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BEHAVIOUR OF ULTRA HIGH PERFORMANCE CONCRETE SLENDER SHEAR WALL WITH DE-BONDED REINFORCEMENT SUBJECTED TO SEISMIC TYPE LOADING

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Abstract

In recent years, Ultra High-Performance Concrete (UHPC) has emerged as a superior construction material. Improved ductility characteristics and seismic performance of UHPC is an important feature for constructing columns and shear walls with high ductility demand. Continued lateral reverse cyclic loading during seismic events necessitate high ductility and energy dissipation demands on the structural components. The UHPC may consist various types of fibres including steel fibres. Control of crack propagation in UHPC due to the presence of fibres effectively makes it a desirable construction material. The present study proposes an innovative method to improve the performance of slender shear wall constructed using UHPC by de-bonding the main vertical reinforcement. The de-bonding of vertical steel reinforcement is enabled through the use of Reinforcement Restraining Collars (RRC) at possible location of formation of plastic hinge in the shear wall under seismic type loading. In this study quarter scale models of UHPC shear walls comprising of hook end steel fibres 0.75 % by volume and with detailing of reinforcement as per IS 13920:2016 were tested. The control specimen without RRCs and other specimens bearing 50mm, 75mm, and 90mm RRCs were prepared and tested under lateral reverse cyclic loading until failure. The studies revealed that the specimens with RRCs exhibit superior characteristics in terms of load displacement hysteresis behaviour, energy dissipation capacity, displacement ductility, stiffness degradation and crack pattern.

Keywords: Displacement ductility; De-bonded reinforcement; Slender shear wall; Ultra high-performance concrete.

1. Introduction

Reinforced concrete shear walls are widely used in places of high seismic risk as the main lateral load resisting system. They provide large lateral stiffness and hence lateral load resistance to the structure. Shear walls possess the capacity to control lateral drift and provide ductility to the structure based on its stiffness. In multi-story structures, shear walls support the multiple floors of the structure ensuring that they do not collapse as a result of lateral movements on seismic events. Shear wall constructed with high strength concretes is economically feasible and simple in the structural design. Ultra-high-performance concrete (UHPC) is an advanced technology in concrete having superior characteristics. It has high strength in compression and tension, ductility and durability. UHPC is a cementitious composite material composed of an optimized gradation of granular constituents having a water to cementitious materials ratio less than 0.25, and a percentage of discontinuous internal fibre reinforcement. It overcomes most shortcomings of normal concrete such as low density, low strength to weight ratio, low tensile strength, low ductility, and volume instability. It has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional and high-performance concretes. The improved flexural capacity and ductility of UHPC makes it a better choice for shear wall and it presents the opportunity to improve both structural efficiency and environmental sustainability. Under lateral cyclic loading, which is the usual loading sequence during seismic events, the main reinforcement bars are prone to reversible buckling and elongation sequences. Providing rebar restraining collars (RRCs) has emerged as a solution for premature buckling of main reinforcement. RRCs are steel tubes that cover the main reinforcement prone to buckling. The present study proposes a method to improve the seismic performance of UHPC shear walls using RRCs.

2. Related Research

2.1 Studies related to Ultra High-Performance Concrete

Ma et al. (2004) conducted comparative investigations on UHPC with and without coarse aggregates. Basalt splits of size 2 mm to 5 mm were used as the coarse aggregate. The UHPC containing coarse aggregate show a noticeable decrease in autogenous shrinkage which proved the risk of microcracks at an early stage. Al-Azzavi et al. (2011) conducted studies on the behaviour of UHPC structures with steel fibres by using two approaches: an experimental investigation of concrete mixes and simulation of the problem studied by other researchers using finite elements. An experimental investigation was carried out to obtain the mechanical properties for two types of UHPC mixes using the pozzolanic admixtures, silica fume and high reactivity metakaolin with different values of steel fibres volume fraction. Su et al. (2016) studied the effects of steel fibres on the dynamic strength of UHPC. Split-Hopkins-Pressure Bar test was used to find the dynamic properties. Varalakshmi and Adisheshu (2016) investigated the physical properties of high-performance concrete (HPC) using silica fume and fly ash as chemical admixtures along with glass fibres. They conducted tests for compressive strength, split tensile strength and flexural strength. Shafieifar et al. (2017) conducted studies on improved behaviour of UHPC compared to normal concrete through experimental as well as numerical study. Experimental tests include cylinder and cube compressive strength, flexural, briquette and splitting tensile strength. The numerical study was conducted using commercial software ABAQUS, and even in the absence of perfect boundary conditions, the numerical results were found in good agreement with the experimental results.

