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Numerical studies on the seismic responses of bridge structures with precast segmental columns

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ABSTRACT

Recently, extensive experimental and numerical studies have been carried out to understand the seismic behaviors of segmental columns. Very limited studies, however, focused on the seismic performances of a whole bridge system with precast segmental columns. This paper carries out numerical studies on the seismic responses of bridge structures with precast segmental columns. For comparison, the seismic responses of the bridge with conventional monolithic columns are also calculated. The two-dimensional (2 D) finite element (FE) models of these two bridge types are developed by using the FE code OpenSEES. The segmental column and monolithic column are simulated by the simplified lumped-mass model and fiber-based model respectively and validated by the previous experimental studies. The calibrated column models are then incorporated into the whole bridge structures to calculate the structural responses. The influences of pounding, frequency ratio and gap size on the structural responses are investigated and discussed. Numerical results show that the bridges supported by the segmental columns or monolithic columns have very different seismic responses.

1. Introduction

To achieve the accelerated bridge construction (ABC), precast segmental columns are more and more widely used in engineering applications recently. Comparing with the conventional cast-in-place monolithic columns, precast segmental bridge columns have many obvious advantages such as the high quality control of fabrication, minimum environmental impact and smaller residual displacement after a severe earthquake [1,2]. Despite these apparent advantages, the constructions of bridges with segmental columns were normally limited in low seismic intensity regions. The application of this bridge type in regions with high seismicity is rare due to the lack of understanding on their seismic performances.

Recently extensive research works have been carried out to investigate the seismic behaviors of precast segmental columns. Hewes and Priestley [3] conducted analytical and experimental investigations on the seismic performances of unbonded post-tensioned precast concrete segmental columns with high and low aspect ratios. It was found that unbonded pre-stressed segmental columns could effectively resist the lateral earthquake loading. However, limited energy was dissipated by the segmental columns. To improve the energy dissipation capability of segmental columns, many different energy dissipation devices have been proposed by different researchers. Chang et al. [4] and Ou et al. [5] advocated the use of continuous mild steel bars, which are also named as ED bars, along the pier segments to improve the energy dissipation capacity. A flag-shape hysteretic behavior with increased energy dissipation capacity was observed in the experimental studies. Experimental results revealed that small residual displacement upon unloading could be obtained if the ED bar ratio is below a certain threshold. Except for ED bars, researches on the external energy dissipaters also have been conducted. Chou and Chen [6] suggested using concrete-filled tubes as external energy dissipaters, and their results showed that the equivalent viscous damping ratio can be obviously increased. Marriott et al. [7] used two different external replaceable energy dissipaters for unbonded pre-stressed segmental piers and obtained considerable energy dissipation when compared with the traditional hybrid ED bar system. Some previous studies (e.g. [8–10]) showed that monolithic connections between first segment and the footing can result in better energy dissipation than segmental connections under seismic loading. The use of other energy dissipaters were also reported including external steel angles and rubber pads [8] and built-in elastomer pad [9]. Besides using dissipaters, improving the material performance of components, such as using high performance ED bars [10] or ductile fiber-reinforced concrete [11], could lead

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to higher drift capacity, greater energy dissipation, and higher lateral strength of the column.

Besides the experimental investigations, a wide range of numerical studies have also been conducted. Solid finite element (FE) model [5,10], fibre-based FE model [12,13] and lumped-mass FE model [5] have been commonly used to capture the local stress of the column or the global response of bridge structure with segmental columns. Detailed 3D solid FE model can capture the local stress or even damage of the column. Its calculation efficiency is however low, which makes it difficult to be applied in the numerical simulation of the whole bridge structure. Fibre-based FE models have been widely used in the seismic response analysis of structures with conventional monolithic piers [14–16]. For the precast segmental columns, complex contact behavior between the segments makes the numerical simulation results with fibre-based model not as good as 3D FE model. Lumped-mass model which assumes the segmental column as a hinge spring with a lumped mass at the top can simulate the global response with computational efficiency. Ou et al. [5] developed a flag-shaped model based on the data from Chang et al. [4] and the 3D FE model. More detailed lumped-mass model which considered the degradation of unloading, reloading and strength [17,18] were developed by using the "Pinching4" material model in OpenSEES [19].

