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Influence of Tie Configuration on Seismic Behaviour of Ultra High Performance Concrete Columns

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Abstract

Ultra-High-Performance Concrete (UHPC) is one of the latest advances in concrete technology as it overcomes the shortcomings of conventional concrete such as low strength to weight ratio, high permeability, low tensile strength, low ductility, and volume instability. Confinement is capable of increasing capacity of the concrete structure to sustain large deformation without a substantial strength loss. The present study discusses the influence of tie configuration, percentage of longitudinal reinforcement and tie spacing in improving the confinement and behaviour of UHPC columns. In order to determine the behaviour of UHPC column, half scaled specimens of original short column with four different tie configurations were used. The configurations considered for the study included a double legged ties (A), welded ties with bars running centrally across the length and width (B), ties with inclined bars connecting two adjacent mid-points (C) and ties with bars connecting two adjacent sides at one-third distances (D). For the same tie configuration, the transverse reinforcement ratios are varied by changing the diameter of the ties. The specimens were tested under quasi static reverse cyclic loading under a constant axial load. The test results were represented and compared in terms of load-deflection envelope, ductility and cracking patterns. Tie configuration C exhibited better performance in stiffness and ductility, when compared with other configurations. For same parameters, "B" and "D" configuration displayed better behaviour than "A" configuration. This variation in performance was due to increase in transverse reinforcement percentage and the consequent effectiveness of core confinement. Transverse reinforcement percentage of "B" and "C" configurations is less than "D" configuration. The enhancements of properties of "B" and "C" configurations are better than "D" configuration. It was due to the effective core confinement of "B" and "C" configuration. For the same tie configuration, ultimate load, initial stiffness and relative ductility increases with increase in transverse reinforcement percentage. UHPC columns with "C" type tie configuration can effectively use in moderate and high seismic areas and its performance can be improved by increasing the transverse reinforcement ratio.

Keywords: Confinement, Cyclic Loading, Ductility, Tie Configuration, Ultimate Load, Ultra High Performance Concrete

1. Introduction

Ultra High Performance Concrete (UHPC) is a concrete mixture having high strength, high durability and greater modulus of elasticity. The addition of some admixtures like fly ash, silica fume and superplasticizer enhance the properties of concrete to a very large extent. UHPC is one of the areas where intensive research is being carried out on its material properties and structural applications.

It is generally known that unconfined UHPC displays more brittle behaviour than normal strength concrete. Confinement is capable of increasing the capacity of the concrete structure to sustain large deformation without a substantial strength loss. The confinement of concrete allows an improvement in the compressive strength of columns in seismic active areas. The parameters such as tie configuration, compressive strength, percentage reinforcement, tie spacing have considerable effect on improving the confinement and behaviour of UHPC column.

2. Literature review

2.1 Studies related to high performance concrete

Lakshmi and Adiseshu (2016) investigated the physical properties of high performance concrete (HPC) using silica fume and fly ash as mineral admixtures along with the addition of glass fibres [1]. They found that the specimens containing 10% silica fume and 0.3% glass fibres and another mix containing 10% silica fume, 10% fly ash and 0.3% glass fibres experienced higher mechanical properties compared to that of the control specimen. Al-Azzawi et al. (2011) studied the behaviour of ultra-high performance concrete structures with steel fibres [2]. Ma and Orgass (2004) conducted comparative investigations on ultra-high performance concrete with and without coarse aggregates by making UHPC with crushed basalt having a particle size of 2 to 5 mm [3]. The results show that the compressive

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strength of UHPC reached the same magnitude as that of mix with particle size smaller than 1.0 mm.

