BEHAVIOR OF UHPC COLUMNS SUBJECTED TO COMBINED AXIAL AND LATERAL LOADING

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INTRODUCTION

Ultra High Performance Concrete (UHPC) is a versatile building material as it is characterized by very high compressive strengths reaching 200 MPa (30 ksi), ductile tensile characteristics, and energy absorption. However, this material is not widely used due to the lack of full understanding of the mechanical and structural behavior and its failure mechanism. Currently, UHPC is commonly used in limited-scale applications, such as joints and connections between precast structural elements. There is still a great potential for application of UHPC in full structural elements, e.g. slender and highly stressed compression members of high rise buildings, industrial buildings, and members with high durability requirements, e.g. bridge columns or structures in aggressive environmental conditions. This study aims at experimentally studying the seismic behavior of four UHPC columns. Four large-scale UHPC columns were tested under axial and quasi-static cyclic lateral loading at the Earthquake Engineering Laboratory at the University of Nevada, Reno. The experimented variables were the reinforcement bars grade, transverse reinforcement ratio and longitudinal reinforcement ratio. The lateral response of these columns is evaluated for damage progression, failure type, peak strength, displacement ductility and steel reinforcement strains. To establish a comparison with conventional columns with grade 60 bars, a normal strength concrete (NSC) column with same dimensions and design as the tested UHPC column is analytically modeled and analyzed under similar loading protocol using OpenSEES. The experimental response of the UHPC column is evaluated and compared to the analytical response of the NSC column with respect to their Force-Drift and Moment-Curvature relationships.

METHODS

To accomplish the objectives of this study, Four UHPC column of the same dimensions and could be considered a 1/5 scale of NSC column used in the California department of transportation Academy Bridge. The specimens' dimensions, as shown in Figure 1, were 58 in and 10 in for the height and the diameter, respectively. The test matrix is shown in Table 1. The test matrix consists of two groups. The first group consists of an analytically investigated NSC column and an experimentally tested UHPC column reinforced with Grade 60 longitudinal bars, this group was intended to mainly investigate the difference in the damage behavior and flexural capacity between the UHPC and NSC column. The second group consisted of three UHPC columns reinforced with Grade 100 high strength steel (HSS) longitudinal rebars of different longitudinal and transverse steel ratios. The variation within this group aimed to investigate the difference in behavior between the Grade 100 and Grade 60 reinforced UHPC columns and to investigate the effect of confinement effect and longitudinal steel ratio. The footing was designed to be capacity protected and consisted of two parts: an UHPC inner part connected to the UHPC column to ensure the continuity of UHPC in the plastic hinge region, and a NSC footing. The plan dimensions were 2×2 ft2 for UHPC and external dimensions of 5×5 ft2 for NSC and both parts were 14 in. deep as illustrated in Figure 1. A cantilever configuration setup was used to test the column as shown in Figure 2. Displacement-controlled slow cyclic loading was applied to the column using a 110-kip servo-hydraulic actuator and the cyclic loading protocol was adopted from FEMA 461 (FEMA 2007) is used where every applied drift cycle is a ratio of the column drift ratio at which the first longitudinal rebar yield. Two full cycles were applied at drift ratios of 0.17%, 0.24%, 0.34%, 0.48%, 0.69%, 0.97%, 1.38%, 1.93%, 2.76%, 3.86%, 5.52%, 7.72% and 10.83% to capture the seismic response of the columns under different levels of drift ratios for different limit states including failure. Figure 3 shows a typical damage for the tested UHPC column at the maximum drift ratio cycle causing column failure. Figure 4 shows the measured hysteresis loops for the UHPC column and the NSC column reinforced with grade 60 longitudinal bars.

From the experimental study, the observed mode of failure for all the UHPC columns was the tensile fracture of longitudinal bars without any cover spalling, longitudinal bars exposure or buckling. The UHPC columns showed adequate ductile response. the drift capacities of the experimented specimens, which is defined to be the lesser of the ultimate drift ratio and the measured drift ratio after 20% drop of the maximum lateral load capacity, were 9.62%, 10.84%, 8.34%, 7.72% and 7.43% for specimens S0, S1, S2, S3 and S4, respectively. Figure 5 shows the average backbone curves for the push and pull directions for specimens S0 through S4. Table 2 shows the average lateral load and drift capacities of the experimented specimens. The UHPC column with grade 60 longitudinal bars showed a lateral load capacity of 2.15 times that of NSC column. UHPC column with Grade 100 longitudinal bars instead of Grade 60 bars showed 25% increase in the lateral load capacity of the column but experienced 23% decrease in the drift capacity. Decreasing the UHPC column confinement by decreasing the transverse reinforcement ratio by 50% has led to an insignificant decrease of only 4% in the lateral load capacity of the column and 7% decrease in the drift capacity. The UHPC column with 1.5% longitudinal steel ratio of Grade 100 bars was observed to have almost the same lateral load capacity as the UHPC column with 2.4% longitudinal steel ratio of Grade 60 bars, but with almost 30% decrease in the drift capacity.

