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Nonlinear quasi-static analysis of hybrid sliding–rocking bridge columns subjected to lateral loading

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ABSTRACT

In this paper, a nonlinear three-dimensional finite element (FE) model for a hybrid sliding–rocking (HSR) column is developed. The HSR columns are segmental members incorporating internal unbonded post-tensioning, rocking joints at the member ends, and intermediate sliding joints along the member height. The HSR columns introduce new design parameters (e.g., frictional properties at the sliding joints, amplitude of joint sliding, number/distribution of sliding joints along the column height) and additional modeling challenges (e.g., contact interactions between adjacent segments and between segments and the internal unbonded post-tensioning tendons) as compared with conventional monolithic or rocking-only members. In the proposed modeling approach, contact interaction amongst adjacent segments and between segments and unbonded tendons are captured. Concrete segments are modeled using solid elements, mild steel reinforcement is modeled by beam elements embedded into the concrete segments, and the unbonded tendons are modeled using truss elements. The FE model was validated against available experimental data and was then used to conduct a parametric pushover study. Variations of the external vertical load were found to have minor effects on the lateral column response. Increase of the initial post-tensioning force resulted in early onset of inelastic response of the tendons, while the peak lateral column strength remained unchanged. Joint sliding increased the lateral deformation capacity of the column. Propagation of sliding from bottom to top and vice versa had small effects on the lateral response of the column. Propagation of sliding was controlled by the friction properties at the sliding joints.

1. Introduction and background

In the U.S., a vast number of "*structurally deficient*" and/or "*functionally obsolete*" bridges (ASCE's Report Card for America's Infrastructure [4]) are in need of immediate retrofit or replacement. To minimize bridge operation disruptions along with the resulting socio-economic impacts, accelerated bridge construction (ABC) techniques have been investigated. Research efforts have primarily focused on bridge systems incorporating prefabricated concrete elements connected together with or without post-tensioning. Segment/member fabrication takes place off-site, whereas assembly is conducted on-site, resulting in significant on-site construction time savings. Further benefits of ABC systems include the reduced total project delivery time, reduced weather-related construction time delays, improved work-zone safety for the traveling public and contractor personnel, reduced environmental impact, high product quality and durability, and potentially lower lifecycle cost.

Early research on ABC focused on improving construction rapidity and resulted in ABC applications in low seismicity areas [15,14]. More recent research efforts have focused on the development of bridge systems that combine construction rapidity with improved seismic performance. These efforts, which have been largely encouraged by the Federal Highway Administration (FHWA) of the U.S. Department of Transportation [56,31], have led to the development of several substructure column systems for seismic applications. These substructure systems include:

- Bents incorporating prefabricated monolithic columns (usually without post-tensioning) connected with the bent cap and the foundation through emulative (of monolithic) connections. Four types of these emulative connections can be found, namely, bar coupler connections [25,52,3,17,43], grouted duct connections [33,22,32,18,51,42,44], gap pocket connections [33,32,44,54], and member socket connections [54,7,26,28,19,55]. A collective description of these emulative connection types is available in Marsh et al. [31].

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- Bents incorporating prefabricated monolithic or segmental columns with end rocking joints and internal unbonded post-tensioning [20,9,21,44,12]. Unbonded post-tensioning provides large ductility capacity and self-centering capabilities. Supplemental energy dissipation to control displacement demands is provided either by internal partially debonded yielding rebar crossing the rocking joints [39,53,30,40,41,45,37] or by externally attached yielding links at the rocking joints [9,30]. Optionally, damage control in the vicinity of the rocking joints is provided through steel jacketing [9,21,2,16], fiber reinforced polymer (FRP) composite jacketing [12], and steel armoring [55].

Recently, a new substructure bent system, employing segmental columns with internal unbonded post-tensioning, end rocking joints and intermediate sliding joints along the column height, was introduced by the author and his colleagues [46,48–50]. The proposed system has been investigated through shake table testing of a large-scale (~1:2.39) two-pier single-span box girder bridge specimen [48,50] as well as quasi-static lateral cyclic loading of pier columns at large drift ratios [49]. The proposed column – termed *hybrid sliding–rocking* (*HSR*) column – provided energy dissipation capabilities (through joint sliding), large deformation capacity (through joint sliding and rocking) and moderate self-centering properties (by the unbonded post-tensioning). The term "*hybrid sliding–rocking* (*HSR*)" was adopted, because of the combination of sliding and rocking joints in HSR columns.

