Numerical Analytical Model for Seismic Behavior of Prestressing Concrete Bridge Column Systems

Zhiqiang Wang¹, Wei Song¹, Yuanyuan Wang¹, Hongyi Wei¹

¹ Department of Bridge Engineering, Tongji University, Shanghai, China

Abstract

Conventional bridge seismic design practices depend on the ductility capacity of bridge columns. However, damaged columns tend to produce large residual deformations following a seismic event due to the formation of a flexural plastic hinge. Improved seismic response can be realized through the use of unbonded post-tensioning prestressing cast-in-place (CIP) column systems or precast segmental column systems. These bridge column systems can produce significantly less residual displacements when compared to a traditional concrete column. Moreover, precast segmental construction can also significantly reduce construction time and minimize construction cost of bridges in highly congested urban environments. Therefore, one research thrust area of bridges is the seismic performance of prestressing CIP reinforcement concrete columns and prestressing precast segmental column systems which were investigated through quasi-static, shake table test and numerical analyses. However, numerical analytical models which can allow for major nonlinear factors of prestressing concrete bridge column systems are not available yet. This paper presents the numerical analytical models which can be easily carried out in the structural analysis software for seismic response of prestressing CIP reinforced concrete and precast segmental bridge column systems. The numerical analytical model consists of segment model, prestressing tendon model and joint model. Segment model is modeled by nonlinear fiber beam-column elements which sophisticated constitutive models are used to simulate the non-linear cyclic behavior of the concrete, reinforcement steel and bonded prestressing tendons. Unbonded prestressing tendons is modeled by “tension-only” bilinear cyclic truss elements, each node of the truss is laterally constrained to the adjacent segmental element node. A group of zero-length element with “compression-only” nonlinear hysteretic springs which allows for damage expected at the segmental joints and gap element is used to model segment-to-segment joints.

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Keywords: Seismic response, numerical analytical model, prestressing concrete bridge column.

¹ Corresponding author: Email: wangzhiq@tongji.edu.cn
1. INTRODUCTION

With the continued expansion of transportation networks and increasing urbanization, there are many cross-strait bridges, urban viaducts and light rail projects constructed now or in the future in China. One key technical problem that we are facing up is the seismic performance and post earthquake serviceability of these bridges in high seismic regions. Conventional seismic design practices of bridges depend on the ductility capacity of columns. However, damaged columns tend to produce large residual deformations after an earthquake due to the formation of a plastic hinge. A method to reduce residual displacements by incorporating an unbonded prestressing tendon at the center of a reinforced concrete column (CIP) was proposed by the Sakai etc. (Sakai and Mahin 2004). The use of unbonded post tensioning of the precast segmental columns to improve the seismic response by allowing the non linear response to be concentrated at the column joints with minimal damage to the column or adjacent bridge components have been investigated by some researches (Mander and Cheng 1997; Hewes and Priestley 2002; Bilington and Yoon 2004; Chung-chen chou and Yu-Chih Chen 2006; et al.). These bridge column systems can produce significantly less damage and residual displacements when compared to a traditional concrete column. The lack of enough understanding of seismic performance of a bridge with unbonded post-tensioning prestressed cast-in-place (CIP) column systems or precast segmental column systems is one of the important reasons which limit the use of such kind of system in China. This paper presents the preliminary results of an ongoing research project that investigates the seismic performance of precast segmental column systems (Wang Y,Y 2010). A brief description and discussion of quasi-static tests on five test units of prestressing bridge column was presented. The numerical analytical models for seismic response of prestressed CIP reinforced concrete and precast segmental bridge column systems were developed. Numerical analysis results of test units followed the model above were presented and validated with experiment results.

2. EXPERIMENTAL RESEARCH

Based on the consideration of lack of enough understanding of seismic performance of a bridge with unbonded post-tensioning prestressed CIP column systems or precast segmental column systems, the influence of prestressing tendon on seismic performance of bridge columns should be studied experimentally. In this research project, we will conduct quasi-static and shake table testing of unbonded post-tensioning prestressed CIP column systems or precast segmental column systems. Here will focus on numerical analytical research of the seismic performance of prestressing bridge columns and comparison with quasi-static test results.

2.1 Description of test units

Five specimens with a 360mm by 500mm cross-section were constructed and tested under cyclic lateral loading to investigate their force – displacement characteristics and failure modes. The test specimens include a conventional reinforced concrete CIP column (S1), an unbonded prestressing CIP column (S2), a bonded prestressing CIP column (S3), an unbonded prestressing precast segmental column (S8) and an hybrid (unbounded and bonded) prestressing precast segmental column (S9). The precast segmental column was made up of three individual segments with dry joint details.

