- Technical Paper -

STRUCTURAL STRENGTHENING OF RC CORBEL SUBJECTED TO LOCAL FAILURE CRITERION BY EXTERNAL CFRP WRAP

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ABSTRACT

External wrapping of fiber reinforced polymer (FRP) composites to strengthen reinforced concrete structure has been proved to be effective in beam and column structures. An experimental investigation has been carried out to study the effectiveness of external application of epoxy-based carbon fiber on RC corbel. Corbel with same geometry and internal reinforcement condition is tested for two different shear span to depth ratio. Designed size of pad to transmit load to corbel is shifted to edge of corbel to characterize local failure criterion. Effect of two different ways of application namely; CFRP full wrap and CFRP up to corbel-column interface, to retrofit corbel, with load bearing pad at its edge is studied. Test result shows externally bonded CFRP can significantly increase ultimate load capacity of RC corbel subjected to local failure criterion but will not be able to recover as much as designed capacity. Test results expressed in load-displacement curve and crack pattern are also verified by non-linear 3D finite element analysis.

Keywords: RC corbel, carbon fiber, structural strengthening, non-linear FE analysis

1. INTRODUCTION

Reinforced concrete corbel is widely used cantilever projection having low shear span to depth ratio. Use of RC corbel is common with precast beam or slab, however, its use to facilitate structural joint in cast-in-situ concrete structure can also be seen. Large number of corbels in both developed and developing countries can be found to be defunctive due to faulty design and overuse. In a case study, several corbels in building structure have found to be failed locally as shown in Fig 1(a) due to faulty design of bearing pad i.e. placing bearing pad at the edge of corbel despite its designed position. Considering its cost, such structures cannot simply be demolished. It is necessary to propose appropriate retrofitting solution for such corbels. Hence, extensive researches are necessary to understand the effectiveness of several retrofitting alternatives to recommend best retrofitting approach to ensure safety and functionality of such corbels.

During the past century, many studies have been carried out to simplify and improve design philosophy of strut and tie model. For corbel having shear span to depth ratio less than unity, ACI allows shear friction design. Regarding position of bearing pad, ACI 318 and BS 1997 recommend to avoid either extension of bearing pad beyond the straight portion of main flexural bar of corbel, or projection beyond interior face of transverse anchor bar (if provided) [1], [2]. However several RC corbels have found to have bearing pad placed at the edge of corbel. By placing bearing pad at edge, a localized failure extending towards the outside edge of corbel is noticed and hence it is termed as local failure criterion. This study aims to address retrofitting requirement of such corbels.

Advanced method like application of external FRP wrap to strengthen corbels could be economical over the traditional method of concrete or steel jacketing. Due to its high strength-weight ratio, durability and easy on site handling, application of FRP is growing. It has also proved to be effective in enhancing shear and flexural capacity in beam and slab[3], axial strain capacity in column [4]. Application of horizontal CFRP laminates has been proved to be effective in shear strengthening of deep beams [5] which is designed on similar principle as corbel.

Several studies conducted on strengthening RC corbels have been focused primarily to address reinforcement congestion problem. Experimental research by Campione et al. 2005 aimed to study the effectiveness of external CFRP wrap on ultimate strength of corbel, which highlights that external application of CFRP is effective to replace shear stirrups of RC corbel [6]. The ultimate capacity enhancement and overall behavior of external CFRP wrap with shear reinforcement in RC corbel is still unclear and needs further research. Also, the complex response of RC corbels is described in design codes in a simplified manner. These formulations are not sufficient to show the real behavior [7]. Hence, necessity of experimental study on CFRP strengthened RC corbel subjected to local failure criterion along with sophisticated 3D finite- element analysis is realized.

