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ULTIMATE STRENGTH OF CONCRETE CORBELS WITH HYBRID REINFORCEMENT AND STRENGTHENED EXTERNALLY BY CARBON FIBER

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Abstract: The purpose of this paper is to establish a finite element model using ANSYS Computer program version 15 that is capable of interpreting the use of internal hybrid reinforcement (consisting of combined CFRP bars and ordinary steel bars) in concrete corbels as well as the possible use of CFRP sheets for strengthening these corbels externally. It is aimed from such analysis to create small size corbels that are capable of resisting higher ultimate loads compared with ordinary R.C corbels. The validity of the proposed F.E model is checked by comparison with previous experimental results which exist for two separate cases. Namely the case of concrete corbels with internal hybrid bars but no external CFRP sheets; and the case of external CFRP sheets but no internal CFRP bars. The proposed F.E model having been verified through close agreement with the results of the existing experimental tests, it is then used to provide new data for estimating the ultimate capacity of concrete corbels containing both hybrid bars as well as external CFRP sheets. It is found that the ultimate strength of concrete corbels can be enhanced by 50% when both CFRP bars and CFRP sheets are used together in the corbels, and that only 30% strength enhancement can be obtained if CFRP bars or CFRP sheets are used separately.

Keywords: *concrete Corbels, CFRP, F.E analysis, ANSYS*

قوة التحمل القصوى للاكتاف الخرسانية هجينة التسليح والمقواة من الخارج بالياف الكاربون

الخلاصة: الغرض من هذا البحث انشاء نموذج باستخدام طريقة العناصر المحددة بالاستعانة ببرنامج انسز (اصدار 15) وذلك لتمثيل التسليح الهجين الداخلي (المتكون من قضبان تسليح الحديد العادي وقضبان التسليح المصنوعة من الياف الكربون) في الاكتاف الخرسانية مع امكانية استخدام شرائط البوليمر المدعمة بالياف الكاربون للتقوية من الخارج. ان هذا التحليل يهدف الى تقليل حجم الاكتاف وزيادة قوة تحملها القصوى للاحمال المسلطة عليها مقارنة بالاكتاف الخرسانية العادية التسليح. وللتحقق من النموذج المقترح تم تدقيقه من خلال مقارنته مع نتائج مختبرية سابقة لدراستين منفصلتين. الاولى هي حالة الاكتاف الخرسانية المسلحة داخليا بقضبان هجينة ولا تحتوي على تقوية خارجية، اما الدراسة الثانية فهي حالة التقويه الخارجية بشرائط بوليمر مدعم بالياف الكربون من الخارج وعدم وجود قضبان الكاربون من الداخل. ان النتائج المستحصلة من نموذج العناصر المحددة المقترح بواسطة برنامج انسز كانت محققة للنتائج العملية التي توصلت اليها الدراستين السابقتين وقريبة جدا منها، وبهذا تم استخدام النموذج الرياضي المقترح لتوفير بيانات جديدة لقيم الحمولة القصوى للاكتاف الخرسانية الهجينة التسليح من الداخل بقضبان الكاربون البوليمرية والمقواة من الخارج بشرائط البوليمر المدعم بالياف الكاربون.
لقد وجد من خلال هذا البحث ان المقاومة القصوى للاكتاف الخرسانية تزداد بنسبة 50% في حالة استخدام تسليح داخلي هجين مع تقوية خارجية بالياف الكاربون، وتزداد بنسبة 30% فقط في حالة استخدام التسليح الداخلي الهجين او التقوية الخارجية بواسطة شرائط البوليمر المدعمة بالكاربون.

1. Introduction

Corbels can be described as a shear transferring device [1]. They are used widely in the industrial buildings such as participating in R.C bridge construction which lay on structural members for bridge superstructure [2].

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Also corbels known as a short cantilever which project from inner face of column to support concentrated loads of precast beams and cranes. They are usually designed to resist direct shear depending on the theory of shear friction [3, 4].

Most structures (including R.C corbels) may exercise excessive cracks at age of beyond 50 years**,** in general they manifested with poor performance under the service load in form of undesired cracking and deflections [5]. For enhancing shear capacity as well as flexural capacity CFRP is used widely to strengthen corbels, such strengthening depends on polymer type, anchorage length, tensile strength and thickness of the concrete member. [6].

2. Previous Experimental Tests

As mentioned before, the experimental results of two previous studies are adopted in this research to verify the validity of the proposed theoretical F.E model. The R.C corbels adopted by the first study will be referred to as corbels A, while those of the second study will be called corbels B.

The first study was made by Al-Nasrawi [7], who tested concrete corbels reinforced internally with hybrid CFRP and steel bars. Six different cases from those corbels are adopted in this research. All the six corbels were similar in dimensions and each had five Ø6^{mm} main bars in it, with same secondary reinforcement and column reinforcement (as shown in Fig.1), and had same material properties (as listed in Table1). The difference between the selected six corbels (as shown in Fig.2) is in the number of each type of reinforcement used; according to which each corbel is named. For example corbel A(50) had in it five steel bars and no CFRP bars, whereas the second corbel A (41) had four steel bars and one CFRP bar, and so on till the sixth corbel A(05) had no steel bars but five CFRP bars. The experimental ultimate loads of all these six corbels are listed in Table2.

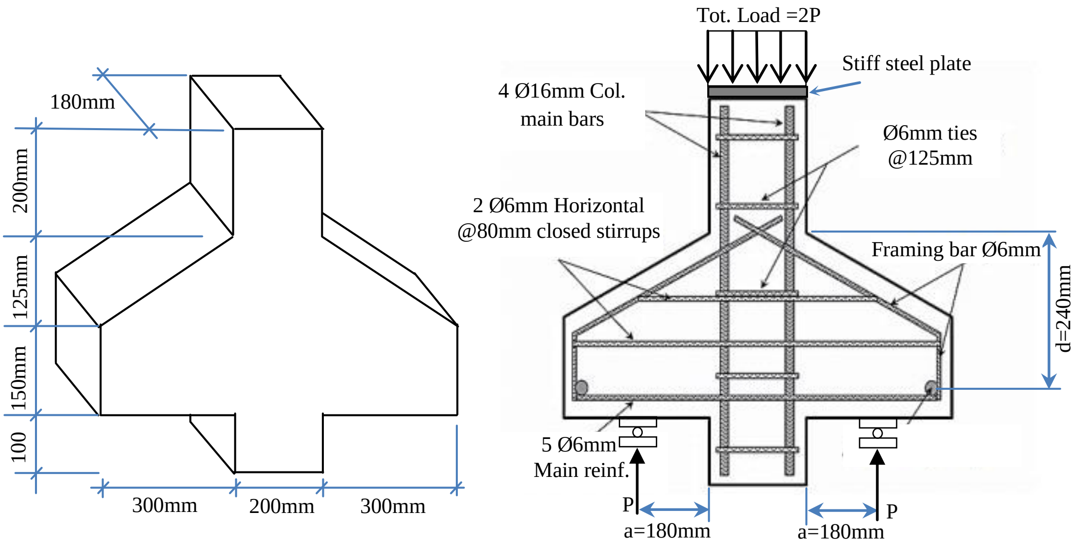


Fig 1: Details of the Reinforced Concrete Corbels Tested by AL-Nasrawi [7]

