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# INVESTIGATE MULTILEVEL SEISMIC RESPONSES OF BASE ISOLATED TALL BUILDING USING TRIPLE FRICTION PENDULUM BEARING

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## *Abstract*

The global trend towards urbanization has led to unprecedented numbers of people working and living in tall buildings. For cities located in regions susceptible to strong earthquake ground shaking, seismic design of these costly, high-occupancy tall building is always a critical concern for engineers and general public. As a minimum requirement for structural safety, seismic design code for general structure is not enough for tall building. Performance design criteria has been proposed for tall buildings in order to achieve not only safety but also seismic resiliency so that they can continue to be functional with lower repair cost and shorter business downtime following a moderate earthquake.

To achieve seismic resiliency in design, new structural systems and energy dissipation device have been studied and implemented. One efficient approach to enhance seismic performance is using seismic isolation. In this paper, a preliminary investigation of seismic responses for a 30-story tall, base isolated steel moment-resisting frame building is conducted by numerical analysis in Open System for Earthquake Engineering Simulation (OpenSEES). Global responses are evaluated in terms of several key engineering demand parameters (EDPs). Particular attention is paid to achieving improved performance by fine tuning the isolator properties under multi-level seismic events. While tuning can be done for many types of isolation bearings, the Triple Pendulum Friction Bearing (TPFB) is used in the study as it allows a wide variety of hysteretic characteristics to be obtained, which can be readily related to physical and mechanical characteristics of the bearing. Parametric studies have been conducted to investigate the sensitivity of global EDPs to different key design parameters of isolator as well as superstructure under different levels of seismic events.

Based on numerical analysis results, the study first evaluates the effectiveness of using base isolation with different isolation periods to reduce seismic responses for a tall building. By comparing global responses from sensitivity studies on different design parameters, the study concludes that the upper structure responses of isolated tall building are mainly affected by radius of sliding surfaces, smaller radius results into better reduction of responses but with larger bearing deformation as trade off. Floor acceleration responses are sensitive to friction coefficients of sliding surfaces, especially for initial friction coefficient. Small initial friction coefficient not only reduces floor acceleration but improves the responses under frequent earthquake event. Large third friction coefficient is beneficial to control the displacement demand of bearing especially under rare event. The study also shows the advantages of TFPB comparing to Single Friction Pendulum Bearing (SFPB) when bearing deformation is small. In addition, the study reveals shorter fundamental period of superstructure leads to better efficiency of base isolation, while the deflection shape of the tall building is insignificant to the responses.

*Keywords: Seismic Isolation; Tall Building; Seismic Resiliency; Parametric Study; Triple Friction Pendulum Bearing*

## 1. Introduction

Tall buildings are often designed using “performance-based design” concepts for seismic consideration, since the special geometries, structural systems and functional importance take them out of the realm of prescriptive building codes [1]. As a result, performance-based earthquake engineering methods [2, 3, 4] are increasingly used to demonstrate the ability of these structures to satisfy not only the minimum code performance criteria but the enhanced objectives set by the owner. These objectives focus on the engineer criteria of different structural, nonstructural parts, whole building performance as well as economy, impact on society under different level seismic events. The core objective is to achieve seismically resilient design which may end up costly using traditional seismic design method.

As an innovative seismic response control technology to achieve seismically resilient design concept, base isolation is widely used but rarely for high rise structure in US; While structural engineers in Japanese are pioneers on the practice of tall building isolation and hundreds of tall buildings are isolated in Japan [5].

From modal analysis of classical structural dynamics, seismic isolation is effective for a horizontally stiff superstructure. For a flexible upper structure like a tall building, it is not convincible that seismic isolation is effective despite the numerous practical cases in Japan. On the other hand, studies on seismic behavior and design of base isolated tall building are also limited with few specific case studies [6, 7, 8]. Therefore, a more general and fundamental investigation on the effectiveness of base isolation applied to tall building is necessary for further research and practice on this topic.

In terms of seismic isolation, different isolators have been invented, studied, manufactured and implemented across the world. The study uses Triple Friction Pendulum Bearing (TFPB) as an example in the investigation due to its large choices of hysteresis behavior and unique adaptive responses under different levels earthquake shakings [9, 10]. TFPB works based on the principle of pendulum motion [11, 12] and its multi stages' behavior can be used to achieve different objectives under different levels earthquake shaking.

In this paper, a built fixed base 30-story building in Japan is taken as prototype structure with seismic isolation implemented at the base. Global responses of superstructure under three levels of earthquake shakings are investigated numerically in Open System for Earthquake Engineering Simulation (OpenSEES) [13]. Responses are represented by four key engineering demand parameters (EDPs) including story drift ratio, story shear, floor displacement and floor acceleration. In the study, particular attentions are paid on evaluating sensitivity of global these responses due to different key design properties of TFPB (isolation period, effective radius, friction coefficients) and the superstructure system (fundamental period, fundamental deflection shape) under multilevel earthquake hazards.

The study shows the effectiveness of using seismic isolation in tall building and the relation between selection of design parameters and the global seismic responses under different levels seismic hazards by parametric studies. Results of the study will give guidance on selection of design properties in preliminary design phase to achieve the enhanced seismic performance of isolated tall building and serve as a basis to future research and investigation on this topic.

## 2. Study Background

### 2.1 Numerical analysis model

In the study numerical time history analysis is conducted in OpenSEES with simplified analysis model.

#### 2.1.1 Superstructure model

Prototype structure considered in the investigation is a built 30-story tall, steel moment-resisting frame building with fundamental vibration period around 3.7 sec. Simplified 2D elastic "stick" model is used in numerical evaluation with one element representing the horizontal shear behavior of each story.

