



# Seismic isolation of structures, Part II: A case study using the RNC isolator

## *Aislamiento sísmico de estructuras, parte II: un caso práctico con el aislador RNC*

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### Abstract

The present paper is the second of two companion papers. The objective of this paper is to minimize twist of isolated asymmetric structures, together with their torsional pounding with adjacent structures, considering insufficient seismic gaps and strong near-fault ground motions. Concisely, the present study attempts to provide efficient seismic isolation under the above challenging conditions. The used isolation system is referred to Roll-in-Cage (RNC) isolator. Among the features of the RNC isolator are two characteristics that help achieving the objectives of the paper. The first is the independency of its bearing and pre-yield stiffness mechanisms. Such independency allows for accurate tuning of the isolators pre-yield stiffness to shift their center of rigidity, at the isolation level, to coincide with the asymmetric superstructure's center of mass above that level. This allows for minimizing the structural twist of an isolated asymmetric structure. The second feature is the inherent buffer mechanism of the RNC isolator, which draws down any possible seismic pounding of the isolated superstructure, with adjacent structures, to occur only within the isolation bearing itself. This leads to seismic pounding-free superstructure under limited seismic gaps. The obtained results show that utilizing the RNC isolator this way is able to minimize, or even eliminate, the out-of-plan displacement responses of asymmetric isolated structures under severe near-fault earthquakes, and consequently, minimizes a major cause of structural damage due to structural torsional pounding with closely spaced adjacent structures under such destructive ground motions.

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**Keywords:** Seismic Isolation; Asymmetric structures; Pounding; FEM; RNC isolator

### Resumen

Este artículo es el segundo de dos artículos complementarios. Su objetivo es reducir la torsión de estructuras asimétricas aisladas, así como el golpeteo torsional con estructuras adyacentes, considerando los casos de espacio insuficiente entre las estructuras y de fuertes movimientos sísmicos por proximidad a una falla, por medio del aislador *roll-in-cage* (RNC). De forma concisa, este estudio intenta proporcionar un aislamiento sísmico eficiente con las condiciones difíciles mencionadas anteriormente. El sistema de aislamiento utilizado hace referencia al aislador RNC. Entre las características del aislador RNC hay dos que ayudan a lograr los objetivos del artículo. La primera es la independencia de sus mecanismos de rigidez de rodamiento y de predicción de rendimiento. Esta independencia permite un ajuste preciso de la rigidez de predicción de rendimiento de los aisladores para desplazar su centro de rigidez, respecto al nivel de aislamiento, para que coincida con el centro de masa de la superestructura asimétrica por encima de ese nivel. Ello permite reducir el giro estructural de una estructura asimétrica aislada. La segunda característica es el mecanismo de amortiguación inherente del aislador RNC, que elimina cualquier posible golpeteo sísmico de la superestructura aislada, con estructuras adyacentes, para que ocurra solo dentro del propio rodamiento de aislamiento. Ello produce una superestructura sin golpeteo sísmico en condiciones de insuficiente espacio para movimiento debido al sismo. Los resultados obtenidos muestran que la utilización del aislador RNC de esta

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manera puede reducir o, incluso, eliminar las respuestas de desplazamiento fuera del plano de las estructuras asimétricas aisladas en terremotos intensos cerca de la falla y, en consecuencia, reduce una causa importante de daño estructural debido al golpeteo torsional estructural con estructuras adyacentes con poco espacio entre sí con movimientos de tierra tan destructivos.

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*Palabras clave:* Aislamiento sísmico; Estructuras asimétricas; Golpeteo; FEM; Aislador RNC

