Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)
22-24July 2008, Zurich, Switzerland

Bond studies of FRP confined hooked bar anchorages in high strength concrete structures

B. Hamad, C. Bou Abs, & F. Ibrahim
American University of Beirut, Beirut, Lebanon

ABSTRACT: The objective of the research reported in this paper was to evaluate the effect of fiber reinforced polymer (FRP) sheets, externally confining high strength concrete beam-column joints, on the bond strength and ductility of the mode of failure of hooked bars anchored in the joints. Twelve beam-column specimens with a nominal concrete strength of 60 MPa, were tested. The specimen simulated the rigid connection of a cantilever beam to a column. It consisted of a vertical beam element anchored in a column base. The tensile reinforcement of the beam consisted of two bars anchored in the base using hooked bar anchorages. The variables were the beam bar size (16, 25, or 32 mm), the confinement mode of the beam bars in the beam-column joint (whether the bars were confined within or outside the column reinforcement cage), and whether or not the joints were externally wrapped with FRP sheets. Specimens where the beam bars were anchored within the column reinforcement cage were referred to as “confined specimens”, and specimens where the beam bars were anchored outside the column reinforcement cage were referred to as “unconfined specimens”. All anchorages were designed to ensure bond splitting failure before the beam bars yielded. The effect of FRP was assessed by comparing the performance of specimens with no FRP with companion specimens that had FRP sheets externally wrapping the beam-column anchorage zones but identical otherwise. Comparison was based on the mode of failure, load-deflection behavior, and the bond strength. FRP sheets were found effective in increasing the anchorage capacity and the ductility of the load-deflection behaviour. The improvement was more significant for the “unconfined specimens” than the “confined specimens”. The conclusions are valid for all bar sizes tested.

1 INTRODUCTION

Tests on concrete beams wrapped with fiber reinforced polymer (FRP) sheets indicated an increase in strength and durability. FRP strengthening has been the subject of experimental and analytical investigations where most of the research work has been focused on mechanisms for flexural and shear strengthening of beam elements or confinement of columns. This form of strengthening has been used for strengthening and rehabilitation of bridges and structures in many areas in the world. The technology has even entered Lebanon with few strengthening applications in various distressed structures.

Previous research reported in the literature indicated the positive effect of carbon fiber reinforced polymer (CFRP) sheets, externally confining normal strength concrete beam-column joints, on the bond strength and ductility of the mode of failure of hooked bars anchored in the joints (Hamad et al. 2007). It was significant to investigate if the improvement in the bond characteristics of the hooked bars would be valid if high strength concrete is used instead of normal strength concrete. Such improvement would encourage the use of CFRP technology in strengthening and retrofitting distressed high strength concrete beam-column joints especially in earthquake-damaged and blast-damaged reinforced concrete structures.

2 EXPERIMENTAL STUDY

2.1 *Design of specimens*

Twelve full-scale high strength concrete beam-column specimens were constructed and tested using the strong floor-reaction wall testing facility in the Materials Testing Laboratory at the American University of Beirut (AUB). The variables were bar size (16, 25, or 32 mm), anchorage mode of the beam bars in the beam-column joint, and whether the beam-column joints were externally confined with CFRP sheets or not. Specimens where the beam bars were anchored within the base column reinforcement cage are referred to as "confined specimens", whereas specimens where the beam bars were anchored outside the column reinforcement cage are referred to as "unconfined specimens". The test specimens are identified in Table 1. The specimens are grouped in three groups each with a different bar size. A four part notation system was used to identify the variables in each specimen. The first part indicated the anchorage confinement mode of the beam bars in the column reinforcement cage: U for unconfined mode (beam bars outside the column reinforcement cage) and C for confined mode (beam bars within the column reinforcement cage). The second part indicates the size of the beam bars in mm (16 or 25 or 32), the third part indicates that high strength concrete was used (H), and the fourth part F is added if the beam-column joint is wrapped by CFRP sheets.

