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Flexural Behavior of Hybrid Reinforced Concrete Beam-Column Joints under Static and Repeated Loads

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Abstract: This study presents experimental investigation and numerical analysis of the flexure behavior of interior beam-column joints made from hybrid concrete (Normal Concrete (NC) and Steel Fiber Reinforced Concrete (SFRC)) or hybrid reinforcement (steel and CFRP bars internally or externally by NSM technique). Nine hybrid reinforced concrete beam-column joint specimens under effect of static or repeated loading with pre-axial compression load were studied and tested within three test groups. Several variables that effect on the behavior of beam-column connection region are investigated such as type of loading (static or repeated), type of hybridization (concrete hybridization or reinforcement hybridization), area of concrete hybridization and the joint enlargement technique. The results showed that using SFRC as replacement concrete at different areas of BCJ under static loading, improved the ultimate load capacity and first, cracking load about (7-13%) and (0-27%), respectively, compared with reference NC joint with increase in the ductility about (11-30%). As well as using the same technique under repeated loading condition showed increasing in ultimate load about (14.3%) with improvement a cumulative ductility about (13%) compared with the reference NC joint. The joint enlargement technique by using SFRC produced increasing of ultimate and first, cracking loads about (27%) and (67%), respectively. On the other hand using CFRP bars as (internal or external) hybridization system (50% of main reinforcement) under static loading caused increments of ultimate and first, cracking loads about (18, 5%) and (33, 67%), respectively, compared with the reference steel reinforced joint while the ductility ratio decreased about (7.4%) and increased about (14%), respectively. As well as the internal hybrid reinforcement system exhibited reduction in a cumulative ductility about (12.5%) under repeated loading. In the numerical analysis, non-linear three dimensional finite elements solution scheme utilizing ANSYS computer program (Version 14.5) was adopted. Comparison between the theoretical and experimental results exhibited reasonable agreement.

Key words: Beam-column joint, hybrid concrete, hybrid reinforcement, flexural behavior, SFRC, CFRP

INTRODUCTION

The beam-column joint is defined as the portion of the column within the depth of the deepest beam that frames into the column (ACI, 2002). Beam-column joints in a reinforced concrete moment resisting frame are critical areas for exchange of loads adequately between the associating components (i.e., beams and columns) in the structure and ensure its continuity (Uma and Jain, 2006). The change suddenly in geometry and the complex nature of stress distribution in the joint are the explanations behind their critical conduct. The joints have limited force carrying capacity, therefore, when they subjected to larger forces during earthquakes or blasts, joints are severely damaged and may lead to catastrophic collapse of the entire building. Repair damaged joints is difficult and thus, should avoid damage. Therefore, beam-column connections ought to have sufficient strength, ductility and energy dissipation to oppose the inside forces caused by the framed members Rajaram *et al.* (2010). Since, the 1960's, many experimental and theoretical investigations have been conducted to investigate the overall conduct of beam-column connection. The examinations for the conduct of hybrid reinforced concrete construction generally were beginning at end of the pervious century. Numerous researches have examined the conduct and quality of hybrid reinforced concrete members with different hybridization techniques.

Leung and Balendran (2003) showed experimental investigation of the load-deflection conduct for the reinforced concrete beams internally by Glass Fibre Reinforced Polymer (GFRP) rods and steel bars. In view of the test outcomes, the bending quality of concrete beams with the hybrid reinforcements is higher than the concrete beams combined with any steel reinforcement bars or GFRP rods. Hadi (2009) explored the impacts of adding steel fibers to high strength concrete of the reinforced concrete columns, especially, to the column cover to make a hybrid concrete construction. It was found that the hybrid cross-sectional sections of column containing both FHSC (Fibrous High Strength Concrete) as external concrete layer and HSC in the center showed more flexible levels than the columns with FHSC through the entire cross section. Mahdi (2015) investigated the conduct and extreme strength of concrete corbels with hybrid reinforcement (steel and CFRP) rebars subjected to vertical distributed applied load. He concluded that a great enhancement in the conduct and the ultimate strength of specimens with hybridization technique of main tension reinforcement also horizontal reinforcement (closed stirrups).

It can be noticed from literature, the hybridization systems of concrete or reinforcement were extensively studied for the ordinary beams, columns, corbels and other structural members but there are few studies on the flexural response of hybrid reinforced beam-column connections. Therefore, the current study will contribute to increasing the knowledge of the conduct of hybrid reinforced concrete beam-column connections under the effect of static or repeated loading.