## 1. Introduction

This paper is the second of two companion papers. It introduces the seismic isolation concept and addresses the possibility of nearly eliminating, or at least minimizing, the torsional responses of isolated asymmetric structures using the Roll-in-Cage (RNC) isolator considering near-fault (NF) ground motions. Then, the outcome of this study is employed into further study on the ability of the RNC isolator to partially and entirely eliminate torsional seismic pounding of isolated asymmetric structures with their closely-space surrounding adjacent structures under the same severe NF ground motions, which are rich of displacement and velocity pulses. To minimize torsional responses, the RNC isolator has an inherently independent bearing and pre-yield stiffness mechanisms. Therefore, the RNC isolators are arranged into four sets with unequal pre-yield elastic stiffness underneath the asymmetric structure. Such different elastic stiffness are accurately tuned to shift the isolators' center of rigidity at the isolation level to coincide with the structural center of mass above the isolation level. To prevent direct seismic pounding of the RNC-isolated superstructure with its closely-spaced adjacent structures, the RNC isolator is provided with an inherent self-stopping (buffer) mechanism to limit the peak lateral bearing displacement and consequently the peak lateral structural displacement to a preset design value by the designer, which is particularly useful in case of having insufficient or limited seismic separation gaps between adjacent structures.

## 2. Dynamic behavior improvement of RNC-isolated asymmetric structures

### 2.1. Torsional response minimization or elimination

In this paper, the RNC isolation is achieved in two different ways. The first is through using one set of RNC isolators having the same characteristics, especially the lateral pre-yield stiffness, one isolator under each column. This achieves seismic isolation but keeps the eccentricities between the structure's centers of mass (CM) and rigidity (CR) unchanged due to the added uniform high flexibility at the isolation level. Therefore and despite the fact that the isolated structure will behave nearly as a rigid body, torsional structural responses will still exist. Alternatively, through the other way of achieving RNC isolation in this paper, the torsional response of the RNC-isolated asymmetric structure is mitigated or even eliminated by using four sets of the RNC isolators, whose horizontal pre-yield stiffness could be selected individually, i.e. an elastic stiffness value in  $X$  direction and

another value in  $Y$  direction for each isolator's set. This allows for shifting the center of stiffness of the RNC-isolated asymmetric structure, at its isolation level, to coincide with its center of mass. As a result, torsional structural responses are theoretically eliminated due to the lateral dominant behavior of the added high flexibility at the isolation level, which has a CR coincident to the CM of the asymmetric structure above the isolation level.

Fig. 1 shows the in-plan arrangement of the RNC isolator's four sets having different lateral pre-yield stiffness to achieve coincidence of the RNC isolators' CR and the asymmetric structures' CM in both  $X$  and  $Y$  directions. The selected values of effective isolator stiffness  $k_{\text{eff}}$  in  $X$  and  $Y$  directions are chosen by trial and error method to achieve a final tolerance of 0.24% and 0.21% in  $X$  and  $Y$  directions, respectively, between the CR at the isolation level and the structure's CM above that level. In this paper, the way of achieving seismic isolation using RNC isolators of different lateral stiffness, to almost eliminate torsional responses, is referred to as "improved" RNC isolation. The other way of seismic isolation using one RNC isolator set with a single value of lateral stiffness is referred to as "non-improved" RNC isolation. The non-improved RNC isolators set has the same in-plan arrangement as in Fig. 1 but with a uniform lateral effective stiffness  $k_{\text{eff}}$  in  $X$  and  $Y$  directions that provides nearly the same isolation period as in the case of improved RNC isolation.

Performing modal analysis using SAP2000, three cases of the asymmetric structure are considered; the fixed-base case, the non-improved RNC isolation case, and the improved RNC isolation case. The fundamental mode's deformed shape of each case is plotted in 3D, with a scale factor of 100, in Figs. 2 and 3. Fig. 2(a and b) shows that the fixed-base asymmetric structure experiences severe torsional response, which is zero at the base mass and maximum at the topmost floor. This indicates that the whole structure is twisted as a vertical cantilever around a vertical axis passing through its CR due to the existing eccentricities between its CM and CR in  $X$  and  $Y$  directions. Fig. 3(a and b) shows the 3D fundamental mode of vibration of the non-improved RNC-isolated asymmetric structure. Since the RNC isolators represent the most flexible part of the isolated structure laterally, their behavior dominates causing the structure to vibrate as a rigid body with almost no relative inner structural deformations. Since the eccentricities in  $X$  and  $Y$  directions between the CM and the CR still exist as they are almost not affected after non-improved RNC isolation, the structure exhibits torsional response but as a rigid body, as demonstrated by Fig. 3(a and b). On the other hand, the result of the proposed method for elimination of torsional structural responses is