Table 1: Properties of the Corbel Materials [7]

Cement	Ordinary Portland cement conforming to Iraqi specification No. 5/1984 [9]
Sand	Natural sand from Al-Najaf city with maximum size of 4.75^{mm} and fineness modulus of 2.46
Gravel	Crushed gravel from Al-Nibaey region with maximum size of 14^{mm}
Concrete Mix	1 cement : 1.8 sand : 2.3 gravel by weight giving average cylinder compressive strength at 28 days age of 30 MPa
Main Steel Bars in Corbel	Ø6^{mm} diameter with fy = 530 MPa, f_u = 646 MPa, E= 200x10^3 MPa, %elongation = 7.46%
CFRP Bars in Corbel	Ø6^{mm} diameter (actual diameter = 6.17^{mm} giving cross sectional area a=29.9^{mm2}), linearly elastic f_u = 2068 MPa, E = 124000 MPa, ultimate strain ε_u= 0.017

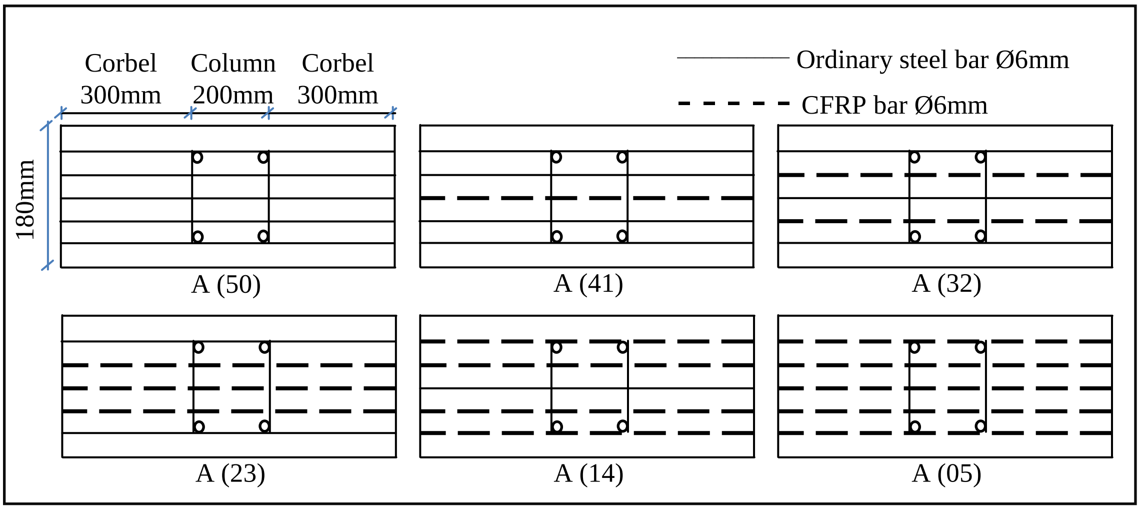


Fig 2: Horizontal Section in Corbels A of AL-Nasrawi [7] Study, Showing the Details of Hybrid Reinforcement in the Selected Six Cases

Table 2: Experimental Ultimate Loads of the Corbels Tested by AL-Nasrawi [7]

Corbel Mark with Description of Main Reinf.	Ultimate Load Capacity (kN)
A (50): Five Steel Bars with no CFRP Bars	125
A (41): Four Steel Bars with One CFRP Bar	132
A (32): Three Steel Bars with Two CFRP Bars	138
A (23): Two Steel Bars with Three CFRP Bars	143
A (14): One Steel Bars with Two CFRP Bars	160
A (05): No Steel Bars with Five CFRP Bars	180

The second study was made by Kadhim [8], who tested R.C corbels having internally two Ø10^{mm} main steel bars but strengthened externally with CFRP sheets of 40^{mm} width and 0.13^{mm} thickness. Eight different cases from those corbels are considered in this research which had same dimensions, main and secondary reinforcement, column reinforcement (as shown in Fig.3) and had same material properties (as listed in Table 3). The difference between the selected eight cases (as shown in Fig. 4) is in the technique of external strengthening by CFRP sheets.

The first corbel named B(control) had no CFRP strengthening, the second corbel named B(H1) was strengthened by one horizontal CFRP sheet, while the third and fourth corbels named B(H2) and (BH3) were strengthened respectively by two and three horizontal CFRP sheets.

The fifth, sixth and seventh corbels named B(H1F), B(H2F) and B(H3F) were strengthened respectively by one, two and three horizontal full wrapped CFRP sheets, while the last eighth corbel named B(V6F) was strengthened by six vertical full wrapped CFRP sheets, three on each corbel. The experimental ultimate loads of all these eight corbels are listed in Table 4.