This paper compares corbel having correctly designed pad at middle (not extending beyond straight portion of bar) with same corbel of having pad at edge,

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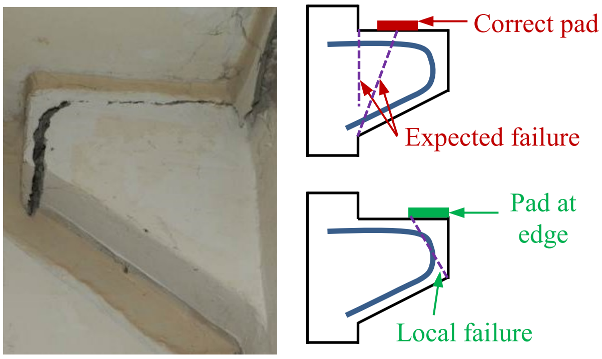
Table 1 Details of test series and specimen

S.N.	Specimen	Shear span a_v (mm)	Main bar, (mm)	Transverse bar (mm)	Fiber application	Fiber layer (n)	f'_c Concrete (MPa)	f_t Concrete (MPa)
1.	D-C	125	2-13D	2-10D	-	-	41.89	2.73
2.	PE-C	220	2-13D	2-10D	-	-	45.52	2.66
3.	L2-CF-PE-C	220	2-13D	2-10D	Up to column	2	46.77	2.84
4.	L1-FW-PE-C	220	2-13D	2-10D	Full wrap	1	42.49	2.28
5.	L2-FW-PE-C	220	2-13D	2-10D	Full wrap	2	43.15	2.40

and investigates effectiveness of CFRP retrofitting on later case through experimental and numerical study. Considering the condition of two way beam junction, application of CFRP sheet up to column face was also studied along with normal full CFRP sheet wrap case.



(a) Observation (b) Mechanism

Fig 1 Local failure of corbel

2. TEST PROGRAMS

2.1 Test Specimens

In total 5 RC corbels of size 250×170×350 and same physical properties were casted and tested for vertical load. Two way corbel having both flexural and shear reinforcement with short column was designed. The details of experimental series are summarized in Table 1 and geometry and setup is shown in Figs 2 & 3 respectively. Different series of test include- (a) control specimen or designed corbel (D-C); (b) corbel subjected to local failure criterion characterized by shifting bearing pad at edge (PE-C); (c) PE-C corbel strengthened with 2 layers of CFRP up to corbel-column interface (L2-CF-PE-C); (d) PE-C corbel strengthened with 1 layer of CFRP full wrap (L1-FW-PE-C); & (e) PE-C corbel strengthened with 2 layer of CFRP full wrap (L2-FW-PE-C). Corresponding names in parenthesis are used to identify the test sets.

In all specimens, main flexural bar of ϕ-13mm was bent so that horizontal stirrups could be supported as shown in Fig 2. Horizontal stirrup in both corbel and column was at the pitch of 100mm. The entire bar used was deformed bar. CFRP sheet of 0.25mm thickness each layer (450g/m^2) was used in all cases. First two series were adopted to verify the occurrence of local brittle cracks due to shifting the bearing pad at edge.

Among three series of CFRP retrofitted case, series 3 (L2-CF-PE-C) was designed to consider the case when beams in both sides exist, in which cross-directional beam doesn't allow use of CFRP beyond the column-corbel interface. Series 4 and 5 were designed to study the effectiveness of full CFRP wrap applicable to case having beam in one direction.

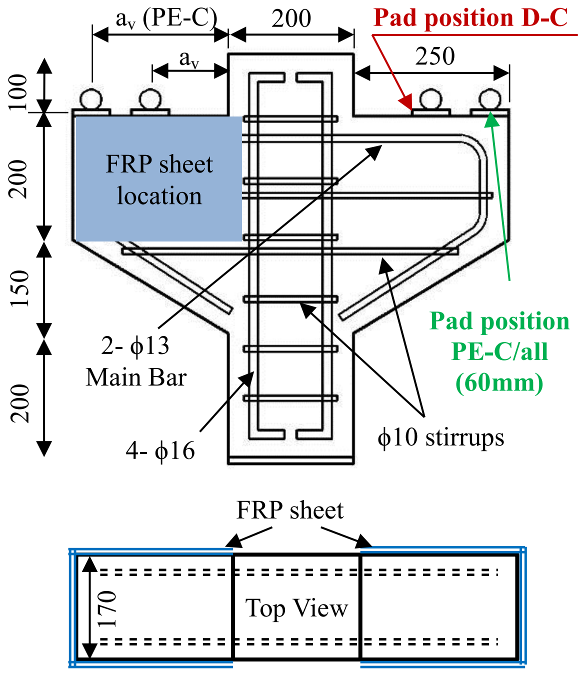


Fig 2 Specimen dimension and rebar details (mm)