#### 2.1.2 Isolator bearing model

Simplified isolator model is built in OpenSEES to mimic the multi-linear shear behavior of TFPB in horizontal direction. For the "stick" superstructure model used in the study, only one TFPB element is added at the base to represent the total isolation plane behavior.

### 2.2 Ground motion time histories

Ground motion records used for time history analysis in the study are selected based on Uniform Hazard Spectrum (UHS) developed for downtown San Francisco site [14]. Three probability of exceedance levels are considered: 50% probability of exceedance in 30 years, 10% probability of exceedance in 50 years, and 2% probability of exceedance in 50 years, 20 time series are selected for each level with the mean spectrum matching the target. For the sake of brevity, these three hazard levels will be described as Frequent, Design level, Rare seismic event in the following discussion.

## 3. Responses under different isolator parameters

For a bilinear isolation bearing, properties of isolator commonly refer to horizontal post yield period and characteristic strength. However, for a TFPB with different sliding stages, horizontal shear behavior is characterized by a combination of varied geometry and physical parameters.

As shown in Fig.1 of a traditional TFPB, sliding periods are determined by the effective radius or effective lengths of each sliding surface while bearing strength is characterized by friction coefficients of each sliding surface. Therefore, two sets of parameters are considered in this part of parametric study: Effective length (Radius) of outer (Lo) and inner (Li) sliding surfaces; friction coefficients of two inner sliding surfaces ($\mu_1$), lower outer sliding surface ($\mu_2$) and upper outer sliding surface ($\mu_3$). Analysis results of sensitive study on these parameters under different levels seismic hazards are discussed in the following sections.

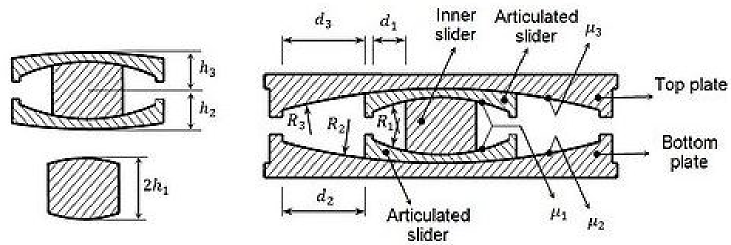



Fig. 1 –Scheme of a traditional TFPB

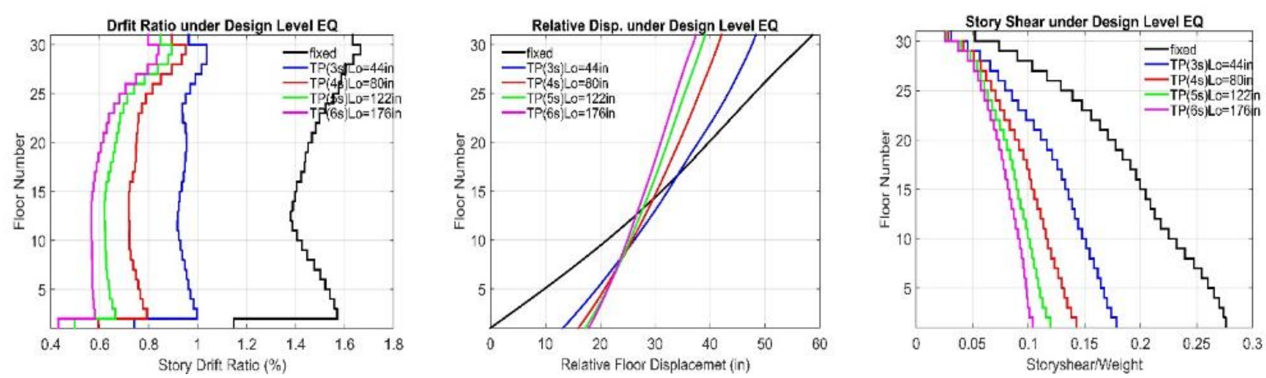
### 3.1 Effects of effective radius

#### 3.1.1 Effects of outer surface radius Lo (isolation period)

Firstly, sensitivity of global responses to the change of Lo is investigated. Lo determines the sliding period of the third which is the main sliding stage of TFPB. Values of Lo considered in this part of study are selected so that main sliding period of 3secs, 4secs, 5secs and 6secs can be achieved. Theses correspond to Lo as 44 inches, 79 inches,122 inches and 176 inches, respectively. The other properties of bearing are kept the same for different cases: with Li=25 inches and friction coefficients as 1% 5% 8%, respectively.

Global responses under design level seismic event are shown in Fig. 2. Firstly, enormous response reduction in the upper building can be achieved using seismic isolation comparing to the fixed base case. Note that the fundamental period of the fixed base prototype building is around 3.7 secs, therefore, even with isolator of a shorter sliding period like 3 secs, responses can still be reduced by almost a half.

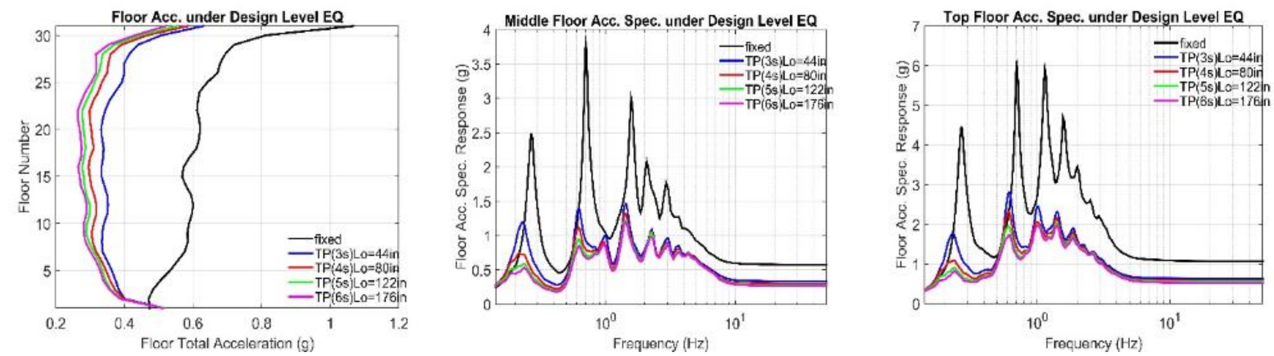
Under design level event, fixed base building will have maximum story drift ratio around 1.5%, which generally indicates light yielding and damage of structural member happens. Using seismic isolation, drift demand can be reduced to smaller than 1% and the upper building will remain almost elastic, which is a great advantage in order to achieve seismically resilient design.




