16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2663 (Abstract ID)

Registration Code: S-I1462913372

UNDERSTANDING AND DESIGN OF SEISMICALLY ISOLATED STRUTURE USING HARDENING OF BEARING

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Abstract

For cities located in regions susceptible to strong earthquake shakings, seismic design of buildings and other facility is always a critical concern for structural engineers as well as general public. Nowadays, with the development of seismic design concepts and tools, structural safety is not the only design objective. The new concept of seismically resilient design, which aims at a higher seismic performance objective such as continually functional and shorter business downtime, is more and more accepted and implemented by earthquake engineering community.

As an innovative seismic response control technology to achieve resilient design concept, seismic isolation has been widely studied and used. Classical idea of seismic isolation uncouples the upper structure movement from ground motion by concentrating displacement demand in isolation plane.

However, when displacement demand is larger than the deformation capacity of isolator bearings, a failure of the isolated system will be expected, either due to the failure of bearings themselves or the large impact force introduced to the upper structure when the horizontal movements of isolator bearings are rigidly stopped. An unacceptable large risk of failure for the isolated system may be expected if the displacement capacity of isolation plane is not large enough. However, it is not economic or even not possible to provide large enough displacement capacity with a bearing designed to have constant low horizontal stiffness.

Instead of using traditional isolator bearing with bi-linear hysteresis behavior, the study uses hardening bearing with increasing stiffness under large displacement and seeks an effective solution to provide enough deformation capacity and safety level for base isolated structure under beyond design seismic scenarios. However, hardening of bearing will introduce large force demand into the superstructure, therefore, the key problem to be solved in this study is how to find the balance point where enough hardening occurs to provide required displacement capacity without introducing too much damage into superstructure.

The study takes Triple Friction Pendulum Bearing (TFPB) as an example of general hardening bearings. Seismic responses of a three story base isolated braced frame prototype structure with TFPB are evaluated numerically. Special attentions are paid to responses under beyond design seismic events when bearing starts to stiffening. Parametric studies have been conducted on key parameters characterizing the hardening of bearing. Based on comparison of numerical analysis results for different cases, recommendation on selection of these parameters are made through a proposed preliminary design approach.

Keywords: Base Isolation; Safety of Isolated Structure; Bearing Hardening; Parametric Study

1. Introduction

Performance-based design concept is increasingly used for seismic design. It demonstrates the ability of structures to satisfy not only the minimum code requirement for safety but more enhanced performance objectives under multi-level seismic events [1]. These objectives focus on the engineer criteria of different structural, nonstructural parts as well as economy impact on society. Core of the concept is to achieve seismically resilient design which may end up costly using traditional method.

As an innovative technology and effective way to reduce seismic responses in structures, seismic isolation serves an important role in achieving seismic resiliency. However, despite the enhanced performance a seismically isolated structure can achieve, safety is still the priority under beyond design and rare seismic events. Safety of base isolated structural system contains two parts: the upper structure safety which is characterized by the dynamic responses of the structure and the isolator bearing safety which requires large displacement capacity. Since seismic isolation works by decoupling the ground movement from superstructure responses and concentrating the deformation demand within the isolation plane, a large horizontal displacement capacity of isolator is commonly required. Current regulation for design of seismically isolated structure suggests the displacement capacity of bearing be selected based on the mean response under maximum considered earthquake (MCEr) level seismic event [2]. However, considering the uncertainty of ground motions and other effects, there is a large chance for this displacement limit being exceeded which may then result into unacceptable failure risk of the isolated system. In addition, if moat walls or other displacement restrained mechanism are used in design, the sudden stop of the isolator movement will introduce large impact load and unpredictable local damage into upper structure. Therefore, a large enough displacement capacity of bearing, larger than code requirement, which can provide acceptable small risk of being exceeded, is essential for consideration of bearing stability and isolated system safety. However, it is commonly not economic or even impossible for a bearing to provide low horizontal stiffness up to that large enough displacement capacity.

A more efficient way to achieve this large displacement demand and to protect both the upper structure and the isolation system from failure is needed. The key issue for the traditional design concept for seismically isolated structure is that the idea of "minimizing damage" is overly used. By using a bearing with constant low horizontal stiffness, decoupling of the upper structure response from ground movement starts when bearing begins to move until bearing displacement capacity is reached. The objective of minimizing damage is achieved and followed by large damage or even sudden failure of the system. Minimizing damage to achieve seismic resiliency is the performance objective under a certain level seismic event. Beyond that and before the system finally fails, the main objective should be remaining safety and a transition from resiliency to failure is desired.

Based on this concept, the study establishes a new behavior objective of the isolated structure under beyond design level seismic event where force demand, yielding and damage are slowly introduced into upper structure. To achieve this behavior, isolator bearing with an increasing stiffness under large displacement is used. By including the hardening portion of bearing, a much larger displacement demand can be achieved.

The study takes Triple Friction Pendulum Bearing (TFPB) as an example in the investigation. As a widely used isolator bearing, TFPB works based on the principle of pendulum motion [3, 4] and the adaptive multi-stage behavior has an increasing horizontal stiffness when displacement is large [5, 6, 7, 8]. Different types of hardening bearings have already been implemented in practice, the study aims to understand how to properly use the hardening of bearing and how to design it to satisfy the safety objective of base isolated structure.

In this paper, a base isolated three story ordinary concentrically braced frame system (BI-OCBF) is taken as the prototype structure, seismic responses under varied earthquake intensities are evaluated through numerical time history analysis conducted in Open System for Earthquake Engineering Simulation (OpenSEES) [9]. Firstly, effect of bearing hardening is evaluated. Parametric studies on key design parameters characterizing bearing hardening are conducted in order to investigate their effects on superstructure responses. Based on numerical analysis results, a simplified preliminary design procedure using TFPB to achieve safety design risk objective for the prototype isolated building is proposed and validated with full risk calculation.