MATERIALS AND METHODS

Research significance: The objective of this research is to conduct an experimental investigation of the maximum strength, cracking patterns, failure patterns, ductility and energy absorption of reinforced concrete beam-column joints made of hybrid concrete or hybrid reinforcement. Studying the factors that influence on flexural conduct of the hybrid BCJs such as loading type (static or repeated), type of hybridization (concrete hybridization or reinforcement hybridization), area of concrete hybridization and the joint enlargement technique. Then assess the legitimacy and exactness to do finite element model to investigate the nonlinear conduct of hybrid reinforced concrete BCJ by using ANSYS (Version 14.5) computer program.

Test program

Description of specimens: The tested reinforced concrete joint specimens were made either normal or hybrid concrete (i.e., replacement of normal concrete by steel fiber concrete at different zones of joint) or hybrid reinforcement (i.e., replacement of steel bars by CFRP bars of internally or externally locations).

All joints are designed to fail in bending before shear in accordance with the design provisions of (ACI-Code 318-14) and (ACI-ASCE 352-02) for type1 interior connection (ACI-ASCE Committee 352, 1991). The experimental program consisted of examining the use of

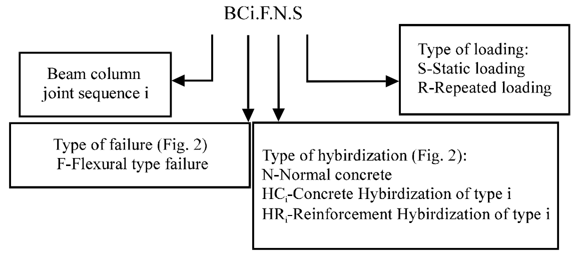

Fig. 1: Beam-column joint specimen identification

three main groups (1-3) where they were (hybrid concrete under static loading, hybrid reinforcement under static loading and hybrid concrete or hybrid reinforcement under repeated loading), respectively. For three groups, nine models of BCJ specimens are tested and the main variables were type of hybridization (concrete or reinforcement), area of concrete hybridization and type of loading (static or forward cyclic). Figure 1 is illustrated the naming convention utilized to determine the beam-column connection specimens. Designation and details of all tested BCJ specimens are reported and displayed in Table 1 (ACI-ASCE Committe 352, 1991).

The geometry of the specimens was comparable total height of column and cross-section dimensions 925 mm and (300×150 mm), respectively while the length of beam and cross-section dimensions were 1500 mm and (225×150 mm), respectively. The concrete covers were about 20 mm of the column, 25 mm of the upper and the lower sides of the beam and 32 for the other sides of the beam. The ends of all beams extended 100 mm beyond the support's centerlines and the steel bar had a 90° hook of length 250 mm at each ends to provide sufficient anchorage. Geometry and detailed reinforcement arrangement of the joint specimens are presented in Table 2 and appeared in Fig. 2.

Material properties: Ordinary portland cement is utilized in casting all the specimens and it is commercially known by name (Jesser). Regular sand from (Wlait-Ali) locale was utilized as fine aggregate with greatest size 4.75 mm. Locally available gravel of 19 mm most extreme size was utilized. Type WSF0213 steel fiber was utilized with Volume fraction of (Vf = 1.0%) and aspect ratio (lf/df = 65) and it was manufactured by company in Jiangxi Province, China according to Anonymous (2011). Normal Concrete (NC) was utilized to cast all specimens with various areas. Steel Fiber Reinforced Cconcrete (SFRC) (with steel fiber 1% of volume percent) was used to hybridization purpose with different areas. Superplasticizer (Sika ViscoCrete 5930-L) was employed for both mixes to give an adequate strength and