(a) (b) (c)

Fig. 2 –Mean responses of the isolated prototype building comparing to fixed base case under design level (10% 50years exceedance level) seismic event. (a) Maximum story drift ratio response (b) Maximum floor relative displacement response (c) Maximum normalized story shear response

Upper structure responses are sensitive to the change of Lo, large value will result into smaller responses but larger bearing displacement demand as tradeoff. However, under design level seismic event, the bearing displacement demand using a 6 secs bearing comparing to a 3 secs bearing only increases from 13 inches to 18 inches, but drift and force demands in the upper structure can be reduced almost by a factor of two.



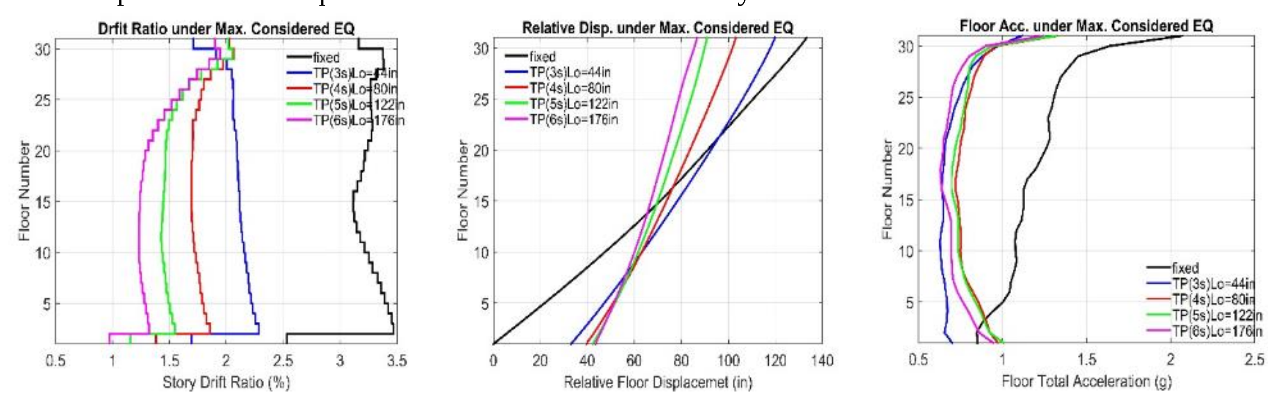

(a) (b) (c)

Fig. 3 – Mean responses of the isolated prototype building comparing to fixed base case under design level (10% 50years exceedance level) seismic event. (a) Peak floor acceleration response (b) Middle level 5% damping horizontal floor spectrum (c) Top level 5% damping horizontal floor spectrum

Floor acceleration responses shown in Fig. 3. Comparing among different isolated cases, acceleration responses are much less sensitive to the change of isolation periods than other responses in Fig. 2. Peak floor acceleration can be reduced by a factor of 2 using seismic isolation. As shown in Fig. 3 (b) and (c), there are a lot of high frequency contents in the response and all peaks are effectively reduced by using seismic isolation. The change of isolation periods has larger impact on low frequency response, therefore, the peak floor acceleration is not sensitive to the change of isolation periods.

Selected responses under rare event (2% 50years exceedance level) are shown in Fig. 4. For the fixed base case, maximum story drift ratio is around 3.5% with elastic superstructure model used in numerical analysis. A residual drift around 2 % may be expected. For base isolated case, minor yielding occurs, which means repair cost and business downtime can be largely reduced after a rare earthquake. Peak floor acceleration can be reduced by a factor of 2 comparing to fixed base case but is not sensitive to different isolation periods as shown in Fig. 4 (c).

Responses under frequent seismic event is not affected by different Lo.




(a) (b) (c)

Fig. 4 –Mean responses of the isolated prototype building comparing to fixed base case under rare (2% 50years exceedance level) seismic event. (a) Maximum story drift ratio response (b) Maximum floor relative displacement response (c) Peak floor acceleration response

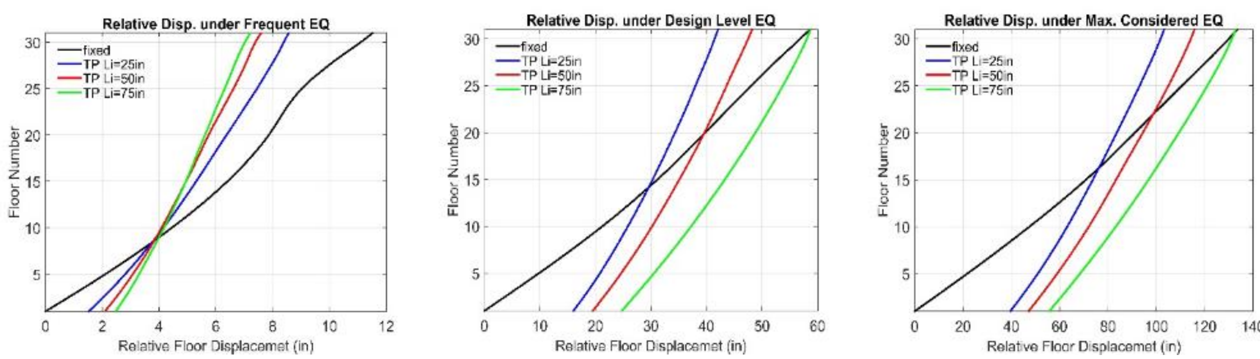
Effectiveness of seismic isolation is evaluated in this part of analysis for the prototype tall building considered. With TFPB, great reduction on global responses can be expected comparing to fixed base case under all level seismic events. Longer isolation period or larger Lo will result into more reduction on story drift ratio and shear demand under design level and rare earthquake events but has little effect on floor acceleration responses.