2. Study Background

2.1 Numerical analysis model

Numerical time history analysis is conducted in OpenSEES with nonlinear structural model in the study.

2.1.1 Superstructure model

Prototype structure considered in the investigation is a three story base isolated ordinary concentrically braced frame (BI-OCBF). Nonlinear analysis model capturing the material and geometric nonlinearity is constructed in OpenSEES with distributed plasticity force-based members [10]. Brace buckling and post buckling behavior as well as low cycle fatigue [11, 12, 13] are considered in the modelling to better capture the behavior of upper structure after yielding.

2.1.2 Isolator bearing model

Simplified isolator model is built in OpenSEES to mimic the multi-linear shear horizontal behavior of TFPB. Note that when bearing displacement capacity is reached, the model uses a stage with large horizontal stiffness to simply represent the behavior of hitting moat wall and displacement restrained rim of TFPB. Friction coefficients for TFPB used in analysis are 1%, 4% and 7% respectively for different sliding surfaces with main sliding isolation period as 5.5 secs.

2.2 Ground motion used in time history analysis

2.2.1 Dispersion ground motion set

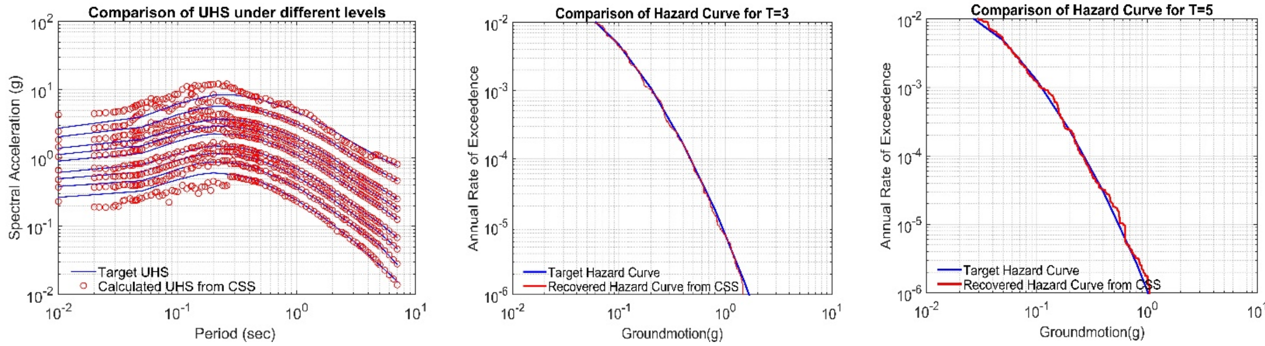
Different sets of ground motion time histories are used for different parts of analysis in the study. The prototype building is fictitiously located at Oakland, California. For evaluation of responses under maximum considered earthquake event, a set of 20 ground motion time histories are selected based on a 2% 50 years' exceedance uniform hazard spectrum (UHS) [14]. Note for simplicity, the term "MCEr level" is used while the actual target spectrum is not code specified MCEr spectrum but 2% 50years UHS.

2.2.2 Increasing intensities ground motion set

For the purpose of parametric study, ground motion with different intensities are used. The set is generated by scaling a single ground motion time history in the MCEr dispersion ground motion set which gives the median responses. The scaling is from 50% to 150% with a scale step as 10%.

2.2.3 Ground motions generated from conditional scenario spectrum (CSS)

For risk evaluation, 596 time histories with optimized rate of occurrence for each time history are selected based on CSS at the site [15]. Seismic hazards at all levels within the period range interested for the site are fully recovered. The recovered hazards are shown in Fig. 1.



(a) (b) (c)

Fig. 1 –Comparison of Target hazard curve and recovered hazard using CSS approach for Oakland site. (a) Comparison of uniform hazard curves at different levels (b) Comparison of hazard curve at 3 secs (c) Comparison of hazard curves at 5 secs

3. Responses Under Bearing Hardening

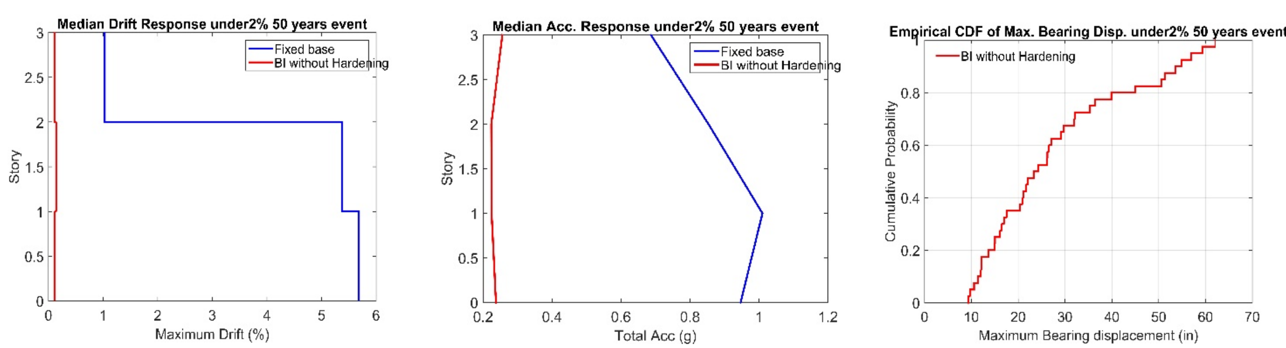
As discussed above, the objective is to use hardening of bearing to transfer force demand into superstructure when bearing displacement is large under rare seismic event. In this section, effects of increasing stiffness of bearing on upper structure responses are evaluated.