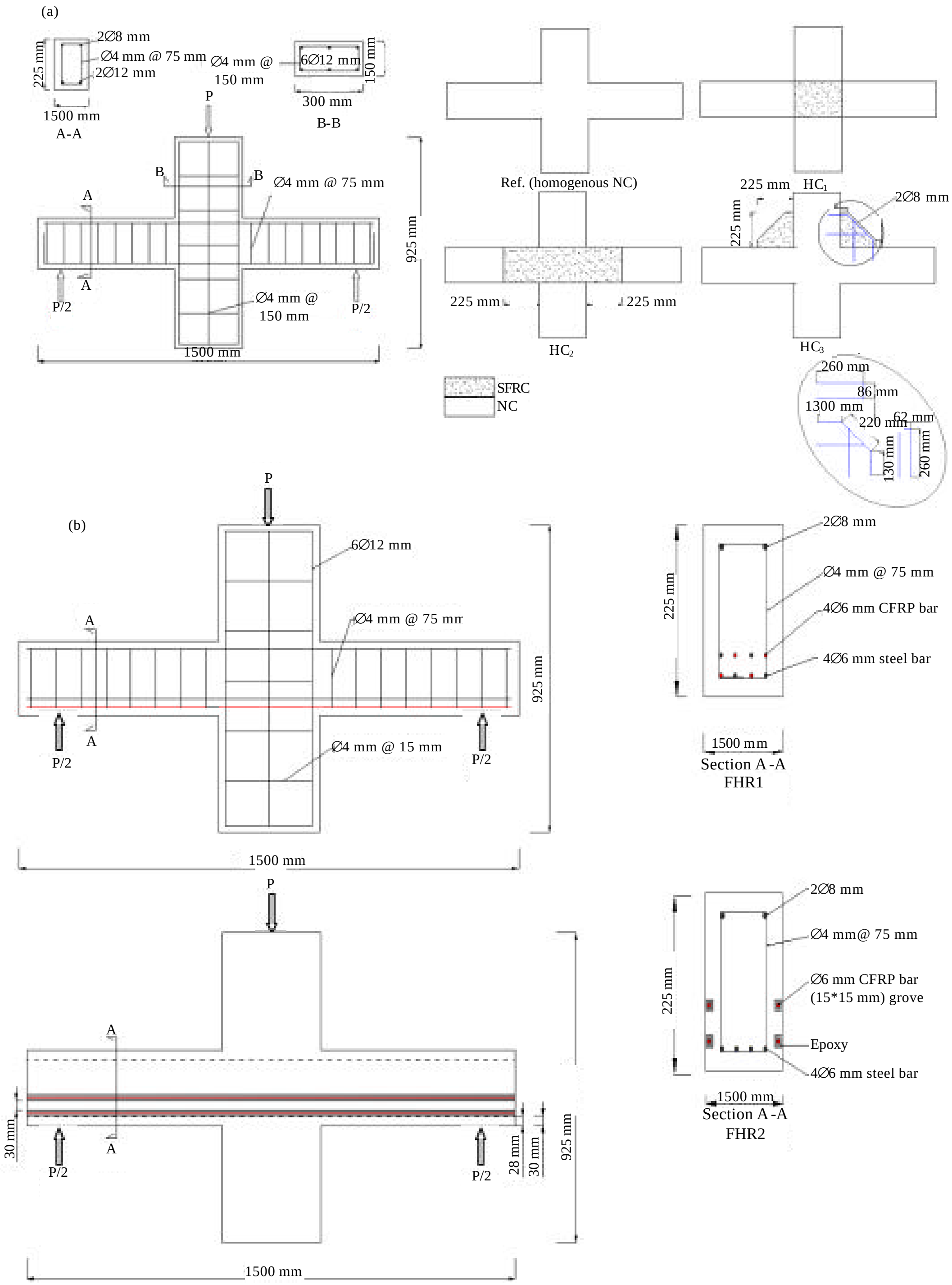

Fig. 2: Details of specimens: a)-(BC1.F.N.S, BC2.F. F.H.C$_1$.S, BC3.F. HC$_2$.S, BC4.F. HC$_3$.S, BC7.F.N.R, and BC8.F.HC$_2$.R) Group (I) and Group (III) BCJs with hybrid concrete (Static or repeated loading) and b) Group (II) and Group (III) BCJs with hybrid reinforcement (internally or externally) (Static or repeated loading)

workability. Several trial mixes have been made and tested at ages of (7, 28 days). The compressive strength was around (30 MPa) at age (28 days) for two types of concrete (NC and SFRC). Table 3 is shown the selected mixtures. The yield strength of steel (fy) of bars (4, 6, 8 and ø12 mm) was (898, 867, 657 and 688 MPa),

Table 1: Designation and details of tested BCJs

Groups	BCJ designation	Type of hybridization	Types of loading
Group (I)	BC1.F.N.S	Ref. (Homogenous NC)	
BCJs with hybrid	BC2.F.HC$_1$.S	HC$_1$	Static loading
concrete	BC3.F.HC$_2$.S	HC$_2$	
	BC4.F.H$_3$.S	HC$_3$	
Group (II)			
BCJs with hybrid	BC5.F.HR$_1$.S	FHR$_1$ (0.5 As +0.5 ACF internally)	
reinforcement	BC6.F.HR$_2$.S	FHR$_2$ (0.5 As+0.5 ACF externally)	
Group (III)			
BCJs with hybrid concrete	BC7.F.N.R	Ref. (Homogenous NC)	Repeated loading
or hybrid reinforcement	BC8.F.HC$_2$.R	HC$_2$	
	BC9.F.HR$_1$.R	FHR$_1$(0.5 As+0.5 ACF internally)	