The beam-column specimen consisted of a 30x30 cm vertical element of height 100 cm, simulating the beam, anchored in a 30x40 cm base of length 120-cm, simulating the column. The tensile reinforcement of the beam consisted of two 16 or 25 or 32 mm bars anchored using standard hooks in the base column. The tension face clear concrete cover to the beam bar was 3 cm. The reinforcement on the compression side of the beam consisted of two 10-mm bars in all specimens. In all specimens, the longitudinal reinforcement of the base consisted of two layers of three 25-mm bars. Whereas the bottom and top concrete cover to the longitudinal bars of the base was 3 cm, the side concrete cover was 3 cm in the "confined specimens" and (3 cm + beam bar size) in the "unconfined specimens". Transverse reinforcement was placed in all elements except at the anchorage zone. Schematic views of typical "unconfined" and "confined" specimens are shown in Figures 1 and 2.

To insure bond splitting failure before the steel yielded, the embedment depth of the tensile bars of the vertical elements in the base column, as measured from the interface to the outside end of the hook, was chosen in all twelve specimens to be shorter than the basic development length l_{dh} for a deformed bar terminating in a standard hook, as specified by the ACI Building Code ACI 318-05 (ACI 2005). The embedment depths were 15 cm for the 16-mm and 25-mm beam bars, and 20 cm for the 32-mm beam bars.

2.2 *Materials*

All bars used in the study had parallel deformation pattern and were from the same heat of steel. The bars were Grade 60 steel and met ASTM A615/A615M-03a specifications (ASTM 2004). A non air-entrained concrete mix was designed to give a nominal compressive strength at 28 days of 60 MPa. The CFRP system used in the study was SikaWrap Hex-230C and the epoxy adhesive used was Sikadur 330. The CFRP sheets are unidirectional with a density of about 2.25g/cm^3, thickness of 0.13 mm, tensile strength of 3,500 MPa, modulus of elasticity of 230 GPa, and elongation at break of 1.5%. The wrapping configuration of all six FRP wrapped specimens is shown in Figure 3.

2.3 *Testing procedure*

The method of loading simulated the reaction conditions at a beam-column joint. The testing frame is shown in Figure 4. A lateral compressive force was applied through a hydraulic jack mounted on the reaction wall at around 15-cm from the tip of the vertical beam element while the base was fixed to the strong floor using threaded rods. The load was applied monotonically in increments of 10 kN. The load and the tip beam deflection at the point of the application of the load were monitored on a computer connected to the testing facility. At each load stage, the crack patterns were marked on the specimen.

Table 1. Identification of the test specimens

Specimen notation	Nominal concrete strength (MPa)	Beam bars (mm)	Anchorage mode of the beam bars in the column	Presence of CFRP sheets
U16H	60	16	Unconfined	No
U16H-F	60	16	Unconfined	Yes
C16H	60	16	Confined	No
C16H-F	60	16	Confined	Yes
U25H	60	25	Unconfined	No
U25H-F	60	25	Unconfined	Yes
C25H	60	25	Confined	No
C25H-F	60	25	Confined	Yes
U32H	60	32	Unconfined	No
U32H-F	60	32	Unconfined	Yes
C32H	60	32	Confined	No
C32H-F	60	32	Confined	Yes