### 3.1.2 Effects of inner surface radius Li

As discussed in previous section, Lo determines the period of main sliding stage of TFPB, while the effective radius of inner sliding surface Li determines the horizontal stiffness of TFPB at the starting sliding stage and final hardening stage. The effect of inner sliding surface radius Li is evaluated in this section. Three different values: 25 inches, 50 inches and 75 inches are considered with other parameters kept the same. Selected results will be shown and discussed in the following.

Floor displacement responses under three level seismic hazards are shown in Fig.5. Benefits of using seismic isolation against fixed base case is obvious from the plots since part of the displacement demand is taken by the movement of isolator. Under design level and rare earthquake events as shown in Fig.5 (b) and Fig. 5(c), different Li do not affect the response in the superstructure, the only difference is bearing displacement demand. Large Li results into greater bearing movement. However, under frequent earthquake level, drift is slightly affected by different selections of Li as indicated in Fig.5 (a).

Floor acceleration response is not shown and it is not sensitive to change of Li before bearing starts hardening. However, since smaller Li results into larger hardening ratio, larger floor acceleration is expected under rare seismic event with smaller Li when hardening happens.




(a) (b) (c)

Fig. 5 –Mean floor displacement responses of isolated prototype building comparing to fixed base case under (a) frequent (50% 30years exceedance level) seismic event (b) design level (10% 50years exceedance level) seismic event (c) rare (2% 50years exceedance level) seismic event.

Overall, different inner sliding surface radiuses do not have large impact on upper structure response, however, they affect the bearing displacement demands under moderate and larger earthquake hazard levels. Smaller Li value will result into smaller bearing displacement demand. However, if bearing starts to harden when displacement demand is large, selection of smaller Li may result into larger floor acceleration response due to the large hardening stiffness of bearing.

### 3.2 Effects of friction coefficients

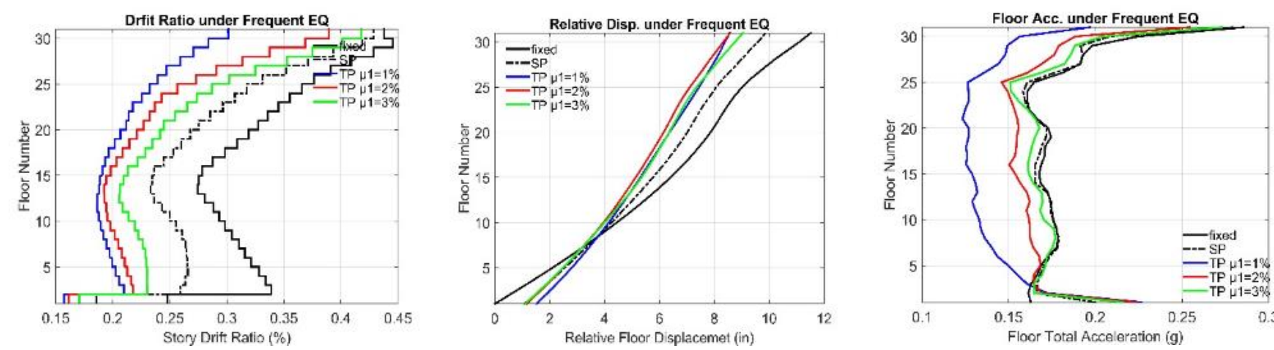
Friction coefficients of sliding surfaces are another set of key design parameters. In this section effect of friction coefficients of each sliding surface is investigated under different level seismic events separately. Sensitivity study of global responses has been conducted on three friction coefficients: $\mu_1$(Friction coefficients of two inner sliding surfaces), $\mu_2$(Friction coefficient of lower outer sliding surface) and $\mu_3$(Friction coefficient of upper outer sliding surface). For comparison, a Single Friction Pendulum Bearing (SFPB) isolated case is analyzed together with cases isolated by TFPB to evaluate the benefits of TFPB over SFPB.

### 3.2.1 Effects of first friction coefficient $\mu_1$

Cases with first friction coefficient as 1%, 2% and 3% respectively are analyzed and compared in this section with other parameters the same. The initial friction coefficient determines the sliding starting point for a TFPB. Therefore, responses under frequent earthquake is first shown in Fig. 6 to evaluate the effect of initial friction coefficient.