CONCLUSIONS

Based on the experimental testing of the UHPC columns and the analytical investigation of the NSC column, the results indicted the following conclusions:

- For the large-scale column tests, the main observed mode of failure for all tested UHPC columns was tensile rupture of the longitudinal rebars without concrete spalling, core damage, reinforcement exposure, or buckling as in a typical NSC column plastic hinge.
- In all of the tested UHPC columns, no cracks were observed until the columns reached 1% drift ratio. Concrete crushing in compression was ultimately observed at large drift ratios but without leading to any significant spalling or loss of the concrete section.
- The UHPC column with Grade 60 rebars showed an adequate ductile behavior with the displacement and curvature ductility found to be 8.4 and 15.4, respectively. These values are comparable to well-designed conventional reinforced concrete seismic columns in high seismic areas.
- In all of the tested UHPC columns, the measured strains in the transverse reinforcement within the plastic hinge region were found to be smaller than 0.1% which indicates insignificant activation of the confinement in the UHPC columns under the combined 5% axial and lateral cyclic loading.
- Overall, the use of UHPC of compressive strength that is almost 6 times that of NSC in addition to superior tensile behavior that results from using 2% steel fibers can lead to an 115% increase in the lateral load capacity and 11% increase in drift or displacement capacity.
- Using Gr 100 HSS rebars instead of Gr 60 rebars with the same longitudinal reinforcement ratio can lead to a 25% increase in the lateral load capacity. This increase when combined with the effect of using UHPC instead of NSC can result in more than double the capacity, which sets the stage for new design opportunities for compact bridge columns.
- Decreasing the transverse reinforcement ratio by half in the UHPC columns resulted in only 4% decrease in the lateral load capacity and 8% decrease in the maximum drift ratio. This confirms that confinement effects in UHPC columns under combined axial and bending might not be as pronounced as the cases of pure axial or applications of high axial loads.

Table 1: Test Matrix

Specimen		Longitudinal Reinforcement		Transverse Reinforcement		Tested Variable	Type of Testing
		#	$\%A_g$	#	$\%A_g$		
Group I (Gr. 60)	S0	6#5	2.37%	#3@2in	1.1%	NSC	Analytical
	S1	6#5	2.37%	#3@2in	1.1%	UHPC vs NSC	Experimental
Group II (Gr. 100)*	S2	6#5	2.37%	#3@2in	1.1%	Gr 100 vs Gr 60	Experimental
	S3	6#5	2.37%	#3@4in	0.55%	Low confinement	Experimental
	S4	6#4	1.53%	#3@2in	1.1%	Low long. steel ratio	Experimental

* Gr. 100 is for the Longitudinal reinforcement only in Group II specimens.

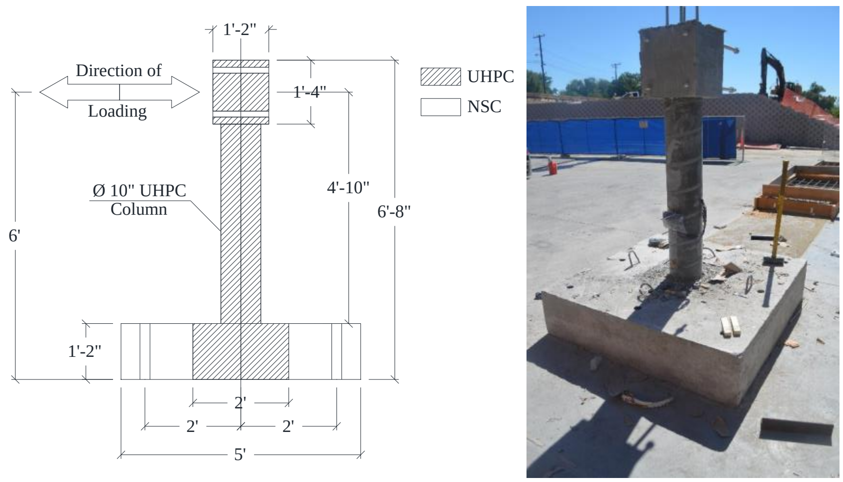

Figure 1: Experimental tested UHPC column dimensions.

