Shake Table Testing of a Damage-Resistant Segmental Double Skin Bridge Column with Self Centering Capability

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ABSTRACT: Under an extreme ground motion, the flexural capacity of a well designed RC column deteriorates due to crushing of core concrete and buckling of longitudinal bars. Hence, the need for developing new cross sections and systems for seismic applications is evident. This paper presents the shake-table test of a proposed damage-resistant segmental double skin bridge column with post-tensioned unbounded strands running through the segments and providing the interface between the segments. The new cross section is a double skin section composed of an outside glass fiber reinforced polymer tube, an inside steel tube, and concrete cast in between the two. The column has the advantages of accelerated bridge construction and self centering due to rocking. The column was subjected to a sequence of scaled near-fault pulse-like ground motion. The column sustained no noticeable damage and the accumulated residual drift was only 0.03% after the sequence of motions up to 250% design earthquake, which caused a peak drift ratio of 8.25%.

1 INTRODUCTION

With the current capacity design concepts, severe damage is often observed in bridges following major earthquakes even for the correctly designed and detailed reinforced concrete (RC) structures. Capacity design concepts allow inelastic response to occur in predefined locations in a structure which leads to structural damage and permanent residual drifts. Essential bridges, post-earthquakes, need to be restored to operation as quickly as possible to avoid any service interruption especially for emergency vehicles. Moreover, repairing RC bridge columns is costly and time consuming.

Severe damage can occur in RC columns especially when subjected to near-fault pulse-like ground motions. They also experience large displacements and residual drifts [Gibson et al. (2002); Phan et al. (2007)]. Severe damage in RC columns in Japan after the 1995 Kobe earthquake was observed and more than 100 RC bridges had to be demolished [Jeong et al. (2008)]. Residual drifts up to 2% were the main reason for demolishing the bridges and they were defined as non-functional as it was difficult to retrieve those residual drifts. Therefore, the new Japanese seismic design specifications are limiting the residual drifts of columns to 1% [Japan Road Association (2002)].

Recently, a segmental precast post-tensioned column system consisting of precast segments stacked over each other and connected by unbonded post-tensioning bars was developed [Chang et al. (2002); Hewes and Priestley (2002); Chou and Chen (2006); Marriott et al. (2009); ElGawady et al. (2010); ElGawady and Sha'lan (2010)]. The segments were reinforced with longitudinal rebar and post-tensioning bars or post-tensioning bars only, and confined using rebar ties, fibre reinforced polymer (FRP) tubes, and/or steel tubes. The segmental columns showed high self-centering capabilities compared to conventional reinforced concrete (RC) columns. Experimental and analytical studies of the self centering capabilities of post tensioned columns were studied and residual drifts of lower than 1% were achieved [Palermo et al. (2007); Wang et al. (2008); Trono et al. (2014)]. Finite element models and design guidelines for segmental columns were also developed [Dawood et al. (2011); ElGawady and Dawood (2012)].

The double skin columns are columns consisting of outer FRP tube, inner steel tube, and concrete in between the two. It was first developed by Montague (1978) in the form of outer and inner steel tubes and was then modified to outer FRP tube by Teng et al. (2005). This system combined and optimized the benefits of all three materials (FRP, concrete, and steel). Several experimental and finite element studies were conducted on the double skin columns under different static and cyclic loading conditions [Teng et al. (2007); Wong et al. (2008); Han et al. (2010); Ozbakkaloglu and Idris (2014); Abdelkarim and ElGawady (2014)].

This article utilizes the superior performance of the double skin cross section along with the advantages of self-centering post-tensioned columns and the benefits of segmental accelerated bridge construction to produce damage-resistant segmental double skin bridge column with self centering capability.

2 EXPERIMENTAL INVESTIGATION

2.1 Overview of the test specimen

The column elevation and cross section and the test setup are illustrated in figure 1. The specimen length scale factor was 4, considering a hypothetical RC fixed base cantilever column with a diameter of 1200 mm as the prototype column. The column was assumed to be in a high seismic zone and the design response spectrum with a return of 10% in 50 years is shown in figure 2.

The column had an outside diameter of 300 mm and an inside diameter of 175 mm and consisted of four segments of 300 mm high each. No rebar was used in the column. Four 12.7 mm diameter posttensioning seven wire strands, each with a cross sectional area of 99 mm^2 were used as the main reinforcement of the column to connect the four segments together with the foundation and the column head. The strands ran through the void provided by the steel tube and were unbonded throughout the length of the column. The initial posttension force was 98 kN in each strand resulting in a total force of 392 kN. The strands were distributed along the edge of the hollow part of the cross section to maximize the distance of the strands to the neutral axis. The mass was provided by a column head of dimensions 1200 mm x 1200 mm x 600 mm and concrete filled steel tubes of dimensions 1925 mm x 600 mm x 500 mm with a total mass of 45 kN.

