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SHEAR BEHAVIOR OF HYBRID REINFORCED CONCRETE EXTERIOR BEAM-COLUMN JOINTS UNDER STATIC AND CYCLIC LOADS

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Abstract

This study presents an experimental investigation of the shear conduct of exterior beam-column joints (BCJs) . That are made from hybrid concrete:(normal concrete and reactive powder concrete), or hybrid reinforcement; (steel and externally carbon fiber reinforced polymer CFRP bars by near surface mounted NSM technique). The experimental investigation involved examining of nine hybrid reinforced concrete BCJ specimens under the effect of static or cyclic loading. The specimens were divided into three groups to investigate the influence of several variables on the structural conduct of BCJ region such as: type of loading (static or cyclic), type of hybridization (hybrid concrete or hybrid reinforcement), area of hybrid concrete, and angle of orientation for NSM-CFRP bars (90° and 45°). The results showed that using of the hybridization technique of concrete at different areas of BCJ under static loading, exhibited improvement in first cracking load and ultimate load by about (17-58) % and (6-53)%, respectively, compared with homogenous NC joint with increase in the ductility about (5-12)%. Also, using the same technique under cyclic loading condition showed increasing in ultimate load about (58%) with improvement a cumulative ductility by about (13%). On the other hand, using NSM-CFRP bars as external hybridization system (50% of shear reinforcement at angle 45°) under static loading is improved the first cracking load and ultimate load about (25%) and (29%), respectively with increasing in ductility about (11%) compared with the steel reinforced joint. So, using the same system under cyclic loading condition increased ultimate load about (26%) and it improved a cumulative ductility about (6%). NSM-CFRP system that used at angle (90°) under static loads is increased the first cracking load and ultimate load about (25%) and (8%), respectively with the improved ductility about (10%) compared with the steel reinforced joint.

Keywords: Beam-column joint, CFRP bars, Hybrid concrete, Hybrid reinforcement, RPC, Shear behavior.

1. 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 [1]. Beam-column joints in a reinforced concrete moment resisting frames are essential areas to interchange the loads effectively between the associating members (i.e., columns and beams) in the building and guarantee its continuity [2]. Sudden changes in geometry and complexity of stresses distribution in the connection are the explanations behind their severe behavior. Since the 1960s, experimental and numerical studies have been directed to consider the general conduct of BCJs but, the researches for the conduct of hybrid reinforced concrete members generally were starting at end of the pervious century. Several studies have examined the conduct and quality of hybrid reinforced concrete structural elements within different hybridization systems.

Hussain et al. [3] showed experimental and theoretical study to investigate the shear conduct of hybrid reinforced concrete I-beams cast monolithically. A new method was introduced by exchanging a specific parts or layers of I-shaped beams by high strength concrete (HSC) or steel fiber reinforced concrete (SFRC). The Experimental outcomes demonstrated that a maximum shear capacity, tensile response are improved and the failure mode is altered. Sharbatdar et al. [4] conducted experimental and numerical investigations to assess the effects of CFRP stirrup distances on the cyclic conduct of concrete exterior beam-column connections. According to the results, the specimens with congested stirrups had not only higher ductility and energy dissipation, but also had additional capacity as much as 12% relative to the non-ductile connection with wider distance stirrups. Abdul Abbas [5] conducted a test for the structural conduct of reinforced lightweight aggregate concrete corbels, strengthened with various formations of CFRP rebars by NSMsystem. The results showed that a significant enhancement in the conduct and ultimate strength of repaired and strengthened reinforced LWAC corbels.

Hybridization techniques can be widely observed throughout the literature for many structural members, but there are few investigations for the shear conduct of hybrid reinforced BCJs therefore; in this research, the joint hybridization techniques are studied. Due to the reinforcement congestion in BCJ and the difficulty of casting that lead to honeycombing in concrete [6]; therefore, in this study, we can rely on NSM-CFRP bars as externally hybridization of reinforcement to mitigate this problem.

The work is planned to provide an experimental examination of the ultimate capacity, cracking patterns, failure modes, ductility and absorbed energy of reinforced concrete beam-column joint made from hybrid concrete or hybrid reinforcement. Concentrating on the factors that effect on shear behavior of concrete connections such as effects of concrete type, type of reinforcement, area of hybridization and nature of loading program. As well as, examining the efficacy of NSM-CFRP bars reinforcement in enhancing the shearing response of concrete connections as an alternative to conventional steel reinforcement.

2. Test Program

2.1. Description of Specimens

The tested reinforced concrete beam-column joint specimens were made of either conventional or hybrid concrete (i.e., replacement of conventional concrete by reactive powder concrete at different areas of connection) or hybrid reinforcement (i.e., replacement of steel bars by NSM-CFRP bars).