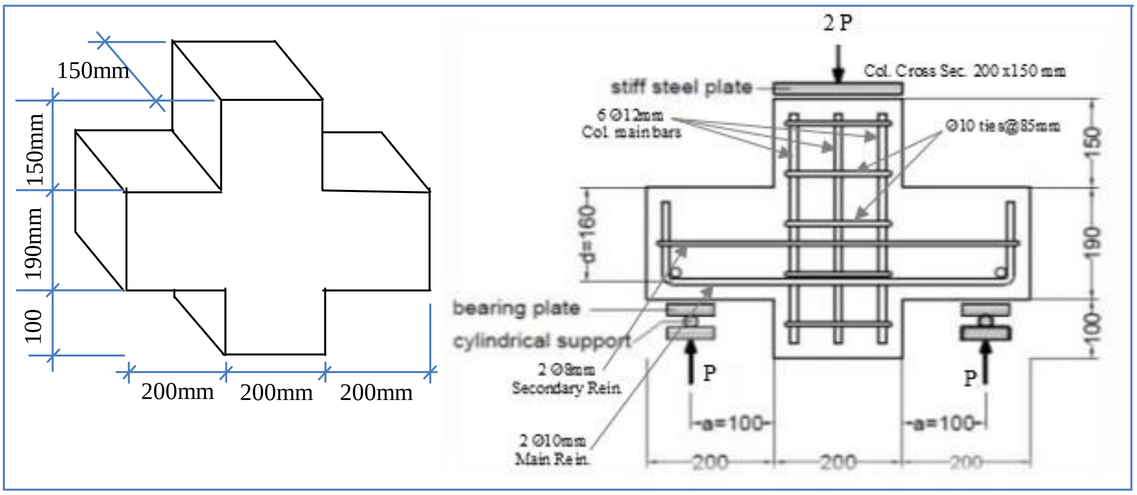


Fig 3: Details of R.C Corbels Tested by Kadhim [8]

Table 3: Properties of the Corbel Materials Used by Kadhim [8]

Cement	*Sulphate resistant Portland Cement conforming to Iraqi specification No. 5/1984 [9]*
Sand	Natural sand from Al-Najaf city with maximum size of 4.75^{mm} and fineness modulus of 2.46
Gravel	Crushed gravel from Al-Nibaey region with maximum size of 12.5^{mm}
Concrete Mix	1 cement : 1.7 sand : 2.2 gravel by weight giving average cylinder compressive strength at 28 days age of 33 MPa
Main Steel Bars in Corbel	$Ø10^{mm}$ diameter with fy = 589 MPa, f_u = 620 MPa, E= $200x10^3$ MPa, %elongation = 8.75%
CFRP Bars in Corbel	40^{mm} width, 0.13^{mm} thickness, tensile strength = 3500 MPa, E=238000 MPa, % elongation at break = 1.8%

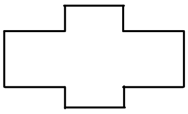
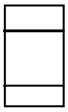
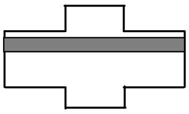
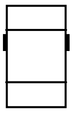
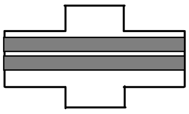
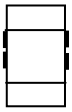
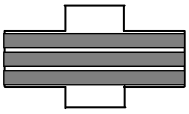
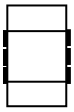
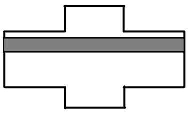
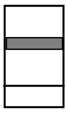
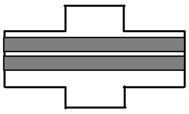
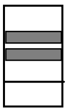
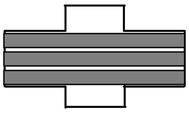
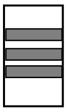
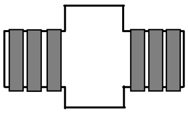
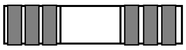
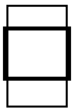
Corbel Mark With Description Of The Strengthening By CFRP Sheets	Front View	Top View	Side View
B (Control): No CFRP Sheets			
B (H1): One Horizontal CFRP Sheet			
B (H2): Two Horizontal CFRP Sheets			
B (H3): Three Horizontal CFRP Sheets			
B (H1F): One Horizontal Full Wrapped CFRP Sheet			
B (H2F): Two Horizontal Full Wrapped CFRP Sheets			
B (H2F): Three Horizontal Full Wrapped CFRP Sheets			
B(V6F): Six Vertical Full Wrapped CFRP Sheets, Three on Each Side			

Fig 4: The Selected Eight Cases of Corbel B of Kadhim [8] Study Showing the Details of External Strengthening by CFRP Sheets

Table 4: Experimental Ultimate Loads of the Corbels Tested by Kadhim [8]

Description of Corbels	*Ultimate Load Capacity (kN)*
B(Control)$_{Ava.}$: No CFRP Strengthening Sheets	113
B(H1): One Horizontal CFRP Strengthening Sheet	133
B(H2): Two Horizontal CFRP Strengthening Sheets	135
B(H3): Three Horizontal CFRP Strengthening Sheets	140
B(H1F): One Horizontal Full Wrapped CFRP Sheet	142
B(H2F): Two Horizontal Full Wrapped CFRP Sheets	149
B(H3F): Three Horizontal Full Wrapped CFRP Sheets	153
B(V6F): Six Vertical Full Wrapped CFRP Sheets	194

3. Finite Element Analysis for the Present Case Study

A finite element analysis using ANSYS program version 15 is carried out in this research to provide original data for estimating the ultimate strength of R.C corbels having hybrid bars (steel + CFRP) and external CFRP sheets. These corbels will be referred to as hybrid corbels C with their shape and dimensions are identical with those adopted by AL-Nasrawi [7].

The shape of the investigated corbels C (being inverted double corbels connected to columns) has an axis of symmetry along the y direction as shown in Fig (5). It can be seen from the figure that such advantage allowed the use of 1/4 the specimen in performing the F.E analysis to reduce disk space and running time of the program. Solid65 element is used to represent RC concrete, which consists of three dimensional 8 nodes element, with each node having 3 degrees of freedom (DOF). The steel and CFRP bars are modeled by link180 element, which consists of two dimensional 2 nodes element with each node having 3 DOF. Perfect bond is assumed to exist between concrete and the reinforcing bars by linking the concrete with any adjacent bar at same nodes. Solid185 element is used to represent the steel plates under the applied load and over the supports which is a three dimensional 8 nodded element with 3 (DOF) at each node. Modulus of elasticity of concrete is taken $E_c = 4700\sqrt{f'c}$ and Poison's ratio for concrete, steel rebars and CFRP rebars are considered equal to 0.2, 0.3 and 0.2 respectively. The tolerance value for the convergence criterion adopted in this non-linear analysis is 0.5%.

