DEVELOPMENT OF ACCELERATED BRIDGE CONSTRUCTION DETAIL FOR SEISMIC REGIONS

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Abstract

This paper provides an overview of current research in development of the seismic detailing of accelerated bridge construction. This study is part of the highway seismic research project conducted by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) and is under the auspices of the Federal Highway Administration (FHWA) Office of Infrastructure, R&D. The research primarily focuses on studying the performance of precast piers and superstructure bridge systems constructed in seismic zones, and providing solutions that can lead to wide spread use of accelerated bridge systems in seismic zones.

Introduction

In the bridge engineering community, increasing attention has been paid to prefabricated bridge construction to accelerate the on-site bridge construction by shifting most of the construction process into precast factory or yard. When compared to conventional bridge construction, the advantages of accelerated bridge construction include reducing traffic disruption, minimizing accidents in the work zone, maintaining construction quality and minimizing the life-cycle cost and environmental impact (TRB, 2006). In spite of the many advantages aforementioned, the use of accelerated bridge construction in high seismic region is still limited. The main reason has been the skepticism on seismic resistance of prefabricated bridges because of the presence of precast joints. To promote this type of bridge construction, a coordinated research project has been initiated at the University at Buffalo under the auspices of the FHWA-funded Highway Project of the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The research primarily focuses on studying the performance of precast concrete piers and prefabricated superstructure systems constructed in seismic zones, and providing solutions that can lead to wide spread use of accelerated bridge systems in seismic zones.

This paper will present the progress of the research on precast piers. The use of precast piers for accelerated bridge construction in regions of low seismicity has been popular over the past 20 years. Texas State Department of Transportation (TxDOT) is one of the state agencies that have been promoting the use of prefabricated bridge elements and systems in the busy urban areas to reduce the impact of on-site bridge construction on the road users. The Pierce Elevated Freeway Bridge Replacement project is a good example that demonstrated the use of precast pier cap to accelerate the on-site bridge construction. The Louetta Road Overpass is another example that used precast pier cap (Billington et al, 1999). In addition, the columns were precast segmentally and were assembled on site within a short construction time. Many other examples involving the effective use of precast concrete piers include Seven Mile Bridge, Sunshine Skyway Bridge, Varina-Enon Bridge, John T. Collinson Rail Bridge (Figg et al, 2004), Linn Cove Viaduct (Muller et al, 1985) and more recently, Victory Bridge in New Jersey. Before this type of pier construction can become

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popular in regions of moderate to high seismicity, rigorous investigation of the methods of seismic design and detailing are required.

In this paper, the analytical models for seismic analysis of precast concrete piers including simplified analytical model and detailed finite element model are introduced. The precast pier investigated in this paper is segmentally constructed and prestressed with unbonded tendons. The use of unbonded tendons has been proven to be capable of delaying or avoiding the yielding of the tendons, thus preserving the necessary clamping force and re-centering capability. To enhance the seismic energy dissipation, bonded longitudinal mild steel bars are provided in the prototype column studied in this paper. Moreover, this paper discusses the results of a parametric study on the amount of mild steel added and observes any correlation with the energy dissipation and residual displacement (re-centering capability). Summary remarks and conclusions are provided at the end of the paper.

Simplified Analytical Model and Behavior of Segmental Column

To understand of the mechanical behavior of a segmental column with unbonded post-tensioning tendon under lateral load and to provide the engineers a simplified method to predict the pushover curve of the column, a simplified analytical model is developed in this research. The simplified analytical model is established using two-stage approach.

