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COMPARISON STUDY OF THE STRUCTURAL PROPERTIES OF BEAM-COLUMN JOINTS USING REACTIVE POWDER CONCRETE (RPC) UNDER REVERSED CYCLIC LOADING

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Abstract

A study of the performance of reinforced normal (ordinary) (NC) concrete and Reactive Powder Concrete (RPC) of Beam-Column Joints under reversed cyclic loading was carried out. For this purpose, specimens of full-scale 3 m in height reinforced beam-column joints made with NC and RPC were investigated. RPC joints were made by mixing 20% of the cement weight using silica fume with adding steel fibres in a dosage of 1.5% of the volume fraction of concrete. The studied properties of hardened concrete were compressive strength, splitting tensile strength and modulus of elasticity. The mechanical properties of joints of RPC type were reasonably improved rather than those of ordinary concrete (NC) joints. It was found that the applied load for RPC joint increased by 26.5 % than the NC joint. The results of the current investigation showed the ability of RPC structural joints to adequately resist vertical and lateral loads in comparison with those of NC joints, this is attributed to the improvement of the mechanical properties and general behaviour of RPC joints. In addition, enhancement of the general behaviour of RPC Beam-Column Joints was shown by the crack pattern, load-deflection trend and amount of strains.

Keywords: Beam-column joints, Reactive powder concrete (RPC), Reversed cyclic loadings, Silica fume and steel fibres.

1. Introduction

Concrete industry has recently succeeded in producing new cement-based materials that have not only higher strength limits but also good durability [1]. Ultra-High-Performance Concrete (UHPC) is one of the products based on using these materials. UHPC is the most durable and is of higher integrity rather than the conventional cement concrete developed in later recent decades [2].

Reactive Powder Concrete (RPC) is a type of UHPC, produced by mixing of high quantities of cement, Silica Fume (SF), superplasticizer, steel fibres, fine sand and a very low quantity of water. This type of concrete, which may but not limited as low permeability, excellent protection against corrosion, high strength in compression and tension and may reach in magnitude more than 200 MPa and 50 MPa, respectively [2], can achieve many advantages. The compressive strength and the flexural strength of RPC are of more than 200 MPa and 40 MPa, respectively [3]. For that, RPC may be considered as the merest suitable applicant for many applications in structural and non-structural fields. For enhancement the properties of RPC, researchers try to develop and produce different ways of construction and several developments for achieving this aim [4]. The development of RPC has the potential to revolutionize the design in precast pre-stressed concrete [2].

In fact, there are unlimited studies on Reactive Powder Concrete some of these studies were here presented.

Collepardi et al. [5] explained that impact of the superplasticizer type, producing an RPC mix with a very low water-cement ratio (w/c), on the strength of RPC in compression was assessed [5]. ASTM type V Portland cement of two kinds A and B were used. The C_3A percentage and specific surface area were 0%, 3400 cm^2/g for cement A, and 4%, 5300 cm^2/g for cement B. Three types of silica fume from different sources and colours were used (white, grey, and dark). Natural sand with 150-400 µm size, precipitated silica fume and 11/0.35 steel fibres were also used. The superplasticizers used to be 1.36 solid percent of a 30% aqueous solution of acrylic polymer (AP), 1.7 solid percent of 40% aqueous solution of sulphonated melamine formaldehyde condensate (MF) and 1.78 solid percent of 40% aqueous solution of sulphonated naphthalene formaldehyde condensate (NF). By vibration, the test samples were condensate and at 20^o C, they were cured. Results revealed that w/c of AP mix was much lower than MF or NF concrete mixes for the same flow without consideration of the types of the cement and silica fume, although the amount of AP (by mass of cement) was less than that of the other chemical admixtures. Compressive strength at age 28 days for the RPC samples with AP was 160 MPa, while it was about 100 MPa with NF or MF chemical admixtures.

The carrying capacity of RPC bridge girders investigated under bursting forces. Three deep beams of RPC type of strength 150 MPa in magnitude were tested. In addition, the Finite Element (FE) analysis was performed on a 35-meter pre-stressed RPC bridge girder. The bridge girder contained no shear or bursting reinforcement but relied on the tensile strength of the concrete to carry these forces. The numerical model indicated that the bridge girder could carry loads well in excess of the design load and in the strength limit condition the girder remained unchecked in flexure. According to Voo et al. [2], in the non-flexural end region of the girder, where a load is usually transferred from the tendon to the concrete, significant tension stresses were calculated but remained within the tension capacity of the reactive powder concrete.