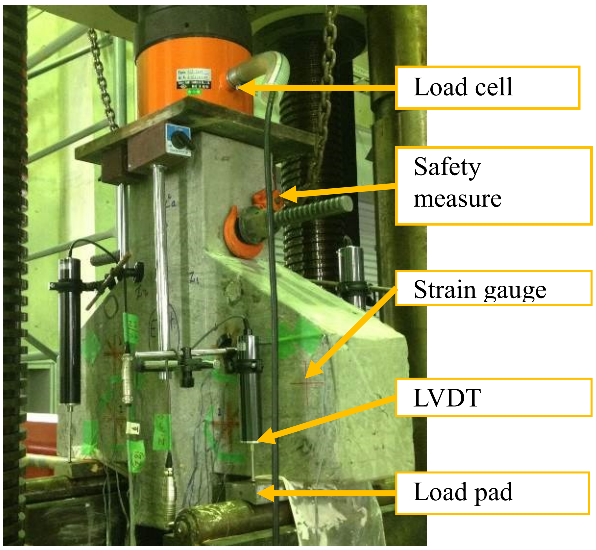


Fig 3 Test setup

Relative displacement was measured between the top plate and main load bearing pads in all 4 points as shown in Fig 3. Thin layer of gypsum was used between the steel plate and specimen to ensure the balance and to fill the gap (if any). For safety during experiment, specimen was hold by a loose cable by inserting a bar in column portion. In all the series, strain in primary flexural reinforcement was measured at middle of corbel. In CFRP retrofitted case, fiber strain was measured near edge of corbel and end of FRP sheet. Strain gauges of 2 mm gauge length were used to measure both steel and CFRP strain. Position of strain gauge for steel strain measurement is shown in Fig 4 (a), and strain gauge for CFRP strain measurement is shown in Fig 4 (b).

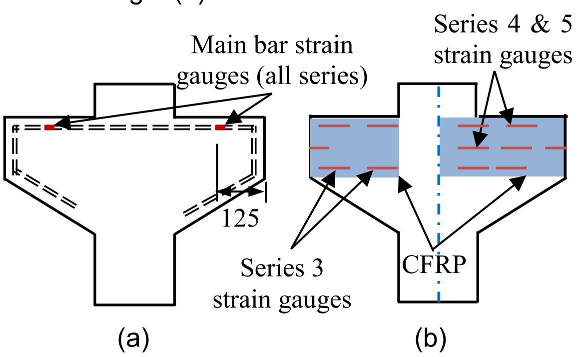


Fig 4 Strain measurement

2.2 Material Properties

Mix design of normal concrete for 28 days compressive strength of 40 MPa was adopted for all specimens. Cylinders were casted for compressive strength test and splitting test to determine corresponding physical properties of concrete and tested on the day of experiment. Basically, all the cylinders and specimens were subjected to moist curing at 20^{0}C constant temperature. Compressive strength of concrete on test day is indicated in Table 1. Minimum concrete cover of 20 mm was maintained from the stirrups. Coarse Aggregate of 20 mm nominal size was used.

Internal reinforcement: Main flexural bar 2-ϕ13 mm (f_y = 490 MPa), closed shear stirrups for corbel 2-ϕ10 mm (f_y = 390 MPa) & closed stirrups for column 6- ϕ10 mm (f_y = 390 MPa) and main bar in column 4-ϕ16 mm (f_y = 490 MPa) were used. Entire CFRP used was sheet type and of having ultimate tensile strength 3400 MPa and initial stiffness 2.45×10^5 MPa. Steel plate of 20 mm thickness was used as load bearing pad and also on top end of column.