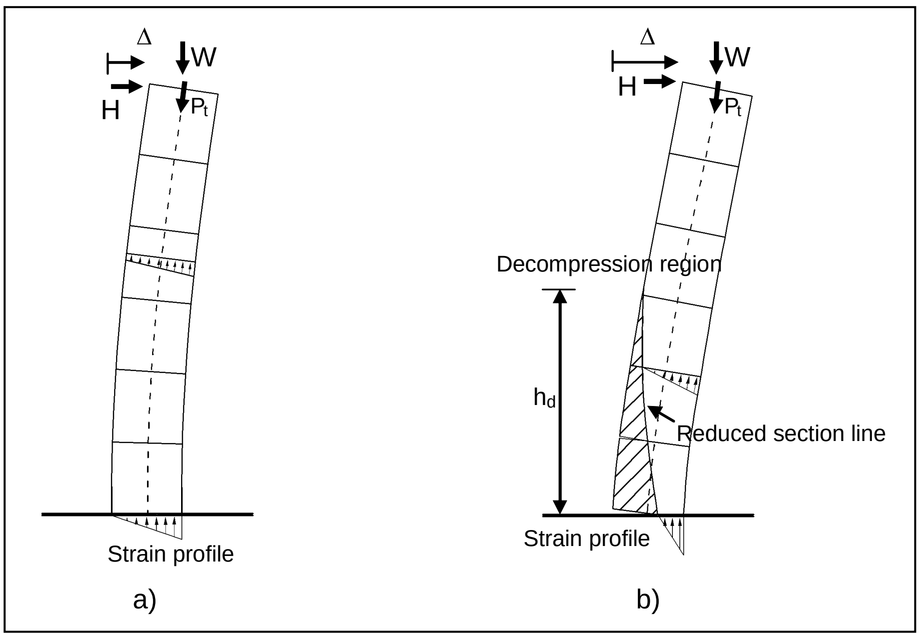

Figure 1. Two stages of segmental column under lateral load, (a) end of pre-decompression stage (b) post-decompression stage.

Pre-decompression Stage

As shown in Figure 1(a), at this stage, although the column is subjected to a lateral load, H, the whole column is in compression due to the gravity load, W, from superstructure and the pre-stressing force of the tendon, P_t. There is no gap opening at the segmental joints at this stage. The column behaves like a conventional column with fixed base. The relationship between lateral force and displacement, Δ, can be calculated using conventional column analysis.

Post-decompression Stage

As the lateral load is further increased, the column starts to enter post-decompression stage where the segmental joints begin to experience gap openings. In this stage, difficulty arises in deriving the simplified analytical solution because, at the segmental joint, the strain compatibility doesn't exist in the portion of the cross-section that is not in contact. To resolve this issue, the column is assumed to take no tensile stress because of the lack of tensile resisting capacity of the segmental joint. Based on this assumption, a region, as shown in Figure 1(b) with hatched lines and is called "decompression region," can be calculated and taken out of the column, resulting in a column with reduced effective sectional width. As the column is further displaced laterally, the decompression region becomes enlarged and the decompression height, h_d, increases, leading to the increase in the number of the joint having gap opening. This geometric nonlinearity results in more flexible behavior at the early stage under lateral load in segmental columns as compared with fixed based conventional column.

The method used in conventional column to calculate the lateral force-displacement curve can then be applied to a segmental column with no tensile strength in concrete. However, due to the increase in the force in unbonded post-tensioning tendons as the column deforms, an iterative procedure has to be implemented to calculate the final force needed to push the column at a given drift level. The additional increment of the force in the tendons can be obtained based on the total elongation of the unbonded tendon, which can be estimated from the vertical and horizontal displacement at the top of the column where the tendons are anchored.

Finite Element Method

Nonlinear three dimensional (3D) finite element (FE) models are developed in this research to capture the detailed distribution of the stress, strain, and displacement of segmental columns under monotonic and reversed loading condition, which is currently unattainable by the simplified analytical model. Concrete damage plasticity model with compressive behavior described by Mander (1988) unconfined concrete model is used in the finite element modeling. Three-step analysis was employed and can be summarized as follows − (1) initiation of contact, (2), removal of constraints, and (3) applying load/displacement.

Step 1: initiation of contact
This step is required to initiate equilibrium condition for the problem. Unsupported elements need to be constrained to prevent any rigid body motion.
Step 2: removal of constraints
All constrained provided to the unsupported element must be removed after contacts were initiated.
Step 3: applying load/displacement
Applied loads or displacements can be added to the problem. The analysis was done incrementally due to nonlinearity nature of gap opening and closing.