All joints are designed to fail in shear before bending in accordance with the design provisions of (ACI-ASCE 352-02), and (ACI-Code 318-14) for Type1 exterior beam-column joints [7]. The test program consisted of examining the use of three main groups (I, II, and III) where, they were (hybrid concrete under static loading, hybrid reinforcement under static loading and hybrid concrete or hybrid reinforcement under cyclic loading), respectively. For three groups, nine specimens of exterior BCJs are investigated and the main variables were type of hybridization (concrete or reinforcement), area of hybrid concrete, the orientation angle of NSM-CFRP bars and type of loading (static or forward cyclic). Figure 1 shows the naming convention used to identify the BCJ specimens. Designation and details of all tested BCJ specimens are reported and listed in Table 1.

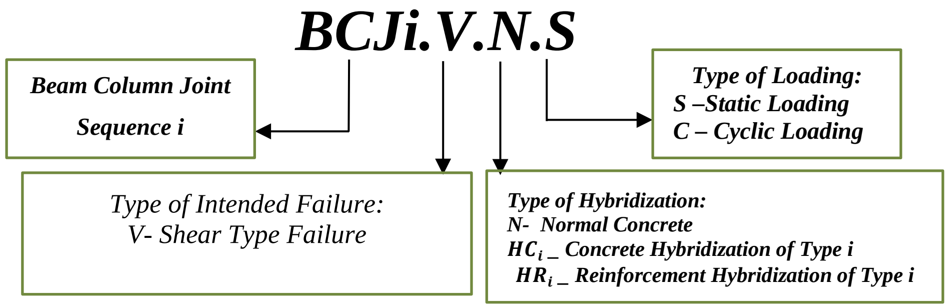


Fig. 1. Designation of tested beam-column joints.

Table 1. Details of tested beam-column joints.

Groups	BCJ Designation	Type of Hybridization	Type of Loading
Group(I) BCJs with Hybrid Concrete	BCJ1.V.N.S	Ref. (homogenous NC)	Static Loading
	BCJ2.V.HC$_1$.S	HC$_1$	
	BCJ3.V.HC$_2$.S	HC$_2$	
	BCJ4.V.HC$_3$.S	HC$_3$	
Group(II) BCJs with Hybrid Reinforcement	BCJ5.V.HR$_1$.S	HR$_1$ (0.5 Avs + 0.5Avcf @90° NSM)	Static Loading
	BCJ6.V.HR$_2$.S	HR$_2$ (0.5 Avs + 0.5Avcf @45° NSM)	
Group(III) BCJs with Hybrid Concrete or Hybrid Reinforcement	BCJ7.V.N.C	Ref. (homogenous NC)	Cyclic Loading
	BCJ8.V.HC$_2$.C	HC$_2$	
	BCJ9.V.HR$_2$.C	HR$_2$ (0.5 Avs + 0.5Avcf @45° NSM)	

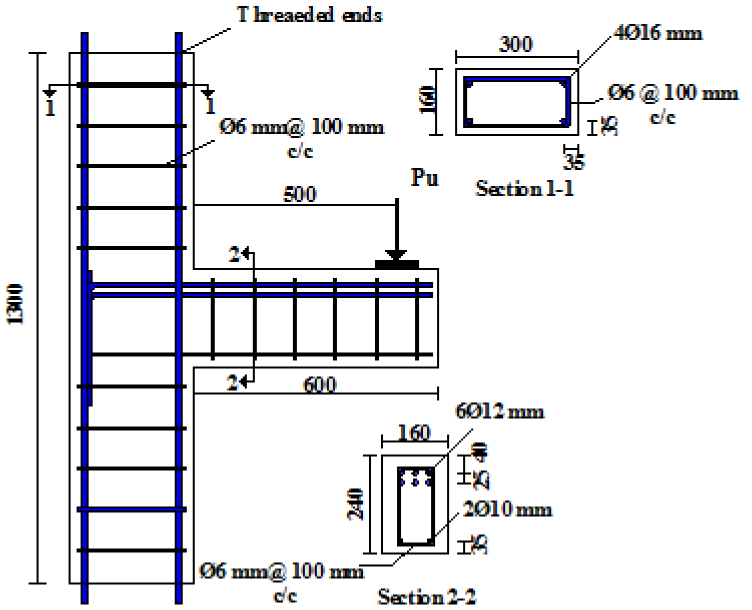
The geometry of the specimens wascompared; total height of column and cross-section dimensions 1300 mm and (160×300) mm, respectively, while the length of beam and cross-section dimensions were 600 mm and (160×240) mm, respectively. The concrete covers were about 20mm of the column, 25mm of the upper and the lower sides of the beam, and 32 for the other sides of the beam. The end of the beam was extended 100 mm beyond the support centerline. Geometry and detailed reinforcement arrangement of the joint specimens are presented in Table 2 and appeared in Figs. 2 and 3.

Table 2. Reinforcement arrangement of tested BCJs.