2.2 Studies on the behaviour of concrete column

Zhu et al. (2016) conducted a study on steel reinforced high strength concrete columns subjected to cyclic lateral load and constant axial load [4]. The authors found that steel reinforced high strength concrete (SRHSC) columns with multiple stirrups and structural steel ratios that are commonly used showed excellent seismic performance. Ahmed and Hany (2015) conducted a study on reinforced concrete columns with improved confinement. Traditional steel ties reinforcement cannot provide superior confinement for reinforced concrete (RC) columns due to the constraints on tie spacing and disturbance of concrete continuity [5]. The results indicated that the columns with lateral reinforcement, consisting of single Expanded Metal Mesh (EMM) layer along with regular tie reinforcement, revealed significant improvement in the strength and ductility. A high reduction in ties volumetric ratio with no loss in ultimate load could be achieved by installing the EMM layer. Mohammadi and Hassan (2015) conducted studies on ultra-high performance fibre reinforced concrete (UHPFRC) columns subjected to axial loading alone [6]. The authors studied the effect of UHPFRC and transverse reinforcement detailing on column performance. Hossam et al. (2014) studied the behaviour of UHPC columns under axial and cyclic lateral loads [7]. Husem and Pul (2007) studied the effect of confinement reinforcement on the behaviour of high strength concrete (HSC) columns using prismatic specimens of square cross sections with four longitudinal reinforcements and the confinement reinforcement in the form of hoops of different spacing [8]. The results showed that the ductility of the HSC was improved by providing such confinement reinforcement. Yong et al. (1998) studied the behaviour of laterally confined high-strength concrete subjected to axial load alone [9]. The authors also proposed an empirical model for the stress-strain curve of rectilinearly confined HSC. Cusson and Paultre (1994) have done an experimental study on high strength concrete (HSC) column confined by rectangular ties subjected to concentric loading [10]. The test results indicate that the concrete core was not effectively confined by simple square ties and cannot be used for ensuring ductile behaviour. The increase of the strength and toughness gains with the enhancement of the longitudinal reinforcement ratio was observed only for well-confined specimens with a large transverse reinforcement ratio. Shamim et al. (1990) did an experimental study on tied concrete columns subjected to axial load and flexure [11]. They investigated the behaviour of column sections confined by rectilinear ties, with varying distribution of longitudinal and transverse steel, varying axial load, changing the spacing of ties and amount of lateral steel. The authors found that lateral steel content and axial load level have considerable effects on the performance of the column behaviour.

2.3 Summary of Literature Review

Most of the studies done by researchers in the field of UHPC were concentrated in developing the mixes and finding the ingredients that will give the best performance concrete. Experimental studies on the behaviour of UHPC columns under axial as well as lateral loading with tie configuration and percentage transverse reinforcement as test variables are limited. Most of the studies on confined UHPC column are done under axial loading; studies with cyclic loading are limited. Studies on the behaviour of UHPC columns confined with different tie configurations are limited. Studies on UHPC columns with ductile detailing subjected to lateral cyclic loading are also limited.

3. Methodology of experimental work

Ordinary Portland cement of 53 grade conforming to IS:12269-2013 [12] was used for the study. Manufactured sand less than 4.75 mm which conforms to IS Zone II was used as fine aggregate. Coarse aggregates of size 12.5 mm and 6 mm were used. Micro silica with a specific gravity of 2.2 was used. The superplasticiser using for the study is Cera Hyperplast XR-W40 with a total solids content of 40% and a specific gravity of 1.11. To improve the properties of the concrete, DURAFLEX fibres compiling to the ASTM A820 (claimed by the manufacturer), Type 1 low carbon drawn wire were used as secondary reinforcement. Two types of fibres – crimped steel fibre of 0.45 mm diameter and 30 mm length and Hook end steel fibres of 0.75 mm diameter and 50 mm length of aspect ratio 60 were used. The mix proportion arrived is given in Table-1.

2.1 Specimen Details

In order to determine the behaviour of UHPC column, half scaled specimens of original short column were made as per the mix designed and the details of specimens are given in the following sections.

The specimen consists of two parts – column and footing. Column has a dimension of 800 x 200 x 200 mm and footing has a dimension of 450 x 450 x 200 mm as shown in Fig.1. These dimensions are the half-scaled values of the dimensions of a short column obtained as per IS 456: 2000 [13]. Four 12 mm diameter bars were provided as longitudinal reinforcement. Rectangular hoops at 100 mm spacing were provided as transverse reinforcement. Special confining reinforcement was provided over a length of 500 mm. For the half-scaled specimen, it was provided over a length of 250 mm. Hence the spacing of was is 50 mm for special confining region.

Table-1. Quantities of materials per cubic metre of concrete

Materials	Quantities (kg/m^3)	Proportion
Cement	499	1
Silica Fume	49.89	0.10
Fine Aggregate	838	1.67
Coarse Aggregate	1062.73	2.13
Water	114.75	0.23
Chemical Admixtures	8.97	0.018