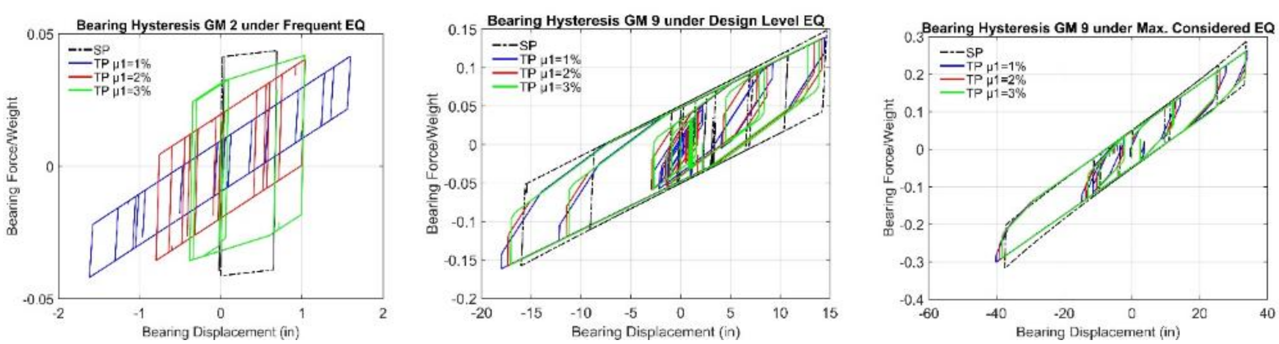
Comparing responses of different TFPB isolated cases, smaller initial friction coefficient result into slightly better responses especially for peak floor acceleration responses. 1% initial friction coefficient can effectively reduce the floor acceleration response while cases with larger initial friction coefficient do not have benefits comparing to fixed base response as shown in Fig.6 (c). SFPB almost does not take effect under frequent earthquake because a large force is needed to trigger the movement of bearing.

Under design level event and rare earthquake events, difference of responses due to first friction coefficients is not pronounced despite some small difference in peak floor acceleration response under design level seismic event. Since the initial friction coefficient mainly affects the hysteresis behavior of TFPB at small deformation range. Comparison of hysteresis behavior under three level seismic events of representative earthquake motions are shown in Fig.7. Clearly, under frequent earthquake, large difference exists with different initial friction coefficients as shown in Fig.7 (a). However, for larger seismic events, hysteresis behavior of different initial friction coefficients is almost the same as shown in Fig.7 (b) and Fig.7 (c).




(a) (b) (c)

Fig. 6 – Mean responses of the isolated prototype building comparing to fixed base case under frequent (50% 30years exceedance level) seismic event. (a) Maximum story drift ratio response (b) Maximum floor relative displacement response (c) Peak floor acceleration response




(a) (b) (c)

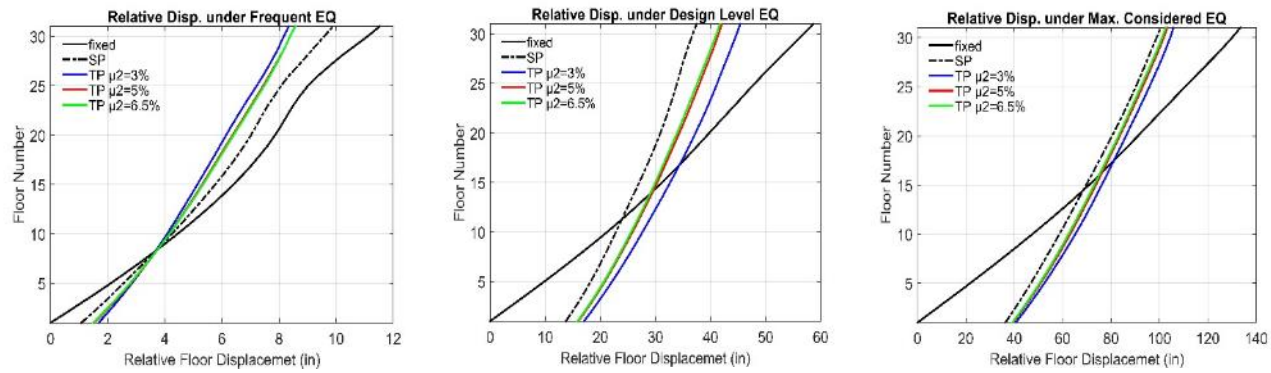
Fig. 7 – Comparison of hysteresis behavior of bearings under three level seismic events considered in the study. Reponses of one representative ground motion under each level are shown. (a) Response under frequent seismic event (b) Response under design level seismic event (c) Response under rare seismic event.

Overall, for the isolated tall building considered in the study, displacement based responses of the upper structure are not affected by the change of initial friction coefficient while floor acceleration response is more sensitive to this parameter, with smaller friction, lower acceleration can be obtained.

### 3.2.2 Effects of second friction coefficient $\mu_2$

Different second friction coefficients with 2%, 5% and 6.5% are evaluated with other parameters the same. Same as initial friction coefficient, the second friction coefficient does not affect the upper structure responses. Peak floor displacement responses under the three level seismic events considered are shown in Fig. 8. From the results, difference of responses on the upper structure can barely be noticed.

As shown in Fig.8, displacement shapes for cases with different second friction coefficients are parallel to each other which indicates drift responses on superstructure are identical. The only difference which can be noticed is slightly smaller bearing displacement demand one can get with larger second friction coefficient. Acceleration responses are not shown here since they are not affected by the change of second friction coefficients at all.




(a) (b) (c)

Fig. 8 –Mean floor relative displacement responses of isolated prototype building comparing to fixed base case under (a) frequent (50% 30years exceedance level) seismic event (b) design level (10% 50years exceedance level) seismic event (c) rare (2% 50years exceedance level) seismic event.