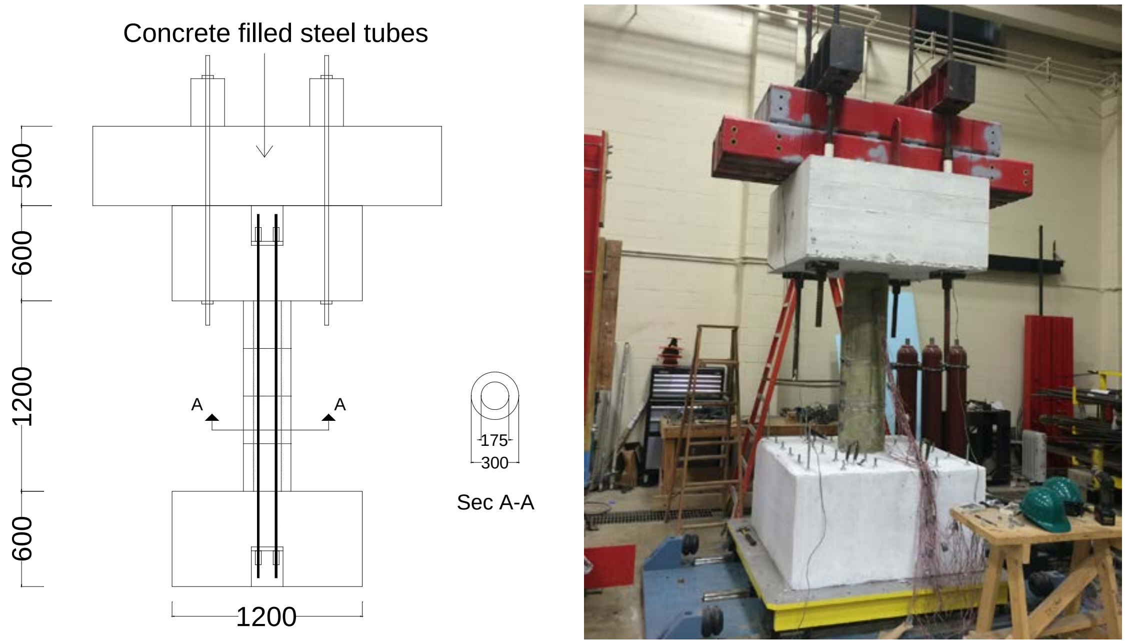

Figure 1. Configuration and dimensions of the test specimen

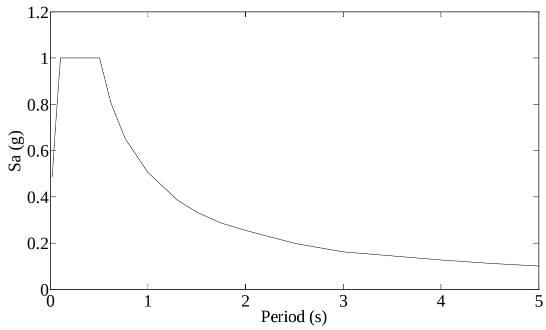

Figure 2. Design earthquake spectrum

2.2 Construction of specimens

The column was constructed using match-casting technique as follows:

1- The foundation of the column was precast with a groove to accommodate the post tension anchorage.

2- The segments were match-cast one by one with the foundation being the bottom form for the bottommost segment and each segment being the bottom surface of the one on top of it, as shown in figure 3. The segments were separated using strong paper towels to provide the necessary match casting with a rough surface without direct contact between the segments.

3- The column head was installed on top of the column.

4- The posttension strands were passed through the segments and anchored to the foundation and the column head.

5- The posttensioning force was applied in steps of 25% of the jacking force in each strand to maintain the column's balance.

6- The concrete filled steel tubes mass was then installed on top of the column head and posttensioned to it using Dywidag bars.

Figure 3. Match-casting of the column

2.3 *Test setup*

The column was fixed to the shaking table using 36 all-threaded bars, each with a capacity of 45 kN. The shaking table was a uni-directional table capable of simulating ground motions using both displacement and acceleration feedbacks. Six accelerometers were used to measure the horizontal accelerations on the shaking table, the column head, the mass, and the segments. Two accelerations were mounted vertically to measure any vertical acceleration in the segments. Eight string potentiometers were used to measure the horizontal displacements along the height of the column. Twelve linear transducers were mounted on the column to measure the vertical openings and horizontal sliding between the segments. Strain gages were mounted to measure strains on the posttension strands along their height, steel tube for the first two segments, and FRP tube for the first two segments. Load cells were placed at the north and south strands to measure the forces in the strands.