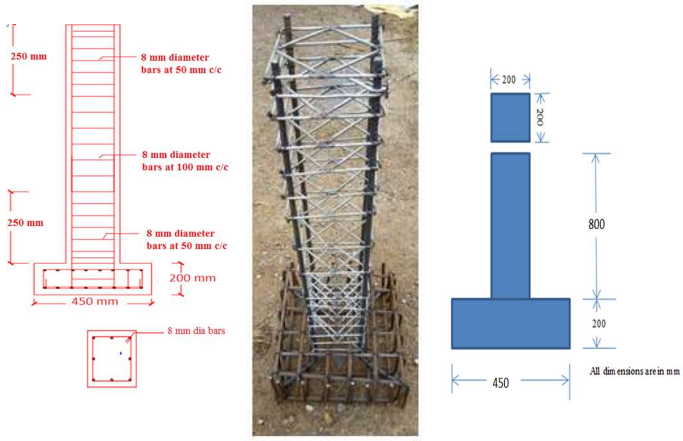

Fig. 1. Details of the specimen

Four different tie configurations were used in the study. For the same tie configuration, the transverse reinforcement ratios are varied by changing the diameter of the ties. For the same tie configuration, the transverse reinforcement ratios are varied by changing the diameter of the ties. That is, three columns are made with same tie configuration and different transverse reinforcement ratio. The tie configurations used are shown in Fig. 2. The transverse reinforcement configurations "B", "C" and "D" used were welded. Designation of the specimen, Tie configuration used for the corresponding specimen and Transverse reinforcement ratio used for each specimen are shown in Table-2.

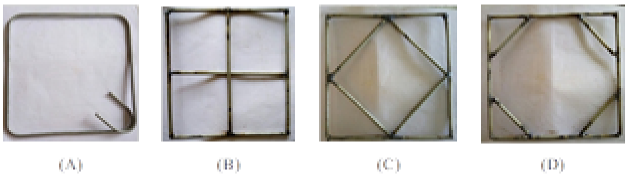

Fig. 2. Tie configurations

Table-2. Details of specimens

Designation	Configuration	Transverse Reinforcement ratio
UHPCA4	A	0.0035
UHPCB4	B	0.0052
UHPCC4	C	0.006
UHPCD4	D	0.0063
UHPCA6	A	0.008
UHPCB6	B	0.012
UHPCC6	C	0.013
UHPCD6	D	0.014
UHPCA8	A	0.014
UHPCB8	B	0.021
UHPCC8	C	0.024
UHPCD8	D	0.025

Fig. 3. Mixing of materials

Fig. 4. Prepared mix

2.2 Experimental investigation of UHPC columns

A schematic diagram of experimental setup is shown in Fig. 4. Lateral loading was given manually with two screw jack placed on either side of the specimen and axial load was given with a hydraulic jack. The experimental test setup in the laboratory is shown in Fig. 5. During testing, the observations were made for each cycle of loading until failure. The displacement controlled loading sequence consisted of drift controlled mode with three increments of 0.125% drift followed by increments of 0.25% up to 0.5% drift. A base fixer was fixed at the bottom plate of testing frame. This support condition was chosen to simulate the fixity condition of the column in the field. The loading history of the cyclic loading is given in Fig. 6.

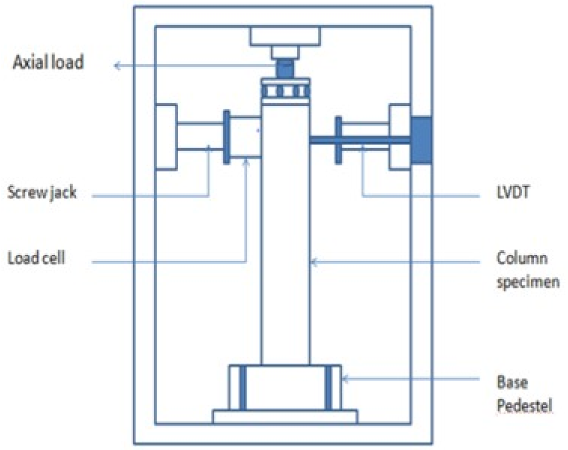

Fig. 4. Schematic diagram of experimental test setup

Fig. 5. Experimental setup in the laboratory

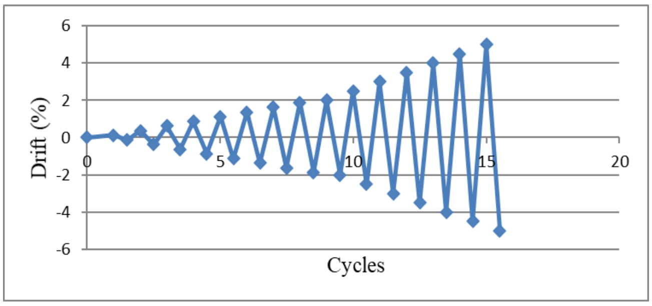

Fig. 6. Loading history of cyclic loading

4. Results and discussions

The deflection at the top of the cantilever column was taken with LVDT in a deflection controlled loading setup and the load deflection curve was plotted. The test results were represented and compared in terms of load-deflection envelope, ductility and cracking patterns. The observations made during test are discussed as follows:

4.1. Load-Deflection Envelope

The maximum loads and displacement obtained in each cycle were used for plotting the load displacement envelope for the tested specimen. The envelope enables the comparison of relative performance of the different specimens. The comparison of load-deflection envelope curves of specimens with 4 mm diameter bars, 6 mm diameter bars and 8 mm diameter bars with four different tie configurations are shown in Fig. 7, Fig. 8 and Fig. 9. The curves are linear up to the formation of first crack. After cracking, the slope of curve decreases whereas displacement increases. In all these four figures, load and deflection was maximum for “C” configuration and best load deflection envelope curve was observed for “C” configuration. “B” configuration was next to “C” configuration. Minimum load deformation capability was observed for “A” configuration. The load deflection envelope curve of “D” configuration was better than “A” configuration.