Four mixes of RPC were prepared composing: cement (904 kg/m^3), silica fume (226 kg/m^3), sand of (0 - 1 mm) in particle size (944 kg/m^3), superplasticizer of carboxylate acrylic (12.3 kg/m^3), w/c ratio 0.24 and four kinds of steel fibre (181 kg/m^3) for each, aiming at testing the influence of the type of steel fibre on the performance of RPC. These four types of steel fibre were namely: brass plated steel (13/0.18), deformed steel (30/0.45), deformed steel (30/0.62) and deformed galvanized steel fibre (30/0.62). It was found that the strength in compression and in flexure of RPC type contained brass plated fibre was more than that for of the other types [6].

An experimental work was executed on RPC hollow reinforced concrete T-beams for studying their behaviour by loading them with pure torsion [7]. These beams were prepared using different dosages of silica fume and different steel fibre contents. It was concluded that the torsional capacity at both cracking and ultimate torques significantly increased. The other strength characteristics of this type of structures have not variation in their magnitudes comparing with that of the reference specimens.

It was found as a result of several tests conducted in UHPC [8], for investigating the effect of short and long fibre types and the size of specimens on the mechanical properties (flexural, compressive and post-cracking capacities) of this type of concrete, that for the smallest samples (prisms) more compressive strength, also the same result was observed for the flexural strength for the same size of specimens. The increase of slenderness decreases the compressive strength of samples, preparing by vibration, while for self-compacting UHPC specimens no effect of slenderness on the results. It was found high flexural strength of UHPC containing zero coarse aggregates that composing coarse aggregates in the mixture. Another finding was the proportioning increase of flexural strength of UHPC with the increase of the fibre volume fraction. Both UHPC containing short and long fibres of a cocktail type with 1% volume fraction also exhibits ductile post fracture behaviour.

It was found that RPC prepared by adding steel fibres to its mix mainly causing an increase of the poor tensile strength of composite cementitious materials. In addition to that, the compressive strength increased for the same proportions of the mix of these materials when they mixed with steel fibres. It may conclude that the improvement of the RPC strength in compression is due to the associated enhancement of the tensile capacity because of the presence of steel fibres. Subsequently, the lateral strain induced by Poisson's ratio decreases under applying the uniaxial compressive load, which leads to an increase in the compressive capacity. However, it was also found that the content of the fibre typically produced more dense and compacted mortar along with fewer air bubbles, attributes that are also beneficial to the material's mechanical properties. The flexural tensile capacity of steel fibre RPC was found to be 19 MPa and that for zero steel fibre RPC was 12.9 MPa [9].

The mechanical properties of RPC were investigated by testing different mixes. These properties were: compressive strength, density, absorption, and flexural behaviour. From this study, a general mathematical model was established for expressing the compressive stress-strain relationships for different RPC mixes. A general mathematical equation for expressing such relationships is derived. The main variables used in the production of the different RPC mixes of the study were three, namely, the type of pozzolanic admixture, the type of fibres and dosage of fibres. The high dosage of steel fibres in RPC mixes causing in increasing the strength in compression and density and reduced its absorption unlike RPC mix using polypropylene fibres. Regarding the compressive stress-compressive strain relationships of RPC, it can be said that no significant impact of the aforementioned main variables of this work. Therefore, the shape of the ascending part of the stress-strain curve did not alter. Meanwhile, the type and the content of the fibres considerably affected the shape of the descending part of the curve. Besides that, more the dosage of steel fibres was the more ductility and toughness [10].

An equivalent bi-linear compressive stress block for RPC sections under pure flexural stress was proposed depending on drafting, stress-strain curves obtained by the experimental work [10]. Based on the proposed bi-linear compression blocks a derivation of a mathematical relationship to enable in the determination of nominal ultimate bending moment capacity (Mn) of RPC singly reinforced rectangular sections. Based on studies by Ibraheem [10] and Al-Hassani and Ibraheem [11], for verification of the accuracy of this equation, the results were compared with that obtained experimentally.

