*17th World Conference on Earthquake Engineering, 17WCEE*
*Sendai, Japan - September 13th to 18th 2020*

# NUMERICAL SIMULATION OF PARTIALLY DEBONDED TENDON SYSTEM IN RESETTABLE SLIDING JOINT UNDER EARTHQUAKE

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## *Abstract*

In an attempt to promote precast segmental bridge construction to regions of moderate-to-high seismicity, segmental columns incorporating resettable sliding joints are devised so as to achieve satisfactory seismic isolation during the initial period of strong shaking in an earthquake and excellent self-centering performance in the subsequent shaking. In particular, the resettable sliding joint consists of three major components: (a) durable low-friction concrete-to-concrete contact surfaces obtained by proper surface treatment and lubrication for easy initiation of transverse sliding between segments; (b) non-planar mating surfaces with gentle guide keys for improved resetting performance at the post-peak stage of an earthquake; and (c) partially debonded tendons that not only allow relative sliding at the mating surfaces, but also provide some restoring force to assist in resetting. The partially debonded tendon comprises a grouted tendon inside a regular duct with a certain length of the duct adjacent to each joint at the mating surfaces wrapped by an annulus of soft resilient material to allow a certain amount of relative sliding movements at the mating surfaces during an earthquake. The sliding and possible opening of the joint at the mating surfaces will induce elongation of the tendon within the length of duct wrapped by soft resilient material and even cracking of the hardened grout, thus resulting in a debonded length locally.

Compared to the fully unbonded tendons, the partially-debonded nature may optimize the restoring force between adjacent segments and help distribute favorably the sliding performance under severe earthquake condition. To better understand the dynamics of segmental columns incorporating resettable sliding joints under earthquakes, simplified numerical studies are carried out in OpenSees environment. Truss elements with co-rotational geometric transformation and tension-only gap material are used to simulate the tendons, while the Flat Slider Bearing Elements with hysteretic friction model and zero-tensile-strength materials are distributed along the gently-keyed interface to simulate the sliding and rocking behavior of joints. Comparing similar joints with different post-tensioning arrangement under several earthquake inputs, it is found that, with proper design of the debonded length of the partially debonded tendons, the overall sliding displacement can be distributed more favorably among individual joints, while negligible residual sliding displacement results indicating excellent resetting performance. Convergence has been achieved in all the simulations, demonstrating that the proposed model is computationally stable and it can be used to further investigate the seismic performance of segmental columns incorporating resettable sliding joints.

*Keywords: Bridges; Dynamic analysis; Post-tensioning; Precast concrete; Resettable sliding joints*

 

## 1. Introduction

As a popular method of Accelerated Bridge Construction, precast concrete segmental construction can cover not only the decks of bridges of short-to-medium spans, but also the columns. The prevalence of segmental column construction in the low-seismicity regions has prompted research in the design of seismic-resistant segmental columns [1], where the non-emulative joints, basically dry connections between segments that allow separation, have been regarded as a promising field of study for improvement. The relative sliding and rocking have been wisely combined with the help of a special duct adaptor designed for mobility of the fully unbonded tendons at the joint interfaces so that the segmental columns can behave in a beneficial hybrid rocking-sliding manner under seismic loading [2]. However, despite survival during an earthquake, noticeable residual relative movements are commonly observed at these sliding joints, where costly repairs may be needed. To achieve satisfactory seismic isolation during the initial period of strong shaking in an earthquake and excellent self-centering sliding performance (i.e. resetting performance) in the subsequent shaking, segmental columns incorporating resettable sliding joints [3] are thus devised to fully utilize the post-peak energy of an earthquake with proper choice of slope inclination and coefficient of friction at the mating surfaces [4].

Actually, segmental structures assembled by post-tensioning with dry connections have existed for a long time. For example, in the research of masonry structures, the overall structural integrity of assembled mortarless bricks is largely determined by the peripheral constraints and the interaction between individual segments as well [5]. Unlike monolithic columns, contributions from vertical tendons of different arrangement are decisive. A partially debonded tendon system may be superior to the fully unbonded counterparts in terms of better control during seismic events [6].

To obtain a quick and reliable estimation of the dynamic performance of segmental columns incorporating resettable sliding joints under earthquakes, simplified numerical studies are carried out in OpenSees environment. Truss elements with co-rotational geometric transformation and tension-only gap material are adopted to simulate the tendons, while the Flat Slider Bearing Elements with hysteretic friction model and zero-tensile-strength materials are verified and distributed along the gently-keyed interface to simulate the hybrid sliding and rocking behavior of joints. Four cases are presented, covering various parameters at the mating surface, different arrangement of the tendons and initial prestressing force, while the performance of the proposed resettable sliding joints will be later discussed in terms of sliding behavior, shaking mode and drift capacity.