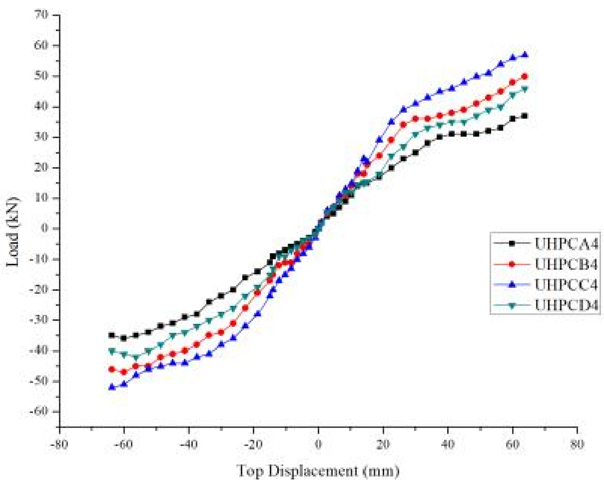

Fig. 7. Comparison of load-deflection envelope curves of specimens with 4 mm diameter bars

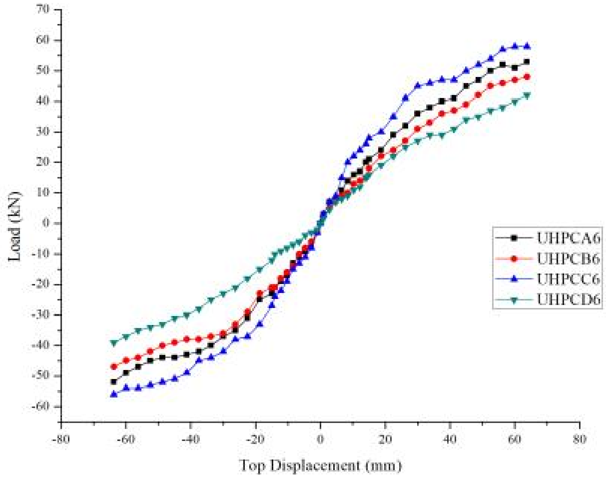

Fig. 8. Comparison of load-deflection envelope curves of specimens with 6 mm diameter bars

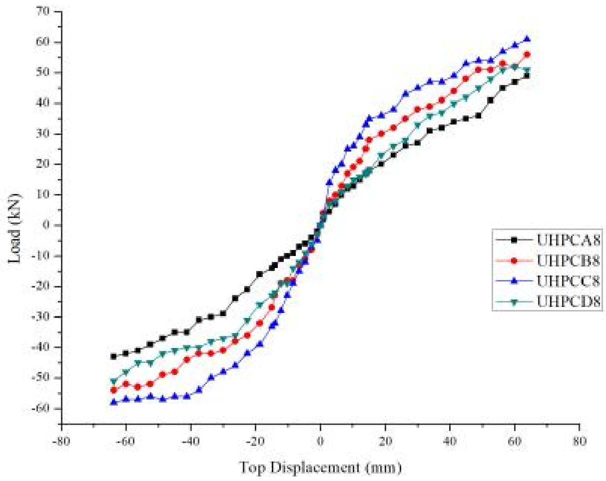

Fig. 9. Comparison of load-deflection envelope curves of specimens with 8 mm diameter bars

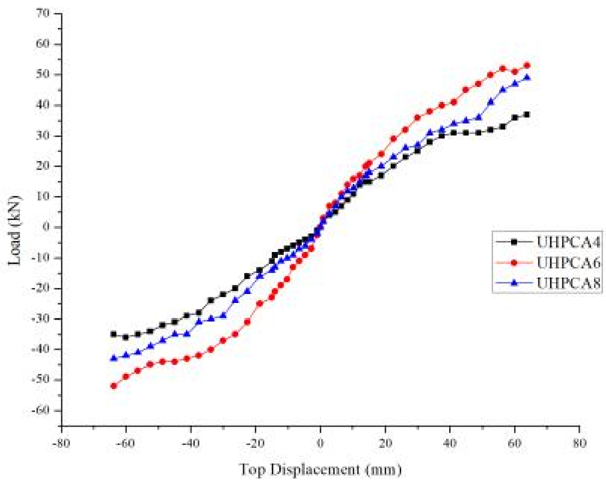

Fig. 10. Comparison of Load-deflection envelope curves of specimens with tie configuration “A”