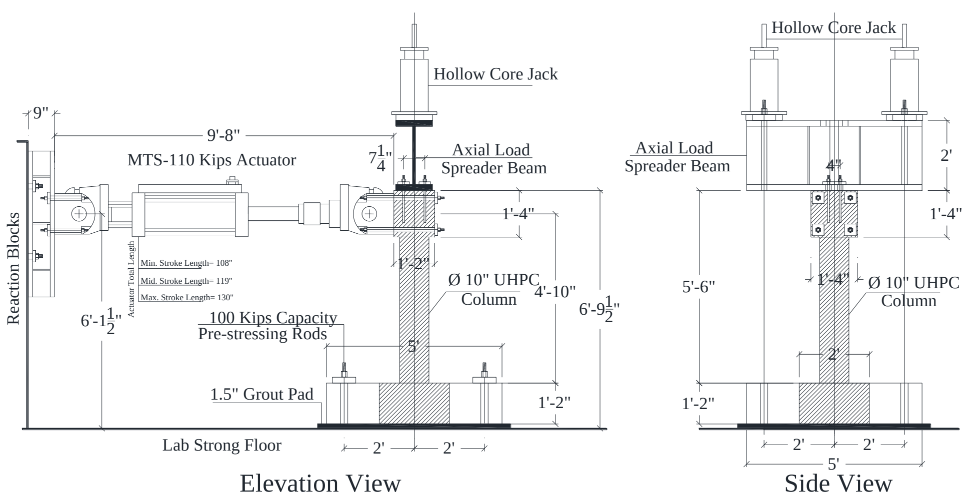

Figure 2: Test Setup for UHPC column under combined axial and bending.

Figure 3: Damage state of UHPC column at 10.83% drift ratio cycle.

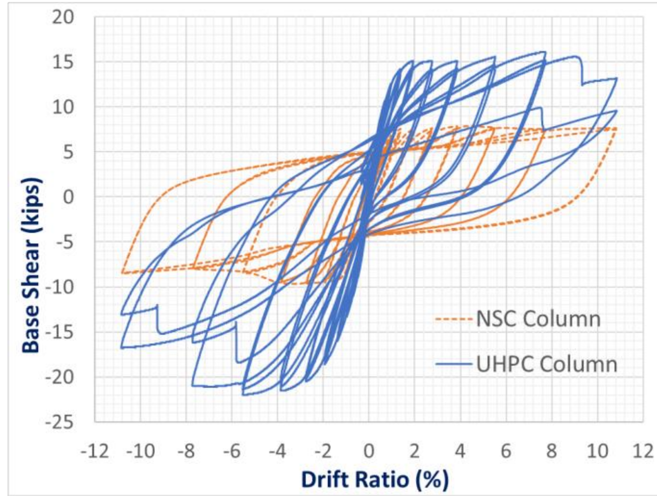

Figure 4: Force-drift hysteretic response of UHPC versus NSC columns.

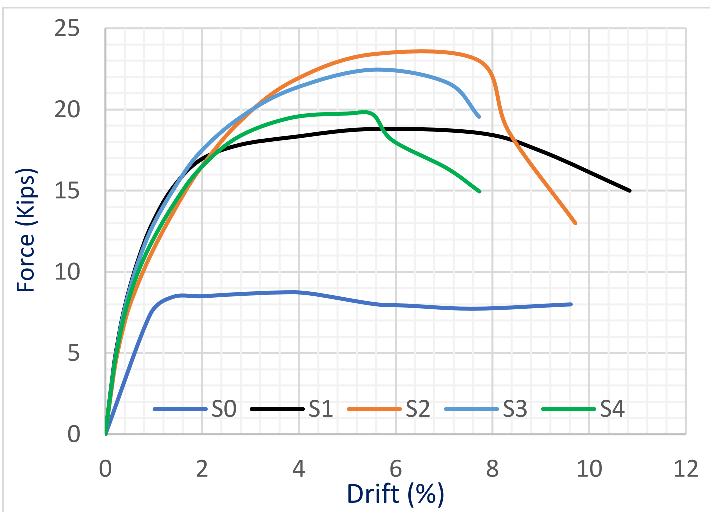

Figure 5: Average force-drift backbone envelopes.

Table 2: Test results summary

	P_{max} (kips)	Drift Capacity (%)
S0	10.44	9.62
S1	18.80	10.83
S2	23.40	8.34
S3	22.45	7.72
S4	19.75	7.43

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