2.2 Studies Related to Behaviour of Shear walls and Debonding of Reinforcement

Zhang and Wang (2000) conducted experimental studies on the failure mechanism of slender shear walls subjected to high axial loading and lateral cyclic loading. The effect of axial load ratio on crack pattern, flexural strength, failure mode and ductility were studied. Mondal et al. (2014) carried out an analytical study to understand lateral load behaviour of squat walls for various aspect ratios and wall reinforcement ratios using ABAQUS software. Failure modes of squat walls were found to change with the percentage of steel in both directions. Hube et al. (2014) investigated the seismic behaviour of slender shear walls as that experienced in the 2010 Maule earthquake. The authors carried out experimental studies after reproducing similar walls. Constant axial loading and quasi static cyclic horizontal loading was applied. Effect of different wall thicknesses, different aspect ratios, vertical and horizontal reinforcement detailing etc. were studied. Gustavo and Kwang (2005) conducted experimental studies on low-rise or squat shear walls with high performance fibre reinforced cement concrete (HPFRCC). Ganesan et al. (2015) carried out quasi static lateral reversed cyclic loading tests on high performance cement concrete (HPC) slender shear walls with and without steel fibres. Dazio et al. (2015) carried out quasi- static and plastic hinge analysis on reinforced concrete structural walls to investigate the effect of different vertical reinforcement contents and different reinforcement ductility properties on the deformation behaviour, hysteric behaviour, failure mechanisms and crack patterns. The experimental results show the importance of reinforcement content and ductility properties of both the web and boundary reinforcement in the deformation behaviour of the walls. Ruangrassamee and Sawaroj (2012) studied the effectiveness of rebar restraining collars (RRC) in the main reinforcement of RC columns. RRCs were provided at plastic hinge locations for all main bars and reverse cyclic loading was applied along with constant axial load. Damage patterns, hysteric behaviour, displacement ductility and strain in steel etc. were observed. Mitra and Bindhu (2015) studied the performance of RC columns with debonded reinforcing bars subjected to cyclic lateral loading. The seismic resistance parameters were found improved for specimens having RRC compared to the normal specimen.

2.3 Research objectives

In the present study, an experimental investigation is carried out to analyse the behaviour of UHPC shear wall with rebar restraining collars at the plastic hinge region of vertical reinforcement subjected to quasi static reverse cyclic loading and to compare the behaviour with that of counterpart UHPC shear wall with conventional reinforcement. The study thus aims to analyse the influence of debonded bars on the performance of UHPC slender wall specimens subjected to quasi static reverse cyclic loading.

3. Experimental Programme

The experiment was conducted for the performance comparison of UHPC shear walls with debonded vertical reinforcement with that of UHPC shear walls with normal vertical reinforcement

3.1 Material Properties and Mix Proportions

The cement used was OPC 53 grade with standard consistency 31 % and 28-day compressive strength of 54.5 N/mm^2. The manufactured sand with specific gravity 2.81 and fineness modulus 2.93 was used as fine aggregate. The aggregate of maximum nominal size 12 mm with specific gravity 2.9 and fineness modulus of 7.7 was used as coarse aggregate. Silica fume of specific gravity 2.2 was also added to attain high strength to UHPC. In order to keep the water binder ratio low, the super plasticiser with a specific gravity of 1.11 was used. The steel fibres complying with the ASTM A820 M04 with a volume fraction of 0.75 % were used as fibres. Hook end loose steel fibres 30 mm long and 0.6 mm diameter with a tensile strength greater than 1100 MPa was used. In order to obtain a mix proportion for UHPC, the guidelines given by Aitcin (2004) which is a modified version of ACI 211.1 is used. The mix proportion for UHPC obtained was 1:0.112:1.643:2.077 with water cement ratio 0.293 and the superplasticizer dosage was 2.8 %.