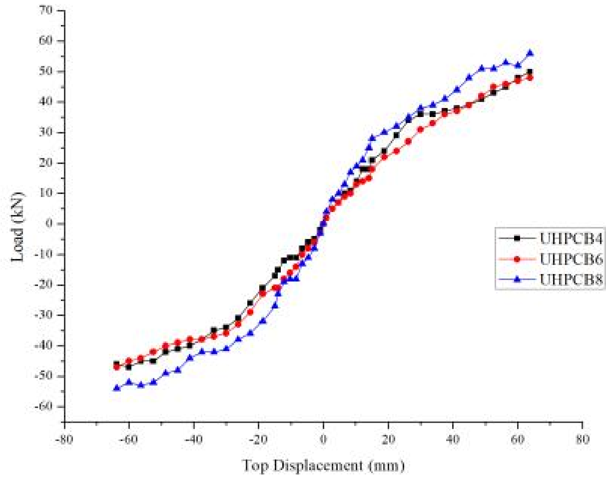

Fig. 11. Comparison of Load-deflection envelope curves of specimens with tie configuration "B"

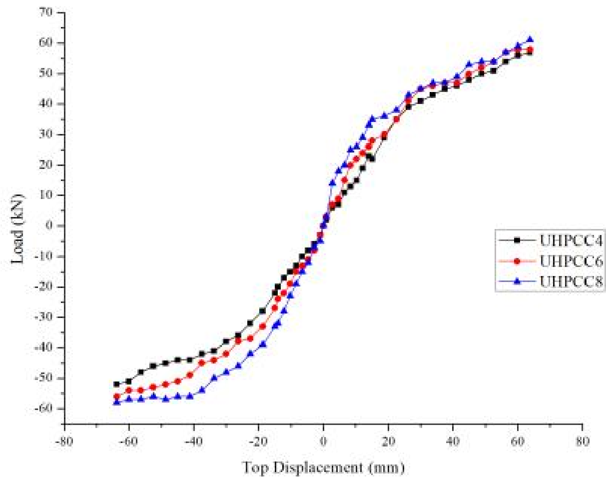

Fig. 12. Comparison of Load-deflection envelope curves of specimens with tie configuration "C"

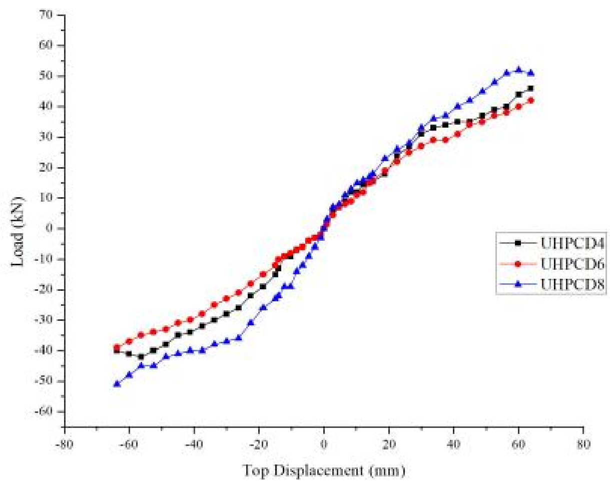

Fig. 13. Comparison of Load-deflection envelope curves of specimens with tie configuration "D"

4.2. First Crack Load and Ultimate Load

The specimen designation, first crack load, displacement at first crack load, ultimate displacement and ultimate load of specimens were listed in Table-3. All the specimens cover 22 cycles of loading. The ultimate load of UHPCB4, UHPCC4 and UHPCD4 specimens were greater than UHPCA4 specimen by 26.4%, 38.2% and 13.7%. The ultimate load of UHPCB6, UHPCC6 and UHPCD6 specimens were greater than UHPCA6 specimen by 26.6%, 33.7% and 17.9% and the ultimate load of UHPCB8, UHPCC8 and UHPCD8 specimens were 15%, 21.8% and 6.8% greater than UHPCA6 specimen. From the test results greater ultimate load was observed for "C" configuration and least was observed for "A" configuration. For the same tie configuration, ultimate load and first crack load increases with increase in transverse reinforcement ratio.