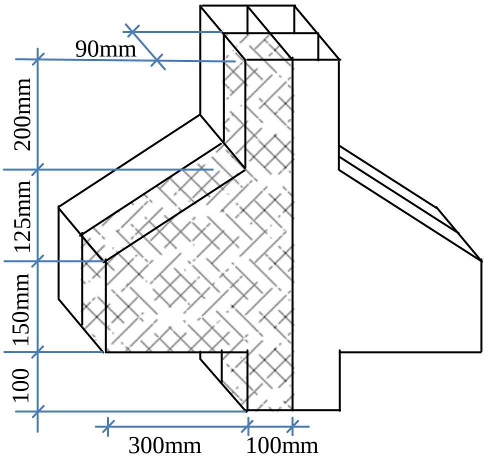
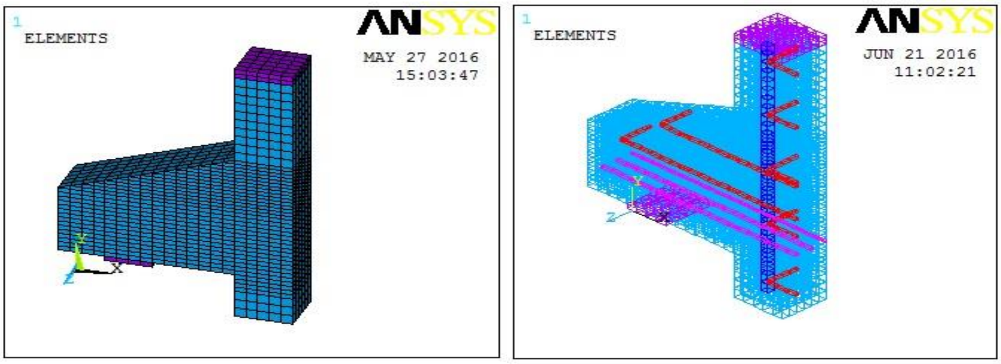


Fig 5: The ANSYS Model Quarter of Corbel C

The validity of this proposed F.E model is checked by applying it to Corbels A (of AL-Nasrawi [7]) and Corbels B (of Kadhim [8]) so that the F.E results can be compared with the corresponding experimental results of the two studies.

This model is first applied to R.C corbels A of AL-Nasrawi [7] (as shown in Fig.6), and the resulting ultimate loads by finite elements are compared with the corresponding values obtained from experiment as listed in Table (5). It can be seen from this table that the maximum percentage difference between ($P_{u - F.E}$) and ($P_{u - exp.}$) is within the average range of ± 6%.



a: Concrete Elements
for Corbel A(50)

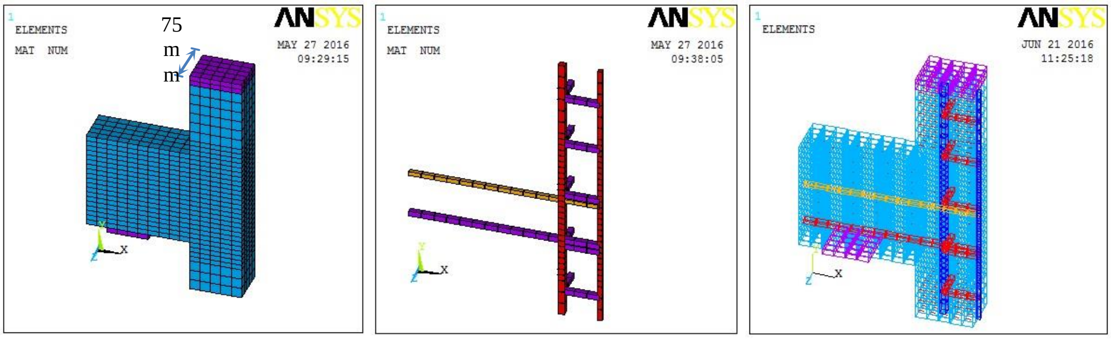
b: Concrete Elements & Reinforcement
for Corbel A(50)

Fig 6: The ANSYS Model for Corbel A(50)

Table 5: Comparison between F.E and Experimental Results for Corbels A

Corbel Name	*Ultimate load (kN)*		$\frac{(P_{u-F.E} - P_{u-exp.})*100}{(P_{u-exp.})}$
	$P_{u-exp.}$	$P_{u-F.E}$	
A (50)	125	133	6.4%
A (41)	132	135	2.3%
A (32)	138	143	3.6%
A (23)	143	150	4.9%
A (14)	160	165	3.1%
A (05)	180	173	-3.9%

Also the F.E model of the present study is applied to R.C corbels B of Kadhim [8] (as shown in Fig.7), (ANSYS models for Corbels B are shown in appendix A, Fig. A1), and the resulting ultimate loads by F.E are compared with the corresponding values obtained from experiment as listed in Table (6). It can be seen from this table that the maximum percentage difference between ($P_{u-F.E}$) and ($P_{u-exp.}$) are within the range of ± 6%.



a: Concrete Elements
for Corbel B(Control)

b: Reinforcement Elements for
Corbel B(Control)

c: Concrete & Reinf. Elements for
Corbel B(Control)

Fig 7: The ANSYS Model for Corbel B(Control)

Table 6: Comparison between the F.E and Experimental Results for Corbel B

Corbel Name	*Ultimate load (kN)*		$\frac{(P_{u-F.E} - P_{u-exp.})}{(P_{u-exp.})} *100$
	$P_{u-exp.}$	$P_{u-F.E}$	
B (Cont.) $_{Ava.}$	113	106	-6.2
B(H1)	133	131	-1.5
B(H2)	135	140	3.7
B(H3)	140	143	2.1
B(H1F)	142	141	-0.7
B(H2F)	149	151	1.3
B(H3F)	153	150	-2.0
B(V6F)	194	189	-2.6

Having verified the validity of the proposed F.E analysis through close agreement with the experimental results for both studies [7&8], the F.E analysis is applied to the new corbels C which contain both hybrid reinforcement and external CFRP sheets. Six cases are investigated, each of which represents a certain combination of ordinary steel bars and CFRP bars.

The number of external CFRP are also varied in the corbels of a specified case giving eight sub corbels headings in each individual case, as listed in Table7, (ANSYS models of the external CFRP sheets for the different cases of Corbels C are shown in appendix A, Fig. A2).