## 2. Partially debonded tendons in Resettable Sliding Joint

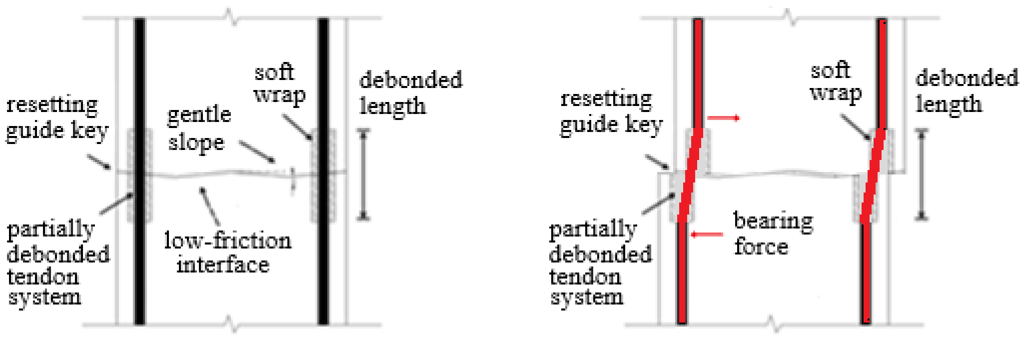


Fig. 1 – Schematic diagrams of resettable sliding joint

The resettable sliding joint as shown in Fig. 1, as a type of hybrid rocking-sliding joint [2], consists of three major components: (a) durable low-friction concrete-to-concrete interface; (b) non-planar mating surfaces with W-shaped gentle guide keys; and (c) partially debonded tendons. Particularly in this study, the partially debonded tendon comprises a grouted tendon inside a regular duct with a certain length of the duct adjacent to each joint at the mating surfaces wrapped by an annulus of soft resilient material to allow a certain amount of relative sliding movements at the mating surfaces during an earthquake.

The merit of this design is that the slope-induced asymmetric sliding behavior helps the sliding segments to self-center themselves under reversed cyclic loading during earthquakes, thus minimizing any residual sliding displacement as if the joints were reset after an earthquake.

## 3. Model verification

There are two major difficulties in modeling the above resetting sliding joints. One of them is to capture the hybrid sliding and rocking interaction between segments with W-shaped inclined mating surfaces. The other is to understand the behavior of the partially debonded tendon system for proper simulation of the participation of adjacent moving segments. It is widely accepted to use no-tension material and tension gap material to simulate possible rocking behavior and tendon force variation, respectively, in dynamic analyses.

The Flat Slider Bearing Element of OpenSees is especially useful in modeling the proposed resetting sliding joints because it can be a zero-length element with a user-defined friction model.

To verify the modeling of the contribution of W-shaped sliding mating surfaces, theoretical kinetic analysis of a rigid block sliding on a W-shaped slope under earthquake excitation was conducted first, and then reproduced in the OpenSees environment using Flat Slider Bearing Element. Fig. 2 shows that the theoretical and numerical results are in good agreement, indicating that the methods used for simulating the resetting sliding joints are reliable. Therefore the model can be improved for analyses of columns built of multiple segments.