4.3. Stiffness Degradation

Stiffness is the load required to produce a unit deflection of the column. The stiffness in a particular cycle was calculated from the slope of the line joining peak values of the lateral load in each half cycle. The stiffness of the column specimen at the end of each cycle has been plotted to observe the stiffness degradation. For the same tie configuration, the initial stiffness increases with increase in transverse reinforcement ratio.

Table-3. Test results

Specimen Designation	First Crack load (kN)	Displacement at first crack load (mm)	Ultimate Load (kN)	Ultimate Displacement (mm)
UHPCA4	17	18.75	40	33.75
UHPCB4	24	18.75	52.8	37.5
UHPCC4	29	18.75	65.71	41.25
UHPCD4	18	18.75	47.14	33.75
UHPCA6	24	22.5	44.28	41.25
UHPCB6	29	22.5	64	45
UHPCC6	35	22.5	74	48.75
UHPCD6	24	22.5	47	41.25
UHPCA8	28	26.25	59	52.5
UHPCB8	35	26.25	74	60
UHPCC8	43	26.25	87	63.75
UHPCD8	28	26.25	73	56.25

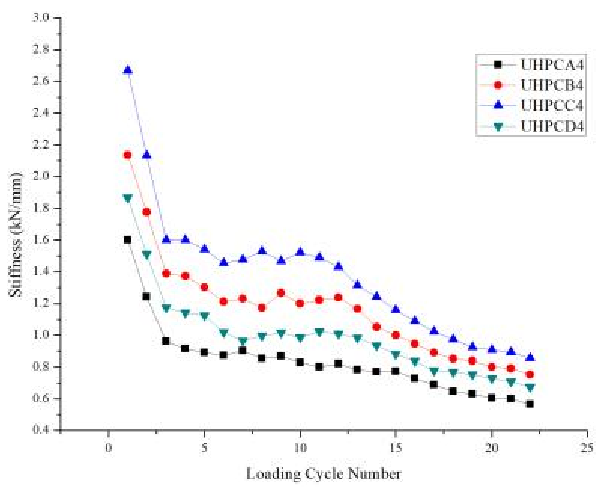

Fig. 14(a). Comparison of stiffness degradation of specimens with 4 mm diameter bars

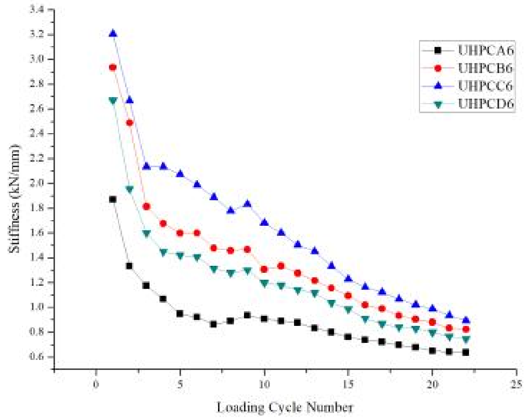

Fig. 14(b). Comparison of stiffness degradation of specimens with 6 mm diameter bars

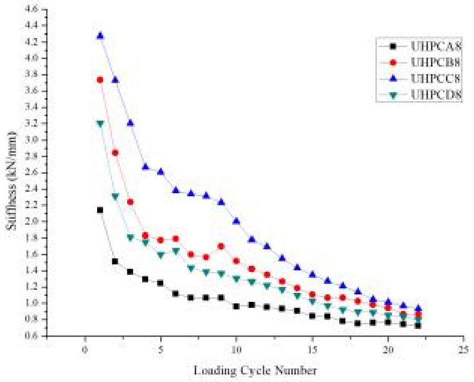

Fig. 14(c). Comparison of stiffness degradation of specimens with 8 mm diameter bars

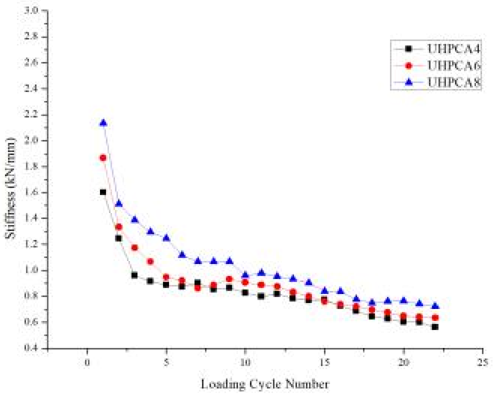

Fig. 15(a). Comparison of stiffness degradation of specimens with tie configuration "A"