Table 7: Cases of Externally and Internally Reinforcement for Corbels C

Case	Corbel Name	Description of Hybrid Corbels C	
		Internal Reinf. Case	External Reinf. Cases
1	C (50)	Five Steel Bars- No CFRP Bars	No CFRP Sheets
	C (50)- H1		One Horizontal CFRP Sheet
	C (50)- H2		Two Horizontal CFRP Sheets
	C (50)- H3		Three Horizontal CFRP Sheets
	C (50)- H1F		One Horizontal CFRP Sheet
	C (50)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (50)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (50)- V10F		Ten Vertical Full Wrapped CFRP Sheets
2	C (41)	Four Steel Bars- One CFRP Bar	No CFRP Sheets
	C (41)- H1		One Horizontal CFRP Sheet
	C (41)- H2		Two Horizontal CFRP Sheets
	C (41)- H3		Three Horizontal CFRP Sheets
	C (41)- H1F		One Horizontal CFRP Sheet
	C (41)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (41)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (41)- V10F		Ten Vertical Full Wrapped CFRP Sheets
3	C (32)	Three Steel Bars- Two	No CFRP Sheets

	C (32)- H1	CFRP Bars	One Horizontal CFRP Sheet
	C (32)- H2		Two Horizontal CFRP Sheets
	C (32)- H3		Three Horizontal CFRP Sheets
	C (32)- H1F		One Horizontal CFRP Sheet
	C (32)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (32)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (32)- V10F		Ten Vertical Full Wrapped CFRP Sheets
4	C (23)	Two Steel Bars- Three CFRP Bars	No CFRP Sheets
	C (23)- H1		One Horizontal CFRP Sheet
	C (23)- H2		Two Horizontal CFRP Sheets
	C (23)- H3		Three Horizontal CFRP Sheets
	C (23)- H1F		One Horizontal CFRP Sheet
	C (23)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (23)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (23)- V10F		Ten Vertical Full Wrapped CFRP Sheets
	C (14)	One Steel Bars- Four CFRP Bars	No CFRP Sheets
	C (14)- H1		One Horizontal CFRP Sheet
	C (14)- H2		Two Horizontal CFRP Sheets
	C (14)- H3		Three Horizontal CFRP Sheets
	C (14)- H1F		One Horizontal CFRP Sheet
	C (14)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (14)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (14)- V10F		Ten Vertical Full Wrapped CFRP Sheets
6	C (05)	No Steel Bars- Five CFRP Bars	No CFRP Sheets
	C (05)- H1		One Horizontal CFRP Sheet
	C (05)- H2		Two Horizontal CFRP Sheets
	C (05)- H3		Three Horizontal CFRP Sheets
	C (05)- H1F		One Horizontal CFRP Sheet
	C (05)- H2F		Two Horizontal Full Wrapped CFRP Sheets
	C (05)- H3F		Three Horizontal Full Wrapped CFRP Sheets
	C (05)- V10F		Ten Vertical Full Wrapped CFRP Sheets

4. Results and Discussions

Table (8) shows the F.E results for the ultimate capacity of the investigated C corbels, (some of ANSYS results for corbels C are shown in appendix A, Figs. A3, A4, and A5). It can be seen from Table (8) that the maximum enhancement in the ultimate load capacity of R.C corbels can be achieved when highest number of internal CFRP bars are used together with highest number of external CFRP sheets (i.e. in corbel C(05)-V10F the obtained percentage increase in P_u is of the order 51.1%). Figs. (8), (9) and (10) are constructed based on the F.E results shown in Appendix A (Figs. (A3), (A4) and (A5) respectively). These figures show respectively the percentage increase in ultimate load capacity of RC corbels when either hybrid reinforcement (Fig. 8), or external CFRP sheets (Fig. 9) or both of them (Fig. 10) are changed in the RC corbels under consideration. It can be seen from Figures (8) and (9) that the percentage increase in P_u when either hybrid reinforcement or external CFRP sheets are used separately is of maximum order 30%. But when both parameters are varied (Fig. 10) the highest percentage increase in P_u is of the order 50%.

Table 8: F.E Results for the Ultimate Capacity of the Investigated C corbels

Case	Corbel Name	Ultimate load Capacity (kN)	$\frac{(P_{ui} - P_{u-C(50)})}{P_{u-C(50)}}$*100
1	C (50)	133	-
	C (50)- H1	149	12.0
	C (50)- H2	154	15.8
	C (50)- H3	162	21.8
	C (50)- H1F	156	17.3
	C (50)- H2F	158	18.8
	C (50)- H3F	168	26.3
	C (50)-V10F	172	29.3
2	C (41)	135	1.5
	C (41)- H1	157	18.0
	C (41)- H2	158	18.8
	C (41)- H3	166	24.8
	C (41)- H1F	156	17.3
	C (41)- H2F	160	20.3
	C (41)- H3F	169	27.1
	C (41)-V10F	176	32.3
3	C (32)	143	7.5
	C (32)- H1	162	21.8
	C (32)- H2	163	22.6
	C (32)- H3	167	25.6
	C (32)- H1F	164	23.3
	C (32)- H2F	166	24.8
	C (32)- H3F	174	30.8
	C (32)-V10F	181	36.1
4	C (23)	150	12.8
	C (23)- H1	164	23.3
	C (23)- H2	170	27.8
	C (23)- H3	173	30.1
	C (23)- H1F	166	24.8
	C (23)- H2F	173	30.1
	C (23)- H3F	174	30.8
	C (23)-V10F	189	42.1
5	C (14)	165	24.1
	C (14)- H1	167	25.6
	C (14)- H2	171	28.6
	C (14)- H3	176	32.3
	C (14)- H1F	170	27.8
	C (14)- H2F	179	34.6
	C (14)- H3F	180	35.3
	C (14)-V10F	194	45.9
6	C (05)	173	30.1
	C (05)- H1	174	30.8
	C (05)- H2	176	32.3
	C (05)- H3	180	35.3
	C (05)- H1F	178	33.8
	C (05)- H2F	182	36.8
	C (05)- H3F	183	37.6
	C (05)-V10F	201	51.1

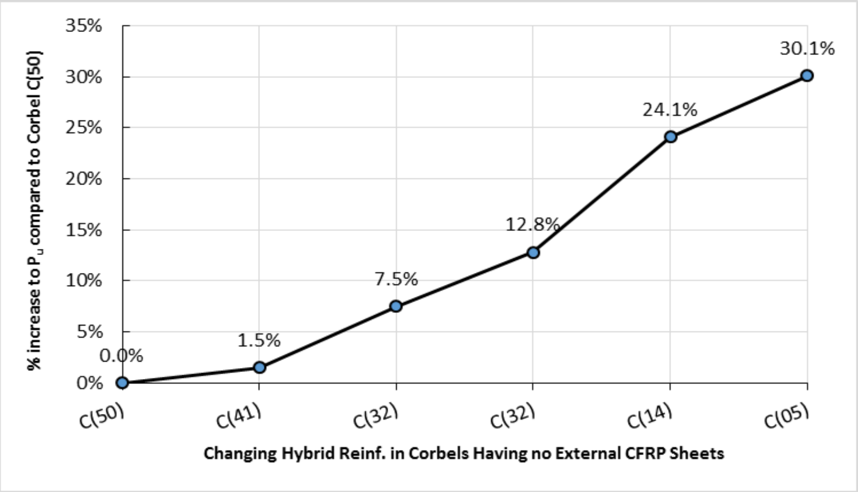


Fig.8: Percentage Increase in Ultimate Load Capacity of Corbels with Hybrid Reinforcement