3.1 Preliminary evaluation of responses under MCEr level event

Firstly, responses of prototype structure with a non-hardening bearing is evaluated under MCEr ground motion set. This preliminary evaluation aims to obtain amplitude and distribution of responses under MCEr level event which will be used in the following study. Selected responses are shown in Fig.2. Huge reduction on upper structure responses comparing to the fixed base case can be obtained as shown in Fig.2 (a) and Fig.2 (b). Large dispersion of bearing displacement demand is expected as shown in Fig.2 (c).

3.2 Evaluation of responses under bearing hardening

Then responses of the isolated prototype building with a hardening bearing are compared with a non-hardening bearing case under different intensities of ground motions. In this part of analysis, the hardening bearing (TFPB) with a displacement capacity of 32 inches (0.8m) is used with other parameters as discussed in section 2.1.2. Upper structure responses under a representative ground motion intensity are shown in Fig.3.



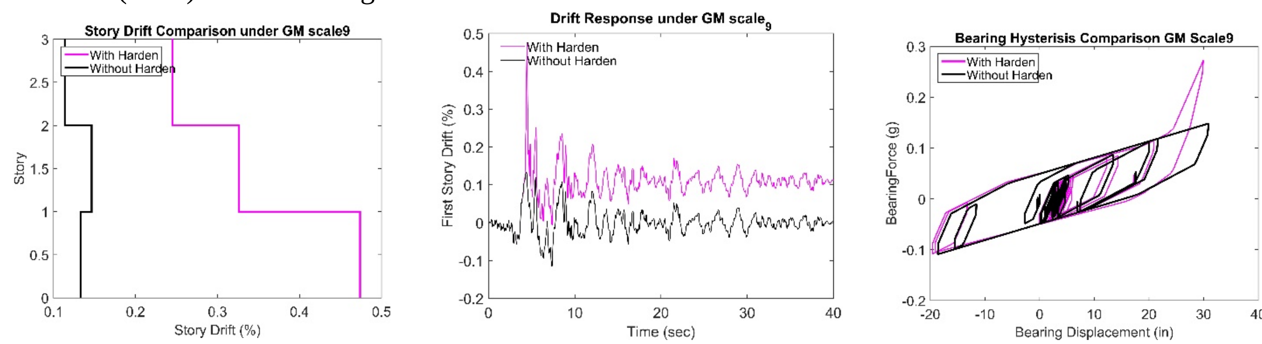
(a) (b) (c)

Fig. 2 –Mean responses of the base isolated (Non-hardening bearing) prototype building comparing to fixed base case under MCEr level (2% 50years exceedance level) seismic event. (a) Maximum story drift ratio response (b) Peak floor acceleration response (c) Bearing displacement demand distribution

Comparing responses between isolated prototype buildings with non-hardening bearing and hardening bearing, drift demand increases from around 0.15% to 0.4% as shown in Fig.3 (a) when bearing hardens and a residual drift around 0.1% is expected as shown in Fig.3 (b). Larger floor acceleration will be introduced into superstructure especially on the lower floor because of the increasing bearing stiffness at the base.

Although drift demand increases by almost a factor of 3 because of bearing hardening, the increased demand is only 0.4%. Buckling of brace members starts to happen and slightly yielding in the upper structure will be expected. Note that the representative ground motion intensity shown in Fig. 3 corresponds to 130% median MCEr level, achieving seismic resiliency and minimizing damage in superstructure should not be the prior performance objective under such rare seismic event. Therefore, the increased responses on superstructure are acceptable for consideration of safety. Comparison of bearing hysteresis is shown in Fig.3 (c). Notice that the maximum displacement demands are almost the same for the two bearings. However, because of the inclusion and usage of hardening portion, a more economic design is obtained.

For example, considering a real bearing which needs to have around 32 inches (0.8m) displacement capacity as indicated in Fig. 3(c), a non-hardening bearing, either single friction pendulum bearing (SFPB) or a lead rubber bearing (LRB) needs to provide 32 inches (0.8m) non-hardening deformation. However, if hardening of bearing is considered and properly used, a TFPB of almost half the size or a LRB which only needs to provide 20 inches (0.5m) non-hardening deformation will be needed.



(a) (b) (c)

Fig. 3 –Responses of the isolated prototype building with hardening bearing and non-hardening bearing under a representative ground motion around 130% median MCEr level. (a) Maximum story drift ratio response (b) First story drift ratio time history response (c) Bearing hysteresis responses

3.3 Summary and discussion

Hardening of bearing will introduce larger responses into superstructure, however, comparing to responses of fixed base case, great reduction can still be achieved. Considering the seismic hazard level that hardening normally happens, the amount of yielding and damage introduced in the upper structure is acceptable. Hardening will not take effect until a rare enough event happens, therefore, seismic resiliency under a moderate or design level seismic event will not be affected.

In addition, as discussed above, the use of hardening portion of bearing will make the bearing design more efficient and economic, in some extreme cases with very large bearing displacement demand due to high safety requirement, it may be the only choice.

The key remaining issue is how to properly implement it in design, how to properly design the bearing so that hardening happens at the correct displacement and results into a failure risk which is acceptable small. In practice, hardening bearings such as LDR, TFPB or HDRB are used for many projects, however, whether they are specially considered and designed so that an acceptable small risk of failure can be achieved is important.