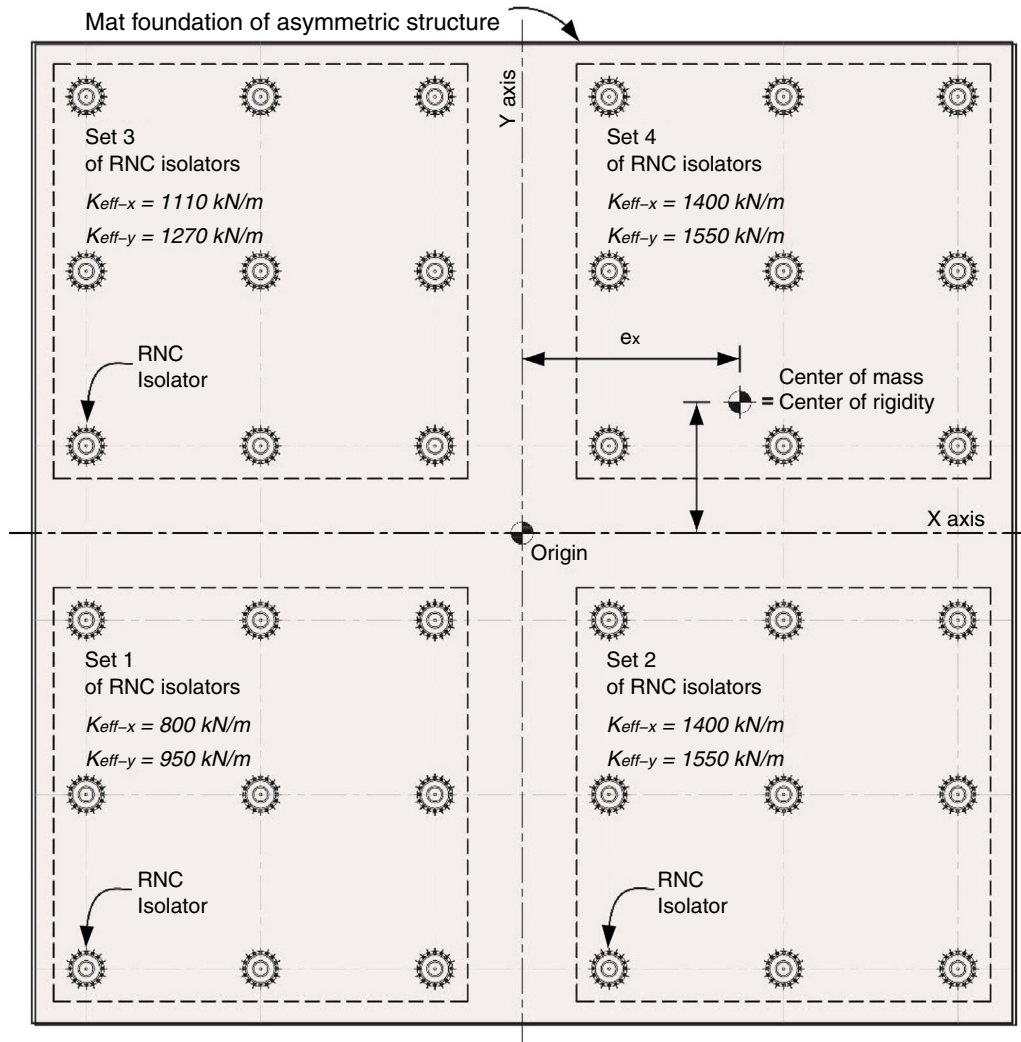


Figure 1. Plan view of the RNC-isolated asymmetric structure's foundation showing the arrangement of RNC isolators and their grouping.

