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Seismic performance of reinforced concrete filled steel tube drilled shafts with inground plastic hinges

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ABSTRACT

The seismic performance of reinforced concrete-filled steel tube (RCFST) drilled shafts, also known as RCFST pile-columns, was examined based on experimental tests conducted on twelve half-scale RCFST specimens at the soil-structure interaction facility at the North Carolina State University, Constructed Facilities Laboratory (NCSU-CFL). The specimens consisted of steel tubes with diameter-to-thickness (D/t) ratios ranging from 48 to 95 that were filled with reinforced concrete. Spirally welded steel tubes with outer diameters (D) of 12″ (305 mm) and 12–3/4″ (324 mm) were utilized. The specimens were tested with aboveground-to-diameter (L_a/D) ratios of 5.5 and 7.5, and they were embedded 14′ (4270 mm) into poorly graded sand (SP). Different levels of soil stiffness were induced in the sand by using a soil-sandwich approach, which allowed for modifying the soil stiffness profile by means of applying a surcharge on the soil surface. Cyclic lateral load was applied by a 100-kip (445 kN), 70-in. (1780 mm) stroke hydraulic actuator, supported on a braced steel frame, and pin-connected to the pile-column head ensuring that the plastic hinge developed below ground. The failure mechanism was controlled by the tensile strain in the steel tube and it was caused by a combination of tube local buckling and tube fracture. First, tube local buckling developed outward at the extreme compression fiber of the section. Tube fracture then occurred in the section with the largest buckle and it extended around about half of the section perimeter. The plastic hinge developed at depths of 2D to 4D. Onset of tube local buckling was observed at higher displacement ductility levels ($\mu = 3$) for specimens using thicker tubes (D/t = 48) than for those using thinner tubes (D/t = 95). The force-displacement response, tensile strain distribution, and hysteretic equivalent viscous damping are discussed in this paper.

1. Introduction

1.1. Background

Reinforced concrete-filled steel tube (RCFST) drilled shafts, also known as RCFST pile-columns, are commonly used for bridge pier construction in regions of high seismic activity. These foundation systems have been shown to provide better performance, in terms of strength and ductility capacity under lateral loading, when compared with traditional systems (e.g., reinforced concrete or steel bridge piers). This system consists of a steel tube filled with concrete and internal reinforcing steel (longitudinal and transverse). RCFSTs offer several benefits, the most important of which are: (1) the shaft serves as a foundation element below the soil surface (pile), and continues as a column aboveground; (2) the steel tube serves as formwork, simplifying construction; and (3) the steel tube provides high levels of confinement, increasing the strength and ductility capacity of the system. Under lateral loads, these elements can experience single or double bending. In the former a single plastic hinge forms below ground, while in the latter two plastic hinges may develop, that is, one at the top at the column-cap beam interface and another one below ground. This study considers RCFST drilled shafts where the plastic hinge develops below ground, and the flexural strength is provided by the steel tube and reinforced core acting as a composite section.

1.2. Past research

Past research efforts have shown that RCFSTs can sustain large inelastic deformations while maintaining strength. The diameter-to-thickness (D/t) ratio influences the strength, tube local buckling, and energy dissipation of the system. Moreover, the internal reinforcing steel impacts the flexural strength but does not affect the overall behavior of RCFST elements. The failure mode is characterized by outward buckling of the steel tube ultimately resulting in tube fracture. This behavior has been established by performing experimental tests conducted in air, that is, either fixed-base cantilever columns or four-

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point bending tests, where RCFST elements are subjected to reversed cyclic loading, most of which are performed on concrete-filled steel tube (CFST) and some on RCFST specimens (e.g., [1–5]).

To the knowledge of the authors, there is no experimental research available regarding RCFSTs where soil-structure interaction and the effects of soil stiffness on the performance of this system are evaluated. Although references directly related to the topic of this research are not available in the literature, there has been substantial research conducted on conventional reinforced concrete (RC) pile columns (e.g., [6–8]).

Chai and Hutchinson [7], for example, conducted four full-scale tests on RC bridge pile-columns embedded in soil, which were subjected to axial load and cyclic lateral loading. They considered two different soil conditions, that is, loose and dense poorly graded sand (SP). The test soil was compacted using a different process in each case, resulting in different soil properties and thus different soil stiffness levels. Their study focused on three key parameters: (1) force-displacement response of the soil-pile-column system; (2) location of the maximum moment below ground; and (3) plastic hinge length. They found that the force-displacement response was dominated by the flexural strength of the pile and thus the stiffness of the soil-pile-column system was not sensitive to the change in density of the soil conditions under consideration. They concluded that the inground plastic hinge is mostly impacted by the aboveground height of the column, that is, the extent of plastic action is longer for taller columns as the moment gradient decreases for such cases. The location of maximum moment varied between twice and three times the pile diameter below the soil surface, and it was shallower for longer columns. They also concluded that the depth to maximum moment was not sensitive to the different soil densities they studied.