In the following section, parametric study will be conducted on the effects of key design parameters which characterize the hardening behavior of bearing. With the analysis results, an idea of how to correctly select the parameters according to specific safety target is summarized and a preliminary design method is proposed and validated.

4. Parametric Study on Hardening Parameters of Bearing

In this section two parameters which characterize the hardening behavior of TFPB will be investigated through parametric study. The two parameters considered are the hardening ratio (α) which is defined as the ratio of the constant hardening stiffness (Stage 5 of TFPB) to the stiffness of main sliding stage (Stage 3 of TFPB) for a TFPB and the hardening displacement (D_h) which is defined as the start point of increasing stiffness when TFPB goes into large horizontal displacement.

Parameter values considered in each analysis case in the parametric study are summarized in Table 1. The median and the standard deviation used to characterize D_h are obtained from bearing displacement demand distribution under MCEr ground motion set as shown in Fig.2 (c).

4.1 Effects of different hardening ratios

Firstly, effects of different bearing hardening ratios are investigated and discussed. Responses of prototype building are evaluated under increasing intensities of ground motions. Selected global responses for different hardening ratio cases are plotted together for comparison under representative ground motion intensity as shown in Fig. 4. The representative ground motion corresponds to an intensity level around 130% median MCEr seismic event, which is the largest intensity evaluated in this part of study that will not result into bearing displacement capacity being exceeded. Thus, effects of hardening on upper structure responses are the largest under this representative ground motion.

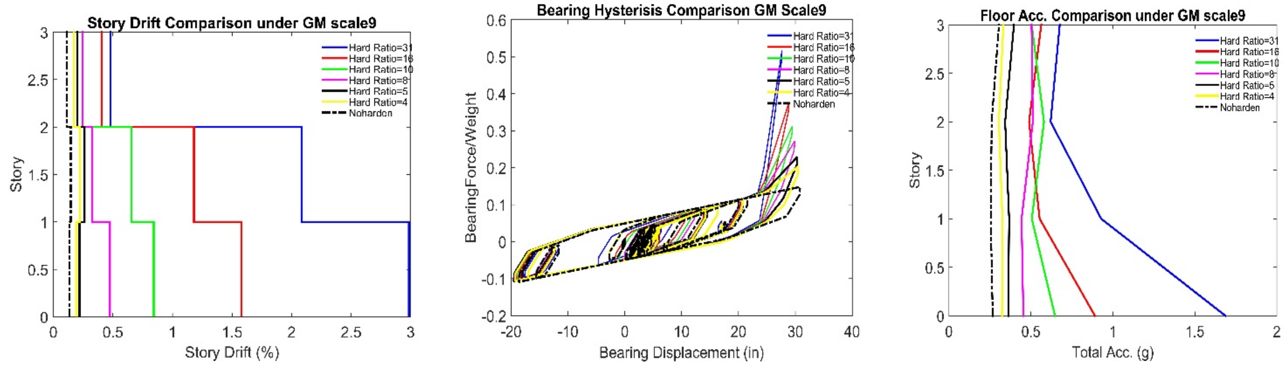
Table 1 – Summary on parametric study cases

	Case	**Harding Ratio α**	**L_1 (in)**	**D_h start (in)**		$D_{capacity}$ **(in)**
Effects of Different Hardening Ratios	1	*31*	5	Median -0.3std	19	31
	2	*16*	10	Median -0.3std	19	31
	3	*10*	15	Median -0.3std	19	31
	4	*5*	30	Median -0.3std	19	31
	5	*4*	40	Median -0.3std	19	31
Effects of Different Hardening Start Displacements	6	8	20	*Median-0.9std*	9	22
	7	8	20	*Median -0.6std*	14	27
	8	8	20	*Median -0.3std*	19	31
	9	8	20	*Median*	23	36
	10	8	20	*Median +0.3std*	28	41
	11	8	20	*Median +0.6std*	33	45
	12	8	20	*Median +0.9std*	37	50

Note: L_1 corresponds to the inner sliding surface effective radius which determines the hardening stiffness of TFPB.

As shown in Fig.4 (a), larger hardening ratio results into increased story drift demand. Hardening ratio smaller than 5 will make almost no difference in responses comparing to the non-hardening bearing case shown as black dashed line. For an extreme case that hardening ratio is around 30, maximum story drift about 3% is expected in the superstructure. For the prototype building evaluated in the study, a 3% drift indicates severe yielding and damage in the upper structure and approximately 2% residual drift will be expected from time history responses. Collapse of the upper structure may not happen, but the damage introduced into upper structure is too much to be accepted. The objective to use hardening of bearing is to gradually transfer the force demand into superstructure and control the damage introduced into the upper structure in an acceptable range. Therefore, a hardening ratio in between is desired

In addition, from Fig.4 (a) and Fig.4 (c), larger responses are concentrated in the lower floor levels since force and acceleration demand are propagated into superstructure by the increasing force of bearing at the base.



(a) (b) (c)

Fig. 4 – Responses of the isolated prototype building under representative ground motion level for different hardening ratios of bearings. (a) Maximum story drift ratio response (b) Bearing hysteresis response (c) Peak floor acceleration response

Then, for further discussion, maximum drift responses for different hardening ratios cases under all ground motion intensities considered are shown together in Fig. 5. As discussed in section 2.2.2, ground motion intensities considered are from around 50% to 200% median MCEr level. Note as shown in Table 1, the displacement capacity for bearings with all hardening ratios have the same displacement capacity as 31 inches (0.79m). When bearing displacement capacity is exceeded, forces will start to shoot up quickly because of the large horizontal stiffness assigned to the bearing as discussed in section 2.1.2. 5% drift is used as an indicator of collapse for the prototype structure and analysis with higher ground motion intensities will stop when drift already reaches 5% as Fig. 5 indicates.