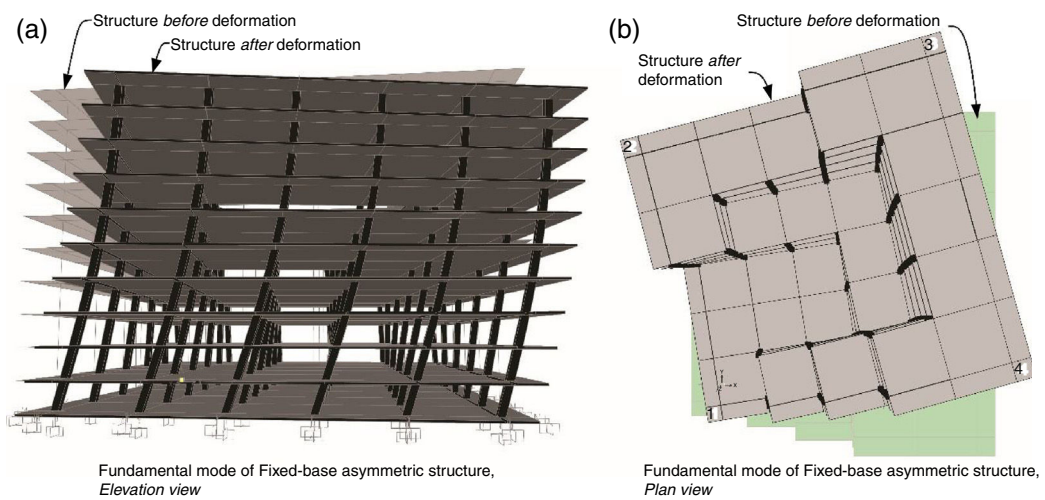


Figure 2. Fundamental mode of vibration of the fixed-base asymmetric structure: (a) elevation view; (b) plan view.

demonstrated by Fig. 4(a and b) using the improved RNC isolation, which aims at forcing the asymmetric structures to behave as the symmetric ones, which exhibit no torsional responses,

in addition to achieving efficient seismic isolation. The isolated asymmetric structure in Fig. 4(a and b) undergoes only translational motion with almost no rotation about any vertical

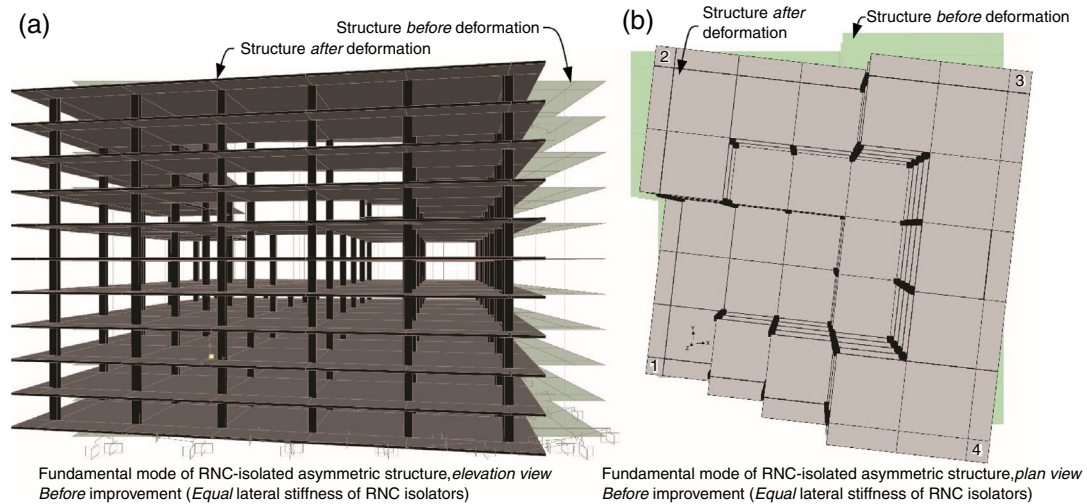


Figure 3. Fundamental mode of vibration of the RNC-isolated asymmetric structure before improvement: (a) elevation view; (b) plan view.