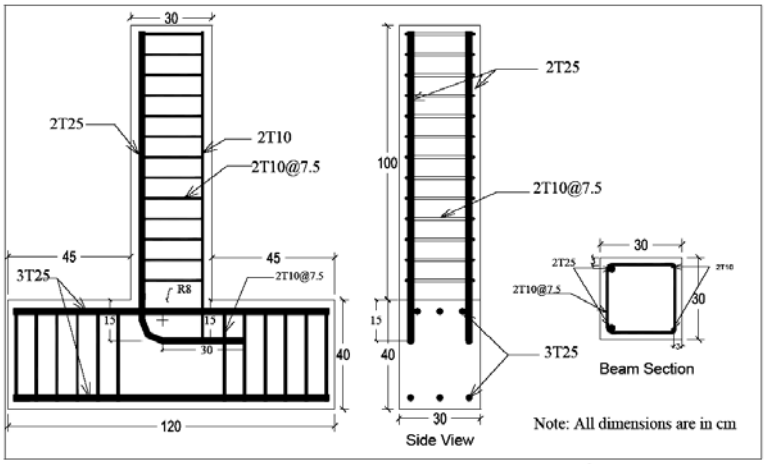

Figure 1. Details of the beam-column specimen U25H; unconfined anchorage mode, 25-mm beam bars.

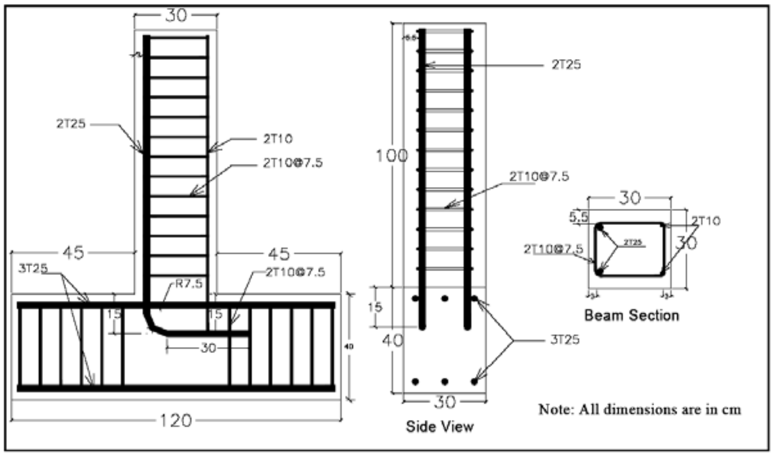

Figure 2. Details of the beam-column specimen C25H; confined anchorage mode, 25-mm beam bars.

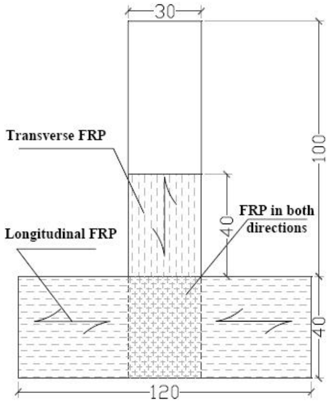

Figure 3. Typical wrapping configuration of the beam-column joint.

Figure 4. Overall view of the test set-up.

3 MODE OF FAILURE

The crack patterns of all “unconfined and “confined” specimens without CFRP wrapping were very similar. The first principal crack was detected at the corner of the beam-column interface on the tension side of the beam at an angle between 20 and 30° with the horizontal, at low loading level. Then, the crack tended to intersect the right corner of the beam-column interface at advanced loading stages. The second principal crack in the base column was diagonal in orientation. It began at about 10 cm below the tension side beam-column corner and propagated along the anchored bars. Other cracks branched from this main crack in a V-pattern towards the top surface of the base element. The final mode of failure was spalling of the side cover normal to the plane of the hook due to the crushing of the concrete at the inner radius of the bend due to the very high local compressive stress concentrations. Two modes of failure of the CFRP sheets were identified. The first was bond failure or peeling of the edge of the vertical sheet off the beam surface. The second was tearing or shearing of the sheets.

4 TEST RESULTS

To allow direct comparison of all test specimens, the corresponding load-deflection data were normalized to a common concrete strength of 60 MPa. The adjustment was made by multiplying the load at each deflection by $(60/f'_c)^{1/4}$, where f'_c is the concrete strength in MPa of the specimen under consideration at the day of testing. Test results are presented in Table 2. The listed data include the specimen notation, the concrete strength at the day of testing, the measured ultimate load P_{max}, the deflection at the tip of the vertical beam corresponding to P_{max}, and the data normalized to a concrete strength of 60 MPa including the ultimate load P_{max} and the corresponding ultimate load ratios.