Table 2: Reinforcement arrangement of tested BCJs

Specimens	Beams	Columns
BCJs with homogenous reinforcement (BCI.F.N.S BC.F.HC$_1$.S BC3.F.HC$_2$.S BC4.F.HC$_3$.S BC7.F.N.R BC8.F.HC$_2$,R)	Deformed compressive steel reinforcement bars (2• 8 mm) Deformed tension steel reinforcement bars (2• 12 mm) (• about 0.8%) Deformed steel reinforcement bars as stirrups (• 4 mm at 75 mm)	Deformed longitudinal steel reinforcement bars (6• 12 mm)
BCJs with hybrid reinforcement (BC.S.F.HR$_1$.S BC6.F.HR$_2$.S BC9.F.HR$_1$.R)	Deformed compressive steel reinforcement bars (2• 8 mm) Deformed tension reinforcement bars *(internal steel bars 4• 6 mm and internal CFRP bars 4• 6 mm) Or *(internal steel bars 4• 6 mm and external CFRP bars 4• 6 mm) Deformed steel reinforcement bars as ties (• 4 mm at 75 mm)	Deformed steel reinforcement bars as stirrups (• 4 mm at 150 mm

Table 3: Properties of NC and SFC mixtures

	Concrete types	
Parameters	NC	SFRC
Water/cement ratio	0.45	0.47
Water (kg/m^3)	158	150
Cement (kg/m^3)	350	320
Fine aggregate (kg/m^3)	575	575
Coarse aggregate (kg/^{3})	1050	1050
Super plasticizer (L/m^3)	2.1*	1.92*
Steel fiber volume fraction V_f (%)	-	1

*0.6 L/100 kg cement

respectively. The Aslan 200/201 CFRP rebar (ø 6 mm) is used as hybrid main reinforcement and its properties as measured by the manufacturer (HB., 2010). Epoxy resin (Sikadur-330) manufactured by Sika company is employed in this study.

Test setup: The hydraulic universal testing machine was utilized to test the BCJ specimens and also the control specimens. The testing machine has a limit of (1000 kN) available in the Structural Laboratory in Civil Engineering Department, Faculty of Engineering, University of Al-Qadissiya as appeared in Fig. 3.

Fig. 3: Testing machine used in this research

Test procedure: All specimens were tested in an inverted position where they exposed to vertical load at the upper end of column and supported by two concentrically supports at the tips of beam as shown in Fig. 3. At first, a constant axial load of 135 kN which is about (20% of the

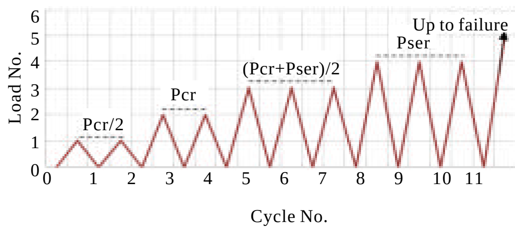

Fig. 4: Loading history of the repeated loaded specimens

axial column capacity) is applied to simulate gravity load on column. After that the load increment was 10 kN along the static loaded specimens test and the deflection was measured at every load step by a dial gauge where installed at the free end of column. For specimens that subjected of forward repeated loading, they subjected to same pre-axial load and tested, according to loading history that based on the static loads for similar specimens as appeared in Fig. 4.

RESULTS AND DISCUSSION

The experimental results of the tested homogenous and hybrid reinforced concrete joints were compared to study the effect of using hybrid concrete or hybrid reinforcement technique on the flexural behavior of BCJs.

Cracking and ultimate loads and failure modes: Table 4 shows a synopsis of the experiential results and the discussion of them is displayed in the accompanying parts. These results including first cracking load of flexural and shear cracks, ultimate loads and their increasing percentages compared with the reference specimens for all the tested BCJ specimens also the modes of failure are reported.

In the experiment, it was found that the specimen suffered from formation of both the flexural and shear cracks and the most first major crack was appeared at the intersection plane of beam with column. Figure 5 listed a load-deflection response of all specimens and Fig. 6 illustrated the failure mode and cracking patterns of them.

Group I (BCJs with hybrid concrete): In this test group, an endeavor to enhance the flexure conduct of beam-column joints that are done by fabricating hybrid system comprises of normal concrete and steel fiber concrete at different areas of joint, Fig. 2. Hybrid system is compared with homogenous joint (i.e., the reference specimen BC1.F.N.S which made from normal concrete only and designed to fail in flexure) to consider the impact of concrete hybridization on the flexure behavior of BCJ under static loading with pre-axial