As shown in Fig.5, if bearing hardening ratio is too large such as 30 represented by the blue line, story drift starts to increase so quickly when hardening starts and upper structure will collapse in an early stage. When using a smaller hardening ratio bearing as indicated by the yellow line in Fig. 5, in the beginning, it behaves similar as the non-hardening bearing, however, when displacement capacity is reached, drift starts to shoot up very fast. From the comparison of numerical analysis results, a hardening ratio in between around 10 is desired.

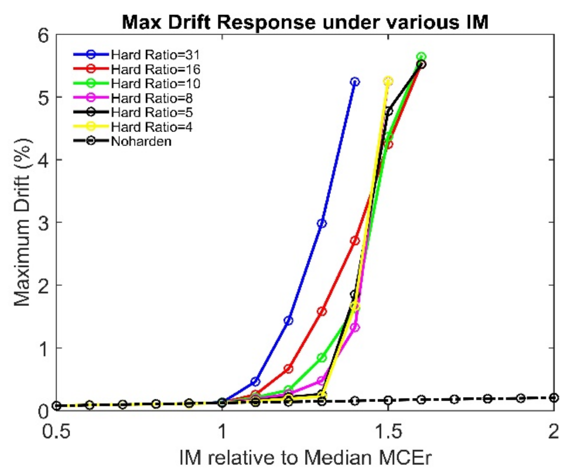


Fig. 5 –Maximum story drift responses under increasing ground motion intensities for different cases with different bearing hardening ratios

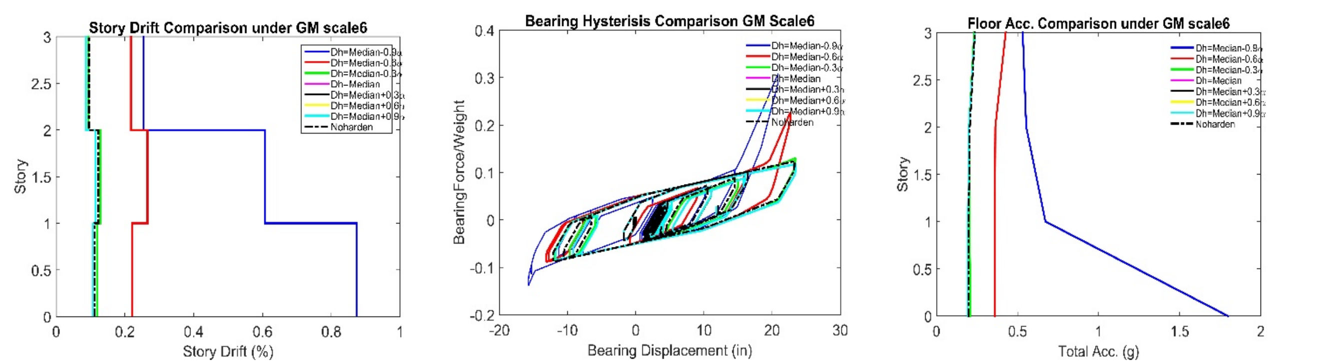
4.2 Effects of hardening start displacement

For a fixed hardening ratio, hardening can start from any displacement. The selection of hardening starting point is more important since it determines how much hardening bearing will undergo and the displacement capacity of a TFPB. Therefore, more importantly, selection of hardening starting displacement (D_h) should be based on the ground motion level where safety is evaluated. Keeps the constant hardening ratio as 8 as suggested from last part of parametric study, cases with different (D_h) are investigated. D_h is characterized by the median and the standard deviation of displacement demand distributions under MCEr ground motion set as shown in Fig.2 (c). Responses under a representative ground motion intensity which corresponds to median MCEr level event is shown in Fig. 6.

Since under median MCEr ground motion intensity, for some cases considered, hardening has not started. Therefore, only two cases show obvious hardening behavior in Fig.6 (b). As shown in Fig.6 (a), large drift response is expected when hardening starts earlier. For D_h equals to median-0.9std which corresponds to almost a half of the median MCEr level displacement demand, maximum drift response will be around 1% under MCER level seismic event. Only minor yielding on the upper structure and brace buckling are expected.

For example, if median MCEr ground motion level is acceptable for consideration of safety, bearing with hardening starts at almost half of displacement demand will achieve this safety objective. Further start will not fully use the hardening portion. On the other hand, earlier start of hardening may result into exceedance of the displacement capacity. Overall, the optimum D_h should be selected so that the displacement capacity of the hardening bearing is not exceeded under the ground motion intensity considered for safety and meanwhile, hardening portion of bearing can be fully used with an acceptable level of damage introduced into superstructure.

Maximum drift in superstructure under different ground motion intensities considered for different D_h are shown in Fig. 7. With the same hardening ratio, the increasing rate of the responses with linearly increasing ground motion intensities are the same as indicated by the parallel lines. The well separated lines for different cases shown in Fig. 7 indicate the strong dependency of final safety level achieved on D_h selected. Therefore, a proper selection of D_h according to the target is essential. For example, if D_h is selected as Median-0.6std, the system will result into upper structure collapse under 130% median MCEr level ground motion. If D_h is selected as Median of MCEr displacement demand, failure under 160% median MCEr level ground motion is expected.