Verification of Analytical Models

The experimental study done by Hewes and Priestley (2002) is first used to verify the analytical models developed in this research, which include the simplified analytical model and FE models. Figure 2(a) illustrates the dimensions of the segmental column specimen. The first segment (S1) was confined with steel jacket. Three-dimensional FE model of this specimen is shown in Figure 2(b). Figure 3(a) shows the comparisons of force-displacement response between FE, experiment, and the simplified analytical model. The results obtained from FE models, simplified analytical model were based on the monotonic loading scheme, while the experimental results were obtained from an envelope of a cyclic response. The results from the simplified analytical approach were developed considering the confining effect but without considering the composite action from the steel-jacket while in FE model, full composite action is assumed. Therefore, the FE results provide an upper-bound solution while the simplified analytical solutions provide a lower-bound solution in this particular case. Figure 3(b) shows the larger gap opening at the joint between S1 and S2 than that between foundation beam and S1 by FE, which conforms to the experimental results. This caused an undesirable behavior of the column due to the likely failure of segment S2, which has much less confinement than S1. Figure 4 shows verification between the results of analytical and experimental study. The experimental study was performed by Chang et al. (2002). Among the four specimens studied results of specimen P1 is presented herein. Specimen P1 consisted of a total of 10 segments. Each segment was 1 meter in height and with hollow cross sections and unbonded tendons. The comparison shows that the pushover curve obtained from simplified analytical model agrees well with that obtained by FE. Both analytical models predict the envelope of the experimental curves very well in the lower drift ratios. However, as the drift ratio exceeds 2%, the analytical models overestimate the response.

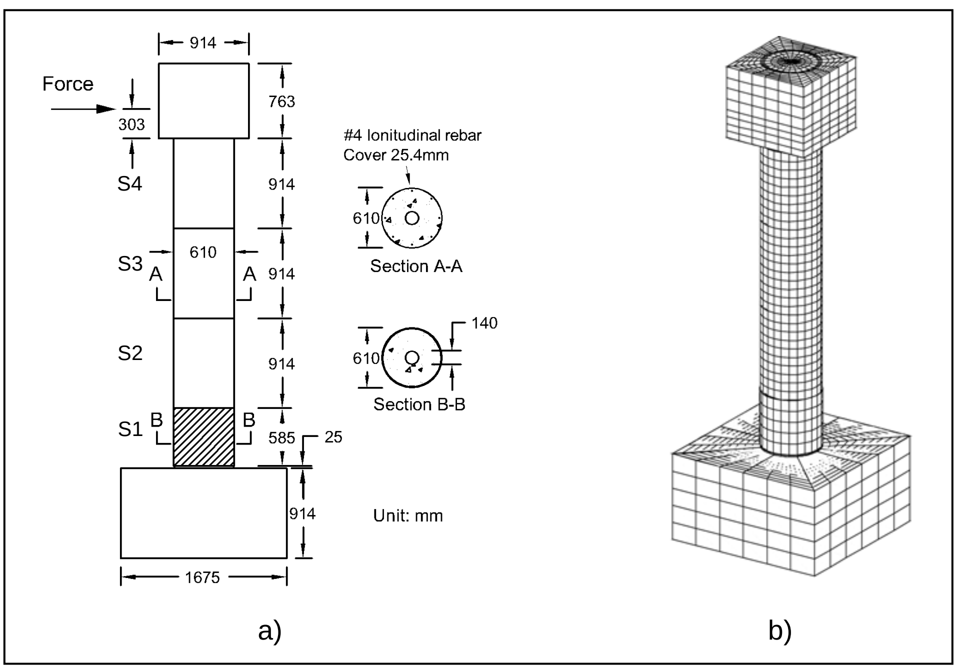

Figure 2. Verification example 1, (a) Segmental prestressed column (Hewes et al, 2002) (b) 3D finite element model