An investigation aiming at the determination of the compressive strength of silica fume (SF) concrete associated with low water-cementitious materials along with superplasticizer of type naphthalene sulphonate was carried out. It was remarked that the increase in compression capacity of this type of concrete ascribed to the less ratio of water-cementitious materials instead of the silica fume as a replacement material of cement. It was also shown that the strength in compression tends to increase with increasing of SF dosage up to 20% and it may be of the maximum value of a 10 to 15% content of (SF) [12].

Researchers have studied Reactive Powder Concrete (RPC), however, considering reinforcing fibres and silica fume is an innovative approach. This work is aimed at a finding of the mechanical properties of RPC beam-column joint (as a part of a mid panel of a building frame) under reversed recycling loadings. For this purpose, it was used silica fume of content was (20%) by adding an equal weight of cement in concrete and steel fibres of dosage was (1.5 %) by the volume fraction of concrete in preparing the beam-column joint.

2. Experimental works

2.1. Materials

For the preparation of materials required for casting specimens and joints ordinary Portland cement (type I) manufactured by Al. Kufa cement plant in Iraq was delivered to the laboratory. The cement was stored in airtight containers. Physical and chemical properties of the used cement are presented in Tables 1 and 2, respectively [13].

The fine aggregate (sand) was furnished from a local quarry named as Al-Akhaider (at the Kerbela Province of Iraq). After sieving the sand, all the particles greater than 600 μm and smaller than 150 μm were removed. Then, the remaining sand of size between 150 μm to 600 μm was washed in tap water and the water decanted over a 150 μm sieve and allowed to drain for 2 minutes, and finally, the sand was dried at 110 ºC for 48 hours before being used. The grain size distribution of the sand was shown in Table 3 [14], while its physical properties are shown in Table 4.

Table 1. Chemical properties of cement.

Oxide composition	% by weight	Limit of Iraqi specification no. 5/1984 [13]
SiO_2	20.60	-
CaO	63.19	-
MgO	4.10	5.0 (max.)
Fe_2O_3	4.20	-
Al_2O_3	4.10	-
SO_3	1.88	2.5 (max.)
Loss on ignition	2.45	4.0 (max.)
Insoluble residue	1.31	1.5 (max.)
Time saturation factor	0.91	0.66-1.02
Main compounds (Bogue's equation):		
C_3S	50.02	-
C_2S	26.23	-
C_3A	4.40	-
C_4AF	13.62	-

Table 2. Physical properties of cement.

Physical properties	Test result	Limit of Iraqi specification No. 5/1984 [13]
Specific surface area (Blaine method), m^2/kg	332.9	230 (min.)
Setting time (Yicale's method):		
Initial setting, hrs: min	2:0	00:45 (min.)
Final setting, hrs: min	4:1	10:00 (max.)
Compressive strength, MPa:		
Three days	21.20	15.00 (min.)
Seven days	30.10	23.00 (min.)

[a]The chemical and physical analysis carried out in the laboratories of the College of Engineering, University of Kufa, Al.Najaf Al-Ashraf, Iraq.

Table 3. Particle size gradation of sand[b].

Sieve size, mm	Passing (%) by weight	
	Specimen	(I.O.S. 45/1984) limitations for zone no. 3 [14]
4.75	96	90-100
2.36	87	85-100
1.18	76	75-100
0.60	60	60-70
0.30	14	12-40
0.15	4	0-10

Table 4. Physical and chemical properties of fine aggregate[b].

Physical properties	Test Result	Limit of Iraqi specification No.45/1984 [14]
Specific gravity	2.60	-
Sulphate content	0.0 61%	0.5 % (max.)
Absorption	0.75%	-

For casting ordinary concrete (NC), the coarse aggregate of crushed gravel of maximum size (10 mm) was delivered from Al.Suwaira local quarry. In Table 5, the particle size gradation was shown [14] and the physical properties of this crushed gravel were listed in Table 6.

Drinking water is used without any impurities for both mixings, casting and curing. Silica fume of grey densified type was furnished by Sika company and added to the concrete mix for preparing the samples of RPC as a replacement material. Its chemical compositions were given in Table 7 [15].