(a) (b) (c)

Fig. 6 –Responses of the base isolated prototype building under representative ground motion level for different hardening start displacements. (a) Maximum story drift ratio response (b) Bearing hysteresis response (c) Peak floor acceleration response

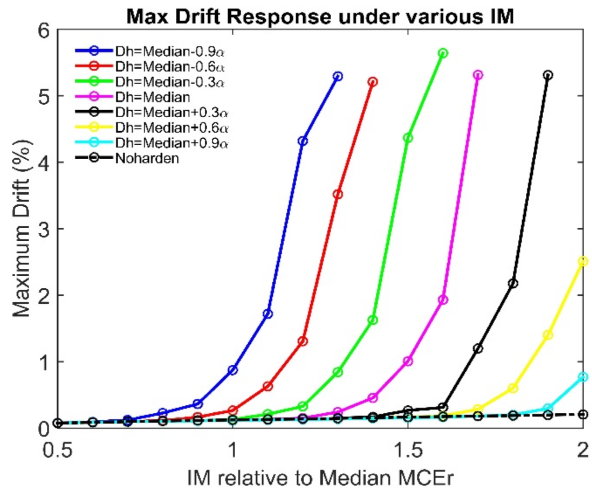


Fig. 7 –Maximum story drift responses under increasing ground motion intensities for different cases with different hardening start displacements

4.3 Further discussion and design guidance

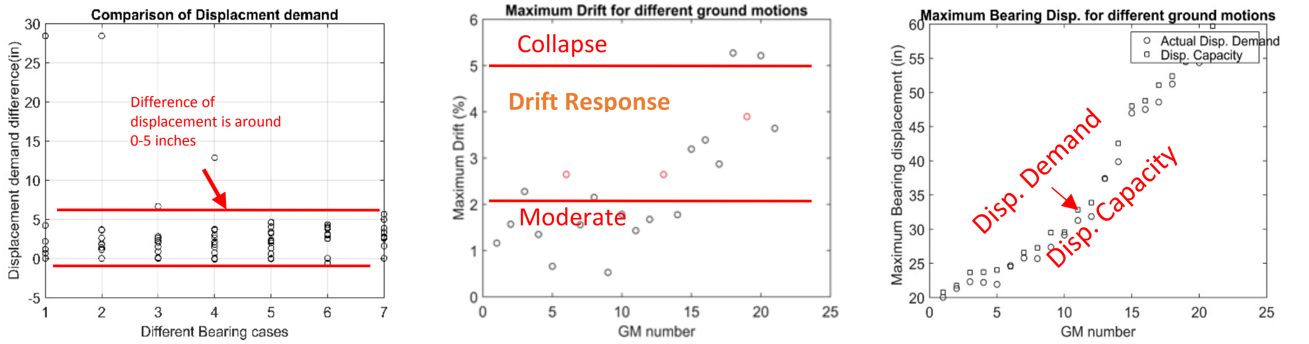
Parametric studies have been conducted to investigate the effect of different hardening ratios (α) and the hardening start displacements D_h on responses under varied earthquake intensities. As discussed in the previous sections, prototype building responses under rare seismic event are very sensitive to the selection of these two parameters especially for the starting displacement of hardening, therefore, proper chosen of these parameters which are consistent with the safety objective is essential.

Hardening ratio as discussed should be selected around 10 based on numerical analysis results. The key issue remaining is how to select the bearing hardening displacement D_h. As discussed in section 4.2, optimized value should fully uses the hardening portion of bearing before the displacement capacity is exceeded. Which simply means that displacement demand under a certain ground motion intensity associated with the failure risk target should match the displacement capacity resulted from the selection of D_h. Then the remaining issue is given a certain level of collapse risk in design, how to obtain the displacement demand (D_{harden}) of the isolator so that a selected D_h will result into the displacement capacity $D_{capacity}$ matching the demand.

4.3.1 Determine displacement demand of hardening bearing (D_{harden})

Determining displacement demand for a hardening bearing is not straightforward since a nonlinear dynamic analysis may be needed due to the possible yielding of the superstructure when bearing hardening starts. Another way to estimate the displacement demand is firstly obtaining the demand of a non-hardening bearing ($D_{N\text{-}harden}$) with exactly same hysteresis comparing to a hardening bearing before stiffening happens, then relate it to D_{harden} using a simplified relation.

Relation between $D_{N\text{-}harden}$ and D_{harden} is evaluated from numerical analysis results conducted in the study for all cases and all ground motion intensities as shown in Fig. 8. Differences of displacement demand are plotted and shown in Fig.8 (a), most of them lie in 0-5 inches (0-0.13m) range. With investigation of different possible relations based on statistics obtained from Fig.8 (a), relation of $D_{harden}=D_{N\text{-}harden}-2.5$ is selected and used for the following discussion. Selection of this relation is based on evaluation and comparison between each possible relations and the out coming responses when each relation is implemented. The one with acceptable upper structure responses and best matches between the displacement capacity and demand is selected. The detail selection and comparison process is not shown in the paper. As shown in Fig.8 (b) and Fig.8 (c), under the relation selected, actually displacement demand is almost the same as the displacement capacity and the upper structure drift responses mostly lie in the range where acceptable damage happened in the upper building.



(a) (b) (c)

Fig. 8 –Responses related to the selection of D_{harden} to $D_{N\text{-}harden}$ relation under varied TFPB cases and ground motion intensities. (a) Difference between displacement responses of hardening and non-hardening bearings (b) Maximum drift responses on selection of $D_{harden}=D_{N\text{-}harden}-2.5$ (c) Comparison of bearing displacement demand and capacity on selection of $D_{harden}=D_{N\text{-}harden}-2.5$

4.3.2 Displacement demand of non-hardening bearing ($D_{N\text{-}harden}$)

As stated in above section, the displacement capacity of the hardening bearing D_{harden} will be determined through the displacement demand of non-hardening bearing ($D_{N\text{-}harden}$). Therefore, the non-hardening bearing displacement demand $D_{N\text{-}harden}$ needs to be obtained firstly.