2.3 Application of CFRP

Entire application of CFRP was done step by step as per manufacturer's guidelines as follows:

(a) Bonding area was roughened and sharp edges were rounded with approx. 20 mm radius.
(b) Primer (FP-NS = 200 g/m^2) was applied over roughened dry surface and cured for minimum 3 hours.
(c) Levelling putty (FE-Z = 1500 g/m^2) was applied to smoothen uneven surfaces and minimum of 24 hours curing time was given.
(d) CFRP sheet was laid after applying one layer resin (FR-E3P = 500 g/m^2) and covered by another layer of resin. For multiple layer of CFRP sheet; one layer resin below and above sheet was maintained.

Test was done after 7 days of complete application of CFRP. In L1-FW-PE-C and L2-FW-PE-C, 200 mm overlap was maintained to ensure anchorage. Typical specimen after CFRP application is shown in Fig 5. Strain gauge over CFRP was applied after resin set hard and with acceptable scrape of resin (with no harm on fiber) so that actual CFRP strain could be measured.

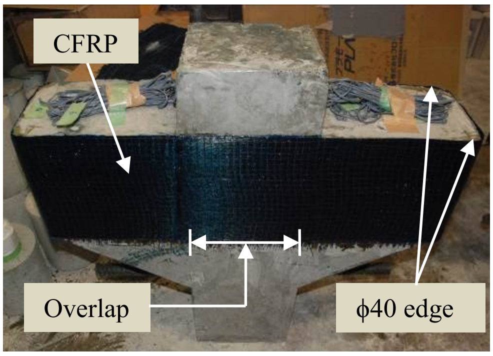


Fig 5 CFRP application details (L2-FW-PE-C)

2.4 Test Setup and Measurement

Test was done by placing inverted corbel on Universal Testing Machine (UTM) as shown in Fig 3. Load was applied at two symmetrically designed pads by moving the base vertically upward by controlling displacement at the constant rate of 0.0084 mm per sec. Relative displacement of load bearing pad at all 4 points was measured with respect to opposite (top) edge of column by using LVDT's. Total load at the top edge of column was measured by using load cell.

3. TEST RESULTS AND DISCUSSION

3.1 Load-displacement Curve

Total load measured at the top end of the column is plotted vs. average relative displacement measured between top end pad and main bearing pads. Load-displacement capacity of all experimental series is plotted as shown in Fig 6. Compressive and tensile strength of concrete was also tested on same day of experiment. It shows no significant variation in physical properties of concrete (See: Table 1) among all series and hence ultimate capacity of all series can be compared.

Load-displacement curve shows 46.5% reduction in ultimate load capacity of RC corbel subjected to local failure criterion i.e. due to shifting pad to edge. In PE-C series, abrupt brittle failure was observed with load noise. In CFRP retrofitted corbels, ultimate load

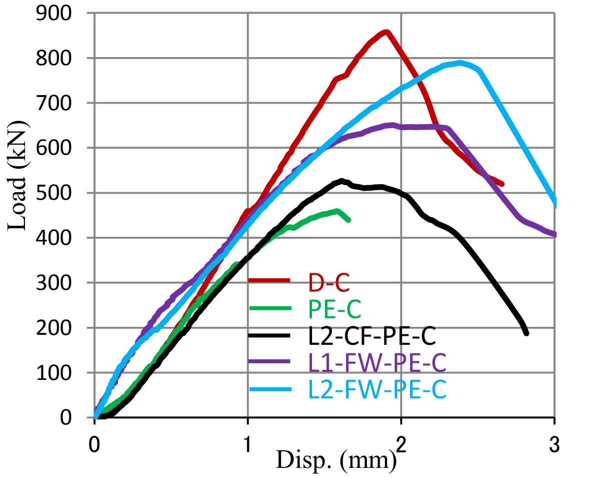


Fig 6 Load-displacement curve (Experiment)

capacity, ductility and post peak behavor is improved more or less. Case L2-CF-PE-C shows only 15% improvement in ultimate load capacity over PE-C. Full wrap case shows better performance than CFRP up to column face, even though less number of layer is used. Case L1-FW-PE-C and L2-FW-PE-C shows 42% and 72% increase in ultimate capacity over PE-C case. Even though CFRP shows good improvement in ultimate load capacity, it couldn't recover the full designed capacity of corbel (capacity of DC) with pad at edge. For practical case of having beam in both way, adopted mothod of CFRP wrap upto corbel-column interface (L2-CF-PE-C) cannot improve capacity so much.

