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Seismic performance of self-consolidating concrete bridge columns

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ABSTRACT

The high amount of confining lateral steel required by seismic design provisions for rectangular bridge columns can cause steel congestion which may hinder the placement of conventional concrete (CC). Self-consolidating concrete (SCC) eliminates or reduces concrete placement and consolidation issues; however, there is limited data on the seismic performance of SCC bridge columns. This study encompassed experimental investigations to assess the stress-strain relationships of SCC mixes and the seismic performance of rectangular SCC bridge columns. SCC and CC rectangular columns were tested. Experimental results showed that the strain at strength and the ultimate strain of SCC are higher than those of CC, while concrete ductility and the elastic modulus of SCC are lower than those of CC. Experimental results of the column tests showed that the use of SCC reduces displacement ductility and energy dissipation but increases drift ratio at failure. The SCC column performance under inelastic cyclic lateral loading was found to be satisfactory and comparable to that of CC columns.

1. Introduction

Self-consolidating concrete (SCC) is a type of concrete that fills formwork and encompasses steel reinforcement in its fresh state under its own weight without the need for mechanical vibration while still maintaining a homogeneous composition [1]. In typical concrete construction, conventional concrete (CC) requires the use of an external means of mechanical vibration in order to fully consolidate during placement and to ensure that the formwork is thoroughly filled without excessive voids. This is especially important in structural applications to ensure that steel reinforcement is completely embedded in concrete.

SCC was developed in Japan in the late 1980s in response to the diminishing durability and overall quality of concrete structures due to a decrease in the availability of skilled workers needed to place concrete that meets code requirements [2]. Since SCC does not require mechanical vibration, it reduces the number of necessary workers and speeds up concrete placement, reducing the overall labor cost on projects. Additionally, SCC ensures peace-of-mind knowing that steel reinforcement in the structure is fully embedded in concrete, and that the appearance of the structure will be satisfactory following formwork removal. SCC eliminates voids on the surface known as "bug-holes" or "honeycombing," a problem common in some structures constructed with improperly consolidated CC. These surfaces require subsequent patching or grouting.

In seismic design of reinforced concrete structures, column critical sections, known as plastic hinges, are detailed for inelastic flexural response in order to dissipate energy from earthquakes. A column's ability to undergo large deformation past its elastic limit and still maintain a large portion of its initial strength is known as ductility [3]. Increased column ductility is required in seismic regions in order to prevent bridge failures and maintain functionality of roadways [4]. In columns designed for moment connections at the footing and bent-cap, plastic hinge regions are located above the column-footing interface and below the column-bent-cap interface. Column transverse confinement steel in these regions is vital in attaining ductile response. Confinement steel prevents premature buckling of compression bars, confines compressed concrete cores, provides clamping of lap-splices, and resists shear forces from lateral loads [3]. In order to provide required ductility in the plastic hinge regions of reinforced concrete columns in seismic regions, design codes specify a minimum amount of confinement steel reinforcement. These design codes include the American Concrete Institute (ACI) Building Code Requirements for Structural Concrete [5], the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications [6], and the American Association of State Highway and Transportation Officials (AASHTO) Guide Specifications for LRFD Seismic Bridge Design [7]. Increased amounts of reinforcement in seismic regions can lead to excessive steel congestion. Consequently, SCC would be an ideal alternative to CC in these applications due to its fresh properties.

Similar to other physical properties of SCC, the elastic modulus is highly dependent on the mixture constituents. Some studies have shown that the elastic modulus is lower for SCC compared to CC of similar compressive strength [8–10], whereas others have shown that the elastic modulus is very similar to that of CC [11,12].

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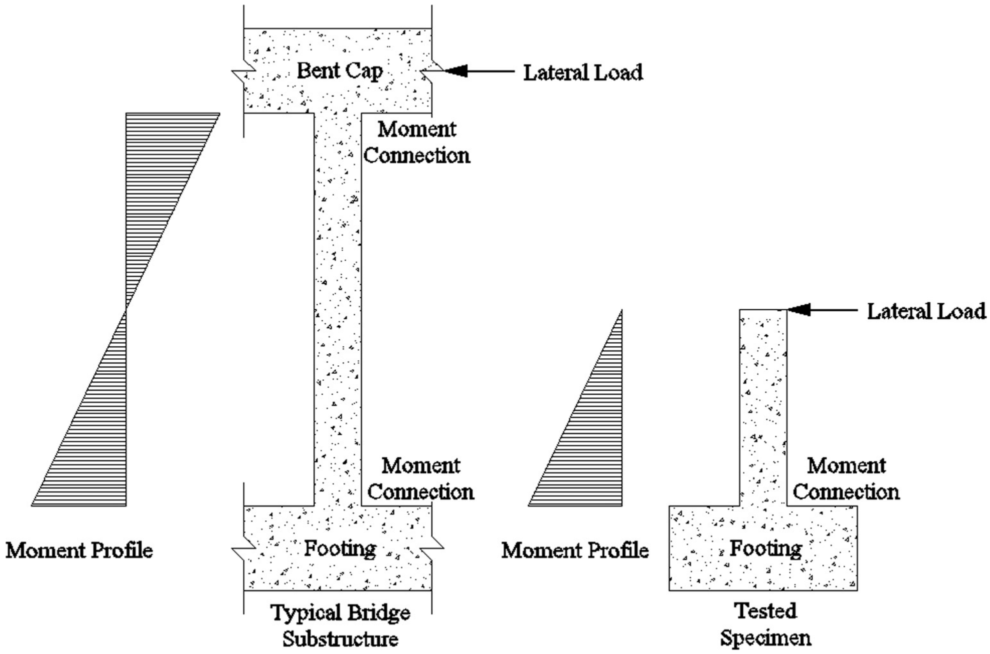