As discussed, the $D_{N\text{-}harden}$ should be determined based on objective hazard level that safety is considered. The objective level can be described as probability under a certain level seismic event, for example, 10% chance of collapse under MCEr level events. However, this description needs knowledge of response distribution under MCEr level seismic events and the term MCEr level is also confusing for different sites. For a better quantified and general term, the study uses risk to characterize the safety level, for example, 1/1000 probability of collapse annually, or a collapse scenario happens with a return period around 1000 years. Relation between risk value and the $D_{N\text{-}harden}$ is established using Conditional Scenario Spectrum (CSS) as discussed in section 2.2.3 which is shown in Fig.9 (a). Then, $D_{N\text{-}harden}$ can be estimated from the relation in Fig.9 (a). For comparison, relation between annual risk value and percentile in MCEr level responses distribution for the same response value is plotted in Fig.9 (b).

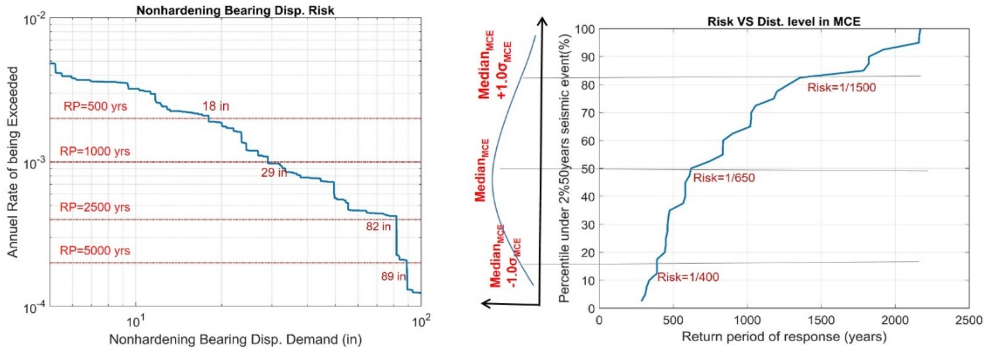
For example, from Fig.9 (b) the median level displacement demand under MCEr level ground motions corresponds to an annual exceedance risk of around 1/650 or return period of 650. The relation in Fig.9 (a) is plotted in log-log scale, and one can see how large bearing displacement demand could be if a lower exceedance risk is desired. Note the relation in Fig.9 (a) depends on specific sites and structural system. The study takes the specific relation obtained from prototype structure analysis as an example to demonstrate how to use the relation in proposed design method. To set up a general relation between non-hardening bearing displacement demand and associated risk, more studies should be done for different analysis cases.

4.3.3 Proposed design concept

Finally, the proposed simplified design procedure of using hardening bearing is shown in Fig. 10. Firstly, two risk levels are provided, one corresponds to the performance objective of minimizing damage and achieving resiliency in the superstructure, the other corresponds to the performance objective of remaining safety. Bearing properties such as isolation period and strength as well as upper structure strength should be selected and designed in order to achieve seismic resiliency under risk level h_1. This part is not the focus of the study, however displacement demand of bearing under h1 risk level ($D_{resiliency}$) needs to be estimated from relation as Fig. 9 (a).

Then under risk level h_2, the non-hardening bearing displacement demand $D_{N\text{-}harden}$ is estimated from relation Fig.9 (a). This step may contain large uncertainty. The relation between the non-hardening bearing displacement demand and a certain risk level needs to be established statistically based on much more analysis results. The study only uses the representative site and the prototype building to establish a specific relation for the special condition in order to demonstrate the proposed procedure.

Then displacement capacity ($D_{capacity}$) for the hardening bearing will be set as $D_{N\text{-}harden}$-2.5 using the relation obtained in previous section. Starting displacement of hardening D_h is back calculated from ($D_{capacity}$), with the hardening ratio around 10. Finally, D_h should be checked so that it is larger than $D_{resiliency}$, which ensures hardening does not start at a risk level that seismic resiliency is still the main concern.



(a) (b)

Fig. 9 – (a) Relation between Non-hardening bearing displacement demand ($D_{N\text{-}harden}$) and associated risk (b) Relation between return period (1/risk) and the percentile in MCEr level response distribution for the same $D_{N\text{-}harden}$ value

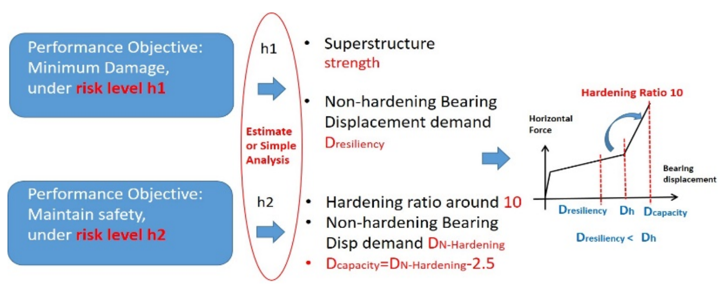
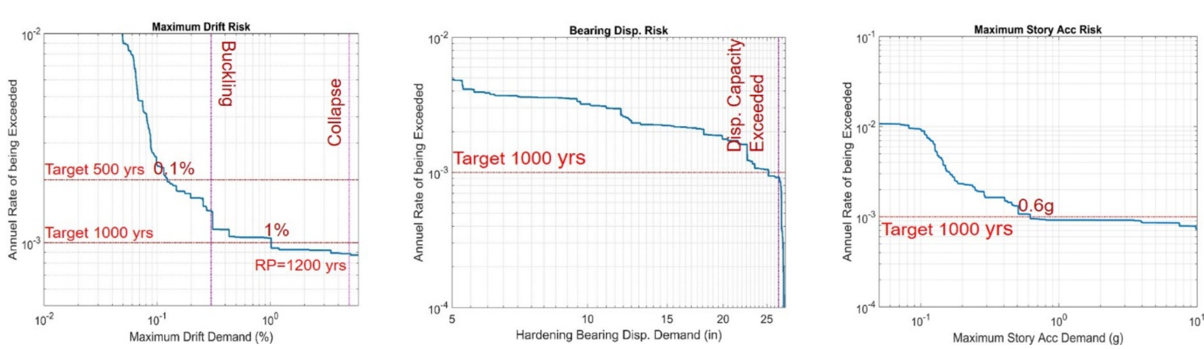