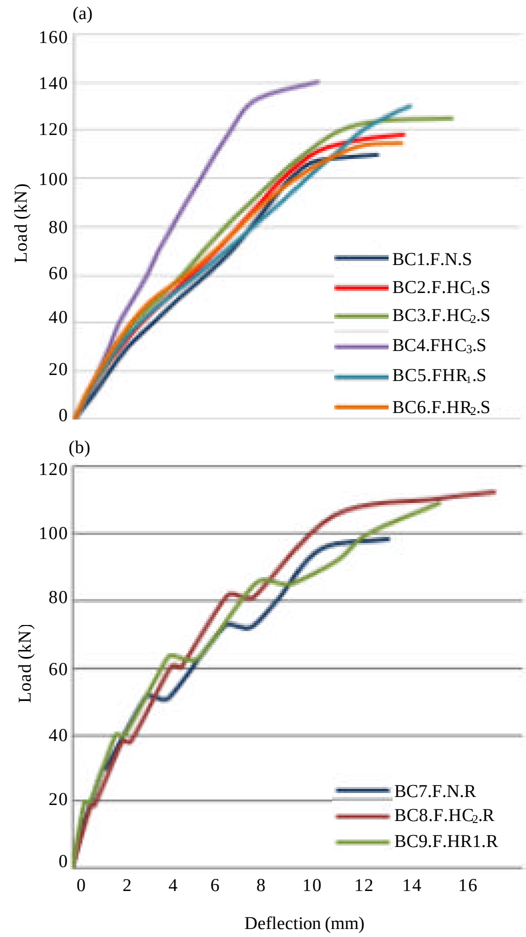

Fig. 5: Load-deflection response of all specimens: a) Reference and hybrid specimens under static loads and b) Reference and hybrid specimens under repeated

compression load. This type of hybridization for specimens (BC2.F.HC_1 .S, BC3.F.HC_2.S and BC4.F.HC_3.S) is caused increasing in first cracking and ultimate loads about (0-67) and (7-27%), respectively, compared with the reference NC joint specimen. The failure mode of this group included basically flexural crack followed by shear crack and concrete crushing at the joint corner (compression zone of the beam and face of column) for all specimens except the enlarged specimen (BC4.F.HC_3.S) showed flexure-shear failure mode.

Group II (BCJs with hybrid reinforcement): Through this test group, two specimens are fabricated from one type of concrete (NC) with idea of hybrid main reinforcement system that comprised of (steel bars and CFRP bars internally or externally by NSM technique) (Fig. 2). This system of hybridization is compared with ordinary joint

Table 4: Summary of the experimental results

Groups/BCJ designation	Cracking load Pcr (kN) Flexure crack	Shear crack	Per(i)-Pcr(r)/Pcr(r)×100%* Flexure crack	Shear crack	Ultimate load (kN)	Pu(i)-pu(r)/pu(r)×100	Mode of failure
Group (1)							
BC1.F.N.S (r)	30	40	-	-	110	-	Beam-flexural compression
BC2.F.HC$_1$.S	30	50	0	25	118	7	Beam-flexural Shear
BC3.F.HC$_2$.S	38	60	27	50	125	13.6	Beam-flexural Shear
C4.F.HC$_3$.S	50	40	67	0	140	27	Beam-flexural shear
Group (2)							
BC5.F.HR$_1$.S	40	80	33	60	130	18	Beam-diagonal Splitting
BC6.F.HR$_2$.S	50	60	67	50	115	5	Beam-flexure debonding
Group (3)							
BC7.F.N.R (r)	10 cyc. 3	20 cyc. 3	-(-67)	-(-50)	98	-(-11)	Beam-flexural compression
BC8.F.HC$_2$.R	20 cyc. 3	40 cyc.5	100 (-47)	100 (-33)	112	14.3 (-10)	Beam-flexural tension
BC9.F.HC$_1$.R	10 cyc.2	40 cyc.3	0 (-75)	100 (-50)	109	11 (-16)	Beam-diagonal plitting

*i Considered BCJ; r reference BCJ

Table 5: Experimental and FEM cracking and ultimate loads and service deflection of BCJs

BCJ designation	First cracking load (kN) Pcr (FEM)	Pcr (EXP)	Pcr $_{(FEM)}$/Pcr $_{(EXP)}$	Ultimate load (kN) Pu (FEM)	Pu (EXP)	Pu$_{(FEM)}$/Pu$_{(EXP)}$	Service deflection (mm) • s (FEM)	• s (EXP)	• s$_{(FEM)}$/• s$_{(EXP)}$
BC1.F.N.S	25	30	0.83	118	110	1.073	5.22	5.71	0.910
BC2.F.HC$_1$.S	25	30	0.83	124	118	1.051	5.09	5.64	0.900
BC3.F.HC$_2$.S	35	38	0.92	128	125	1.024	4.93	5.51	0.890
BC4.F.HC$_3$.S	40	40	1.0	145	140	1.036	3.56	4.05	0.870
BC5.F.HR$_1$.S	36	40	0.9	130	130	1.000	6.02	6.85	0.870
BC6.F.HR$_2$.S	41	50	0.82	121	115	1.052	4.98	5.43	0.910
BC7.F.N.R	15 Cyc. 2	10 Cyc. 3		107	98	1.092	5.53	5.74	0.960
BC8.F.HC$_2$.R	19 Cyc. 2	20 Cyc. 3		116	112	1.036	5.86	6.10	0.960
BC9.F.HR$_1$.R	20 Cyc. 1	10 Cyc.2		115	109	1.055	6.70	6.93	0.970