3.2 Initial Stiffness

In experiment, lower stiffness was reported than that in simulation. Reason being crushing of gypsum layer used between pad and specimen at lower load. And effect was reflected in measurement of relative displacement between steel pads. To confirm such scenario another corbel was tested for two different approach of displacement measurement viz. (a) between small plates attached to concrete points and (b) between load bearing plates & result is plotted as shown in Fig 7.

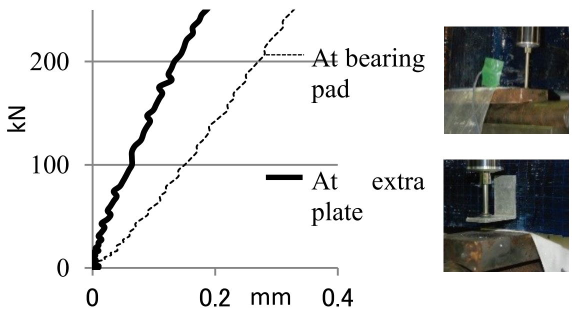


Fig 7 Reason for lower stiffness in experiment

3.3 Failure Pattern

Surface cracks in corbels were marked in D-C and PE-C case, and will be shown in comparison with analysis result later in Fig 10 (a) and (b). In both cases, initial flexural crack was appeared at shear friction plane. Final failure in D-C is governed by crushing of concrete in compression strut connecting inside edge of pad to opposite end of corbel as shown in Fig 10 (a). In PE-C case, secondary crack was opened at similar position as D-C got final failure crack. But final failure in PE-C was governed by tertiary cracks opened and propagated quickly towards the outer edge of corbel.

In CFRP wrap cases, neither CFRP was ruptured nor concrete surface crack could be captured and hence actual failure pattern in CFRP retrofitted case cannot be explained from experimental result. Hence to explain failure modes clearly and to carry out further parametric study efficiently, non-linear 3D FE analysis was carried out.

4. NON-LINEAR 3D FE ANALYSIS

In this study, non-linear 3D FE analysis was done by using COM3D based on Elasto-Plastic and Fracture (EPF) model. The EPF model idealizes uncracked concrete as combining plasticity and continuum fracture, which represents the permanent deformation and loss of elastic strain energy absorption, respectively[8].

A finite element mesh having average element size of 15mm was generated as shown in Fig 8. Rebar was modeled as steel element and plain concrete model was adopted for concrete elements. Three dimensional zoning concepts[8] was implemented such that fracture energy of concrete element far from bar was reduced as compared to that of concrete element adjacent to bar considering steel-concrete bond transfer. It is expressed in post-cracking concrete tension model as:

$$\sigma_t = f_t\,(\varepsilon_{tu}/\varepsilon_t)^c \qquad (1)$$

Where,

σ_t, f_t, ε_{tu} and ε_t are average tensile stress, direct tensile strength, cracking strain & average tensile strain respectively. 'c' is parameter describing the inclination of descending envelope curve and is the cracking strain[8]. After sensitivity analysis and based on its relationship with element size, average value of C-parameter was taken as 1.10 for plain concrete element away from bar.