Another relevant study was completed in 2015 by Brown et al. [1]. The purpose of the study was to assess the impact of the D/t ratio on the strain limit states of tube local buckling and fracture. As such, they conducted four-point bending experimental tests on twelve RCFST piles with outer diameters of 20″ (508 mm) to 24″ (610 mm) and thickness values such that (D/t) ratios within 33 and 192 were considered. In addition, they addressed the equivalent viscous damping and provided insight on issues of confinement and analysis methods for RCFST members. Regarding the variation on the D/t ratio, they concluded that energy dissipation is greater for specimens with smaller D/t ratios (i.e., those with thicker tubes). Also, they concluded that early onset of tube local buckling does not affect the strain limit of tube fracture for tubes with larger D/t ratios (thin tubes), as they reached the same ductility level as the thicker tubes (smaller D/t ratios). Moreover, they concluded that only the flexural strength is affected by the amount of longitudinal internal reinforcement, which means that strain limit states are governed by tensile strains in the steel tube. They also developed an expression for the tensile strain prior to onset of tube local buckling and suggested a value of 2.5% for the tensile strain at tube fracture. The latter is consistent and further validates experimental observations of other authors (i.e., [3,5]). Lastly, and based on experimental and analytical studies, they showed that the Mander et al. model [9] can be used to characterize the stress-strain behavior of confined concrete in RCFST members. They suggested that strain compatibility and equilibrium apply up to the onset of tube local buckling, which enables the use of a linear strain profile for moment-curvature analyses; Brown et al. [1] argued that even beyond tube local buckling they observed results in good agreement with the experimental data.

1.3. Scope and layout

The goal of the research described herein is to study the effect that the relative soil-structure stiffness has on the lateral performance of RCFST pile-columns. For that purpose, the results of an experimental program along with a discussion are presented to provide insight into the seismic performance of RCFST drilled shafts. As such, this article elaborates on the failure mechanism, force vs. displacement response, strain limit states, equivalent viscous damping (EVD), and the impact of soil stiffness. The article is organized as follows: first, details of the experimental program are described in Section 2. Then, Section 3 presents experimental observations and discussion of results. Lastly, conclusions are presented in Section 4.

2. Experimental program

Twelve half-scale experimental tests were conducted on pinned-head RCFST shafts embedded in soil under reversed cyclic loading in the soil-structure interaction facility at the North Carolina State University, Constructed Facilities Laboratory (NCSU-CFL). The main variables studied were the diameter-to-thickness (D/t) ratio, soil stiffness, and aboveground length-to-diameter (L_a/D) ratio. The internal reinforcement (longitudinal and transverse) was kept constant as past research has shown that it only increases the flexural strength without modifying the ultimate limit state [1]. Different soil stiffness levels were achieved by applying a surcharge loading on the soil surface as explained in subsequent sections.

The experimental program was divided into three phases, each one of which consisted of experimental testing of four RCFST specimens. The main testing parameters are summarized in Table 1. The symbol "⁎" in Table 1, next to the values corresponding to a D/t ratio of 95, represents a particular feature observed from Test 3 and Test 4. Upon further examination of the inside of the spirally welded tubes, it was determined that the thin wall tubes which made up Test 3 and Test 4 were not welded along the inside surface. It will be shown in

Table 1
Experimental test matrix.

Test no.	Diameter		Nominal thickness		D/t ratio	Soil surcharge		Aboveground height	
	mm	(in)	mm	(in)		kPa	(ksf)	m	(ft)
1	305	(12.00)	6.35	(0.250)	48	None	None	1.68	(5.50)
2	305	(12.00)	6.35	(0.250)	48	46.1	(0.96)	1.78	(5.83)
3	324	(12.75)	3.42	(0.135)	95*	None	None	1.68	(5.50)
4	324	(12.75)	3.42	(0.135)	95*	46.1	(0.96)	1.68	(5.50)
5	324	(12.75)	3.42	(0.135)	95	None	None	1.73	(5.69)
6	324	(12.75)	3.42	(0.135)	95	46.1	(0.96)	1.79	(5.88)
7	324	(12.75)	4.76	(0.188)	68	None	None	1.76	(5.77)
8	324	(12.75)	4.76	(0.188)	68	46.1	(0.96)	1.76	(5.77)
9	305	(12.00)	6.35	(0.250)	48	46.1	(0.96)	1.75	(5.75)
10	305	(12.00)	6.35	(0.250)	48	92.1	(1.92)	2.36	(7.75)
11	324	(12.75)	3.42	(0.135)	95	92.1	(1.92)	2.36	(7.75)
12	324	(12.75)	4.76	(0.188)	68	92.1	(1.92)	2.36	(7.75)

* Particular feature observed on spirally welded tubes.