Fig. 10 – Scheme of the proposed design concept using a hardening bearing

4.4 Validation of proposed method

Conditional Scenario Spectrum (CSS) method is used to validate the proposed design method by comparing the actual risk of responses and the target. The first performance objective of achieving resiliency will not be validated here, the objective for safety consideration is investigated. A collapse risk level h_2 of 1/1000 is assumed to be the target. Following the method proposed in last section, $D_{N\text{-}harden}$ is 29.5 inches (0.75m) from Fig.9 (a). Then with the relation proposed in the study, $D_{capacity}$ is calculated as 27 inches (0.69m). With other parameters of TFPB, same as the values used in the study, and a hardening ratio 8, the hardening displacement D_h is calculated as 13.7 inches (0.35m). With the designed TFPB, full risk calculation is conducted using ground motion sets generated from CSS. Results are shown in Fig. 11.



(a) (b) (c)

Fig. 11 –Responses risk using proposed design procedure. (a) Maximum story drift ratio response risk (b) Maximum bearing displacement demand risk (c) Peak floor acceleration response risk

From results shown in Fig.11 (a), the resulting collapse risk is around 1/1200 if 5% drift is used as a simplified indicator of upper structure collapse. This actual risk level obtained is slightly smaller than the target risk of 1/1000. Fig.11 (b) shows the bearing displacement response risk. The designed bearing displacement capacity has a risk of being exceeded around 1/1100, almost the same as the target of 1/1000. In terms of floor acceleration response as shown in Fig. 11 (c), a 0.6g peak floor acceleration will be expected with a 1/1000 risk of being exceedance.

Overall, from the numerical analysis results, the proposed design method using hardening of bearing to achieve the target collapse risk level is efficient and does not have much redundancy for the bearing design, with resulting risk of responses almost the same as target. With a 27 inches (0.69m) TFPB, a collapse risk objective around 1/1200 can be achieved as shown in Fig.11. If hardening of bearing is not used, to achieve the same performance objectives, a bearing which can provide 30 inches (0.76m) displacement capacity with a low horizontal stiffness will be needed. Which means for a rubber bearing, hardening can not starts before 30 inches' (0.76m) shear deformation and for a SFPB, twice the size of bearing is needed comparing to a TFPB. Therefore, the use of hardening in bearing design for rare seismic event is efficient.

5. Conclusion and Discussion

In the study, responses of a seismically isolated prototype 3-story ordinary concentrically braced frame system (BI-OCBF) using hardening bearing (TFPB) under rare seismic events are investigated. Responses under varied earthquake intensities are evaluated to fully understand the behavior of the isolated prototype structure under bearing hardening. Particular attentions are paid for sensitivity study on responses to the key design parameters characterizing the hardening behavior of bearing. With the understanding from the parametric analysis results, a preliminary design procedure is proposed in order to correctly and efficiently use hardening of bearing to economically achieve a certain safety level for seismic isolated structure. The procedure is implemented and validated with a simplified example for the prototype building. Some key conclusions are summarized below:

Firstly, seismic isolation is very effective on reducing drift, force and acceleration demand for a braced frame upper structure, a reduction factor of 10 can be achieved for the prototype building. Large uncertainty in bearing displacement demand will be expected due to the ground motion uncertainty.

Hardening of isolator bearing will increase responses on the superstructure especially for the lower part of the building. The amount of damage or yielding introduced into the upper structure depends on the hardening ratio and where hardening starts.

For a TFPB, a hardening ratio around 10 is recommended if hardening of bearing is used in design. The hardening start displacement on the bearing is an important parameter to select. The selection of this displacement point in design should be based on the target safety level. A proposed design concept using hardening of bearing is proved to be efficient and validated.

The key objective for the study as stated in the introduction part of the paper is to evaluate the proposed design concept for an isolated structure under beyond design and rare seismic event: When minimizing damage or achieving resiliency is not the priority under rare seismic event, safety of the isolated system is the main objective. And gradually transferring yielding and damage into superstructure by using hardening of bearing is more efficient than still using bearing to take most of the displacement demand. The study uses a specific type of hardening bearing and a prototype structure to validate this concept, to understand the behavior and achieve this concept with a proposed design method obtained from parametric study results. The risk evaluation shows the great feasibility of using hardening of bearing to realize the proposed design concept.

However, to fully evaluate this design concept and implement the idea of using hardening bearing for general cases, more studies are needed on different kinds of systems and conditions. The study should be set as a basis and guidance for future study on this topic.

6. Acknowledgements

The author appreciates the support from Pacific Earthquake Engineering Research Center (PEER) and Earthquake Protection System (EPS) on the study.

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