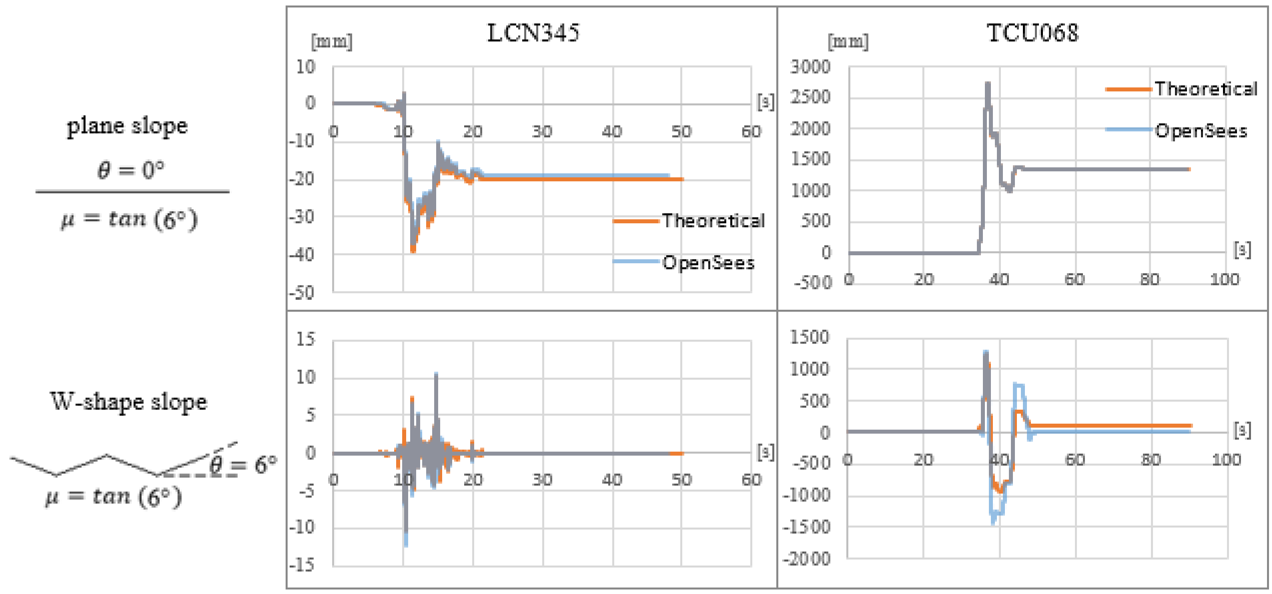


Fig. 2 – Theoretical and numerical results of a rigid block sliding on a plane slope and on a W-shaped slope under excitation of earthquake inputs (normalized to 1.0g)

## 4. Case studies

A series of parametric studies of four 5-segment columns as shown in Table 1 were carried out to further understand the dynamics of the proposed system. In these simplified linear simulations, the top mass is set to be much larger than the weight of the column, and the tendon and concrete outside the unbonded zone are assumed to be perfectly bonded. The parameter G denotes the total gravity force, including those resulting from the column itself and the top mass. The column in Case I had a high initial prestressing force, while the rest had negligible initial prestressing force just to keep the tendons taut. The column segments are regarded as rigid blocks and the excitation input from Landers LCN345 was scaled to a maximum PGA of 1.0g expressed in terms of the acceleration due to gravity g. In each case, time history analysis was carried out for at least 15 seconds after cessation of earthquake excitation.

Table 1 – Key parameters of case studies

| Parameters | Case I | Case II | Case III | Case IV |
|---|---|---|---|---|
| Coefficient of friction (CoF: μ) | 0.6 | 0.05 | 0.05 | 0.05 |
| W-shaped slope inclination (φ) | 0 ° | 3 ° | 3 ° | 0 ° |
| Prestressing arrangement | Fully unbonded | Fully unbonded | Partially debonded | Partially debonded |
| Initial Prestressing force | 3.0 G | 0.0 G | 0.0 G | 0.0 G |