(a) Average: 0.883; 1.039; 0.892; (b) 1.061; 0.963

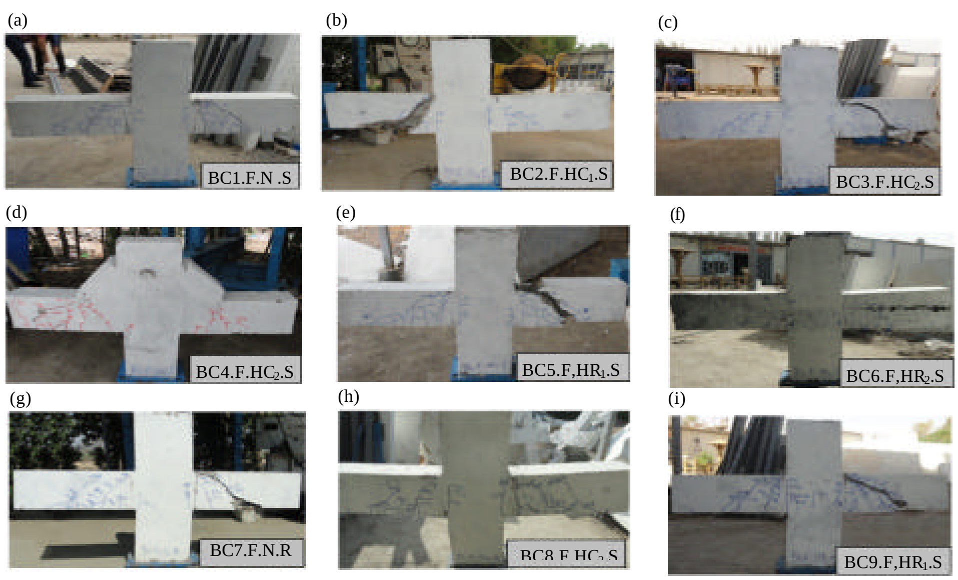

Fig. 6: a-i) Modes of failure and cracking patterns of all specimens at failure

(i.e., the reference specimen (BC1.F.N.S) which reinforced by steel only and designed to fail in flexure) to consider the impact of the hybrid reinforcement technique on the flexure behavior of BCJ under static loading with pre-axial compression load.

Using CFRP bars as (50% internal main reinforcement) in tension zone of beam section (for specimen BC5.F.HR_1.S) is produced increasing in first cracking and ultimate loads about (33 and 18%), respectively, compared with the reference specimen. Semi-brittle diagonal splitting failure occurred for this specimen due to brittle behavior of CFRP rebars. On the other hand using CFRP bars as (50% external main reinforcement by NSM technique) in tension zone of beam section (for specimen BC6.F.HR_2.S) is produced increasing in first cracking and ultimate loads about (67 and 5%), respectively, compared with the reference specimen. Then, FRP debonding in one sides of the beam occurred for this specimen and followed by beam flexure failure.

Group III (BCJs under repeated loading): In this group, three BCJ specimens made from either hybrid concrete (NC and SFRC) or hybrid reinforcement (steel and CFRP bars internally as main reinforcement), Fig. 2. They subjected to repeated loading with pre-axial compression load to study them behavior under repeated loading as shown in Fig. 4. The specimen with normal concrete (BC7.F.N.R) is considered as reference specimen for third test group that designed of flexure failure. The first crack formed early due to the repeated loading which caused reduction in the joint stiffness as well as the ultimate load decreased about (11%) compared with the same specimen under static loading condition (BC1.F.N.S) and the mode of failure was flexure compression failure.

For specimen with hybrid concrete (NC and SFRC) (BC8.F. HC_2.R), the first cracking and ultimate loads were (47 and 10%) less than the same specimen under static loading (BC3.F.HC_2.S) but they were (100 and 14.3%) more than the reference joint (BC7.F.N.R), respectively. The mode of failure was flexure tension failure. For specimen with hybrid reinforcement (steel and CFRP bars internally as 50% main reinforcement) (BC9.F. HR_1.R), the first cracking and ultimate loads were (75 and 16%) less than the same specimen under static loading (BC5.F.HR_1 .S), respectively, due to fatigue of the joint under repeated loading condition.