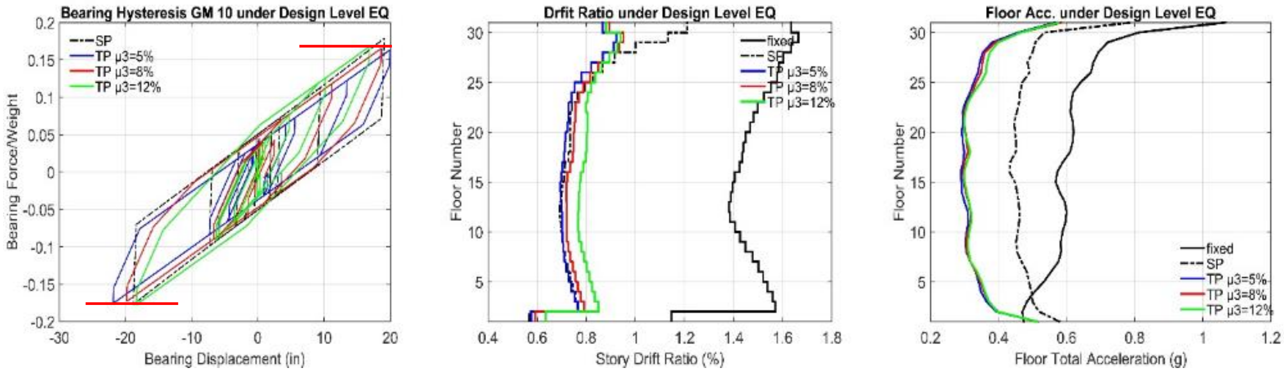
Overall, second friction coefficient has almost no effect on global responses of the isolated tall building. Note that the comparison for different cases with varied second friction coefficients reflects only the influence of second friction coefficient. Since in this part of parametric study, when considering each different friction coefficients, hysteresis behavior is adjusted for each case so that the remaining behavior is exactly the same except the portion where a certain friction coefficient affects. Therefore, no other effect is introduced but the friction coefficient evaluated.

### 3.2.3 Effects of third friction coefficient $\mu_3$

Finally, different third friction coefficients (5%, 8%, 12%) are considered to evaluate the sensitivity of responses to this largest friction coefficient. Third friction coefficient determines the final yielding strength before the main sliding stage of TFPB starts.

Under frequent earthquake event, since the deformation of TFPB is small, third friction coefficient has not been reached in the bearing hysteresis yet, therefore, the global responses are not affected.

Under design level and rare seismic events, influences of different third friction coefficients of TFPB start to be noticeable. Since the yielding forces are different, with same displacement, larger third friction coefficient will result into more hysteresis damping. Therefore, bearing deformation demand is affected by third friction coefficient. However, for responses of superstructure, which is mainly affected by isolator force, since all the cases will end up with the same force level, responses actually end up similarly. To illustrate this point, results of isolator hysteresis behavior together with drift demand and acceleration demand under design level event is shown in Fig. 9. Notice that the bearing forces all end up with almost the same level despite the bearing displacement is different as shown in Fig. 9 (a). Story drift and floor acceleration responses shown in Fig.9 (b) and Fig. 9 (c) are almost the same for different TFPB cases.

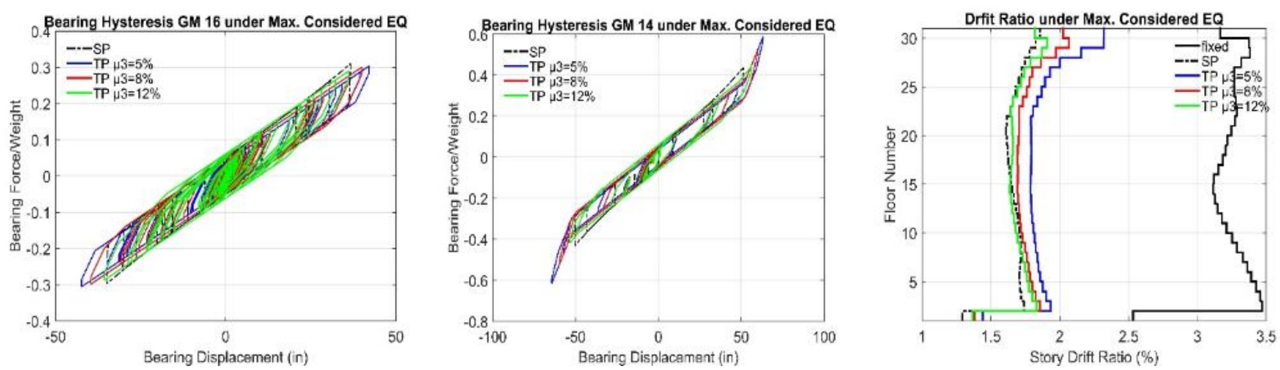



(a) (b) (c)

Fig. 9 – Responses under design level seismic event (10% 50years exceedance level). (a) Bearing hysteresis response under a representative ground motion (b) Maximum story drift ratio response (c) Peak floor acceleration response

Under rare seismic event, there are slightly differences in global responses as shown in Fig. 10 (c) and larger third friction coefficient results into smaller response, which seems to be contrast as what normally known since larger yield force should result into larger force demand on the upper structure. However, when bearing displacement demand is large, isolator yielding forces will not dominant the total force in the isolator. At the start of sliding, bearing with large third friction coefficient apparently has larger total force. Then force increases due to deformation of bearing and this part of force is larger for the case with smaller friction coefficient since displacement is larger, thus total force is larger as shown in Fig. 10 (a) below. Another reason is for some of the rare ground motion records evaluated, TFPB starts to harden. Large friction coefficients result into smaller displacement demand and smaller portion of hardening, which can be seen in Fig.10 (b) below. Therefore, smaller responses of upper structure are expected for large third friction coefficient under rare seismic event.

Overall, third friction coefficient does not effectively affect responses under frequent or design level seismic events. However, under rare earthquake event, large third friction coefficient is more beneficial to have both smaller superstructure response and bearing response.




(a) (b) (c)

Fig. 10 – Responses under rare seismic event (2% 50years exceedance level). (a) Bearing hysteresis that hardening does not start. (a) Bearing hysteresis that hardening starts (c) Maximum story drift ratio response

## 3.3 Summary on effects of bearing properties

Sensitivity studies have been conducted to investigate the effect of bearing properties on global responses of base isolated prototype building. Great reduction on seismic response of upper structure can be achieved using isolation especially for TFPB. Comparing to bilinear hysteresis bearing, TFPB has great advantage on reducing responses under frequent earthquake and floor acceleration response.