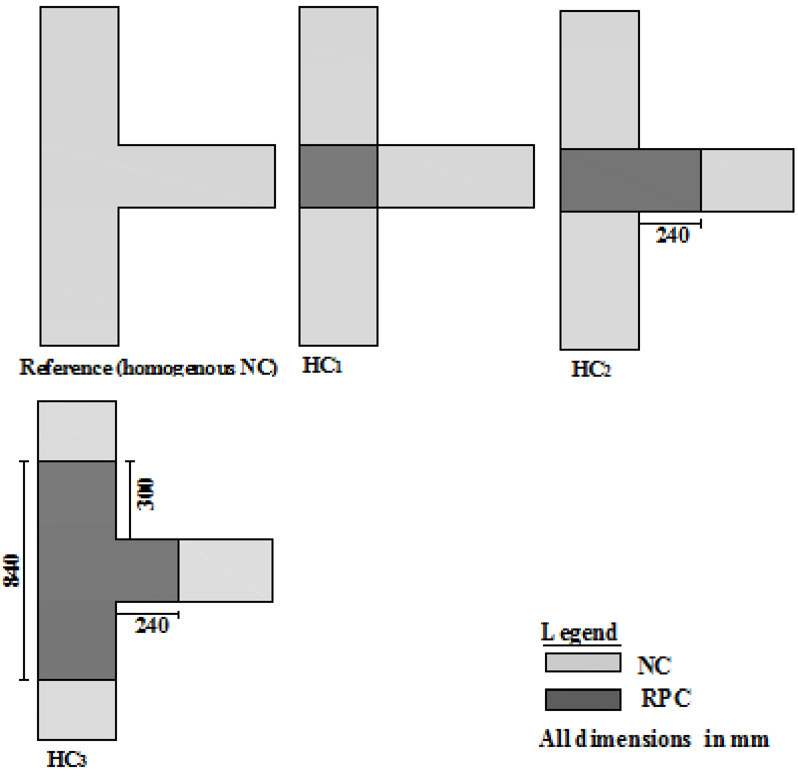
	Beam	Column
BCJs with Homogenous Reinforcement **BCJ1.V.N.S** **BCJ2.V.HC$_1$.S** **BCJ3.V.HC$_2$.S** **BCJ4.V.HC$_3$.S** **BCJ7.V.N.C** **BCJ8.V.HC$_2$.C**	- Deformed compressive steel reinforcement bars (2Ø10 mm) - Deformed tension steel reinforcement bars (6Ø12 mm) - Deformed steel shear reinforcement bars as stirrups (Ø6 mm at 100 mm)	- Deformed longitudinal steel reinforcement bars (4Ø16 mm) - Deformed steel reinforcement bars as ties (Ø6 mm at 100 mm)
BCJs with Hybrid Reinforcement **BCJ5.V.HR$_1$.S** **BCJ6.V.HR$_2$.S** **BCJ9.V.HR$_1$.C**	- Deformed compressive steel reinforcement bars (2Ø10 mm) - Deformed tension steel reinforcement bars (6Ø12 mm) - Deformed steel shear reinforcement stirrups (Ø6 mm at 200 mm) - Deformed CFRP bars as shear reinforcement ∗(NSM bars Ø6 mm at 200 mm @90°) or ∗(NSM bars Ø6 mm at 200 mm @45°)	- Deformed longitudinal steel reinforcement bars (4Ø16 mm) - Deformed steel reinforcement bars as ties (Ø6 mm at 100 mm)

2.2. Material properties

Ordinary Portland cement manufactured in Iraq named (LION) was used throughout this investigation. Sand (nature fine aggregate) utilized in this research were from (AL-AKAIDUR) region in Iraq with maximum size 4.75 mm for NC and 0.6mm for RPC. Coarse aggregate (locally available gravel) of 14 mm the greatest size was utilized for NC. Silica fume (MEYCO MS610 grey densified) from (BASF) the Chemical Company was used in RPC. The steel fiber type WSF0213 was used in RPC with aspect ratio (Lf/Df= 65), and was manufactured by the company in Jiangxi Province, China according to (ASTM A820-11) [8]. Normal concrete (NC) was employed to pour all the specimens. Reactive powder concrete (RPC) (with steel fiber 1% of volume percent) was utilized to hybridization purpose with various areas. Superplasticizer (Sika Viscocrete 5930-L) is used for both mix to give sufficient strength and workability. Several trial mixes have been made and tested at ages of (7, 28 days). The compressive strength at age (28 days) was around 30 MPa for NC and 120 MPa for RPC. Table 3 shows the selected mixtures. The yield strength (fy) of steel bars (ø6, ø10, ø12 and ø16mm) was (521, 465, 487 and 517 MPa) respectively. The Aslan 200/201 CFRP bars (ø6mm) is utilized as hybrid shear reinforcement and its properties as measured by the manufacturer (Hughes Brothers [9]). Epoxy resin (Sikadur-30) manufactured by Sika Company is employed in this work.