On the other side, the first cracking load was equal to the reference specimen (BC7.F.N.R) while the ultimate load was larger about (11%). The mode of failure was diagonal-splitting failure. This mean that the internal hybrid reinforcement as main reinforcement gave larger load carrying capacity than the reference specimen but in the same time it changed the failure mode from ductile flexure failure to brittle shear failure due to low modules of elasticity of CFRP bars.

Ductility: Ductility is usually defined as the energy absorbed by the materials until the failure has been completed (Hussain *et al*., 1995). In the current study, ductility factors are evaluated according to the vertical displacement at final load divided by vertical displacement at the service load (approximately 65% of ultimate load) (Russell, 2003). Also, the experimental cumulative ductility values are investigated for all specimens that subjected of forward cyclic loading. The cumulative ductility is defined to any load point as the sum of the ductility at greatest load level accomplished in every cycle until the cycle considered. In general, the specimens with hybrid concrete and subjected to static loading (BC2.F. HC_1.S, BC3.F. HC_2.S and BC4.F.HC_3.S) are exhibited higher ductility factor about (11, 30 and 14%) than the reference specimen (BC1.F.N.S), respectively, due to high modulus of elasticity of steel fiber. On the other hand, the specimen with reinforcement hybridization technique by using CFRP bars as (internal or external) main reinforcement (BC5.F.HR_1.S and BC7.F.HR_2 .S) showed decreasing in ductility about (7.4% for the first joint) and increasing about (14% for the other joint) compared with the reference specimen (BC1.F.N.S) due to effectiveness of the external reinforcement technique in improvement of the ductility. The cumulative ductility values for the repeated loaded joints (BC8.F.HC_2 .R and BC9.F. HR_1.R) were increased about (13% for the first joint) and reduced about (12.5% for the other joint) compared with the homogenous reference joint (BC7.F.N.R).

Absorption of energy: When the beam-column joint is exposed to cyclic loading, some energy is absorbed in each load cycle that is fairly equal to the work in straining or deforming the structure to the limit of deflection. Absorption of cumulative energy during various load cycles were calculated as the sum of the areas under the hysteric loops from the load versus deflection diagram (Muthuswamy and Thirugnanam, 2014). Accumulative absorbed energy values for the joints (BC8.F.HC_2.R and BC9.F.HR_1.R) were improved about (42 and 5%) compared with the reference joint (BC7.F.N.R), respectively.

Comparison between experiment study and numerical analysis: Experimental and numerical results are compared and the conduct of the internal beam-column connection region was comparable. Table 5 presents this comparison

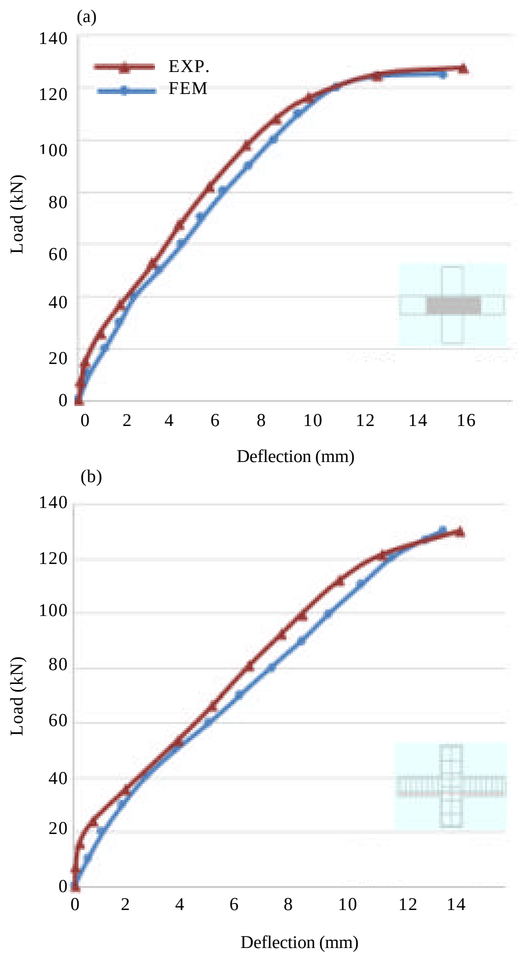

Fig. 7: Experimental and FEM load-deflection curves of some static loaded BCJs: a) Deflection (mm) BC3.F.HC$_2$.S and b) Deflection (mm) BC5.F.HR1.S