Table 5. Grading of coarse aggregate[b].

Sieve size, mm	Passing (%) by weight	
	Specimen	Limits of IOS No. 45/1984 [14]
20	100	100-95
14	80	-
10	37	30-60
5	2	0-10

Table 6. Physical and chemical properties of coarse aggregate[b].

Physical properties	Specimen	Limits of IOS No. 45/1984 [14]
Specific gravity	2.65	-
Sulfate content(SO_3)	0.073 %	≤ 0.5 %
Chloride content(Cl)	0.092 %	≤ 0.1 %
Absorption	.65 %**0**	-
Loose bulk density kg/m^3	1500	-

[b]The chemical and physical analysis carried out in the laboratories of the Najaf Technical Institute/Al-Furat Al-Awsat Technical University, Al.Najaf Al-Ashraf, Iraq.

Table 7. Chemical properties of silica fume[c].

Oxide composition	Abbreviation	Oxide content (%)	Limit of specification requirement (ASTM C 1240-04) [15]
Silica	SiO_2	94.87	85.0 (min.)
Alumina	Al_2O_3	1.18	-
Iron oxide	Fe_2O_3	0.09	-
Lime	CaO	0.23	-
Magnesia	MgO	0.02	-
Sulphate	SO_3	0.25	-
Potassium oxide	K_2O	0.48	-
Loss on ignition	L.O.I.	2.88	6.0 (max.)
Moisture content	-	0.48	3.0 (max.)

[c]Test results were obtained by implementing the tests at the quality control laboratory of Al.Kufa Cement Factory, Al-Najaf Al-Ashraf, Iraq.

The steel fibres of hooked ends and mild carbon steel were used in this work. The characteristics of the steel fibre presented in Table 8 [16].

A High Range Water Reduction Agent (HRWRA) was added to the mix as a superplasticizer, commercially named Glenium 51, which conforms ASTM C494 type a [17]. Table 9 shows the properties of this type of superplasticizer.

Two sizes of steel reinforcing deformed bars were used as longitudinal reinforcement and as closed stirrups of diameters (φ = 12 mm) and (φ = 8 mm), respectively. Values for yield stress, ultimate strength, yield strain and ultimate strain for each bar size are given in Table 10.

Table 8. Properties of steel fibre*.

Configuration	Property	Specification
	Description	Hooked
	Length	30 mm
	Diameter	0.375 mm
	Density	7800 kg/m3
	Tensile strength	1800 MPa
	Modulus of elasticity	200GPa
	Aspect ratio(Lf/Df)	80

*As furnished by the manufacturer.

Table 9. Properties of superplasticizer type Glenium 51*.

Form	Viscous liquid
Commercial name	Glenium 51
Chemical	Sulphonated melamine and naphthalene formaldehyde
Composition	**Condensates**
Subsidiary effect	Increased early and ultimate compressive strength
Form	Viscous liquid
Colour	Light brown
Relative density	1.1 gm/cm^3 at 20º C
pH	6.6
Viscosity	128 ± 30 cps at 20º C
Transport	Not classified as dangerous
Labelling	No hazard label required
Chloride content	None

*As supplied by the manufacturer.

Table 10. Reinforcing steel properties*.

Bar size, φ	Yield stress (MPa)	Yield strain	Ultimate strength (MPa)	Ultimate strain
8 mm	467	0.0024	714	0.184
12 mm	708	0.0034	740	0.051

*Tests were conducted by the laboratory in the College of Engineering, University of Al-Muthanna, Samawa, Iraq, using computerized digital Universal Machine manufactured by Alfa company.

2.2. Experimental program

2.2.1. Joint experimental specimens

Two beam-column joints simulated a mid-panel joint of a building frame, namely, ordinary concrete (NC) and RPC were designed as per ACI352R-02 [18] requirements. The column is 3000 mm in height with cross-section dimensions of (250×250) mm. The beam's length is 1750 mm from the face of the column at its free end with a cross-section of (250×250) mm. A schematic diagram is shown in Fig. 1 represents both types of joints showing the details of reinforcement.