3.2 Reinforcement details of specimens

The shear wall specimens were cast using the UHPC mix proportion obtained by the studies in section 3.1. The wall portion has a dimension of 1625 mm x 750 mm x 75 mm and the foundation block has a dimension of 1150 mm x 450 mm x 100 mm. The wall specimen is a quarter scale model of a slender shear wall having a dimension of 6500 mm x 3000 mm x 300 mm. Four specimens were cast out of which one was without rebar restraining collars for longitudinal bars and other specimens each with 50 mm, 75 mm and 90 mm long collars for vertical bars. RRCs used in this work were MS tubes of 8 mm inner diameter and 1 mm thick.

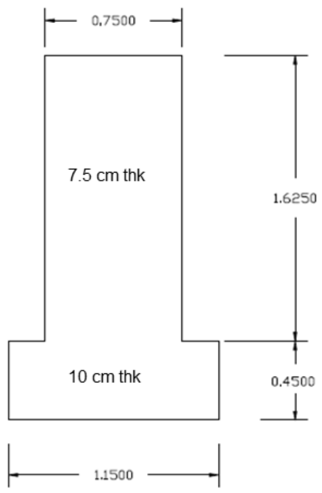

Fig. 1 – Specimen dimensions

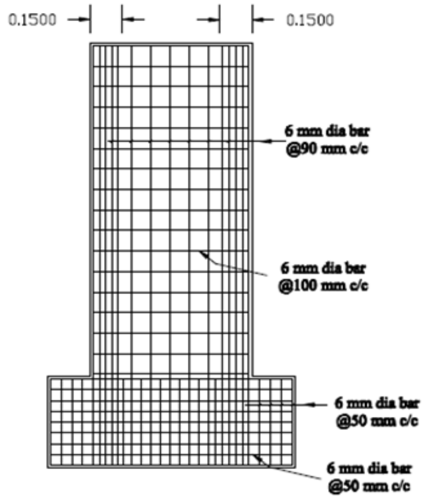

Fig. 2 – Reinforcement details of specimen

Table 1 – Specimen details

Designation of Specimen	Length of rebar restraining collar (mm)
USW1	Nil
USW2	50
USW3	75
USW4	90

Fig. 3 – Reinforcement cage for specimen without collars (USW1)

Fig. 4 – Reinforcement cage for specimen USW2

Fig. 5 – Reinforcement cage for specimen USW3

Fig. 6 – Reinforcement cage for specimen USW4

3.3 Experimental investigation of shear wall specimens

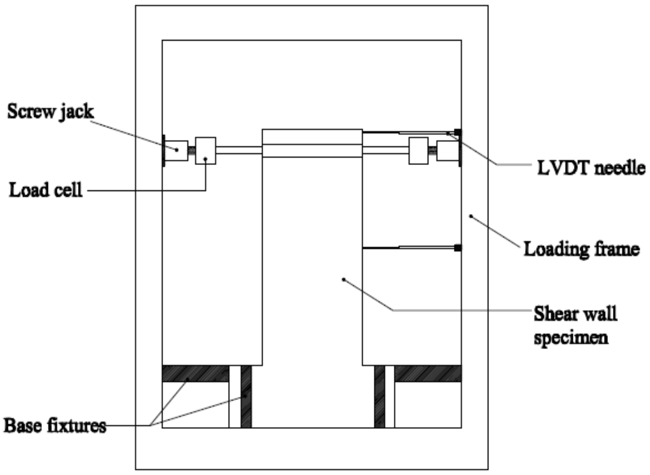

Fig. 7 – Schematic diagram of Experimental setup

Fig. 8 –Experimental setup in laboratory

A schematic diagram of the experimental setup is shown in Fig.7. The test setup provides boundary conditions similar to actual boundary conditions for a typical shear wall. Two screw jacks of 60 t capacity were used for lateral loading. LVDT needle was attached at the upper end of the wall near the loading position. The experimental setup in the laboratory is shown in the Fig.8. The specimens were subjected to lateral reverse cyclic loading until failure. Lateral displacement was applied as half rotation of screw jack and corresponding load and displacement were noted. First cycle consisted of one full rotation of screw jack in both forward and reverse directions and the procedure continued until failure. The graph showing displacement increments at load points for each cycle as per the screw jack rotations is shown in Fig. 9.