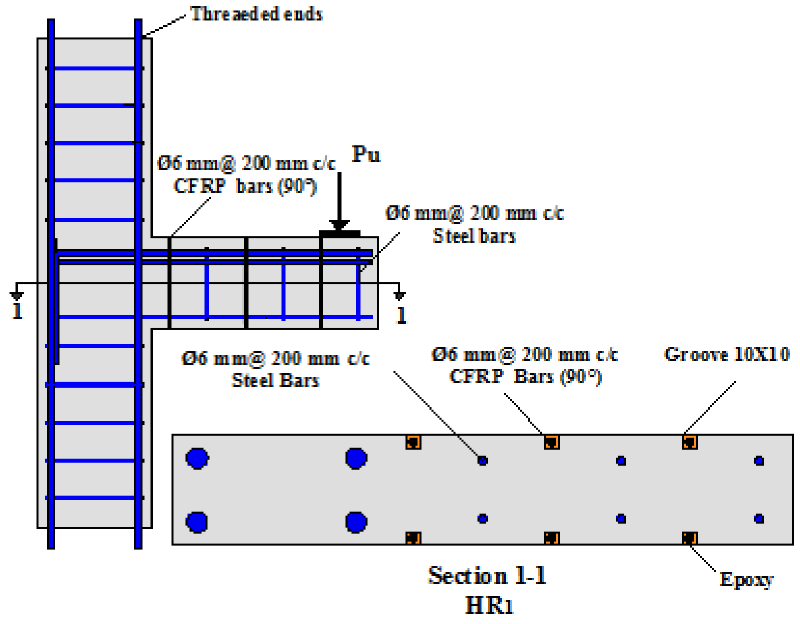


(a) Details of reinforcement for specimens with hybrid concrete.

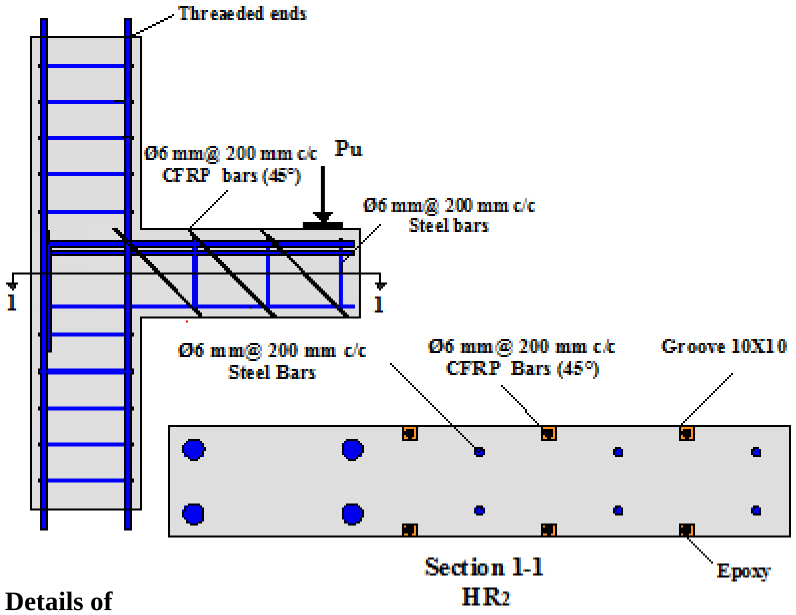


(b) Details of hybrid concrete specimens.

Fig. 2. Details of specimens in Group(I) and Group(III) (BCJs with hybrid concrete).



(a) Details of specimen with hybrid shear reinforcement at angle 90°.



(b) Details of specimen with hybrid shear reinforcement at angle 45°.

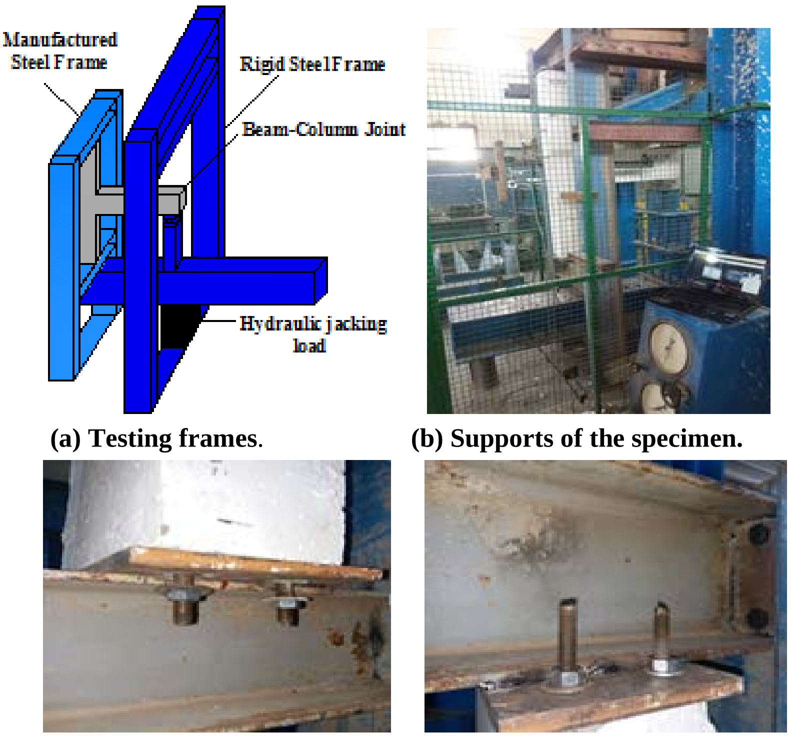
Fig. 3. Details of specimens in Group(II) and Group(III) (BCJs with hybrid shear reinforcement (by NSM)).

