 80 kN (i.e. 130% of cracking load for the control specimen). No other cracks were found until reaching the ultimate load caring capacity. The ultimate load increased to 220 kN (i.e. 120% of reference corbel ultimate load). At failure, similar to specimen (32HOR) cracks at the end of strips was observed then a explosive failure occurred. It was expected that this specimen would give the best results or at least like specimen (61DIG) with diagonal strips only. The interpretation of the specimen behavior was that the amount of epoxy under the diagonal strips was much more than required. This amount of epoxy resin was necessary to balance with the upper part where the horizontal strips were attached. That is, the behavior of this specimen was affected by the presence of the horizontal strips below the wythe of diagonal strips. Thus if the arrangement was reversed the results have been different.

Theoretical Analysis

Theoretical verification of three specimens was carried out by linear analysis using the multi purpose finite element program "ANSYS 5.5". In this study the 3-D solid element "Solid 95" was used to model the reinforced concrete of the corbel. This element is a higher order version of the 3-D eight-node isoperimetric brick element, with mid-side nodes. This element is defined by 20 nodes having three degrees of freedom at each node (translations in the nodal x, y, and z directions). Also, the available element in this program called "Conta174" was used to model the bonding epoxy resin. This element was used to represent contact and sliding between the 3-d element "target surface" and a 2-d "deformable surface". CFRP strips were modeled using the eight-node shell element "Shell93" which has six degrees of freedom at each node (translations in the nodal x, y and z directions and rotations about the nodal x, y and z axes). This element has plasticity, stress stiffening, large deflection, and large strain capabilities.

Verification of Finite Element Model

In order to verify the finite element model presented above a comparison between theoretical and experimental results are illustrated in *table 1.* The results indicate a good agreement between the theoretical and experimental study before the initiation of the cracks and diverges after cracking. This is due to neglecting the nonlinear behaviour after cracking in the theoretical idealization.

Table 1. Comparison between Experimental Results and Theoretical Results.

Specimen	Strains at first crack at the intersection point between column face and the corbel horizontal surface		
	Experimental ($X\ 10^{-3}$)	Theoretical ($X\ 10^{-3}$)	% Deviation
CONT	0.22	0.19	13%
11HOR	0.37	0.44	16%
21HOR	0.510	0.586	15%
Average			15%

Conclusions And Recommendations

Based on the observations of the experimental work and the results of the theoretical analysis; the following conclusions are made for reinforced concrete short cantilevers reinforced with CFRP strips:

- External strengthening of a corbel using CFRP can enhance the corbel capacity when the CFRP is adequately arranged. The use of CFRP as diagonal strips increased the ultimate load carrying capacity of the corbel by 70% of control specimen ultimate load carrying capacity. All the other corbels tested have ultimate loads higher than that of the control specimen with the difference ranging between 8% and 30%.

- Most of the corbels showed a brittle mode of failure, the stiffness of all specimens was increased so they failed suddenly with no adequate warning. However all upgraded specimens show cracking loads of 70-80% of its ultimate load. On the other hand specimen (82HAD) which had two wythe of CFRP diagonal and horizontal strips showed an apparent delay of cracking up till 85% of its ultimate load.
- The actual stress in all the CFRP strips is less than its ultimate capacity, which happened in all the specimens due to de-bonding of the strips and spalling of concrete cover. It is recommended in the future research to reduce the amount of CFRP strip to try to reach the optimum amount of CFRP strips.
- From specimen (82HAD), it is not recommended to use two wythe of CFRP as used for specimen (82HAD). This leads to high thickness of adhesive in local areas and no effect of the upper layer in the results.
- It is not recommended to stop the CFRP strips before he end of the corbel. The distance left is the weaker part where cracks were propagated.

References

1. Abou-Elez A. Y. (1997), "Behavior Of Reinforced Concrete Columns Confined With Advanced Composite Materials", Ph. D. Thesis, Minia University, Egypt.
2. Abdul-Wahab H. M. (1989), "Strength of Reinforced Concrete Corbels With Fibers", ACI Structural Journal, V.86, No. 1, pp. 60-66.
3. Birkelend, P. W., and Birkelend, H. W. (1966), "Connections in Pre-cast Concrete Construction", ACI Journal, V. 63, No. 3, PP. 345-368.
4. Futtuhi I. Nijad (1987), "SFRC Corbel Tests", ACI Structural Journal, V. 84, No. 2, PP. 1198-123.
5. Futtuhi I. Nijad (1990), "Column Load Effect On Reinforced Concrete Corbels", ASCE, Journal of Structural Engineering, V. 116, No. 1, PP. 188-197.
6. J. I. Hofbeck, I. O. Ibrahim, and Mattock H. Alan (1969), "Shear Transfere in Reinforced Concrete", ACI Journal, V. 66, No. 2, PP. 119-128.
7. Leonhardt F., and Monning E. (1975), "Lectures On Concrete Construction, Part 2, Springer-Verlag, New York.
8. Mattock H. Alan (1976), "Design Proposals For Reinforced Concrete Corbels", PCI Journal, V. 25, No. 3.
9. Norris Tom, Saadatmanesh Hamid and Ehsani R. Mohamed (1997), "Shear and Flexural Strengthening of R/C Beams with Carbon Fiber Sheets," ASCE, Journal of Structural Engineering, V. 123, No. 7, pp. 903-911.
10. Walraven, J. C. (1981), "Fundamental Analysis of Aggregate Interlock", ASCE, Journal of Structural Engineering, V. 11, No. 11, PP. 2245-2270.