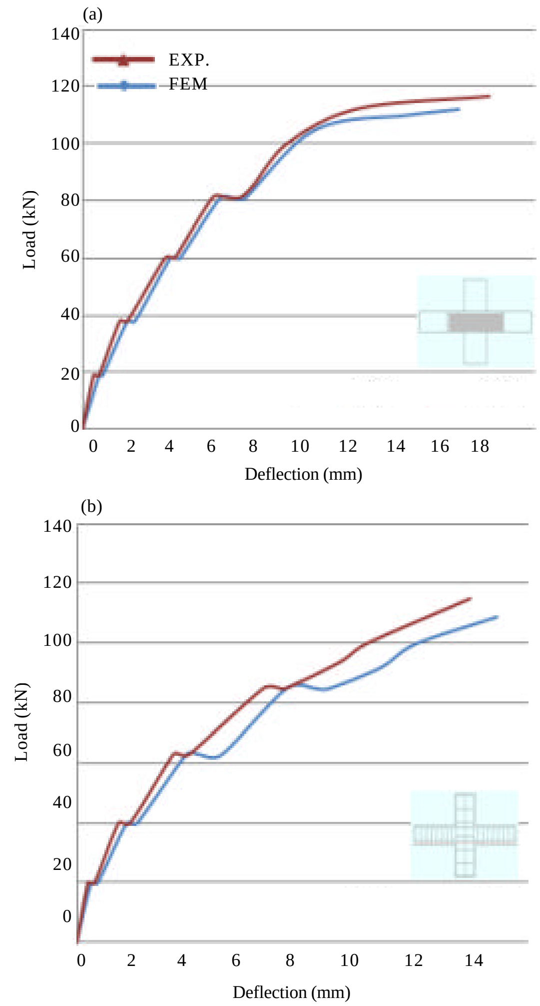

Fig. 8: Experimental and FEM envelope curves of some repeated loaded BCJs: a) BC8.F.HC$_2$.R and b) BC9.F.HR1

of the first cracking and ultimate loads and deflection at service load for all specimens. The service load is considered as 0.65 of the ultimate load (Russell, 2003).

It can be observed, the results of first cracking and ultimate loads and service deflection obtained from the FEM analysis exhibited approbation with the experimental values. For the repeated loaded specimens, the deflection values at service load of the final cycle are mentioned. The differences as average of the first cracking and ultimate loads and service deflection were about (11.7% for static loaded models, 3.9 and 6.1% for static and repeated loaded models and 10.8 and 3.7% for static and repeated loaded models), respectively. Figure 7 and 8 display the load-deflection plots for some beam-column joints acquired from the theoretical and experimental results for static and repeated loaded specimens, respectively.

CONCLUSION

In view of the experimental testing results and numerical analysis for the hybrid reinforced concrete BCJs, the following conclusions can be stated within the scope of this study. The beam-column joint specimens that adopted the concrete hybridization technique (by SFRC at different areas) under static loading condition, the ultimate and the first cracking loads increased about (7-13.6%) and (0-27%) compared with homogenous NC joint, respectively. For tested beam-column joint which adopted the joint enlargement technique by SFRC, the ultimate and the first cracking loads increased about (27 and 67%) compared with homogenous NC joint, respectively.

Using CFRP bars as internal hybridization system (50% of main reinforcement) has a significant effect on first cracking and ultimate loads where the increments were about (33 and 18%), respectively. On the other side using NSM-CFRP bars as external hybridization system (50% of main reinforcement) produced increase in first cracking load about (67%) and slight increment of ultimate load was about (5%).

For joints with (hybrid concrete or hybrid reinforcement as main reinforcement) under repeated loading, the ultimate load capacity increased about (14.3, 11%) with respect to the reference joint, respectively. The joints with hybrid concrete under static loading exhibited an increase in ductility between (11-30%) compared with homogenous NC joint. For hybrid internal reinforcement joint (50% CFRP as main reinforcement), it showed decrease in the ductility about (7.4%) due to brittle behavior of CFRP bars while the joint with hybrid external reinforcement by NSM technique had increasing about (14%) due to effectiveness this technique in improvement of the ductility. The cumulative ductility values are increased about (13%) for joint with hybrid concrete while it decreased about (12.5%) for the joint with internal hybrid reinforcement due to brittle behavior of CFRP bars. The specimens with hybrid concrete technique had more energy dissipation capacity than that adopted the hybrid reinforcement technique. The external reinforcement system for two faces of joint is reduced the congestion of reinforcement and formation of cracks were reduced too.

Using the hybridization technique of concrete do not effect on the mode of failure of specimens but the hybridization technique of reinforcement (as internal main reinforcement) altered the failure mode from ductile flexure to brittle shear failure due to lack coefficient of elasticity of CFRP rebars. The analytical results gave acceptable agreement with the experimental results for all specimens.

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