Table 3. Properties of normal concrete (NC) and reactive powder concrete (RPC) mixtures.

Parameter	Type of concrete	
	NC	RPC
Cement (kg/ m^3)	407	1000
Micro silica fume (kg/m^3)	----	245
Sand (kg/ m^3)	733	1000
Gravel (kg/ m^3)	936	----
w/cementitious ratio	0.45	0.168
Steel fiber volume fraction Vf (%)	----	1
Super plasticizer % by weight of cementitious material	1	6

2.3. Test setup

The universal hydraulic testing machine was utilized to test the beam-column joint specimens and additionally the control specimens. The capacity of the test apparatus (1000 kN) is in the structural laboratory of the Civil Engineering Department, Engineering Faculty, University of Kufa. The machine has been modified for testing beams to the test of external BCJs within the locally available possibilities by manufacturing an additional steel frame for the purpose of fixing the ends of the column , as shown in Fig. 4.



(a) Testing frames. **(b) Supports of the specimen.**

(c) Bottom end of RC. column. **(d) Upper end of RC. column.**

Fig. 4. Testing machine.

2.4. Test Procedure

All specimens were tested in an inverted position where, they were exposed to vertical load at the bottom end of beam and fixed by two supports at the ends of column, as shown in Fig. 4. Initially, the specimen was loaded by 5 kN to seat the supports and the system of loading, then unloading to zero. Subsequently, the load increment was 10 kN along the static loaded specimens test and the deflection was measured at every load step by a LVDT where fixed at the free end of beam. For specimens that are subjected to forward cyclic loading; are tested according to loading program which depends on the static loads for similar specimens, as shown in Fig. 5.

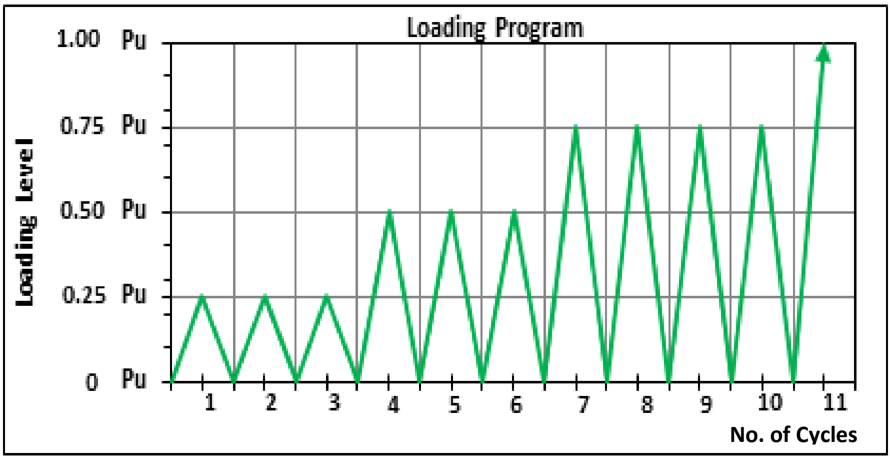


Fig. 5. Loading program of the cyclic loaded specimens.

3. Results and Discussion

Experimental results of the tested homogenous and hybrid reinforced concrete connections were compared to study the influence of using hybrid concrete or hybrid reinforcement concept on the shear conduct of the BCJs such as ultimate and cracking loads, mode of failure, ductility and energy absorption.

3.1. Cracking and ultimate loads and modes of failure

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

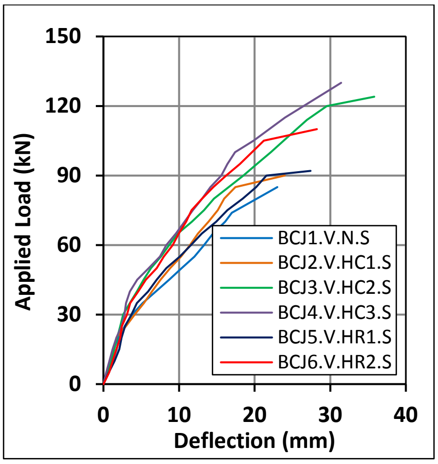
In the experiment, it was found that the specimen suffered damage in the form of both flexural and l shear cracks, and the most first cracks were appeared at the junction of beam and column face. Figure 6 shows a load-deflection response of all specimens and Fig. 7 listed the failure mode and cracking patterns of them.

Table 4. Summary of the experimental results.