Fig. 1. Typical multi-column bridge bent compared to the tested columns.

While there have been many research studies conducted regarding SCC material properties, few have focused on the structural performance of SCC columns, and even fewer have investigated the structural performance of SCC columns under seismic loads. Restrepo et al. [13] investigated the seismic performance of reinforced concrete bridge columns constructed with high performance steel and concrete. The objectives of the study were to compare the performance of a column reinforced with high strength steel to that of a column reinforced with conventional ASTM A 706 steel, and also to examine the effect that incorporating SCC in both columns had on their performance. Results indicated that the use of SCC had no overall effect on column performance (Restrepo et al. [13]). However, this study did not compare the results of SCC columns to CC columns as the main purpose of it was to compare the performance of different steel types.

Said and Nehdi [14] studied the seismic behavior of full-scale structural frame column-joint connections. The objective of the study was to compare the behavior of a beam-column joint constructed with SCC and subjected to reverse cyclic loading to a joint subjected to the same loading conditions but constructed with CC. Results indicated that each specimen exhibited similar performance until a drift of approximately 4.5%, after which the load-carrying capacity of the SCC specimen deteriorated rapidly. Overall, the CC specimen attained a displacement ductility and drift of 6.0% and 9.0%, respectively, whereas the SCC specimen attained a displacement ductility of 5.0 and a drift ratio of 7.9%. Additionally, joint energy dissipation of the CC specimen, defined as the cumulative area between load-displacement curves, exceeded that of the SCC specimen by 38%. Overall, the researchers concluded that SCC beam-column joints may not have the same load-carrying capacity under extreme seismic conditions as CC joints. They believed that the reduction in coarse aggregate content in SCC reduced its contribution to shear resistance compared to CC. They recommended that more studies are needed to investigate the behavior of SCC in plastic hinge regions under seismic loads, with emphasis placed on the effect of varying coarse aggregate sizes and amounts [14].

The motivation behind this research comes from the fact that no previous studies were conducted to compare the seismic performance of SCC to CC for bridge columns. There are three main reasons why there could be significant difference in performance. The composition of SCC is typically very different compared to CC since it usually contains fine fillers and smaller-sized aggregates. Previous studies showed some differences in the stress-strain curve between SCC and CC which indicates that the stress-strain curve under dynamic loading could also be different. Some studies on structural elements other than bridge columns, such as the aforementioned one conducted by Said and Nehdi [14], found significant differences between SCC and CC.

Two main objectives were addressed during the course of this study. The first objective was to evaluate the stress-strain relationship of SCC and compare it to CC under uniaxial compression. The second objective was to evaluate the ductility of reinforced SCC bridge columns under combined axial and reverse cyclic lateral loads and compare it to CC bridge columns.

2. Methodology

Four 12 in. (304.75 mm) × 12 in. (304.75 mm) bridge columns were designed, constructed, and tested in the J. Lohr Structures Laboratory at South Dakota State University for this study. Two parameters were varied: the type of concrete used, and the axial load level. Two of the columns were constructed with SCC and the other two with CC. Within each concrete group, an axial load index of 7.5% was applied to one column, while the other was subjected to 15% axial load index. Specimens subjected to 7.5% axial load index were labeled CC1 and SCC1, while specimens subjected to 15% axial load index were labeled CC2 and SCC2. Axial load index is defined as the axial load divided by the product of the concrete compressive strength and the gross cross-sectional area of the column. The selected axial loads are typical in bridge columns.

2.1. Design of specimens

Test specimens were designed to represent approximately one-third scale models of bridge columns. The columns were supported by rectangular footings which transferred the applied axial load to the floor of the laboratory. Columns were considered fixed at the footing and free at the top where the lateral load was applied. The location of lateral load application represented an inflection point of a column with moment connection at both ends. This test setup produces a moment profile representative of one-half of a column with moment connections in the footing and bent cap. A representation of this is shown in Fig. 1. The moment profile that a column of a bridge would develop under seismic loads is shown on the left side of the figure, and the scaled column and experimental loading setup is shown on the right side of the figure.