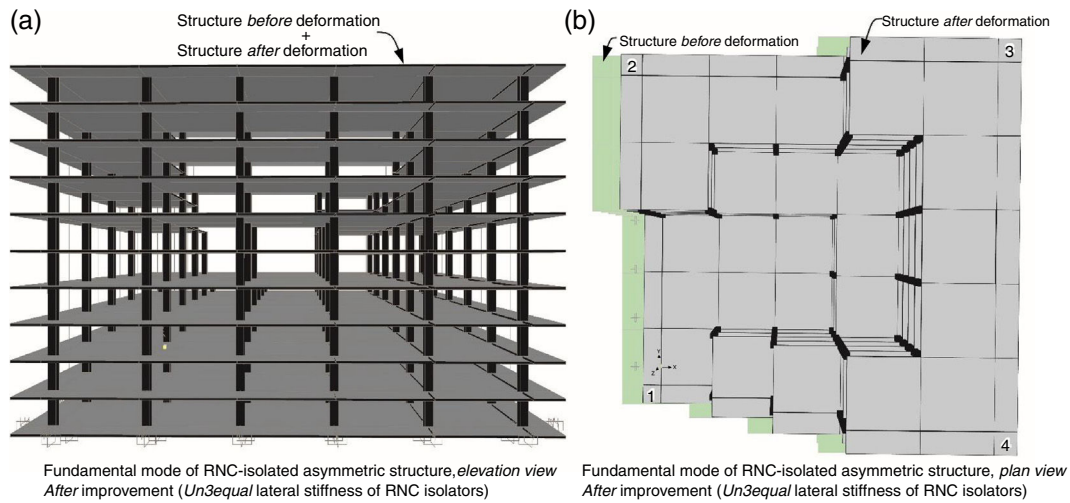


Figure 4. Fundamental mode of vibration of the RNC-isolated asymmetric structure after improvement: (a) elevation view; (b) plan view.

axes. This is mainly attributed to the elimination of eccentricities between both CM and CR of the isolated asymmetric structure by means of introducing four sets of flexible RNC isolators having a CR coincident to the structure's CM.

More assessment of the improved RNC isolation is carried out through performing nonlinear time history analysis using SAP2000. The main objective is to check the out-of-plan peak displacement responses of the topmost four corner points shown in Figures 2(b), 3(b) and 4(b) under uni- and bidirectional NF ground motions of Table 3, companion paper Part I. The results are shown in Figs. 5–7 under unidirectional  $X$ , unidirectional  $Y$  and bidirectional  $XY$  seismic components, respectively, considering fixed-base, non-improved and improved RNC isolation cases. Under unidirectional  $X$  ground motions, Fig. 5(a–c) show both in-plan and out-of-plan peak displacement structural responses, at the topmost four corner points, considering fixed-base, non-improved and improved RNC isolation cases, respectively, at an isolation period of 3.0 s. At each corner point, the in-plan peak displacement response is normalized to itself, while the out-of-plan response is normalized to the

corresponding in-plan one. According to Fig. 5(a and b), it seems obvious that the peak out-of-plan displacement response represents around 30–50% of the corresponding in-plan displacement response at the same corner point considering fixed-base and non-improved RNC isolation cases, respectively. Such amount of out-of-plan responses under unidirectional  $X$  ground motion is attributed to the out-of-plan structural eccentricity  $e_y$  of 0.9020 m. On the other hand, such out-of-plan peak displacement responses in  $Y$  direction are nearly nonexistent in the case of improved RNC isolation in Fig. 5(c) due to minimizing  $e_y$  to zero with a final tolerance of 0.21%.

In Fig. 6, the same normalized response quantities of Fig. 5 are reproduced under unidirectional  $Y$  ground motions. According to Fig. 6(a and b), the main obvious observation is that the out-of-plan peak displacement responses are significantly higher than those of Fig. 5(a and b), although the excitations in Fig. 6 are less stronger than those of Fig. 5. These out-of-plan responses represent around 60–140% of the corresponding in-plan peak displacement responses at each corner point. Certainly, this is attributed to the high out-of-plan eccentricity  $e_x$  of 2.5098 m.