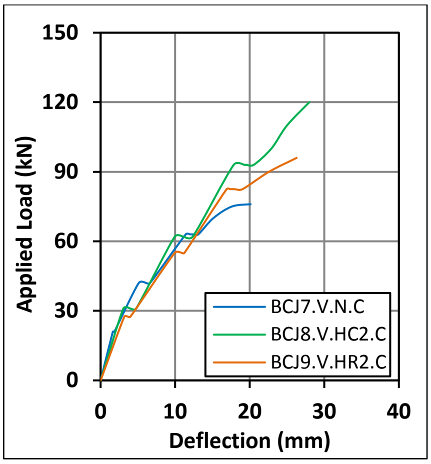
Groups	BCJ Designation	Cracking Load P_{cr} (kN)		$\frac{P_{cr(i)} - P_{cr(r)}}{P_{cr(r)}} x100\%$*		Ultimate Load P_u (kN)	$\frac{P_{u(i)} - P_{u(r)}}{P_{u(r)}} x100$*
		Flexure Crack	Shear Crack	Flexure Crack	Shear Crack		
I	BCJ1.V.N.S	12	45	--	--	85	--
	BCJ2.V.HC$_1$.S	14	55	17	22	90	6
	BCJ3.V.HC$_2$.S	17	70	42	56	125	47
	BCJ4.V.HC$_3$.S	19	90	58	100	130	53
II	BCJ5.V.HR$_1$.S	15	56	25	24	92	8
	BCJ6.V.HR$_2$.S	15	85	25	89	110	29
III	BCJ7.V.N.C	12 cyc.1	40 cyc.4	-- (0)	-- (-11)	76	-- (-11)
	BCJ8.V.HC$_2$.C	16 cyc.1	60 cyc.5	33 (-6)	50 (-14)	120	58 (-4)
	BCJ9.V.HR$_2$.C	15 cyc.1	55 cyc.5	25 (0)	38 (-35)	96	26 (-13)

* *i* :-Considered BCJ, *r* :- Reference BCJ

Note: The values in the brackets represent to the decrement in the cracking and ultimate loads for cyclic loaded specimens relatively to similar specimens under static loading condition.



(a) Reference and hybrid specimens under static loads.



(b) Reference and hybrid specimens under cyclic loads (envelope curves).

Fig. 6. Load - Deflection diagrams of all specimens.

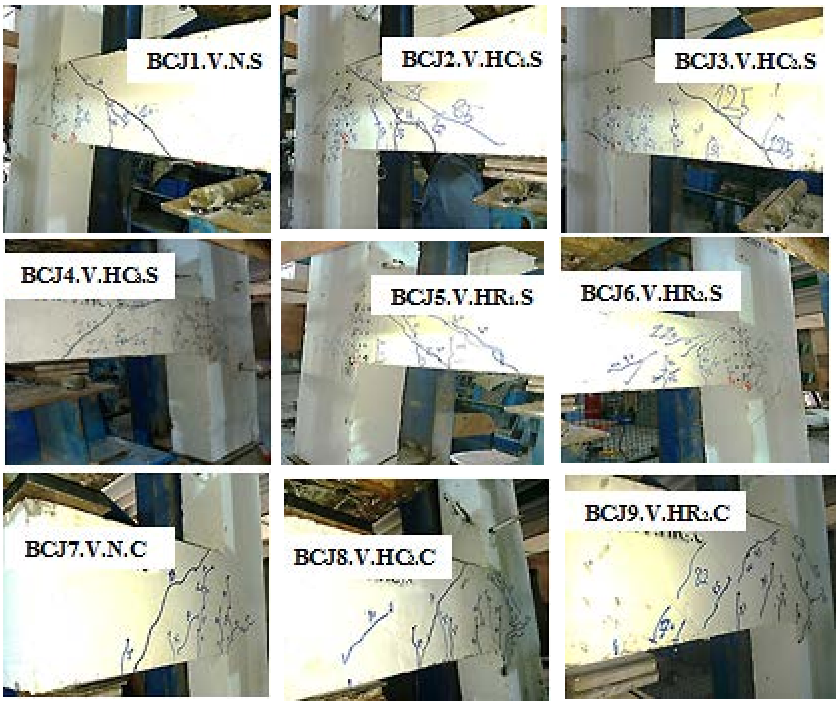


Fig. 7. Cracking patterns and failure modes of all specimens.

3.1.1. Group I (BCJs with hybrid concrete)

In this test group, a try to improve the shear conduct of beam-column joints that are done by fabricating hybrid system comprises of normal concrete and reactive powder concrete at different regions of connection, see Fig. 2. The hybrid system is compared with homogenous connections (i.e. the reference specimen BCJ1.V.N.S made from normal concrete only and designed to fail in shear) to study the influence of concrete hybridization on shear behavior of beam-column connection under static loading.

This type of hybridization for specimens (BCJ2.V.HC$_1$.S, BCJ3.V.HC$_2$.S and BCJ4.V.HC$_3$.S) caused increasing in first cracking and ultimate loads by about (17-58)% and (6-53)%, respectively compared with the homogenous NC joint specimen. The cracks developed rapidly within hybrid area but with less crack widths than the homogenous specimen. Finally, the major shear crack is occurred in the beam outside of hybridization region that caused the failure of these specimens at ultimate load.