Compared to other systems, the HSR columns offer an alternative energy dissipating mechanism through joint sliding (as opposed to the energy dissipating links used in rocking-only columns), which does not cause damage, other than wearing of the joint interface and small concrete spalling in the vicinity of the joints [48,49]. Peak and residual joint sliding is controlled by the geometric properties of the duct adaptors. Residual column deformations due to residual joint sliding are small, because [48,50]: (i) the maximum sliding amplitude at a single joint is small (<2–3% of cross-section depth), and (ii) not all residual joint sliding is in the same direction, due to the reversing direction/polarity of earthquake ground shaking. Moreover, residual joint sliding can be restorable using hydraulic means. Joint sliding also provides a mechanism to increase the deformation capacity of rocking columns, which can be particularly useful for columns of lower aspect ratios (short columns).

The HSR columns introduce: (i) ***new design parameters***, such as the frictional properties at the joint interfaces, the amplitude of the joint sliding and the number/distribution of sliding joints along the column height, and (ii) ***additional modeling challenges*** (compared to conventional and rocking-only columns), such as contact interactions between adjacent segments (sliding and rocking) and between segments and the internal unbonded post-tensioning tendons (bearing forces at sliding joints). Development and validation of design methods, and performance assessment of the HSR columns requires modeling approaches capable of capturing critical response properties of the HSR columns. In this paper, a three-dimensional finite element model of the HSR concrete column considered in the aforementioned experimental studies is generated using the ABAQUS general purpose finite element analysis software [11]. The model is validated against the experimental data of the quasi-static testing study of Sideris et al. [49], and is subsequently used in a parametric study investigating the effect of design and loading parameters on the lateral strength and deformation capacity of HSR columns. This research is part of an ongoing effort to study the response of HSR columns and develop performance-based design strategies for bridges with HSR columns.

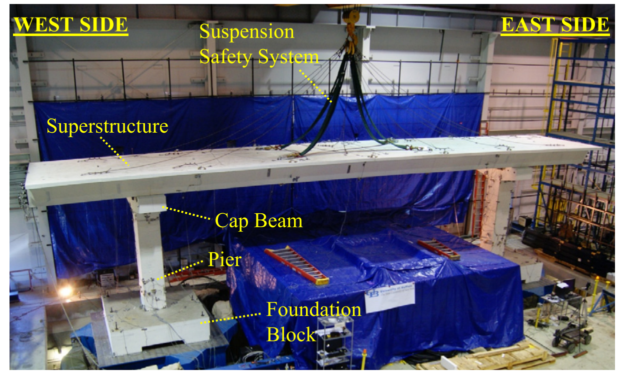

Fig. 1. Precast concrete segmental bridge specimen in the Structural Engineering and Earthquake Simulation Laboratory at the University at Buffalo.

2. Scope

The primary objectives of this study are: (i) Development of a finite element (FE) model capable of capturing critical response characteristics of HSR columns, such as contact interactions between adjacent segments and between segments and the internal unbonded tendons, (ii) Validation of the FE model against experimental data from the quasi-static testing of HSR columns conducted by Sideris et al. [49], and (iii) Parametric study through quasi-static pushover analyses studying the effects of design and loading parameters on the lateral strength and deformation capacity of HSR columns. The selected parameters include the external vertical load, the initial post-tensioning load, and the friction properties at the sliding joints. Investigation of the energy dissipation capabilities, self-centering properties and dynamic response characteristics of HSR columns are beyond the scope of this paper. A discussion on these topics can be found in other studies [46,48–50].

3. Experimental investigation

The experimental investigation of interest to this study included the quasi-static lateral cyclic testing of a HSR single-column pier [46,49]. The pier was identical to the piers of the large-scale single-span precast concrete segmental bridge (see Fig. 1) subjected to a series of shake table tests by Sideris et al. [48,50].

The pier specimen (see Fig. 2) consisted of a five-segment HSR column of hollow square cross-section, a cap beam of trapezoidal solid section and a foundation block; all post-tensioned together by eight internal unbonded tendons of diameter of 0.6 in. [1.52 cm]. The transverse mild reinforcement of the column segments included #3 closed ties in each wall providing volumetric reinforcement ratios of 0.0198 and 0.014 in the wall parallel and wall normal direction, respectively. The longitudinal mild reinforcement of the column segments included #3 straight bars that provided a volumetric ratio of 0.025. For the computation of the reinforcement ratios the volume/area enclosed by the ties/stirrups was considered. The post-tensioning tendons were cold-drawn, low relaxation, seven-wire monostrands conforming to Gr. 270 per ASTM A416/A416M [5]. The concrete material had a 28-day nominal strength of 5 ksi [34.5 MPa]. The mild reinforcing steel conformed to Gr.60 per ASTM A615/A615M [6].

The initial post-tensioning load was approximately 20 kips [89 kN] per tendon. The tendons were accommodated by ducts of interior diameter of 0.9 in. [2.29 cm]. Duct adaptors made of PVC and having interior diameter of 1.375 in. [3.49 cm] and height of 1.5 in. [3.81 cm] were used in both ends of all column segments.