Global responses are sensitive to different bearing properties, drift and story shear demand are mainly affected by the change of outer sliding surface radius or the isolation period of the main sliding stage of TFPB.

Large period results into smaller responses. The inner sliding surface radius does not quite affect the superstructure response but has a large impact on bearing displacement demand.

The upper structure response is not sensitive to the change of friction coefficients of bearing, however, floor acceleration response is sensitive to the change of initial friction coefficient. With smaller value results into smaller peak floor acceleration. Large third friction coefficient will result into slightly better global response under rare event.

Therefore, the radius of the sliding surface for the isolation system considered in the study is the primary parameter affecting responses of superstructure and needs to be considered in the first place in design. Friction coefficients or yielding force of the bearing is a secondary parameter which can be properly selected to further adjust the response especially for floor acceleration response.

Sensitivity of global responses of TFPB isolated tall building to different bearing properties are show in Table 1.

Table 1 – Summary on sensitivity of global responses to bearing design properties of TFPB

| **Seismic level considered** | **50% 30years level** | **10% 50years level** | **2% 50years level** |
|---|---|---|---|
| **Floor acceleration** | $\mu_1$ (+) | $\mu_1$ (+) | $\mu_3$(-), Li (-) |
| **Story drift ratio** | $\mu_1$ (+) | Lo (-) | Lo (-) |
| **Story shear force** | $\mu_1$ (+) | Lo (-) | Lo (-) |
| **Bearing displacement** | $\mu_1$ (-) | Lo (+), Li (+), $\mu$3(-) | Lo (+), Li (+), $\mu_3$ (-) |

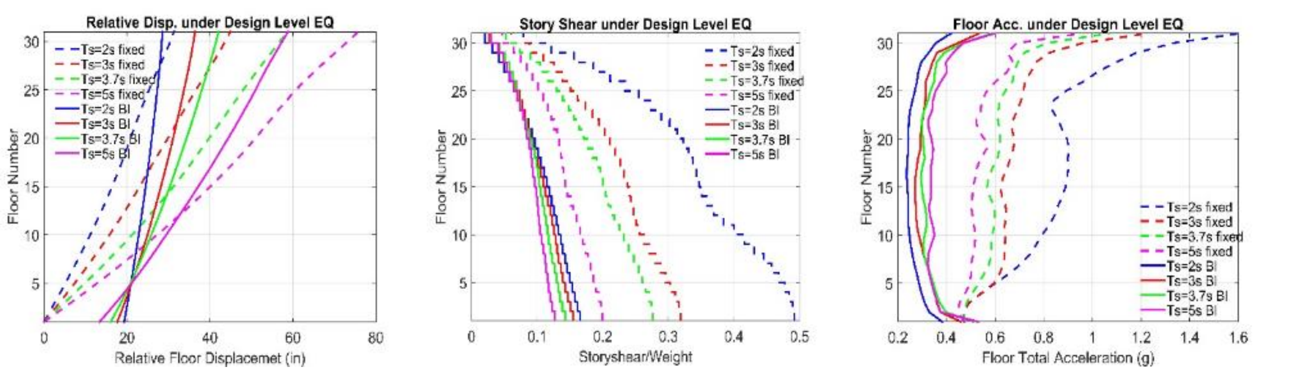
Note: + means larger value results into lager response, - means larger value results into smaller response

## 4. Responses under different superstructure properties

In this section, sensitivity of the isolated prototype building responses due to different superstructure key properties are investigated. Fundamental period of the superstructure (Ts) and the fundamental deformed shape are the two parameters considered. Responses and conclusions are briefly discussed in the following sections.

### 4.1 Effects of superstructure fundamental period (Ts)

The superstructure fundamental periods considered in the parametric study are 2sec, 3sec, 3.7sec (original prototype structure fundamental period) and 5sec. Story horizontal stiffness distribution along height and other properties remain the same for different cases. Bearing used in this part of study are TPFB with friction coefficients of 1% 5% 8% and 4 secs as main isolation period. Superstructure global responses under design level seismic event are shown in Fig. 11 below.




(a) (b) (c)

Fig. 11 – Mean responses of the isolated prototype buildings with different fundamental periods comparing to fixed base cases under design level (10% 50years exceedance level) seismic event. (a) Maximum floor relative

displacement response (b) Maximum normalized story shear response (c) Peak floor acceleration response

For a fixed base structure, smaller drift ratio but larger force and floor acceleration demand will be expected for a shorter fundamental period as shown in the comparison of dashed lines in Fig. 11. However, when the structure is isolated, because of the larger difference in superstructure stiffness and isolation stiffness, one with short fundamental period will undergo larger bearing displacement as shown in Fig.11 (a). Drift response in the superstructure will be reduced enormously for those with shorter superstructure fundamental period.

For force demand and acceleration demand as shown in Fig. 11(b) and Fig.11(c), differences in fixed base responses diminished after being isolated because the differences of isolator forces due to different isolator displacements are much smaller due to its low sliding stiffness. Therefore, with shorter superstructure fundamental period, one can expect better efficiency in terms of reducing force and floor acceleration demand using seismic isolation while the bearing displacement demand will be larger. However, for larger fundamental period superstructure, isolation is still effective.

Responses under frequent and rare event will not be discussed further since the conclusions are the same. It reveals the fact that seismic isolation works better for a stiffer superstructure. However, for cases with upper structure whose fundamental period is difficult to reduce to a small value, seismic isolation still works fine and has much smaller responses comparing to the fixed base case.