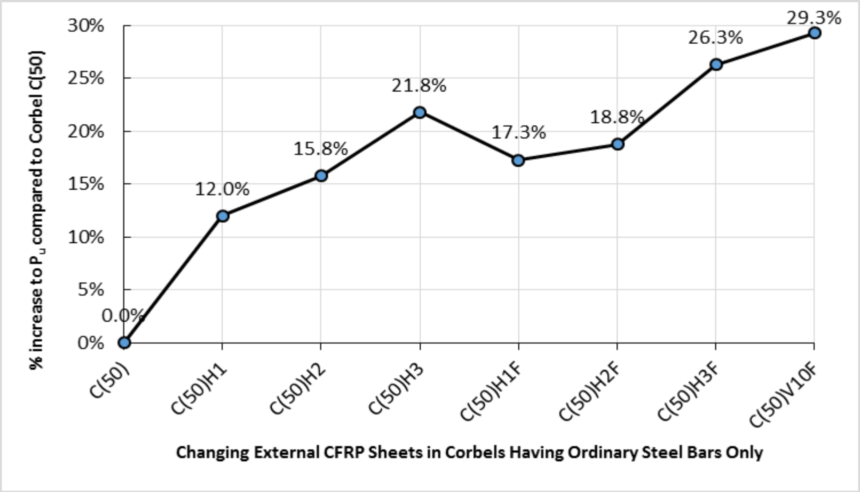


Fig.9: Percentage Increase in Ultimate Load Capacity of Corbels with External CFRP Sheets

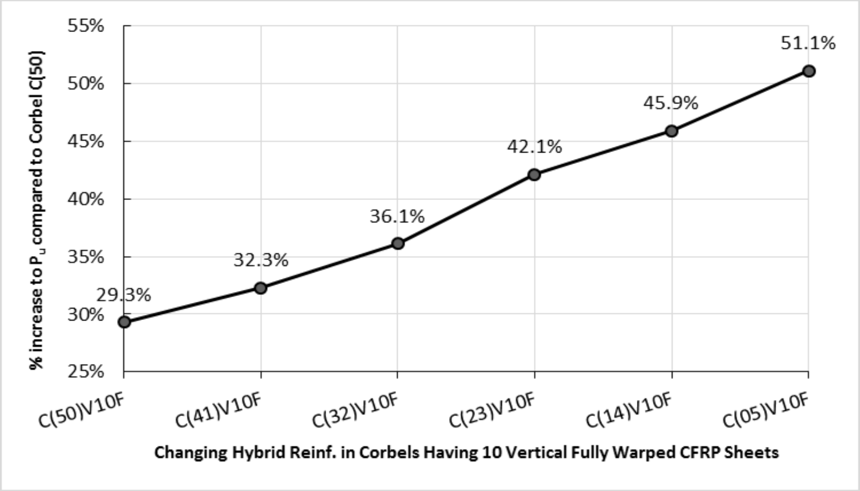


Fig.10: Percentage Increase in Ultimate Load Capacity of Corbels with Both Hybrid Reinforcement and External CFRP Sheets

5. Conclusions

Based on the experimental results of existing tests and the theoretical results of the present F.E analysis (by ANSYS program version 15) for RC corbels, the following conclusions can be drawn;

1. Using CFRP bars with ordinary steel bars as main reinforcement in RC corbels increase the ultimate load capacity of the corbel. When the ratio of CFRP bars to ordinary steel bars is increased in a concrete corbel, the corbel can sustain a higher ultimate load.
2. Using external CFRP sheets is found to increase the ultimate strength of RC corbels and highest increase in load is achieved with highest number of external CFRP sheets used.

3. For the investigated R.C corbels, the percentage increase in ultimate load for the case of no external CFRP sheets but varying the hybridization ratio of main reinforcement in the corbel is obtained to be of the order 30%.
4. For the investigated R.C corbels, the percentage increase in ultimate load for the case of using only ordinary steel bars (with no CFRP bars) and using external CFRP sheets is found to be of the order 30% also.
5. When both hybrid reinforcement (steel bars + CFRP bars) and external CFRP sheets are used in RC corbels of the present investigation, the percentage increase in ultimate load of the corbel is obtained to be of the order 50%.

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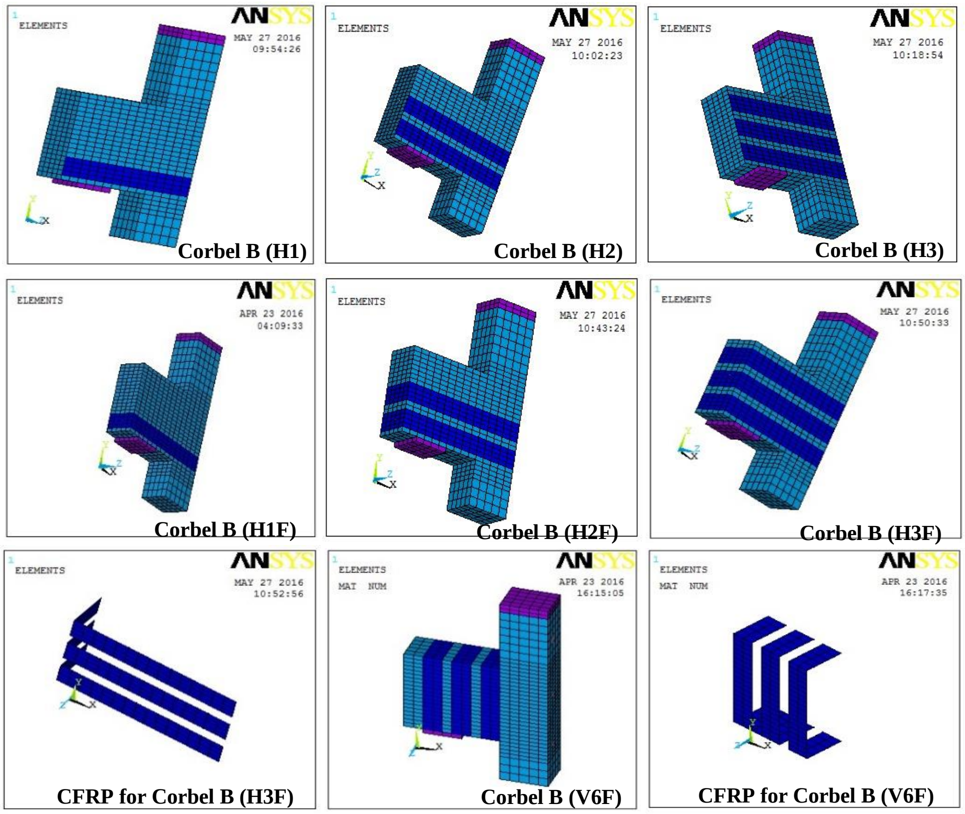
7. Appendix – A