The existing of prestressing tendons and the type of prestressing tendons (S2, S3, S8 and S9) are of the prime research interest in the test. Table 1 shows main features of the test specimens. Fig. 1 shows their cross section details. The lateral loading point was 1750 mm high from the top surface of the footing (aspect ration is 4.86), and designed to failure in flexure modes. The concrete compressive design
strength is 32.4 MPa. The reinforcing bars with expected yield strength of 335 MPa are used for both longitudinal and hoop reinforcement. The prestressing tendons in S2, S3 S8 and S9 consisted of six 15.2 mm (7D5 mm) diameter low-relaxation steel prestressing strands with expected ultimate strength of 1860 MPa. The design axial stress given by prestressing was 3.2 MPa. A constant axial compressive force of 576 kN was applied to the columns to simulate gravity service loads. The test setup is shown in Fig. 2.

Table 1: Details of specimens

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Longitudinal rebar</th>
<th>Prestressing Tendons</th>
<th>Shear reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rein. Area ration</td>
<td>Tendon Area ratio</td>
<td>Bonded type</td>
</tr>
<tr>
<td>S1</td>
<td>CIP 26D12 1.63%</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S2</td>
<td>CIP 26D10 1.13%</td>
<td>6×7D5 0.46%</td>
<td>Unbonded</td>
</tr>
<tr>
<td>S3</td>
<td>CIP 26D10 1.13%</td>
<td>6×7D5 0.46%</td>
<td>Bonded</td>
</tr>
<tr>
<td>S8</td>
<td>Precast 26D10 1.13%</td>
<td>6×7D5 0.46%</td>
<td>Unbonded</td>
</tr>
<tr>
<td>S9</td>
<td>Precast 26D10 1.13%</td>
<td>6×7D5 0.46%</td>
<td>Unbonded and bonded</td>
</tr>
</tbody>
</table>

A quasi-static cyclic lateral load was applied at the top of column by a servo-controlled hydraulic actuator. The tests were conducted in displacement control up to ±2, 3, 5, 7, 10, 15, 20, 25, 30 mm..., and reversed cyclic loading ended when the load carrying capacity went below 85% of the observed peak load.

2.2 Test observations

Five test columns exhibited flexural ductile response, as is visible in the lateral hysteretic force – displacement response plots at different drift levels shown in Figs. 5 and 6. Compared with S1 (Fig. 5a) conventional concrete bridge column, S2, S3, S8 and S9 (Figs. 5b, 5c, 6) with prestressing tendons reduce residual displacement of columns. Figure 5 and 6 implies more energy dissipation and residual displacement of CIP prestressing columns S2, S3 compared to a precast prestressing segmental column S8, S9.
The segmental column experience opening-closing at the segmental joint under cyclic loading, has no plastic hinge mechanism at the bottom of the column that commonly was seen in conventional columns. Concrete crushing was observed at the region in the bottom segment near the footing. Thus, the similar displacement capacity while less damage to the system is achieved. Figure 6 illustrates segmental bridge column S8 with unbonded systems, the tendons can be designed to remain elastic thus retaining their effective prestress after cyclic loading and allowing minimal residual displacements. Moreover, figure 6 also shows the unbonded prestressing columns S8 have lower hysteretic energy dissipation compared to S9 unit with hybrid (bonded and unbonded) prestressing column (Fig. 6a and Fig. 6b).

Although a significant amount of gap opening was observed at critical segmental joint at the bottom of the test for the segmental columns, the shear still could be successfully transferred across the segmental joint without using shear keys.

### 2.3 Numerical analytical model

In the present study, a numerical analytical model approach of prestressing bridge column systems (CIP or precast segment construction) was developed to capture numerous physical characteristics and seismic performance based on theory of elastic-plastic fiber beam-column element. These characteristics include: crushing of extreme concrete fibers, yielding of PT tendons which across the segment joints (unbonded and bonded), and physical characteristics of the segment-to-segment joints, and energy dissipation et al. The analytical model consists of segment model, prestressing tendon model and joint model. The detailed finite element model of prestressing bridge column has been created using the computer software OpenSees.

Segment model was that segment of column was modeled by nonlinear fiber beam-column elements which sophisticated constitutive models were used to simulate the non-linear cyclic behavior of the concrete, reinforcement steel.