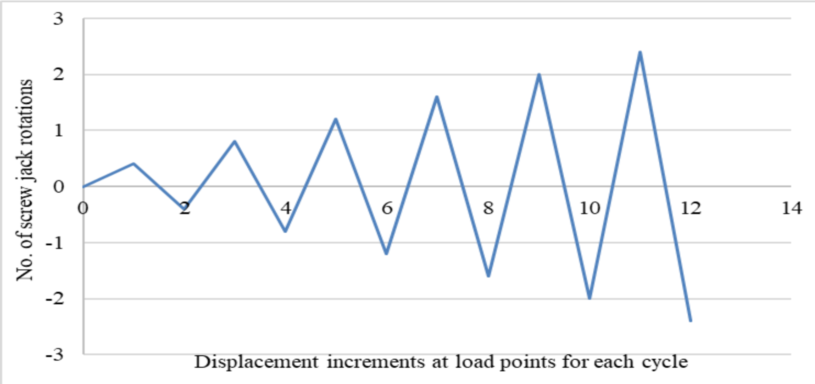

Fig. 9 –Displacement increments for each cycle as per the screw jack rotations

4. Discussion of test results

4.1 Load - displacement hysteresis behaviour

The structural behaviour of UHPC shear walls was elastic in nature up to the first crack. After the first crack stiffness degradation was noticed for each specimen showing increased deflection with respect to the applied load. The initial cycles are stiffer and after the initial crack, the curves become flatter as the displacement increases; giving more area in each curve showing the increasing energy dissipation. The load-displacement hysteresis loops of each specimen are shown in Fig. 10 to 13.