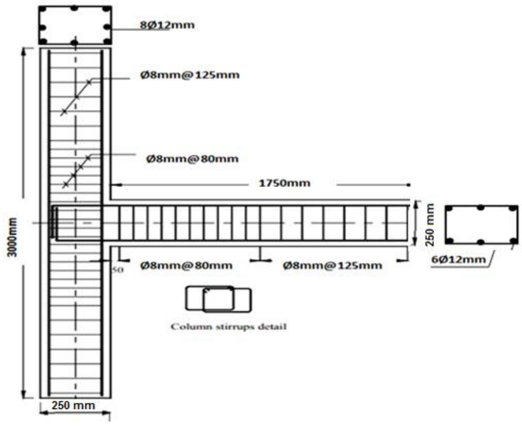

Fig. 1. Schematic diagram showing reinforcement details and dimensions of beam-column joint for both types; NC and RPC.

Moulds:

Two plywood moulds were used to cast NC and RPC specimens of the present work. The moulds are off base and movable sides. The thickness of plywood is (18 mm). The sides were fixed by screws to form a T shape with rectangular blocks. Before pouring the concrete, the moulds should be cleaned and oiled carefully. Then the rebars mesh was placed in its correct position, then the moulds with mesh placed on a vibrating plate, which would be used for producing the joints. Figure 2 shows a photo of plywood mould.

Fig. 2. Plywood moulds.

Concrete mix design:

As per the requirements of ACI 211.4R-93 [19], a reference concrete mix of zero silica fume and steel fibres (NC) was prepared to aim at producing concrete of 62 MPa capacity in compression at the age of 28 days. The proportioning was by weight and the water-cement ration (w/c) was 0.30 and containing cement, fine aggregate, coarse aggregate, superplasticizers and water. For preparing RPC, another mix was designed to determine the silica fume (SF) dosage by weight of cement and the required volume fraction of steel fibres to be mixed with cement, fine sand, superplasticizers and water. Table 11 presented the two mixes for NC and RPC concrete.

Table 11. Concrete mixes.

Contents	NC	RPC
Cement	550 kg/m^3	550 kg/m^3
Water	165 litres	165 litres
Fine aggregates	855 kg	855 kg
Coarse aggregates	765 kg	-
Water cement ratio	0.30	0.30
Silica fume%	-	20
Steel fibres % by volume fraction	-	1.5
SP/C*	0.65	0.65

***Superplasticizer content.**

Test arrangement and procedure of application of loading to joints

The specimens were placed in the experimental arrangement after casting by 28 days. The hydraulic jack applies the axial load to the column firstly by 10% of the expected design load to be stable before the process of applying the reversed loading at the beam tip [20]. The column was supported at the top by a roller, which moves vertically within a vertical slot. The bottom end of the column was simply supported to produce a reaction against the load applied to the beam end. A vertical loading applied through a hydraulic jack connected to load cell within the jack plunger. Figure 3 shows the test arrangement. The loading up process, including the application of the vertical load to the beam tip up to a certain value, then the unloading would be to ensure reversed direction for the second stage of loading in order to get a full cycle of loading. When each cycle of loading another increment of loading would be applied respectively, until the occurrence of a failure of the joint. For measuring the diagonal concrete strains at points located at beams were measured using a mechanical gauge of Demec type (Lc = 0.002 mm), by this gauge the concrete surface strain at every loading stage could be measured. The gauge consists of aluminium discs with a 10 mm diameter along with a 1.5 mm diameter hole at the centre. These gauges were identified as gauge A and gauge B, glued and positioned as shown in Fig. 4.

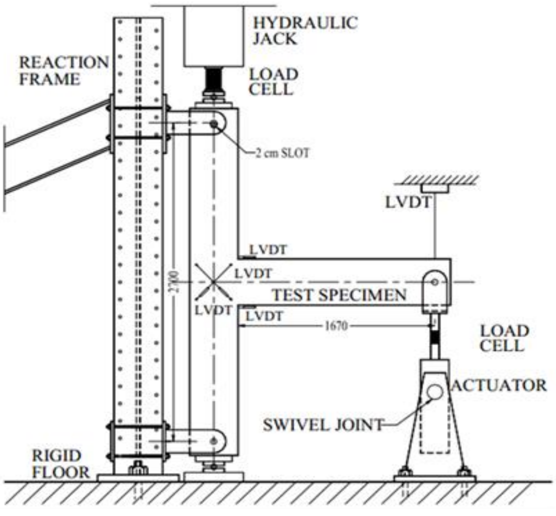

Fig. 3. Setup of experiment.