Compared to the extensive experimental and numerical studies on the seismic performances of segmental columns, the investigations on the seismic responses of a whole bridge system with segmental columns are rare and no study that compares the seismic responses of a bridge with segmental columns and with conventional monolithic columns can be found in literature yet. To the best knowledge of the authors, only the following two papers reported the seismic responses of a whole bridge system with precast segmental columns. Sideris et al. [20] carried out a series of shake table tests on a hybrid sliding-rocking (HSR) posttensioned segmental bridge system. The HSR joints were designed to exhibit sliding (slip-dominant, SD) or rocking (rocking-dominant RD) property to mitigate the applied seismic loading and reduce damage. Experimental results showed that the SD joints provided high energy dissipation and moderate self-centering capability. The RD joints, on the other hand, exhibited high self-centering but low energy dissipation capability. Zhang [13] conducted numerical and experimental investigations to evaluate the feasibility of applying steel fiber reinforced self-consolidating concrete to precast unbonded post-tensioned segmental bridge columns in moderate-to-high seismic regions. The test results showed that segmental columns have excellent self-centering capability. Two types of cap beam-superstructure connections, i.e., a connection with non-seismic rubber bearing and a fixed connection, were experimentally tested. Testing results revealed that the fixed connection could induce more impact force at the first joint of the segmental column (counting from the base to the cap beam) comparing with the one with non-seismic rubber bearings.

Many previous experimental and numerical investigations (e.g. [3]) indicated that segmental columns have smaller initial stiffness and smaller energy dissipation capacity than monolithic columns. Moreover, the opening at the joint interfaces may influence the integrity of the columns. These factors may result in large relative displacements between adjacent superstructures of the bridge, which in turn can lead to higher pounding potentials compared to the bridges with conventional monolithic columns. Seismic induced pounding responses between bridges with segmental columns are therefore believed critical and should be considered in the analyses. No literature, however, reports the seismic induced pounding responses between adjacent bridge structures with precast segmental columns though the researches on the conventional bridges are very extensive. For example, Guo et al. [21] carried out shake table tests on a 1:20 scaled two-span base-isolated bridge to investigate pounding behavior of adjacent superstructures. Li et al. [22] experimentally evaluated the influence of spatially varying ground motions on the pounding behavior of three adjacent bridge segments. He et al. [23] conducted large scale (1:6) experimental studies on the pounding responses between two bridge frames. Two boundary conditions, i.e. the fixed foundation and rocking foundation, were tested to investigate the influence of foundation types. Compared to the relatively less experimental studies, the numerical investigations on the pounding responses are extremely rich. Many pounding models (including the stereo-mechanical method, impact element method and 3D arbitrary pounding method) and finite element models (including the lumped mass model, beam-column model, distributed mass model and detailed 3D FE model) have been adopted by different researchers. Hao et al. [24] summarized these methods and models and discussed the pros and cons of these methods. These investigations revealed that pounding can significantly influence the adjacent bridge structural responses, and it may lead to local damages or even collapse to the bridge structures. Many methods have also been proposed to mitigate these adverse effects. Shrestha et al. [25] provides an intensive review on the devices to protect bridge superstructures from pounding and unseating damages. It should be noted that all the studies were focused on the bridge structures with conventional monolithic bridge columns, no literature reports pounding responses between adjacent bridge structures with segmental columns yet.

This paper carries out numerical simulations on the seismic responses of bridge structures with precast segmental columns by using the finite element code OpenSEES. For comparison, the seismic responses of the bridge with conventional monolithic columns are also calculated. Seismic induced pounding responses are considered in the numerical simulations. The hysteretic behaviors of the segmental column and monolithic column are firstly modelled and validated by the experimental results. The validated column models are then applied to the whole bridge systems to calculate the structural responses. The influences of pounding, frequency ratio and gap size are investigated and discussed. It should be noted that ground motion spatial variations and soil-structure interaction (SSI) can further influence the structural responses. Not to further complicate the problem, they are not considered in the numerical simulations.

2. Bridge model

Without loss of generality, a typical five-span continuous bridge extensively investigated by other researchers (e.g. [13,20,26]) is adopted in the present study as the reference bridge model with minor modifications on the span length and pier height. Fig. 1 shows the elevation view of the bridge and Fig. 2(a) shows the cross section of the box-girder. As shown, this bridge is a single cell box-girder bridge with a width of 8.4 m and height of 1.8 m. The length of the side span is 20 m and the lengths of the three middle spans are 30 m. The height of the four piers is 10 m. One expansion joint is located at the middle of the bridge and another two locate at the abutments. The size of the expansion joints is 0.1 m. For easy reference, the parameters of the girder and columns are presented in Table 1.

To investigate the influence of different column types, segmental column and monolithic column are considered in the present study. Wang et al. [27] carried out large-scale experimental studies to investigate the hysteretic behavior of segmental columns, the specimen experimentally investigated in [27] is directly used in the present study and Fig. 2(b) shows the details of the segmental column. As shown, the column includes 9 segments (S1 to S9). The height of the bottom segment is 2 m and the height of the rest 8