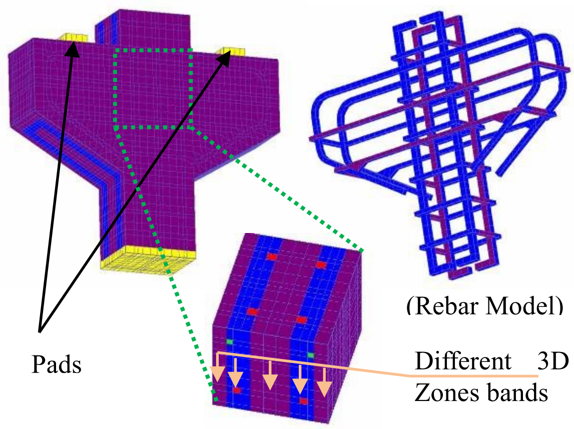


Fig 8 3D FE model created by COM3D

Rebar was modeled as rectangular element having equivalent area as that of round bars. Properties of CFRP and steel bar were adopted from manufacturer's specification. Value of tensile and compressive strength of concrete was taken from corresponding tests. Initial stiffness was calculated as per ACI guidelines[2]. CFRP was modeled as steel element having same thickness as specified fiber thickness. Perfect bond model was adopted between CFRP and concrete because no failure was seen in the bond elements in experiment. After experiment, CFRP sheets were peeled off manually and thin layer of concrete was seen on the attached CFRP surface, which confirmed no failure in bond itself.

4.1 Analysis Results

Analysis result is expressed in load displacement curve and principal strain diagram. Numerical load-displacement behavior is shown in Fig 9 and cases are shown by line with same color as experimental result in Fig 6. Visible concrete crack in series D-C, PE-C & L2-CF-PE-C is tallied with principle strain contour as shown in Fig 10 (a), (b) & (c). Principle strain contour verifies good agreement with visible surface cracks and hence failure pattern in other cases where cracks are not seen; can be better explained based on analysis results.

Load-displacement curve shows that analysis results follow the same trend with experimental results; however, in all cases including case with no CFRP, ultimate load capacity is overestimated. This signifies the necessity of further improvement in direct tensile properties taken from splitting test and tension stiffening parameters. Initial stiffness in experimental D-C, PE-C & L2-CF-PE-C case is significantly lower than analysis, which is due to fault in displacement measurement in experiment as shown in Fig 7 but in L1-FW-PE-C & L2-FW-PE-C correct measurement method was implied and hence better match was observed between experimental and analytical stiffness. Both experimental and simulation result verifies the sharp drop in load carrying capacity due to local Failure criterion and further improvement in load capacity after using CFRP wrap. In analysis, L2-CF-PE-C, L1-FW-PE-C & L2-FW-PE-C shows 11%, 21% and 52 % improvement in load capacity respectively.

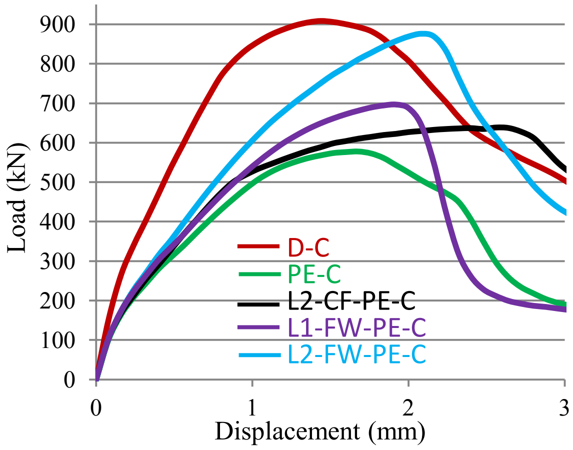
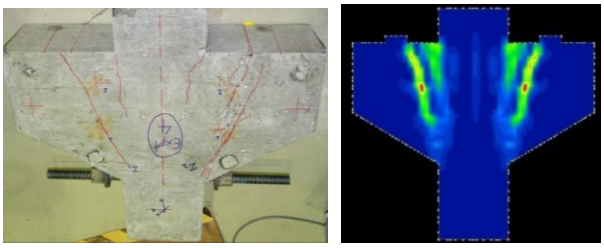


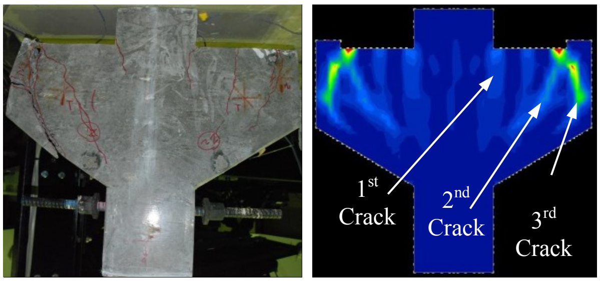
Fig 9 Load-Displacement Curve (Simulation)

Though, overall capacity in all cases is overestimated, CFRP improvement as a percentage of PE-C is underestimated even though steel model and perfect bond is used.