Load-deflection curves for the four tested 16-mm bar specimens are shown in Figure 5. The four curves are almost identical up to a load of 30 kN above which the “unconfined specimen” U16N deviates clearly from the three other specimens and flattens until a well-defined peak is achieved at a load of 57.6 kN corresponding to a deflection of 7.5 mm. The other three specimens remain gaining load with increase in deflection. When compared with the “unconfined specimen” U16N, the increases in the ultimate load are 39% for U16N-F, 37% for C16N, and 49% for C16N-F. The increases in the deflection at the tip of the vertical beam element as compared with the “unconfined specimen” U16N are 49% for U16N-F, 59% for C16N, and 89% for C16N-F.

Table 2. Test results.

Specimen notation	Concrete strength at the day of testing (MPa)	Ultimate load P_{max} (kN)	Displacement at P_{max} (mm)	Normalized ultimate load (kN)	Ratio of ultimate loads*
U16H	60.6	57.8	7.5	57.7	--
U16H-F	60.6	80.4	11.2	80.2	1.39
C16H	60.6	79.4	11.9	79.2	1.37
C16H-F	60.6	86.0	14.2	85.8	1.49
U25H	61.8	71.8	10.1	71.3	--
U25H-F	61.8	106.4	16.9	105.6	1.48
C25H	64.7	101.6	13.9	99.7	1.40
C25H-F	64.7	116.2	20.9	114.0	1.60
U32H	61.8	147.5	24.0	146.4	--
U32H-F	61.8	170.9	27.3	169.6	1.16
C32H	64.7	175.5	24.6	172.2	1.18
C32H-F	64.7	186.9	27.6	183.4	1.25

* This is the ratio of the ultimate load of a tested specimen of a given bar size relative to the unwrapped and “unconfined” specimen in the group.

Load-deflection curves for the four tested 25-mm bar specimens are shown in Figure 6. When compared with the U25N, the increases in the ultimate load are 48% for U25N-F, 40% for C25N, and 60% for C25N-F. The increases in the deflection at the tip of the vertical beam element as compared with U25N are 67% for U25N-F, 38% for C25N, and 107% for C25N-F. On the other hand, load-deflection curves for the four tested 32-mm bar specimens are shown in Figure 7. When compared with U32N, the increases in the ultimate load are 16% for U32N-F, 18% for C32N, and 25% for C32N-F. The increases in the deflection are 14% for U32N-F, 3% for C32N, and 15% for C32N-F.

5 CONCLUSIONS

In the three groups of specimens with different bar sizes, confinement of the beam-column anchorage zone either by anchoring the beam bars within the base column reinforcement cage or by external wrapping of the beam column joint with CFRP sheets or by applying both confinement strategies, lead to improvement in the ultimate load capacity and the corresponding deflection at the tip of the vertical beam. The “confined” specimen with the beam bars confined within the base column reinforcement cage and with CFRP sheets externally confining the beam-column joint, reached the highest ultimate load and achieved the largest specimen deflections at ultimate as compared with the three other specimens in the same bar size group. The results indicate the significance of FRP confinement in improving the bond performance of and the ductility of the mode of failure of high strength concrete beam-column connections.

6 REFERENCES

Hamad, B., Ibrahim, F., and Bou Abs, C. 2007. Bond Studies of Hooked Bar Anchorages Confined with FRP in Normal Strength Concrete Structures. *Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures, FRPRCS-8,* Patras, Greece.

ACI Committee 318, Building Code Requirements for Reinforced Concrete and Commentary (ACI 318-05/ACI 318R-05), *American Concrete Institute*, Farmington Hills, Michigan, 2002.

ASTM A615/A615M-03a, “Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement,” 2004 Annual Book of ASTM Standards, V. 01.04, *American Society for Testing and Materials*, West Conshohocken, PA, 318-322.