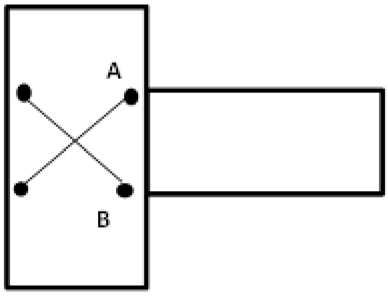

Fig. 4. Schematic diagram showing locations of Demec points on joint surface.

2.2.2. Structural properties of NC and RPC

The experimental program of this work was included assessment of four (4) structural properties of both types of concrete, i.e., for the ordinary concrete (NC) and the RPC concrete. The four properties were investigated: the compressive strength, (*f'c*); the flexural strength (modulus of rupture, *fr*); the splitting tensile strength, (*ft*); and the static modulus of elasticity test, (*Ec*). These properties were determined by taking the average of the results of three samples, after hardening at 28 days age, for each characteristic. The investigated properties were tabulated in Table 12 along with the standards that were followed in preparing and calculations for each. The mix proportions used in preparing samples for each one of these characteristics were the same used for casting the joints as specified in Table 11.

Table 12. Hardened concrete properties.

Property	Standard issue
Compressive strength of concrete, (*f'c*)	ASTM C39-03 [21]
Flexural strength of concrete (modulus of rupture),(*fr*)	ASTM C78-02 [22]
Splitting tensile strength of concrete, (*ft*)	ASTM C496-04 [23]
Static modulus of elasticity test, (*Ec*)	ASTM C469-02 [24]

3. Experimental Results

3.1. Results of mechanical properties of hardened concrete

The results of the determination of structural capacities for both NC and RPC were tabulated in Table 13.

Generally, by the results presented in Table 13, the mechanical properties of RPC show an increase in their magnitudes than those of the conventional (ordinary) concrete (NC). This fact attributed to the existence of both additives, silica fume and steel fibres.

Table 13. Values of mechanical properties of hardened concrete at age 28 days (NC and RPC).

Concrete type	Properties			
	***f'c*, MPa**	***fr*, MPa**	***ft*, MPa**	***Ec*, GPa**
NC	62	5.35	7.43	36
RPC	84	6.62	8.89	42

3.2. Ultimate load

The results of testing the RPC beam-column joint were presented here in comparing with those obtained by testing the reference joint produced by using ordinary concrete identified by NC. Both types of joint were investigated under reversed cyclic loading. The ultimate load of the RPC joint increased by 26.5 % more than the ultimate load obtained from the NC joint as presented in Table 14.

Table 14. Ultimate loads of the beam-column joints specimens.

Joint type	Applied ultimate load (kN)	Increase percentage in ultimate load with respect to reference joint
NC (reference)	620	-
RPC	784	26.5 %

3.3. Load-displacement response

For each of the beam-column joint, the envelope of the beam tip load-displacement relationships drafted in Fig. 5. It was shown that for both types of concrete (NC) and (RPC) the trend of the envelopes increased approximately linearly, i.e., the joints behave in elastic mode up to approximately 25% of the ultimate load, after that the behaviour was changed to plastic one until the failure. In general, the resistance capacity to the applied load shown by RPC concrete was more than that obtained by NC joint. Figures 6 and 7 show the load-strain curves for both NC joint and RPC joint respectively. From these two figures, it can be seen that for both NC and RPC joint, the relation was linear at low load levels, but it became nonlinear for all regions as the load increased at earlier stages due to cracking in concrete.

For RPC joint, the load capacity is more than that for NC joint for all stages of loading. This may be attributed to the improvement of strength properties of the concrete with silica fume and steel fibres. When comparing the figures for RPC joint and NC joint, it was noticed that at the strain 0.003, which can be called the first crack load, where the ultimate load for both types approximately, started and this load was more than that for NC joint for the two Demec strain points (A and B). At the same trend, it can be noticed for the crack load (the load at failure). Furthermore, the RPC concrete shows more ductility than the NC concrete, therefore, it was seen that at the maximum load the strain was more than that of NC Beam-column joint.