## 4.2 Effects of superstructure fundamental deflection shape

Superstructures which have different deflection shapes (First mode deformation shape) with the same fundamental period (3.7 sec as original prototype building) have been investigated in this part of study. Four different horizontal stiffness distributions along height have been considered as shown in Fig. 12 below.

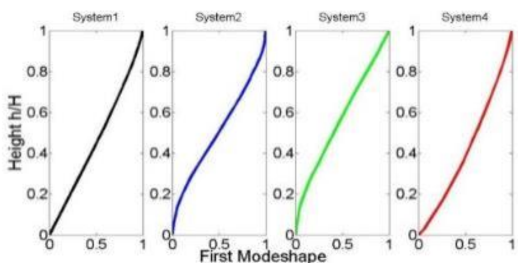
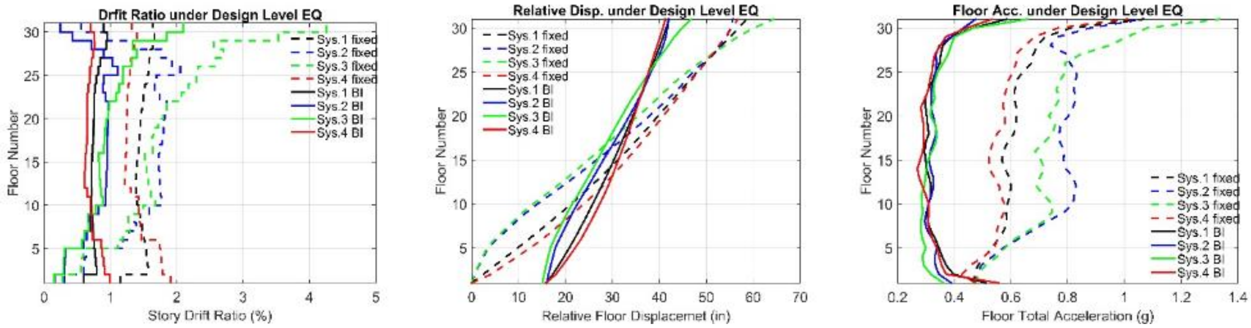



Fig. 12 –Different deflection shapes considered.

Global responses under design level seismic event are shown in Fig. 13. For the fixed base case, as shown in Fig. 13 (b), the total maximum floor displacement response preserves the fundamental deformation shape of the building. And so does the drift ratio along height. After being isolated, the displacement shape of the building remains the same as fixed base case, however, the amplitude of responses within the superstructure is smaller. The isolator responses are not affected by different superstructure deflection shapes as shown in Fig. 13(b) that the deformations in isolation plane are almost the same at the base. Drift responses are reduced but with the same distribution along height as fixed base case.

For floor acceleration response, not only the response amplitude is largely reduced by using seismic isolation, difference of response shapes along height for different cases are almost diminished. Responses under frequent and rare seismic events are not shown and discussed since they yield the same conclusion.

Overall, the fundamental deflection shape of the tall building does not affect the effectiveness of seismic isolation. The difference on the upper structure responses due to different stiffness distribution along height is preserved after using seismic isolation for displacement based response, while for acceleration response, this different is diminished.




(a) (b) (c)

Fig. 13 – Mean responses of the isolated prototype buildings with different fundamental deflection shapes comparing to fixed base cases under design level (10% 50years exceedance level) seismic event. (a) Maximum story drift response (b) Maximum floor relative displacement response (c) Peak floor acceleration response

## 5. Conclusion

The study investigates the effectiveness of using seismic isolation for tall building and the sensitivity of seismic responses of isolated tall building to different key design parameters of isolator and superstructure. Conclusions and findings are based on numerical analysis results using simplified model of a 30 story tall building with TFPB implemented at base. Responses are evaluated under three level seismic hazard conditions.

Comparing with fixed base building, seismic isolation is very effective in reducing superstructure responses for the prototype tall building even with an isolation period closed to the fundamental period of the building.

TFPB has great advantage in reducing upper structure responses comparing to SFPB under frequent earthquake event especially for floor acceleration response.

The upper structure drift ratio and story shear demand are most sensitive to the isolation period. Larger outer sliding surface radius or larger main sliding period results into smaller responses but larger bearing deformation demand as trade off. Bearing deformation response is also sensitive to the inner sliding surface radius of TFPB, where smaller value results into smaller response.

Friction coefficients of TFPB does not quite affect the upper structure drift or force demand but affect the floor acceleration response. Especially for initial friction coefficient, smaller initial friction coefficient will result into smaller floor acceleration response. The change of third friction coefficient does not affect the superstructure response much but will reduce the bearing displacement demand with large value and limit hardening when bearing displacement demand is large so that smaller portion of damage will be propagated up to the superstructure.

The superstructure properties do not affect the isolated prototype building much, however, smaller fundamental period of superstructure is desired since it results into larger bearing displacement demand and smaller relative deformation in the superstructure, the effectiveness of seismic isolation will be more pronounced. The fundamental deflection shape of the tall building will determine the maximum displacement shape responses along the height for the tall building no matter for fixed base case or base isolated case. It will not affect the effectiveness of seismic isolation system.

The study uses elastic stick model in OpenSEES for 2D analyses, however, for some cases under rare seismic event, yielding in the superstructure happens due to the hardening of TFPB. Therefore, a nonlinear superstructure model will be needed to better capture the behavior of the isolated building under rare seismic hazards. Meanwhile, in some of the analysis cases in the study, tension force does develop in the outer bearing because of overturning effect and uplifting of TFPB may be expected. A more detailed bearing model which captures the 3D movement and uplifting and post-uplifting behavior will be needed for future study. However, this study provides essential basic theory and conclusions on the behavior of TPFB isolated tall building under multi-level seismic hazards and gives guidance on design and more advanced study on this topic.

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