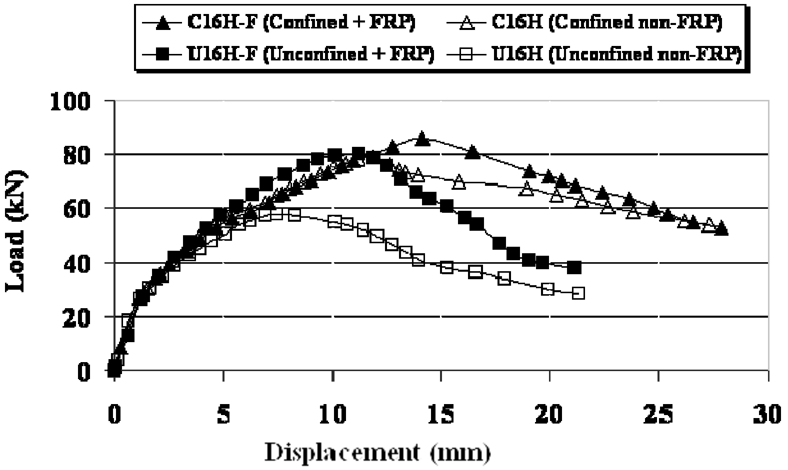

Figure 5. Load-deflection curves for the 16-mm bar specimens.

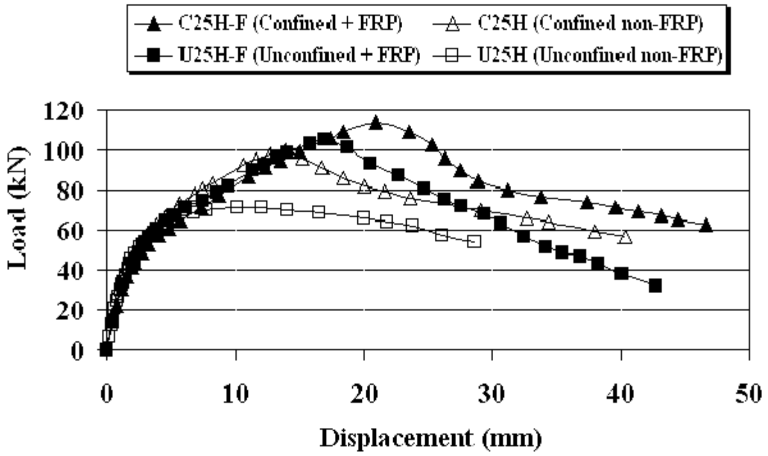

Figure. 6. Load-deflection curves for the 25-mm bar specimens.

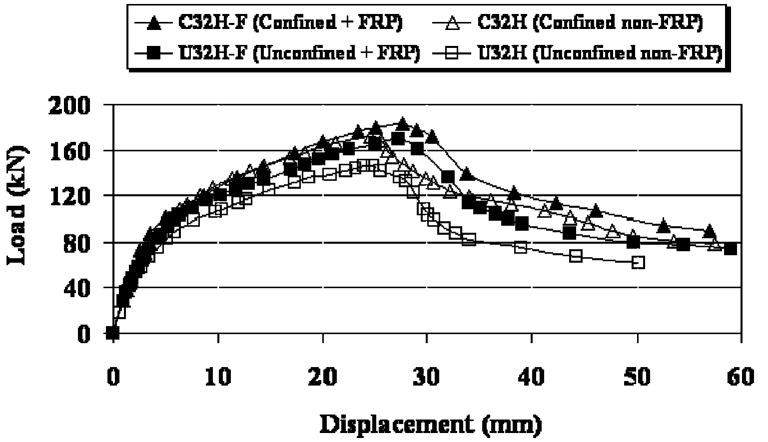

Figure 7. Load-deflection curves for the 32-mm bar specimens.