The column was subjected to a sequence of a scaled near-fault pulse-like ground motion. The selected ground motion was Northridge-01 1994 earthquake at "Rinaldi Receiving Station". The selected ground motion was scaled to the design spectrum shown in figure 2. The column was subjected to a sequence of the scaled ground motion starting at 10% of the design earthquake to 250% design earthquake with steps of 10% increments giving a total of 25 ground motions. A white noise test with duration of 75 s and 0.02g amplitude of acceleration was run before each ground motion to determine the change in the fundamental period of the column.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Measured force and displacement response

Figure 4 illustrates the force versus drift response of the column at different stages of the tests. The column behaved in a rocking response with multiple rocking during each ground motion. The multiple rocking along with the confinement provided by the FRP provided the energy dissipation in the system. Figure 5 illustrates the dynamic backbone curve; which is the envelope of the peak force versus peak drift ratio of the column during the test. The lateral capacity of the column was 34.4 kN after being subjected to the sequence of ground motions up to 120% of the design earthquake and the ultimate drift was 8.25% after 250% of the design earthquake.

3.2 Observed damage

The column had no apparent damage in the FRP tube. The concrete was exposed in the first segment and no damage was observed, as shown in figure 6(a). Minor damage was observed at the toe of the column as minor concrete spalling and bulging of the FRP, as shown in figure 6(b).