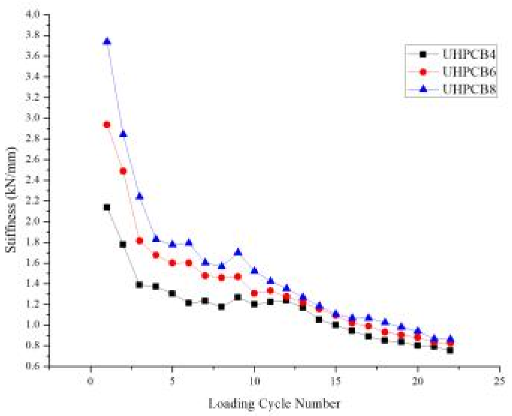

Fig. 15(b). Comparison of stiffness degradation of specimens with tie configuration "B"

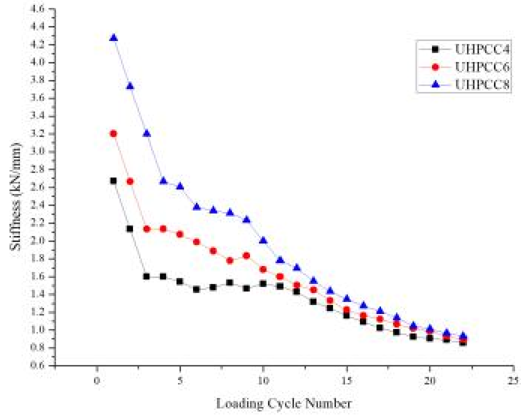

Fig. 15(c). Comparison of stiffness degradation of specimens with tie configuration "C"

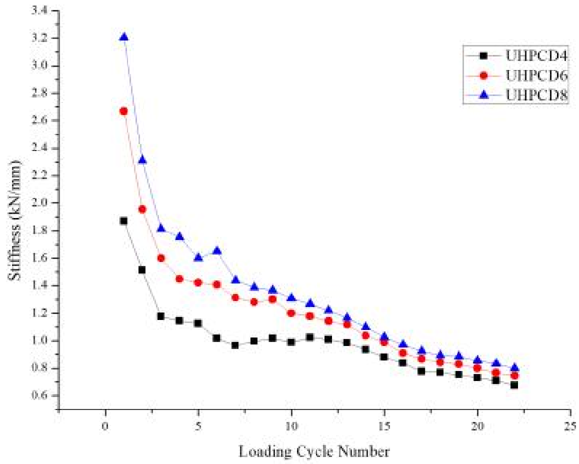

Fig. 15(d). Comparison of stiffness degradation of specimens with tie configuration "D"

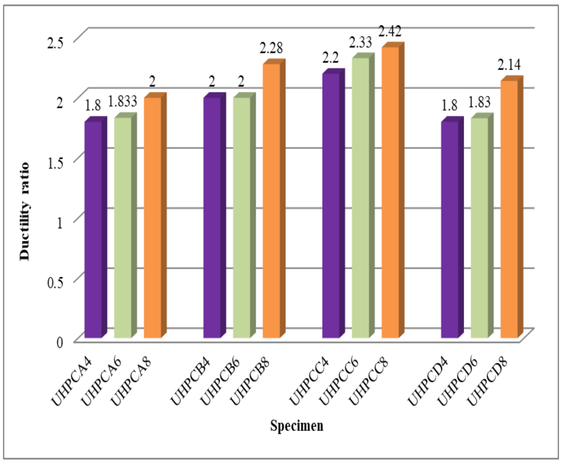

Fig. 16. Comparison of ductility ratio of specimens with same tie configuration and different transverse reinforcement ratio

4.4. Ductility Ratio

Ductility of a structure is its ability to undergo large inelastic deformations before failure. In seismic design, the ductility of a member is expressed as the ultimate deformation to the deformation at first yield.

The comparison of ductility ratio of specimens with same tie configuration and different transverse reinforcement ratios are shown in Fig. 16. Greater ductility was observed for specimens with 8 mm diameter bars and least was observed for specimens with 4 mm diameter bars. That is, for the same tie configuration ductility ratio increases with increase in transverse reinforcement ratio.

4.5. Cracking Patterns

For specimens with 4mm diameter transverse reinforcement bars, the specimen with "A" configuration showed the earliest flexural crack formation at the eighth forward cycle. This was followed by "B" type and "C" type specimens, and both of them showed flexural cracks in the ninth reverse cycle. The C configuration showed the best ductile behaviour as the initial cracks only appeared at the eleventh forward cycle. Crack patterns of specimens with tie configurations "A", "B", "C" and "D" made with 4 mm diameter bars are shown in Fig. 17(a), Fig. 17(b), Fig. 17(c), and Fig. 17(d) respectively.