3.1.2. Group II (BCJs with hybrid shear reinforcement)

Through this test group, two specimens were fabricated from one type of concrete (NC) with idea of hybrid shear reinforcement system that comprises of (steel bars and CFRP bars externally by NSM technique), see Fig. 3. This system of hybridization is compared with ordinary joint (i.e., the reference specimen BCJ1.V.N.S which is reinforced by steel only and designed to fail in shear) to investigate the influence of the reinforcement hybridization technique on shear conduct of beam-column connection under static loading.

The external hybridization technique of 50% shear reinforcement by (3-Ø6mm at 200mm) NSM-CFRP bars on the two faces of the beam at angle (90°) (specimen BCJ5.V.HR_1.S) is caused increasing in first cracking and ultimate loads about (25% and 8%), respectively compared with the reference specimen. The failure of this specimen was identified as shear failure. On the other hand, using the same technique but at angle (45°) (specimen BCJ6.V.HR_2.S) is showed increasing in first cracking and ultimate loads about (25% and 29%), respectively compared with the reference specimen. The failure of this specimen was identified as flexure failure.

3.1.3. Group III (BCJs under cyclic loading)

In this group, three beam-column joint specimens made from either hybrid concrete (NC and RPC) or hybrid reinforcement (steel and CFRP bars as shear reinforcement externally at angle 45° by NSM system), see Figs. 2 and 3. They are subjected to forward cyclic loading to study them' structural conduct under cyclic loading, as shown in Fig. 5.

The specimen with normal concrete (BCJ7.V.N.C) is considered as reference specimen for third test group that is designed of shear failure. It can be noticed that, the first cracking load equal to the same specimen with static loading condition (BCJ1.V.N.S), and then reduction in ultimate load capacity about (11%) due to the cyclic loading which caused the fatigue of the joint. The mode of failure was shear failure.

For specimen with hybrid concrete (NC and RPC) (BCJ8.V.HC_2.C),the first cracking and ultimate loads were (6% and 4%) less than the same specimen under static loading (BCJ3.V.HC_2.S), but they were (33% and 58%) more than the homogenous connection (BCJ7.V.N.C), respectively. The failure occurred after the formation numerous diagonal cracks between the supporting point toward the column interface with less widths.

For specimen hybrid reinforcement (steel and CFRP bars as external shear reinforcement at angle 45° by NSM technique) (BCJ9.V.HR_2.C), the first cracking load is equal to the same specimen that subjected to static loading (BC6.V.HR_2.S) but, it is increased about (25%) compared with the homogenous specimen (BCJ7.V.N.C). Also, the ultimate load of this specimen was (13%) less than the similar specimen under static loading condition and (26%) larger than the homogenous specimen (BCJ7.V.N.C). The external hybrid reinforcement as inclined shear reinforcement at angle (45°) by NSM system is changed the failure mode from undesirable shear failure to desirable flexure failure with little reduction in the ultimate load capacity.

3.2. Ductility

Ductility is defined as energy absorbed through materials up to the failure has been completed [10]. In the current study, ductility ratios are assessed according to the vertical displacement at maximum load divided by vertical displacement at the service load (approximately 65% of maximum load) [11]. Also, the experimental cumulative ductility values are investigated for all specimens that are subjected to forward cyclic loading. Cumulative ductility is defined to any point of load as the sum of the ductility at the level of maximum load in every cycle until the specified cycle [12]. In general, the specimens with hybrid concrete under static loading (BCJ2.V.HC$_1$.S, BCJ3.V.HC$_2$.S and BCJ4.V.HC$_3$.S) are showed increasing of the ductility factor about (5%, 12% and 7%) than the reference specimen (BCJ1.V.N.S), respectively due to due to high ductility of reactive powder concrete. While, the specimens with external shear reinforcement by NSM technique (BCJ5.V.HR$_1$.S and BCJ6.V.HR$_2$.S) are exhibited improvement in the ductility about (10% and 11%) compared with the reference specimen (BCJ1.V.N.S). The cumulative ductility values for the specimens (BCJ8.V.HC$_2$.C and BC9.V.HR$_2$.C) under cyclic loading condition were increased about (13% and 6%), respectively compared with the reference joint (BCJ7.V.N.C). Table 5 illustrates the ductility factor (μ) of the tested BCJs which subjected to static loading, while Fig. 8 shows the cumulative ductility values of the tested BCJs which subjected to cyclic loading.

Table 5. Ductility factor of tested BCJs subjected of static loading.