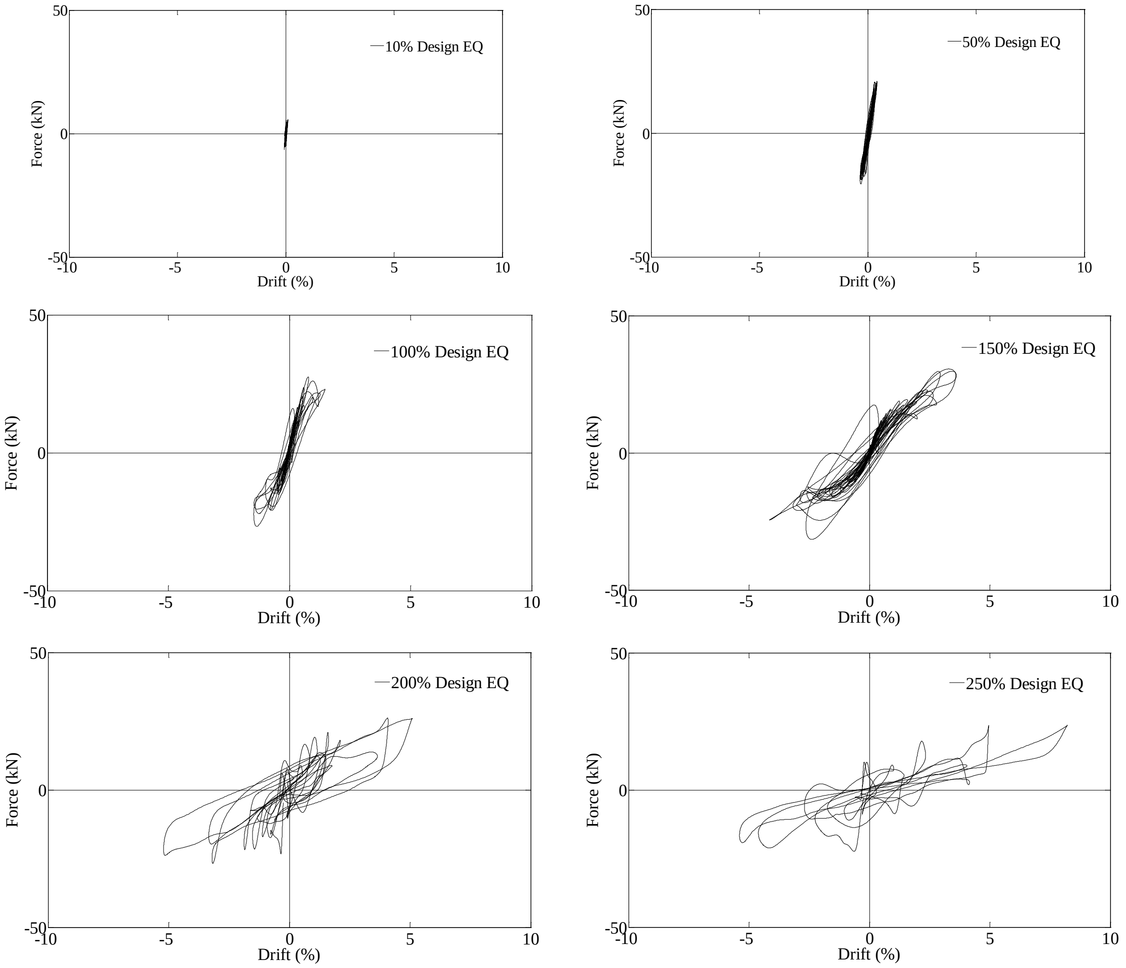

Figure 4. Measured force versus drift ratio at different stages of the test

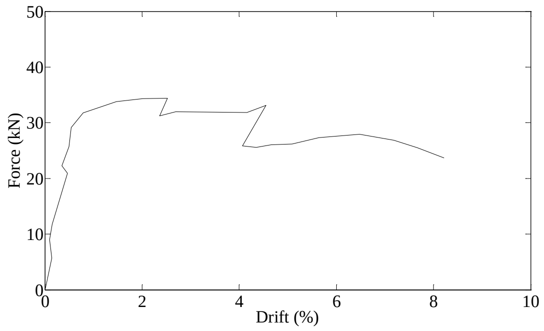

Figure 5. Dynamic backbone curve


(a)

(b)

Figure 6. Damage at the end of the test

3.3 Re-centering capability

The column had an excellent re-centering capacity with only 0.03% residual drift after the sequence of ground motions from 10% to 250% of the design earthquake. Figure 7 illustrates the response history of drift for the 250% of the design earthquake motion and shows clearly no residual drift at the end of the test.

3.4 Rocking of the column

Figure 8 illustrates the rocking of the column along the sequence of ground motions. Very large opening at the base of approximately 22 mm was recorded. This large opening accommodated the drift requirement and the full closure of the opening resulted in no residual drift.

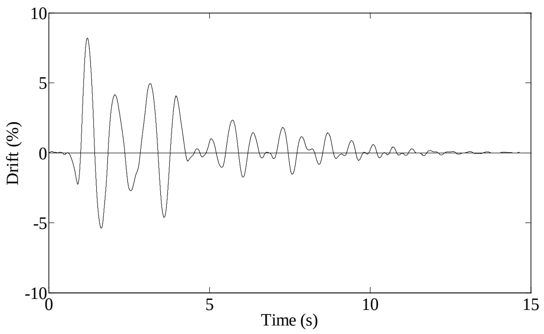

Figure 7. Response history of drift at 250% of the design earthquake

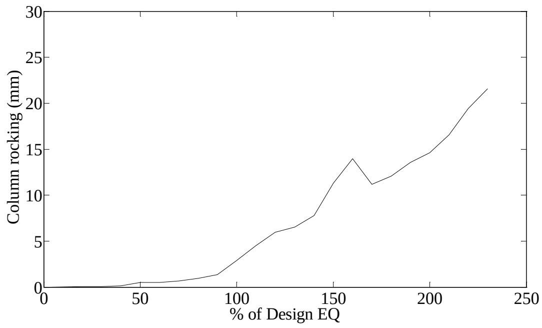

Figure 8. Rocking response of the column along the tests

4 CONCLUSIONS

This paper presented shake-table testing of a damage-resistant segmental double skin bridge column with self centering capability. The column inherits the combined advantages of all its components as follows: The column benefits from the confinement of the FRP along with its corrosion resistance from the double skin section. The column also utilizes the re-centering capability of the unbonded posttensioned system. In addition, the column accelerates the bridge construction due to its segmental nature and its light weight because of the hollow cross section.

The column was subjected to a sequence of a scaled ground motion starting at 10% of the design earthquake to 250% design earthquake with steps of 10% increments giving a total of 25 ground motions. The lateral capacity of the column was 34.4 kN after being subjected to the sequence of ground motions up to 120% of the design earthquake and the ultimate drift was 8.25% after 250% of the design earthquake. The lateral response can be characterized by self-centering capability as well as hysteresis energy dissipation resulting from the rocking of the column and the confinement of concrete. No apparent damage was observed with minor damage at the toe of the column as minor concrete spalling and bulging of the FRP. The column exhibited an excellent re-centering capability with only 0.03% residual drift after being subjected to the sequence of ground motions. Large rocking of 22 mm was recorded during the test, which accommodated the required lateral drift.

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