Prestressing tendon model includes simulation of unbonded and bonded prestressing tendon. Unbonded prestressed tendons was modeled by “tension-only” bilinear cyclic truss elements, each node of the truss is laterally constrained to the adjacent segmental column element node. Bonded prestressing tendons were based on the section discretization into fibers of beam-column element with uniaxial hysteretic material models which used to simulate the non-linear cyclic behavior of tendons. No bond-slip of the bonded tendon was considered.

Joint model was used to simulate physical characteristics of the segment-to-segment joints. It consists of a group of zero-length element with "compression-only” nonlinear hysteretic spring element which allows for concrete damage expected at the segmental joints and gap element is used to model opening and closing of segment joint, see Figure 3. Zero-length nonlinear elements are placed at the edges of the cross-section and gap elements are placed in the middle of the cross-section depth. No sliding is considered at the segment-to-segment joints.

Figure 4 shows the analytical models of five test units (S1, S2, S3, S8 and S9) based on the proposed model approach. The support footing was modeled as rigid beam element. Nonlinear fiber beam-column element was used to simulate column segment. Bonded tendons were modeled as fibers of section with the prestressing tendon material. Unbou nded tendon of column was modeled by truss element with an initial strain representing the prestressing force and restrained to the segmental column only at the anchor points on each end of the unit. An external axial vertical force was applied to the top of the columns to represent the service load acting on the bridge’s superstructure.
2.4 Numerical analytical investigation

In order to ensure that the developed numerical analytical model accurately represents the key physical characteristics, the analytical model must be validated to physical experiments. The developed analytical model was employed to simulate five the test units under cyclic loading. Detailed finite element models of five test units (see Figure 4) from the experiment by Liu et al (Liu 2008), see Figure 1, were created using the computer software OpenSees. The joints, bonded and unbonded prestressing tendons and concrete segment were simulated as mentioned models the context. Static cyclic lateral load analyses are performed. The analytical force-displacement curves of specimens were compared with experimental results shown in Figure 5 and 6.

Firstly, Figure 5a presents a comparison of the analytical lateral force-displacement result with the experimental result of conventional concrete column, shows that the developed analytical model can be used to simulate reasonably key characteristics of reinforced concrete bridge piers. Therefore, it ensures the analytical model can capture material nonlinear characteristics of the concrete segment.

Secondly, Figure 5b and 5c show the comparison between the analytical results of unbonded (S2), bonded (S3) prestressing CIP column and test results, the backbone curve and energy dissipation match the experimental results for both small and large displacements. This illustrate the developed analytical model can effectively present the mechanical property of unbonded and bonded prestressing tendons of CIP column.
Thirdly, for precast segmental bridge columns, behavior of segmental joints was emulated with mentioned joint model above. Sixteen zero-length nonlinear elements with “compression-only” nonlinear hysteretic springs allowing for concrete crush at the segmental joints are placed symmetrically at the edges of the cross-section and five gap elements are placed in the middle of the cross-section depth. Figure 6a and 6b show the analytical force-displacement curves of precast segmental prestressing bridge columns which are respectively unbonded (S8) and an hybrid (unbounded and bonded) prestressing precast segmental column (S9). To compare the test result of S8 and S9, the backbone curve, yield displacement and energy dissipation match the experimental results reasonably. However, the comparison also indicates that the residual displacements of analytical simulation currently were smaller than experimental results.

Based on the comparison between analytical and experimental results of test units, see Figure 5 and 6, the developed modeling approach matched the experimental results very well.
3. CONCLUSIONS

This paper discusses analytical model to emulate the seismic behavior of the prestressing bridge columns, the numerical analyses and experimental research results conducted in this study revealed that:

1) The numerical analytical models which can be easily carried out in the structural analysis software for seismic response of the prestressing bridge columns were developed. Especially for segmental joints, a group of parallel zero-length element with “compression-only” nonlinear hysteretic springs which allows for concrete damage expected at the segmental joints and gap element is used to simulate mechanical characteristics of the segment-to-segment joint.

2) Compared with experimental results of prestressing bridge columns, analytical simulation demonstrates the developed numerical analytical model which provides the reasonable accuracy.

3) Some key parameters of the developed numerical model need further to calibrate by more physical experiments of prestressing bridge columns to improve its accuracy and suitability, especially on predicting residual displacement.

4) Moreover, no sliding at the segment-to-segment joints and bond slip of the bonded tendons were considered.

Acknowledgements

This research is supported by the National Science Foundation of China (NSFC) under Research Grant No.50508032 to Tongji University. The findings, observations and conclusions contained herein, however, are those of the authors and do not necessarily represent those of the sponsoring organizations.

References