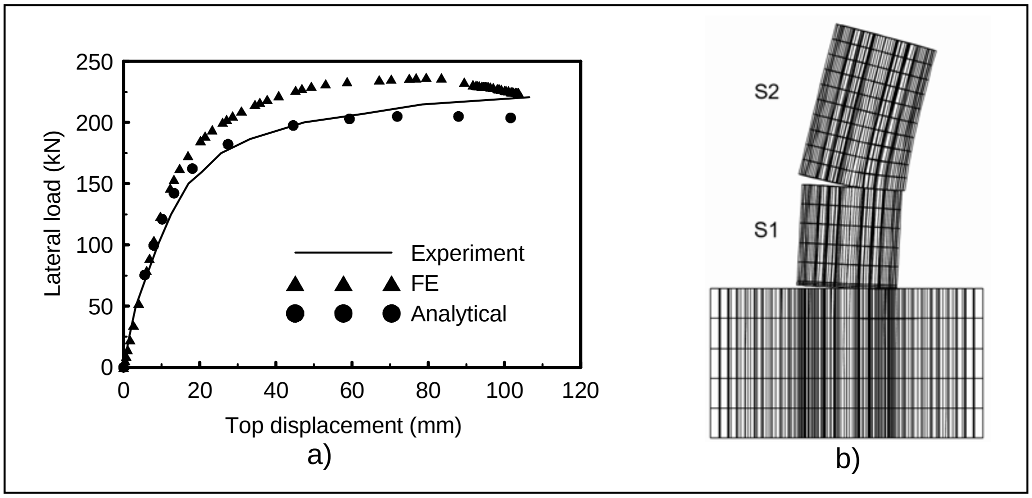

Figure 3. Verification example 1, (a) Comparison of pushover curves (b) Gap openings

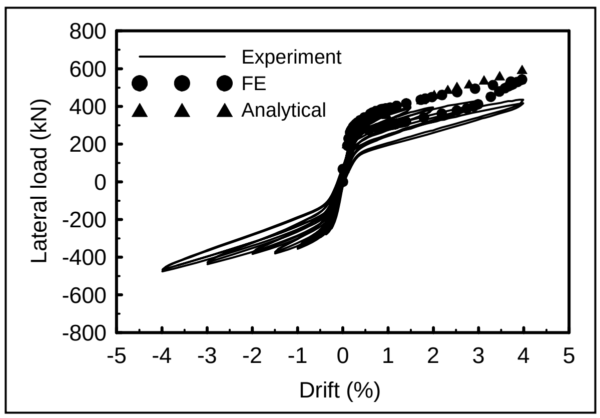

Figure 4. Verification example 2.

Parametric Study

As shown previously, segmental columns normally exhibit lower seismic energy dissipation than conventional reinforced ones because of the discontinuity created by segment joints. To enhance the energy dissipation of this type of column, bonded mild steel reinforcement can be added across the segmental joints (Chang, 2002). A parametric study is conducted herein using the developed FE model to investigate the effect of the amount of mild steel reinforcement. The prototype column used in the parametric study consists of six precast concrete segments of 1m×1m×1m (see Figure 5). The unconfined concrete compressive strength, $f_c^{'}$, is 28 MPa at the strain of 0.002. An unbonded post-tensioning tendon is used at the center of the cross section. The total axial load from the dead load and prestressing force is $0.1 f_c^{'} A_g$. A_g is the cross-sectional area of the column. Two different systems are considered, which can be distinguished by the amount of mild steels extended across segment joints. System 1 does not have mild steel across the joints.

Flexural strength is provided by prestressing forces and the shear resistance at the joints relies on interfacial friction. Seismic energy can be dissipated through material damping and inelastic straining of the concrete. System 2 contains mild steel bars across the joints. Typically, compression members require the minimum longitudinal steel that is 1% of the gross sectional area (AASHTO 2002). In this study, three different steel ratios, i.e. 0.38%, 0.70% and 1%, are considered. Mild steels are expected to provide additional energy dissipation.

By varying the steel ratio, a parametric study is performed to investigate the correlation between the equivalent damping ratio (a measure of energy dissipation capability) and the residual displacement (self-centering capability). Equivalent viscous damping ratio, ξ_{eq}, is computed based on an empirical formula in (Chopra 2000),

$$\xi_{eq} = \frac{1}{2\pi}\frac{E_D}{ku_{max}^2} \tag{1}$$

where E_D is the area enclosed in an hysteresis loop, k is the secant stiffness, and u_{max} is the maximum displacement. It is found that increasing the steel ratio will increase the equivalent damping ratio as well as the residual displacement, as shown in Figure 6 and Table 1. When the steel ratio is increased from 0% to 0.38%, the equivalent damping ratio is significantly increased with residual displacement being nearly the same. If the steel ratio is further increased from 0.38% to 0.7%, both equivalent viscous damping ratio and the residual displacement increase appreciably. This implies that if the post-earthquake serviceability is of great concern, then the steel ratio, representing the amount of the mild steel crossing the segment joints, may have to be limited to a certain value between 0.38% and 0.7%, under a total axial load of $0.1 f_c^{'} A_g$.