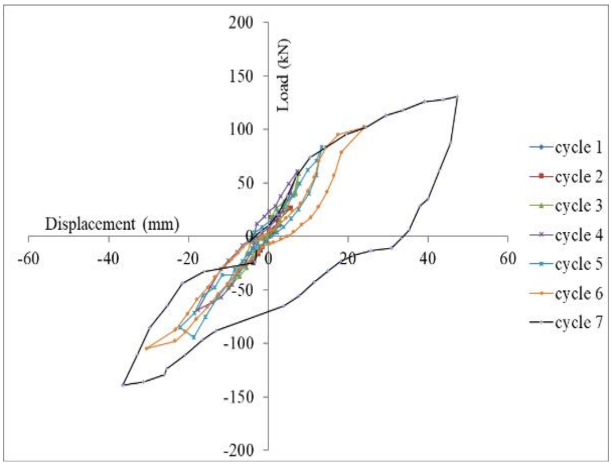

Fig. 10 –Load- displacement hysteresis curve of USW1

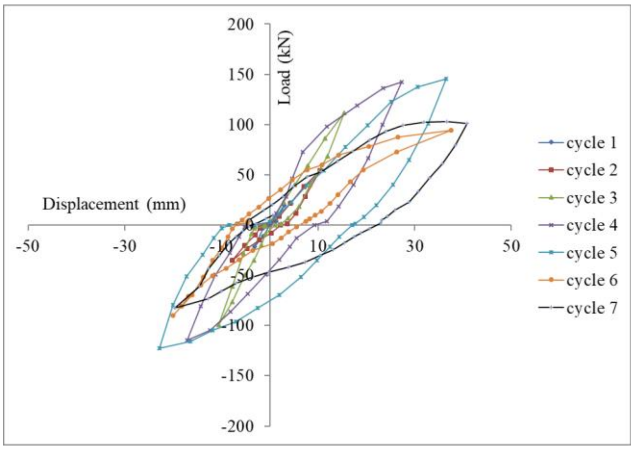

Fig. 11 –Load- displacement hysteresis curve of USW2

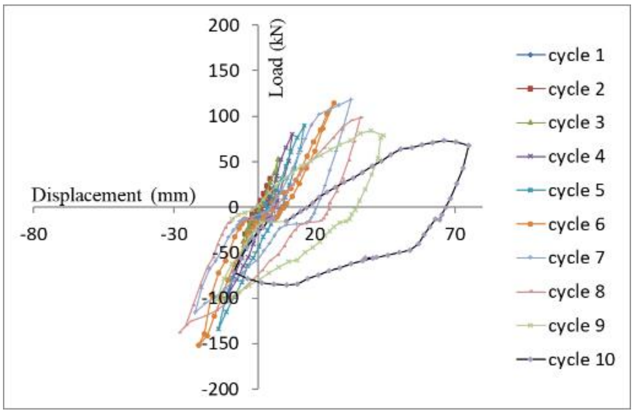

Fig. 12 –Load- displacement hysteresis curve of USW3

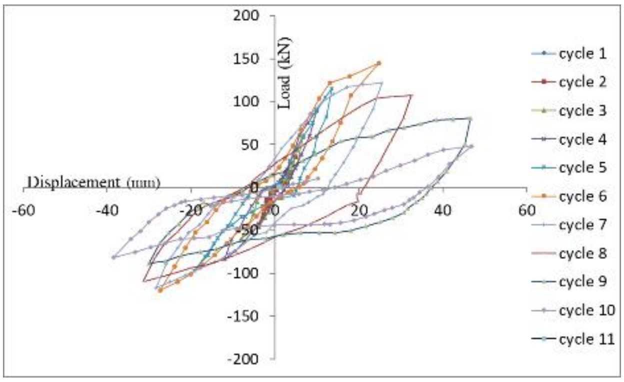

Fig. 13 –Load- displacement hysteresis curve of USW4

The largest area for the hysteresis loop is found for USW3 having a slight increase from that of USW4. The hysteresis loop area of USW2 is increased from that of USW1 by 5.35%. The area under hysteresis loop of USW3 and USW4 are larger than that of USW1 by 27.5% and 23.5% respectively

4.2 Load-Displacement Envelopes

The load-displacement envelopes were plotted with maximum load and displacement values in each half cycle of loading. The envelope plot for all specimens is shown in Fig. 14. The envelopes give a comparison of the specimen without RRC collars at the plastic hinge region and the specimens with RRC collars. The comparison in terms of deflection and corresponding load value show that specimens with RRC collars have superior characteristics compared to USW1. In the initial cycles the curves are linear. After cracking, the slope of the curve goes on decreases with decrease in stiffness. The post-yield deformation capacity is improved for the specimens with RRC collars.

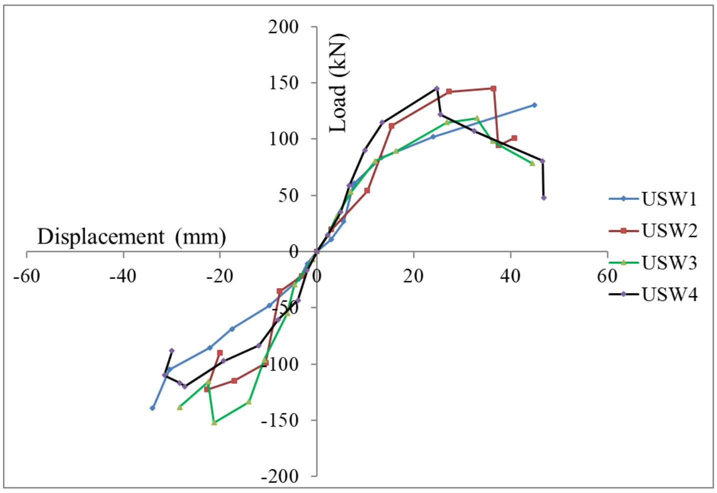

Fig. 14 –Load- displacement envelope curve for tested specimens

4.3 First Crack Load and Ultimate Load

The first crack load and the ultimate load for all specimens and corresponding displacement are shown in Table 2. It is evident from the Table 2, that the ultimate load carrying capacity is improved in specimens with RRCs for vertical reinforcement at the plastic hinge region.