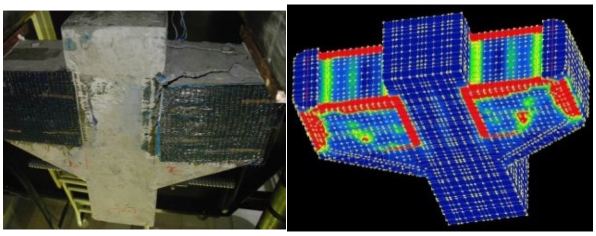
Furthermore, comparison on experimental crack pattern (Fig 10 left) and analysis strain contour (Fig 10 right) shows very good agreement in failure mode in all cases.



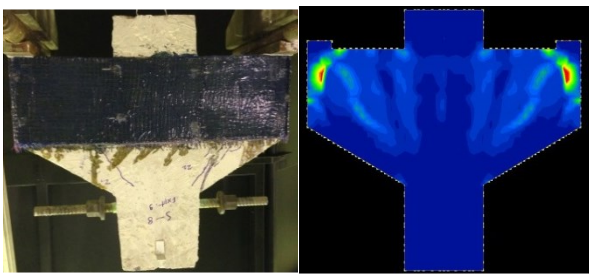
(a) D-C



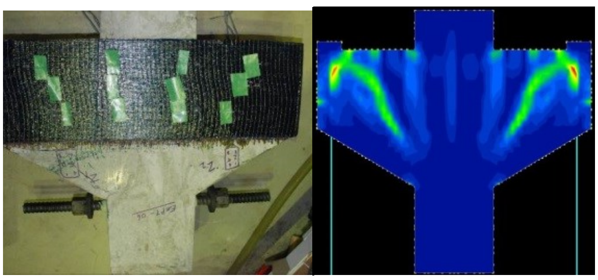
(b) PE-C



(c) L2-CF-PE-C



(d) L1-FW-PE-C



(e) L2-FW-PE-C

Fig 10 Experimental cracks & strain contour by 3D FE analysis

In L2-CF-PE-C, debonding of concrete cover along with CFRP is well simulated as shown in Fig 10 (c). In both, L1-FW-PE-C & L2-FW-PE-C, final collapse is due to localized concrete failure as captured in Fig 10 (d) and (e). Effectiveness of L2-FW-PE-C over L1-FW-PE-C may be due to the higher confinement of former one, which may have contributed to postpone the occurrence of brittle local crack. In L2-FW-PE-C, higher strain in concrete in compression strut is generated than in L1-FW-PE-C before outwards strain localization occurs as shown in Fig 10(d) and (e). None of CFRP retrofitted case shows failure of bond between concrete and fiber sheet. Measured strain in CFRP at ultimate load is lower than its ultimate capacity in all CFRP strengthened cases as found by Zhang et al (2004) in their research[5]. In none of the cases, rebar is yielded except D-C case.

5. CONCLUSIONS

Based on five different series of experimental and numerical study on RC corbels, following conclusions can be made:

- Placing bearing pad at the edge of RC corbel may cause significant drop in its load carrying capacity.
- CFRP wrap to strengthen RC corbel subjected to local failure criterion is effective to enhance ultimate load capacity but incapable to maintain confinement so that expected failure along compression strut is found.
- CFRP full wrap is effective than CFRP wrap up to column-corbel interface in such application.
- CFRP wrap up to column-corbel interface for practical application case having two way beams is not so effective.
- Non-linear 3D FE analysis can model RC corbel with CFRP wrap with similar trend and matching failure behavior.

Further research is necessary to study effectiveness of fiber anchor to prevent delamination of CFRP with concrete cover in L2-CF-PE-C case. Effect of higher number of layer of CFRP should be carried out in such full wrap. Advance concept to model CFRP as having unidirectional fiber embedded in epoxy resin by using 3D FE analysis is also necessary.

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