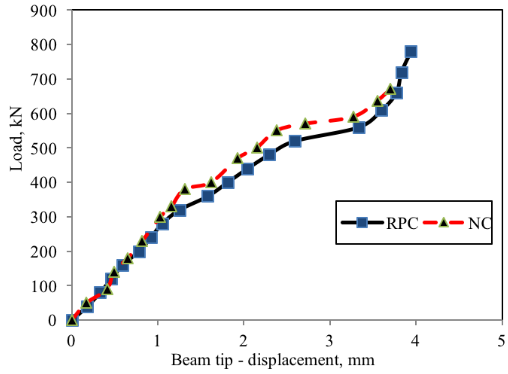

Fig. 5. Load-displacement curves for both joint types, NC and RPC.

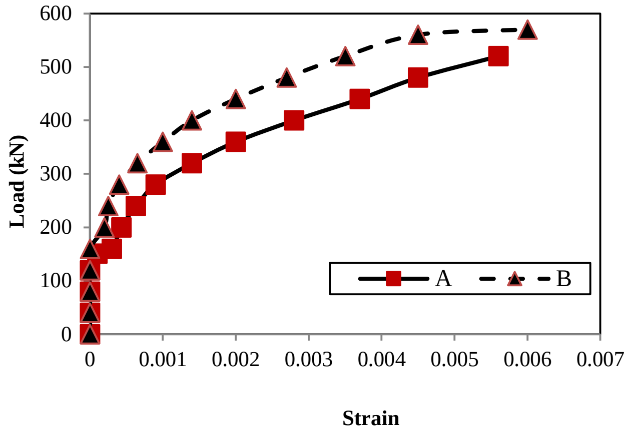

Fig. 6. Load- strain curve for (NC) beam-column joint.

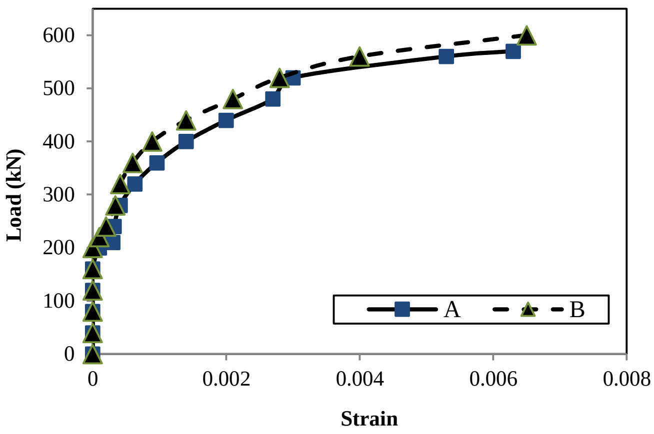

Fig. 7. Load-strain curve for (RPC) beam-column joint.

4. Conclusions

Based on the results obtained from the investigation beam-column joints under application of reversed cyclic loading produced by ordinary concrete (NC) And Reactive Powder Concrete (RPC), where NC joint used as a reference for comparison, the following concluding points can be drawn:

- RPC rather than NC achieved a significant improvement in the properties of hardened concrete. The adding of silica in a dose of (20 %) by weight of cement and 1.5 % of steel fibres in volume fraction of concrete increases compressive strength, flexural strength, splitting and modulus of elasticity by amount in percentage as 26.5 %,19.6 %, 23.7% and 16.6% respectively compared with NC specimen.
- The ultimate load for RPC Beam-column joint was significantly higher than that for NC joint by 26.5 %.

- A stiffer load-deflection response is observed for Beam-column joint prepared with Reactive Powder Cement comparing with the response of control Beam-column joint (NC joint).
- The increases in first crack load and ultimate load for RPC are due to existing the steel fibre in a volumetric ratio. This can be attributed to the steel fibres across the initial flexural cracks, which restricts growth and extension of the cracks. Thus, the steel fibre transmits the tensile stresses uniformly to the concrete surrounding the cracks, resulting in more bearing capacity. This tends to improve the bond between the matrix and the reinforcing bars.
- The performance of RPC joint under shear stress in the joint panel was better than that of the NC joint regarding cracking and deformations.

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