Conclusion

Through the development of the analytical and finite element models, the seismic behavior of precast segmental columns is investigated in detail. The analytical model proposed is consistent with the one used in conventional bridge columns and can be implemented using common sectional moment-curvature analysis software combined with a post-processing program. The finite element method developed in this research is capable of predicting the behavior of a segmental pier system under reversed loading condition and providing detail stress, strain, displacement contour, etc, helping engineers examine the system from a microscopic point of view.

By varying the steel ratio, a parametric study is performed to investigate the correlation between the equivalent damping ratio (energy dissipation capability) and the residual displacement (self-centering capability). It is found that increasing the steel ratio will increase the equivalent damping ratio as well as the residual displacement. If the post-earthquake serviceability is of great concern, then the steel ratio, representing the amount of the mild steel crossing the segment joints, may have to be limited to a certain value below 0.7%.

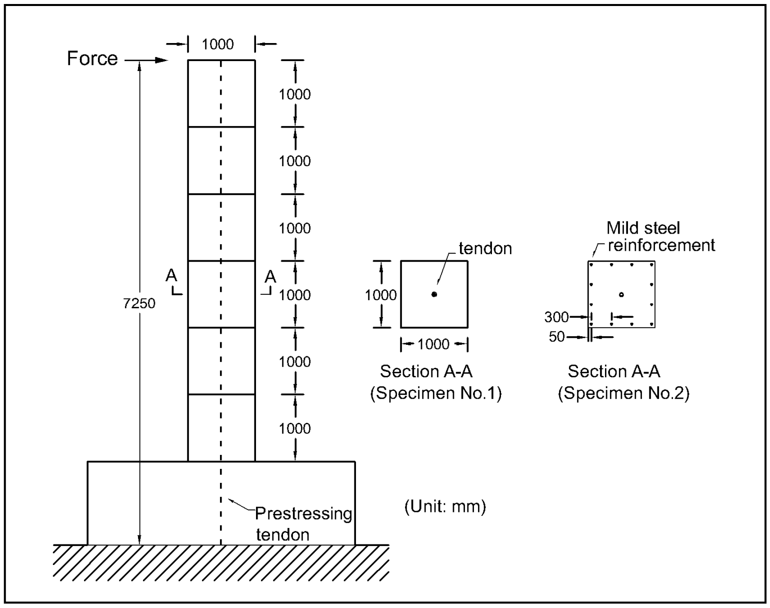

Figure 5. Prototype column

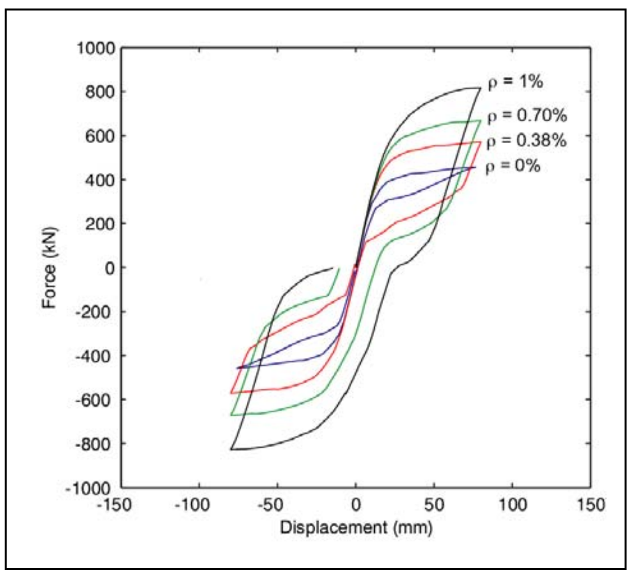

Figure 6. Hysteretic behaviors of columns with varying steel ratios, ρ.

TABLE I. PARAMETRIC STUDY RESULTS

Steel Ratio ρ (%)	Equivalent Viscous Damping ξ_{eq} (%)	Residual Displacement Δ_{res} (mm)
0.00	3.9	1.16
0.38	12.0	1.47
0.70	17.0	12.5
1.00	17.9	26.5

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