BCJ Designation	Service Deflection, Δs (mm)*	Ultimate Deflection, Δu (mm)	Ductility Factor, μ ($\frac{\Delta u}{\Delta s}$)	$\frac{\mu_i - \mu_r}{\mu_r} * 100\%^{(**)}$
BCJ1.V.N.S	10.24	22.2	2.16	-------
BCJ2.V.HC$_1$.S	10.36	23.38	2.26	5
BCJ3.V.HC$_2$.S	14.61	35.42	2.42	12
BCJ4.V.HC$_3$.S	14.15	32.44	2.30	7
BCJ5.V.HR$_1$.S	11.58	27.39	2.37	10
BCJ6.V.HR$_2$.S	12	28.73	2.40	11

* Δs = Deflection at service load (Pser.=0.65 Pult.) [11]

** μ_r= Ductility of the reference BCJ., μ_i =Ductility of the considered BCJ.

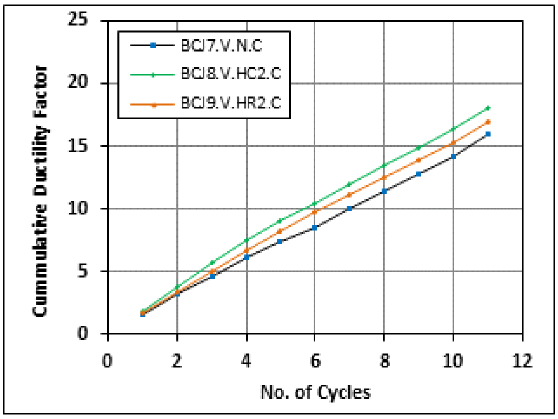


Fig. 8. Variation of cumulative ductility factor of specimens subjected to cyclic loads.

3.3. Absorption of Energy

When the BCJ is exposed to a cyclic loading, some energy is absorbed in every loading cycle that is equal to the work in straining or deforming the structure to the extent of displacement. The absorbed energy was measured as the area under the hysteresis loop of the load versus deflection plots [13]. The cumulative absorbed energy of the BCJ was calculated by including the energy absorption capacity of the connection through every cycle [12]. The values of cumulative energy absorption for the connections (BCJ8.V.HC$_2$.C and BCJ9.V.HR$_2$.R) were more about (114% and 93%) compared with the reference specimen (BCJ7.V.N.C), respectively. Figure 9 shows the cumulative energy absorption versus number of cycles for all the BCJs that subjected of forward cyclic loading condition.

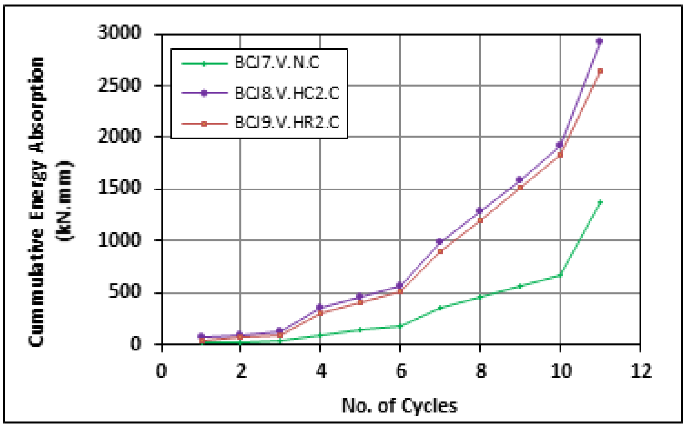


Fig. 9. Variation of cumulative energy absorption for specimens subjected to cyclic loads.

4. Conclusion

In light of the results of the experimental tests for the hybrid reinforced concrete exterior BCJs, the following conclusions can be mentioned within the scope of this study:

- The beam-column joints that adopted the concrete hybridization technique (by RPC at different areas) under static loading condition, the first cracking and ultimate loads capacity increased by about (17-58)% and (6-53)%, respectively compared with the homogenous NC joint.
- Using NSM-CFRP bars as external hybridization system (50% of shear reinforcement at angle 45°) had an important effect on first cracking and ultimate loads where, the increments were about (25% and 29%), compared with the steel reinforced joint, respectively. On the other hand, using the same technique at angle 90°exhibited increasing in first cracking and ultimate loads about (25% and 8%), compared with control joint, respectively.
- The ultimate loads capacity increased about (58%) and (26%) for joints under cyclic loading with (hybrid concrete and hybrid reinforcement as shear reinforcement), respectively.
- The joints with hybrid concrete exhibited increments in ductility between (5-12)% compared with homogenous NC joint. For hybrid external reinforcement joints (50% CFRP as shear reinforcement at angle 45° and 90°), the ductility factor is improved about (11% and 10%), respectively. The cumulative ductility values are increased about (13% and 6%) for joints under cyclic loading with (hybrid concrete and inclined external hybrid shear reinforcement), respectively.
- Absorbed cumulative energy for specimens with (hybrid concrete or inclined external hybrid shear reinforcement) exhibited increase about (114%, 93%) compared with the ordinary joint, respectively.

- The external reinforced joint at angle (45°) showed better performance with higher strength and lower diagonal cracks formed in the joint than that at angle (90°).
- Using the hybridization technique of concrete do not influence on the failure mode of specimens while, the externally hybrid reinforcement technique (as shear reinforcement at angle 45°) altered the failure mode from undesirable diagonal–shear to desirable flexure failure due to effectiveness of this technique.

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