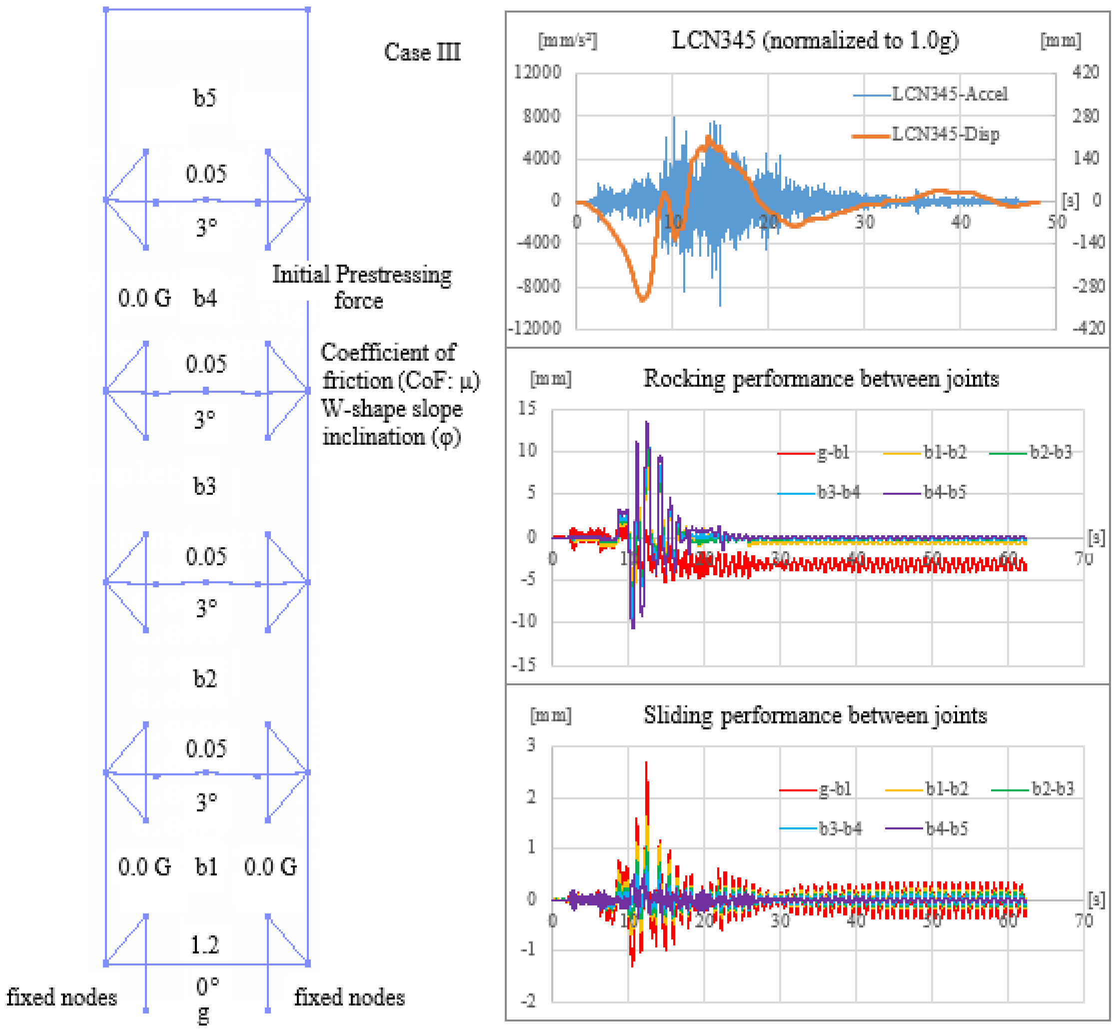


Fig. 3 – Case III: Schematic diagram of construction and responses under LCN345 earthquake

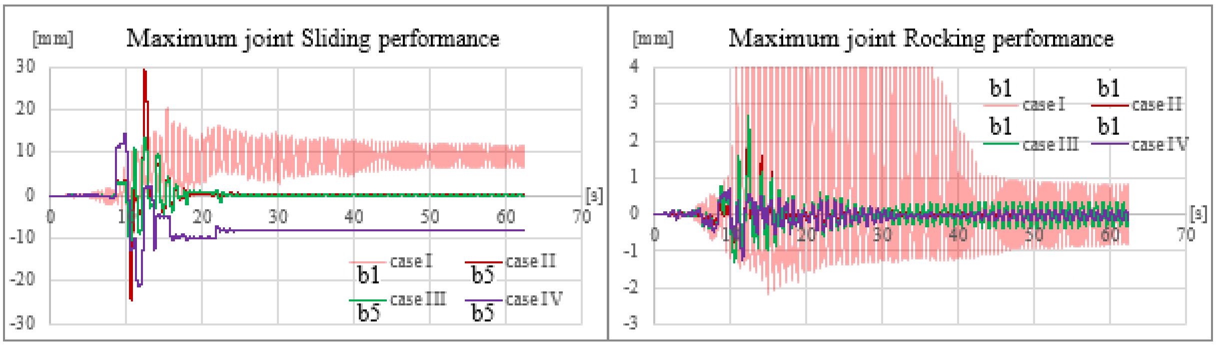


Fig. 4 – Maximum joint rocking and sliding displacements in four cases

Fig. 3 and Fig. 4 show that the maximum rocking occurred at the bottom joint of the column while the maximum sliding happened at the top joint if the CoF was set to be low enough. Negligible residual sliding displacements were obtained in all cases with 3° W-shaped mating surfaces. The sliding displacement was distributed more evenly among all joints in cases using partially debonded tendons.

## 5. Conclusions

Based on the numerical analyses conducted, the following conclusions can be drawn.

(a) The hybrid sliding and rocking performance of segmental columns with resettable sliding joints was captured by a simplified numerical beam model incorporating Flat Slider Bearing Elements and co-rotational Truss Elements under OpenSees environment.

(b) The unfavorable rocking behavior (with low energy dissipation) will be largely alleviated by introducing sliding mechanism to the segmental column.

(c) The low values of initial tendon force and CoF at the interfaces of segmental columns with resettable sliding joints facilitated better seismic isolation and resetting performance. Adopting partially debonded tendon arrangement will further help in optimizing the sliding displacement among all the joints. Given a rather gentle slope at the W-shaped mating surfaces, the initial tendon force and CoF should be chosen tactfully without compromising their resistance against non-seismic horizontal loading conditions, such as the expected wind load.

## 6. References

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