Corbel B (H1)

Corbel B (H2)

Corbel B (H3)

Corbel B (H1F)

Corbel B (H2F)

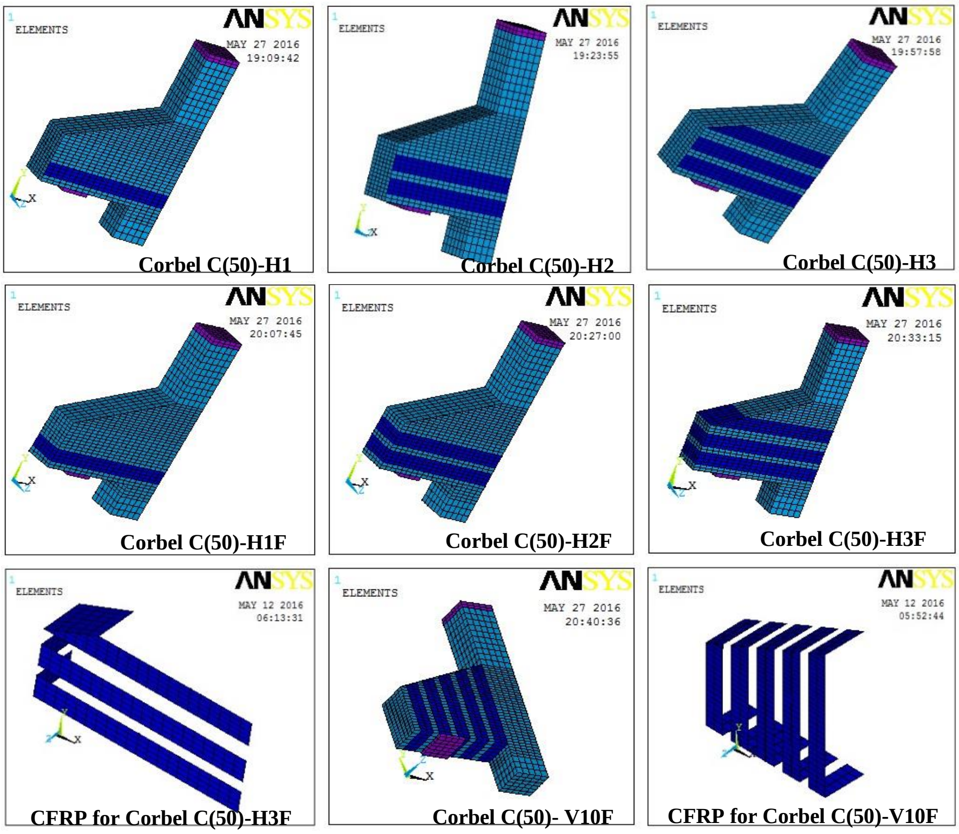
Corbel B (H3F)

CFRP for Corbel B (H3F)

Corbel B (V6F)

CFRP for Corbel B (V6F)