Table 2 – First crack load and ultimate load of specimens

Specimen	First crack stage				Ultimate stage				Failure cycle
	Cycle	Load (kN)	Displacement (mm)	% increase in load	Cycle	Load (kN)	Displacement (mm)	% increase in load	
USW1	3	50	6	--	7	139.30	34	--	8
USW2	3	76.6	7.8	53.2	5	145.19	36.5	4.23	8
USW3	3	52.97	7	6	6	152.06	21.3	9.16	9
USW4	3	58.86	6.7	17.7	6	145.19	24.8	4.23	11

For the specimens with debonding collars, cracks widened slowly and the specimens underwent more number of cycles before failure compared to the specimen without RRC. The fibre bridging phenomenon in the UHPC matrix have contributed towards the increase in the ultimate load of each specimen and the specimens with RRCs have shown higher values of initial crack load as well as ultimate load. The increased first crack load and ultimate load carrying capacity of specimens with RRC indicate that RRCs have imparted increased flexural rigidity to the buckling prone longitudinal bars of USW2, USW3 and USW4 on experiencing compressive stress under lateral cyclic load and hence the premature buckling is resisted. Ultimate load carrying capacity of USW2, USW3 and USW4 are 4.23 %, 9.16 % and 4.23 % respectively higher than that of USW1 whereas the first crack load is 53.2 %, 6 % and 17.7 % higher respectively than USW1.

4.4 Stiffness degradation

The stiffness of wall specimens, when subjected to cyclic lateral load, decreases with the increasing loading cycle due to flexural cracking of concrete and flexural yielding of reinforcement. Table 3 shows the stiffness values of each specimen at each cycle. The stiffness in a particular cycle was calculated from the slope of the line joining peak values in each cycle. It can be observed that the stiffness decreases as the number of cycles increase. From the table 3, it can be seen that the initial stiffness of USW1 is lesser than that of other specimens. Also USW3 and USW4 have exhibited better stiffness characteristics compared to USW1 and USW2.

Table 3– Stiffness at each cycle

Cycle	Stiffness of specimen at each cycle			
	USW1	USW2	USW3	USW4
3	6.14	8.11	8.20	8.09
4	5.22	5.79	7.70	7.93
5	4.77	4.52	7.33	6.46
6	3.80	3.20	5.58	5.08
7	3.41	3.03	4.15	4.42
8			3.65	3.39
9			2.53	2.20
10			1.67	1.52

4.5 Energy Dissipation Capacity

The cumulative energy dissipation of each specimen at each cycle is given in Table 4.

Table 4 – Cumulative Energy Dissipation Capacity of each Specimen

Cycle	**Energy Dissipation Capacity (kNmm)**			
	USWI	**USW2**	**USW3**	**USW4**
3	123.48	469.23	132.09	237.59
4	543.87	3025.13	528.39	719.66
5	684.20	7395.88	1274.14	1326.36
6	1631.11	8888.23	2071.99	2114.94
7	8228.33	12475.95	5014.80	5601.51
8	15150.81	15961.29	8638.72	10174.49
9			12608.38	15701.98
10			19316.07	18710.61

From Table 4, it is observed that the cumulative energy dissipation capacity is highest for USW3, having a value 27.5 % greater than that of USW1. The specimen USW4 has the next higher value for energy dissipation capacity; 23.5 % greater than that of USW1. USW2 has a value of energy dissipation capacity 5.35 % higher than that of USW1. This comparison clearly shows that the debonding of main reinforcement using RRCs yields superior energy dissipation capacity to the shear wall under lateral cyclic loading.

4.6 Displacement Ductility

Table 5 – Displacement ductility of each Specimen

Specimen Designation	**Pu_{+ve}(kN)**	**$0.8Pu_{+ve}$(kN)**	**first crack load +ve(kN)**	**Δu_{+ve}(mm)**	**Δy_{+ve}(mm)**	**Pu_{-ve}(kN)**	**$0.8Pu_{-ve}$(kN)**	**first crack load -ve(kN)**	**Δu_{-ve}(mm)**	**Δy_{-ve}(mm)**	$\mu = \frac{\Delta u(\text{average})}{\Delta y\ (\text{average})}$
USW1	130.47	104.38	50	45	14.67	-139.30	-111.44	-68.67	-34	-28.56	1.83
USW2	145.19	116.15	86.32	37.07	17.42	-122.63	-98.1	-76.62	-22.8	-12.16	2.02
USW3	118.7	94.96	52.97	36.3	12.55	-152.06	-121.65	-54.94	-22.31	-13.59	2.24
USW4	145.19	116.15	58.86	28.11	13.24	-119.68	-95.74	-60.82	-30.52	-12.75	2.26

The ductility ratio (μ) for USW2, USW3 and USW4 are found higher than that of USW1 by 10.4 %, 22.4 % and 23.5 % respectively (table 5). This shows the superior ductile behaviour of the specimens with RRC compared to the specimen without RRC.