In specimens with 6 mm diameter bars, the specimens with A and D configuration developed flexural cracks at the ninth reverse cycle, whereas the specimens with B configuration and C configuration developed initial cracks during the tenth reverse cycle and twelfth reverse cycle respectively. Crack patterns of specimens with tie configurations "A", "B", "C" and "D" made with 6 mm diameter bars are shown in Fig. 18(a), Fig. 18(b), Fig. 18(c), and Fig. 18(d).

For specimens with 8 mm diameter bars, the specimen with "A" type configuration developed the earliest flexural cracks at the ninth reverse cycle on the front face, followed by the specimen with "D" configuration at the tenth forward cycle and "B" configuration at eleventh reverse cycle. Initial cracks were observed in the specimen with "C" configuration in the fourteenth forward cycle on the front face. Crack patterns of specimens with tie configurations "A", "B", "C" and "D" made with 8 mm diameter bars are shown in Fig. 19(a), Fig. 19(b), Fig. 19(c), and Fig. 19(d).

Minor cracks were observed for specimens with "C" configuration at higher loads compared with other configurations. This shows the more ductile behaviour of "C" configuration. The number of cracks was less in all the specimens. It may be due to the fibre content in the mix, which can arrest the crack propagation. Flexural mode of failure was observed in all the UHPC columns. All the specimens failed by the formation of major crack at the interface of column and footing.

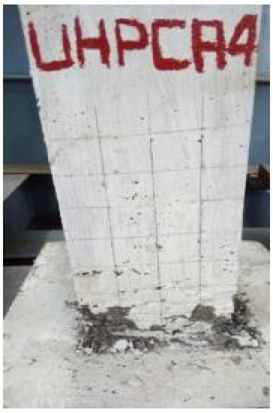

Fig. 17(a). Crack pattern of

Fig. 17(b). Crack pattern of

UHPCA4

UHPCB4

Fig. 17(c). Crack pattern of UHPCC4

Fig. 17(d). Crack pattern of UHPCD4

Fig. 18(a). Crack pattern of UHPCA6

Fig. 18(b). Crack pattern of UHPCB6

Fig. 18(c). Crack pattern of UHPCC6

Fig. 18(d). Crack pattern of UHPCD6

Fig. 19(a). Crack pattern of

Fig. 19(b). Crack pattern of

UHPCA8

Fig. 19(c). Crack pattern of UHPCC8

UHPCB8

Fig. 19(d). Crack pattern of UHPCD8

5. Conclusion

Based on experimental investigations on the behaviour of UHPC column subjected cyclic lateral loading, following conclusions are arrived:

i. The ultimate load of the column specimens having ties with inclined bars connected to two adjacent mid-points (C) with a percentage variation of 31.23% was the highest. For specimens having welded ties with bars running centrally across the length and width (B) and for ties with bars connecting two adjacent sides at one-third distances (D), the percentage variation was 22.66% and 12.8%, when compared with double legged ties (A).

ii. Relative ductility of columns having tie configurations of welded ties with bars running centrally across the length and width (B), with ties consisting of inclined bars connected to two adjacent mid-points (C) and for ties with bars connecting two adjacent sides at one-third distances (D) with respect to double legged tie (A) configuration are 1.11, 1.23 and 1.02.

iii. Considering the initial stiffness, columns with ties consisting of inclined bars connected to two adjacent mid-points (C) performed well. This configuration was followed by columns having welded ties with bars running centrally across the length and width (B). The initial stiffness of columns having ties with bars connecting two adjacent sides at one-third distances (D) was rated next.

iv. The flexural mode of failure was observed in all the UHPC columns, because of the ductile detailing of reinforcement and high performance concrete.

v. Ties with inclined bars connected to two adjacent mid-points (C) showed better performance in stiffness and ductility, when compared with other specimens. The specimen having welded ties with bars running centrally across the length and width (B) and specimen having ties with bars connecting two adjacent sides at one-third distances (D) showed better behaviour than the specimen with double legged ties (A). This variation in performance was due to the increase in transverse reinforcement content and effective core confinement.

vi. Transverse reinforcement ratio of the specimen having welded ties with bars running centrally across the length and width (B) and specimen having ties with of inclined bars connected to two adjacent mid-points (C) was less than that of the specimen having ties with bars connecting two adjacent sides at one-third distances (D). But the enhancements of properties of "B" and "C" configurations are better than "D" configuration. It was due to the effective core confinement of "B" and "C" configuration.

vii. For the same tie configuration ultimate load, initial stiffness and relative ductility of the specimen increase with an increase in transverse reinforcement ratio. Hence UHPC columns having ties with inclined bars connected to two adjacent mid-points (C) can effectively use in moderate and high seismic areas and its performance can be improved by increasing the transverse reinforcement ratio.

Disclosures

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