Fig. A1: ANSYS Models for Corbels B



Corbel C(50)-H1

Corbel C(50)-H2

Corbel C(50)-H3

Corbel C(50)-H1F

Corbel C(50)-H2F

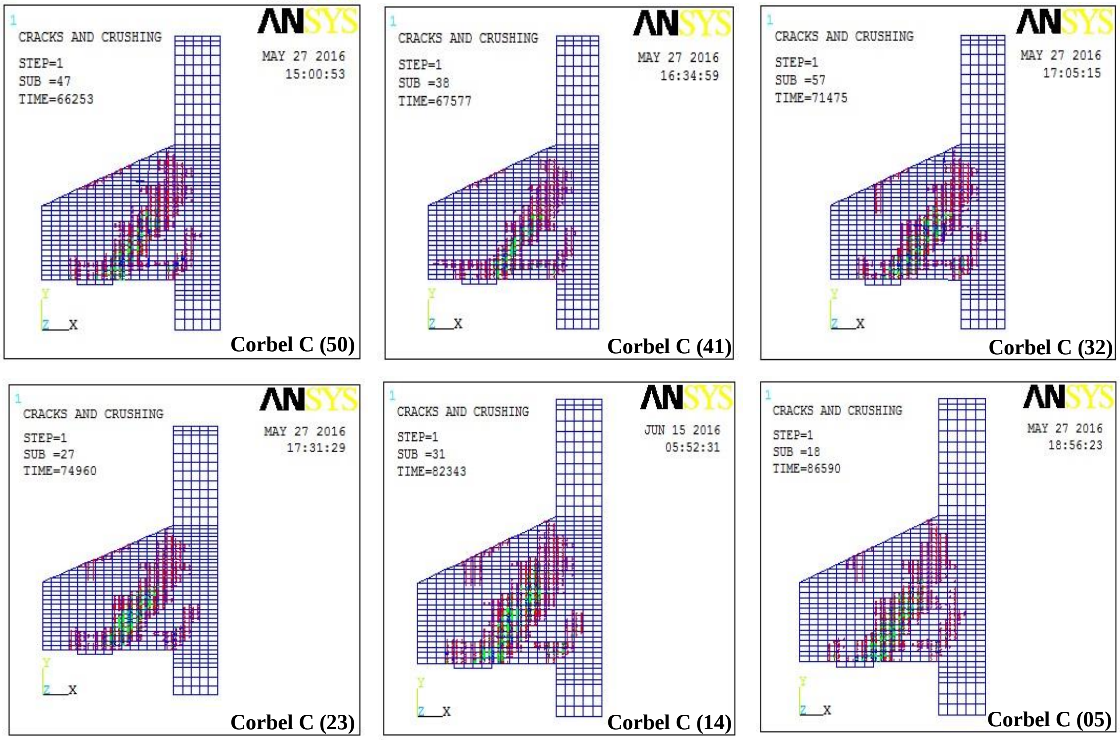
Corbel C(50)-H3F

CFRP for Corbel C(50)-H3F

Corbel C(50)- V10F

CFRP for Corbel C(50)-V10F

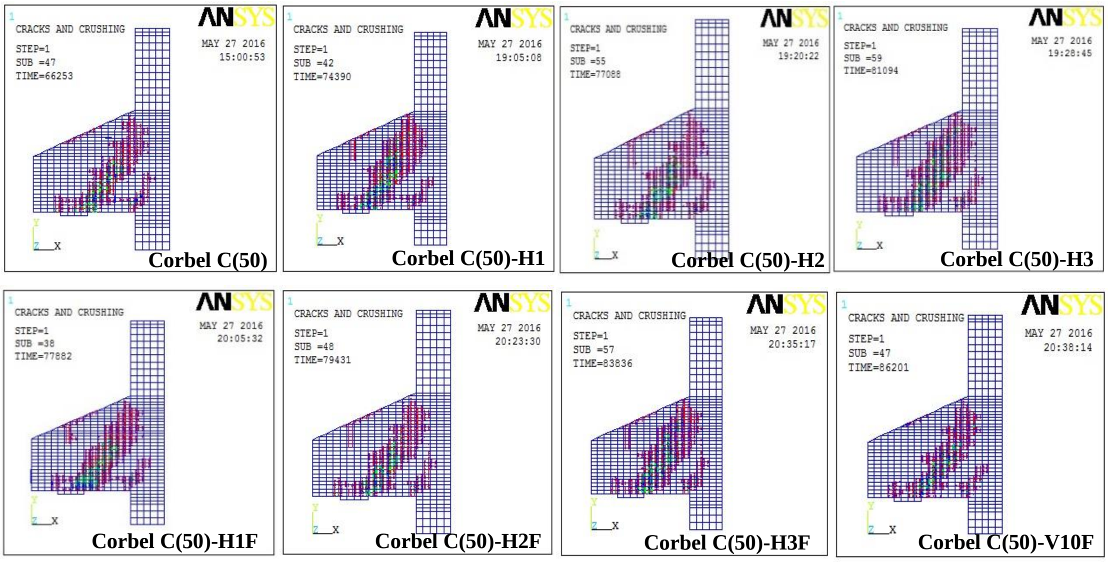
Fig. A2: ANSYS Models for Corbels C(50) with Different Cases of External CFRP Sheets



Corbel C (50) **Corbel C (41)** **Corbel C (32)**

Corbel C (23) **Corbel C (14)** **Corbel C (05)**

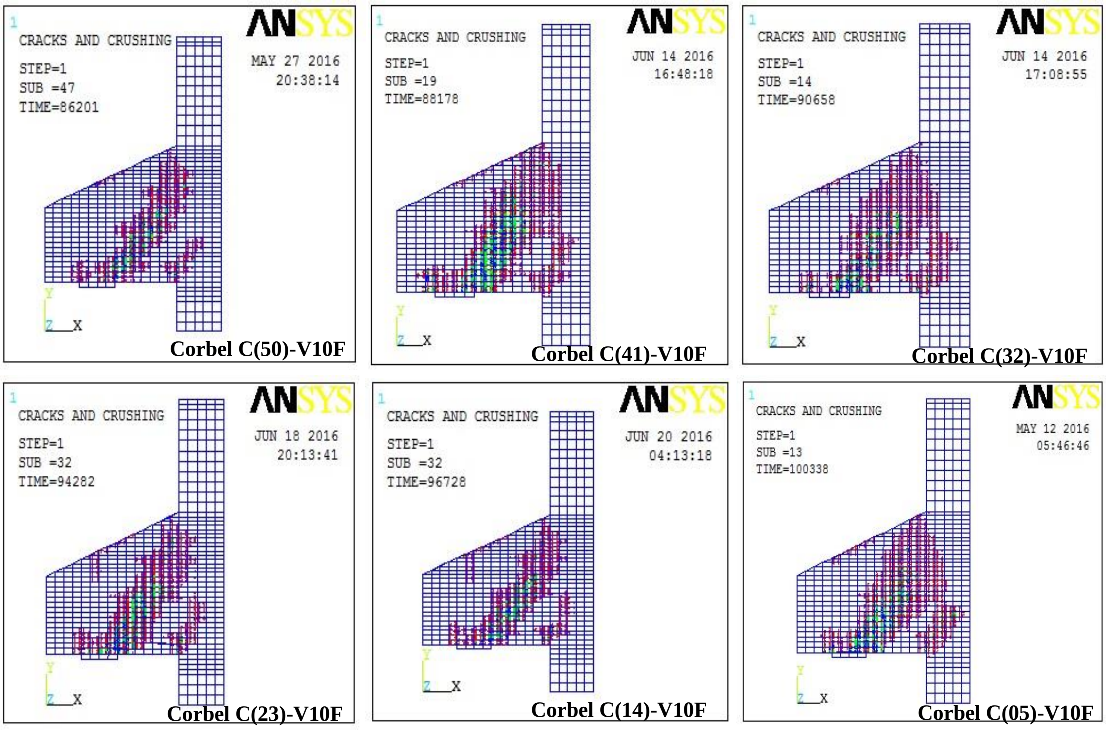
Fig. A3: ANSYS Results for Corbels C Having Different Numbers of Internal CFRP Bars but no External CFRP Sheets



Corbel C(50) **Corbel C(50)-H1** **Corbel C(50)-H2** **Corbel C(50)-H3**

Corbel C(50)-H1F **Corbel C(50)-H2F** **Corbel C(50)-H3F** **Corbel C(50)-V10F**

Fig. A4: ANSYS Results for Corbels C with no CFRP Bars but different Cases of CFRP External Sheets



Corbel C(50)-V10F **Corbel C(41)-V10F** **Corbel C(32)-V10F**

Corbel C(23)-V10F **Corbel C(14)-V10F** **Corbel C(05)-V10F**

Fig. A5: ANSYS Results for Corbels C Having Different Numbers of Internal CFRP Bars and 10 Vertical External CFRP Sheets