4.7 Crack Pattern and Failure Mode

All specimens show mostly similar crack pattern under lateral cyclic loading. Main cracks which lead to failure of the structure were horizontal flexural cracks at the bottom portion near to the interface of wall web and foundation. Horizontal cracks which initiated at earlier cycles got widened and successive widening was continued until failure of the structure. Along with horizontal flexural cracks, a series of inclined cracks were observed on the walls which were slowly widened against the direction of loading in each half cycle. Figs. 15 to 18 show the photographs of tested specimens USW1, USW2, USW3 and USW4, in which the cracks developed at the interface of wall and foundation horizontally. Hence the mode of failure of all specimens is flexural mode.

Fig. 15 –Crack Pattern for specimen USW1

Fig. 16 –Crack Pattern for specimen USW2

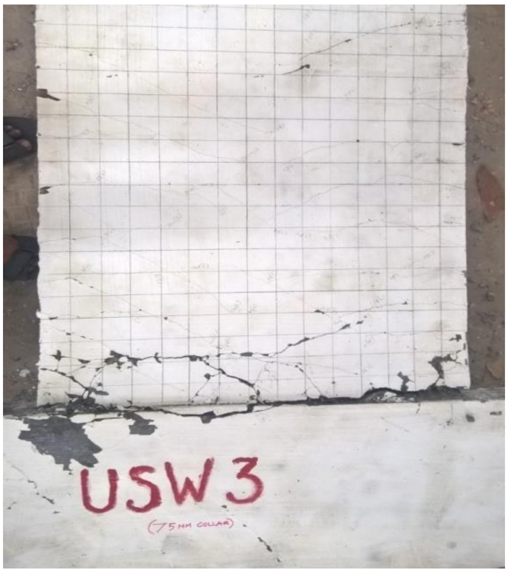

Fig. 17 –Crack Pattern for Specimen USW3

Fig. 18 –Crack Pattern for specimen USW

For all the specimens, it was observed that in the failure cycle, the outermost vertical reinforcement was broken followed by concrete crushing in the outer region.

5. Conclusion

From the comparative studies on UHPC shear walls with rebar restraining collars (RRCs) provided at possible plastic hinge region and UHPC shear walls without RRCs under lateral cyclic loading, the following conclusions are arrived. The shear wall specimens with RRCs have shown superior strength characteristics. The first crack load of specimens USW2, USW3 and USW4 are 53.2 %, 6 % and 17.7 % higher than that of control specimen USW1. Similarly, the ultimate load carrying capacity of specimens USW2, USW3 and USW4 are 4.23 %, 9.16 % and 4.23 % respectively higher than that of control specimen USW1. The higher value of first crack load as well as ultimate load value show that the rebar buckling and post rebar buckling characteristics of the specimens with RRCs are improved. The initial stiffness of USW1 was found lower than that of specimens with RRC collars. Stiffness degradation was found lower for USW3 and USW4 compared to USW1 and USW2.The specimens with RRC have shown superior ductility characteristics compared to the control specimen. The ductility ratio for USW2, USW3, USW4 are found higher than that of USW1 by 10.4 %, 22.4 % and 23.5 %. The shear wall specimens with RRCs have shown superior hysteresis characteristics. Hysteresis loops of specimens USW2, USW3 and USW4 cover more number of cycles with wider loops and having more energy dissipation than the control specimen. The cumulative energy dissipation capacity of specimens USW2, USW3 and USW4 are higher than that of USW1 by 5.35 %, 27.15 % and 23.5 %. All the shear wall specimens exhibited flexural failure mode. Along with the main horizontal crack at the bottom, a series of inclined cracks were observed on the web which was dense in USWI compared to the other specimens with RRCs. It is concluded that the UHPC shear walls with RRCs provided at plastic hinge location of vertical bars for debonding the vertical reinforcement from the concrete matrix are found to be superior in terms of first crack and ultimate load capacity, stiffness, ductility and energy dissipation capacity and shall be used in buildings in earthquake prone zones.

6. Acknowledgements

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