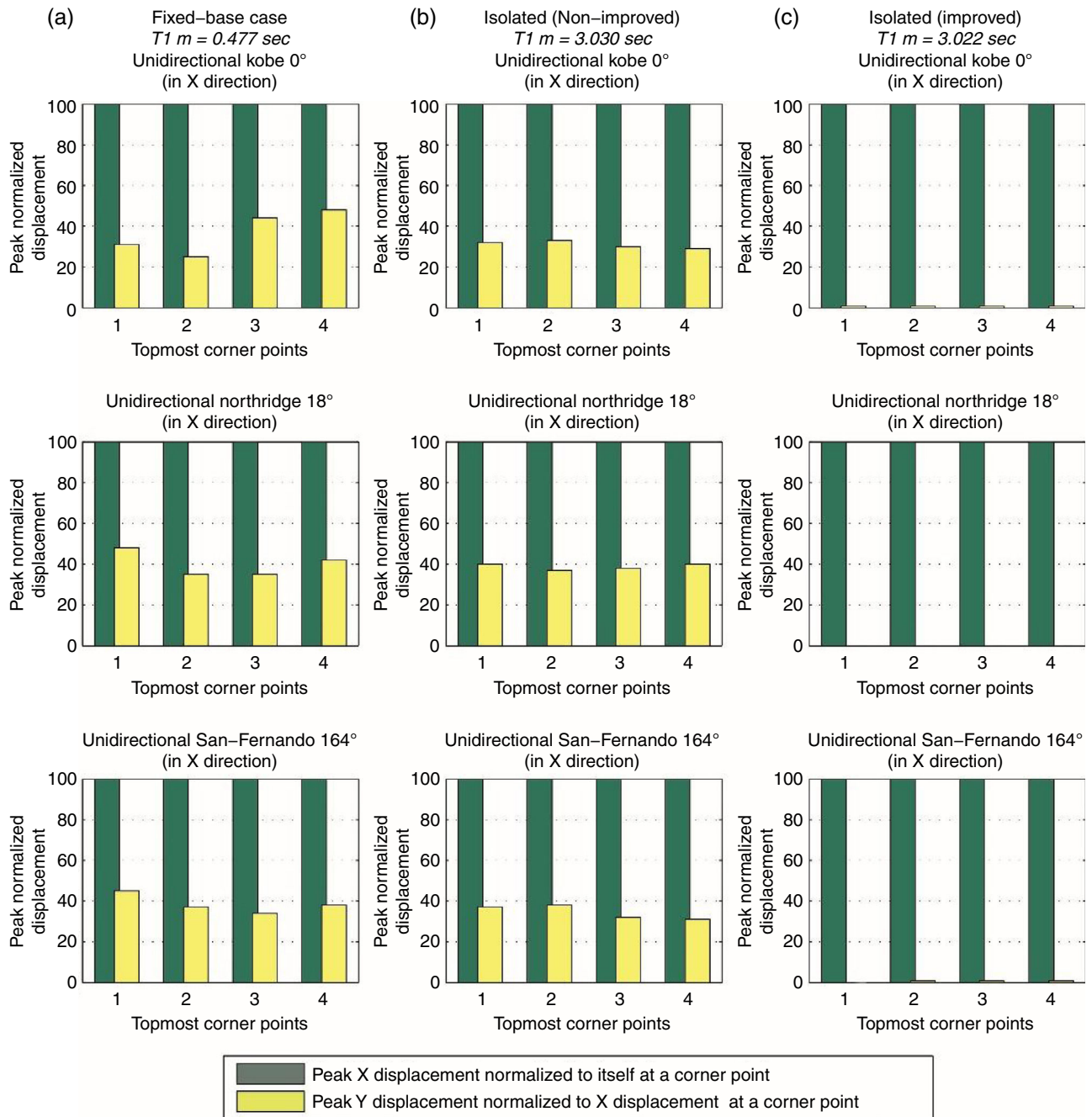


Figure 5. Normalized peak displacements in X and Y directions at the topmost corner points of the asymmetric structure under the unidirectional components Kobe 0°, Northridge 18° and San Fernando 164° earthquakes in X direction: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

Such eccentricity is minimized to zero with a final inaccuracy of 0.24% by means of the improved RNC isolation to output minimal out-of-plan peak displacement responses in X direction, as demonstrated by Fig. 6(c).

Under bidirectional ground motions, the peak relative displacement responses, at the same four corner points, are found for the same three cases of fixed-base, non-improved and improved RNC isolation. The results are shown in Fig. 7(a–c). Although the  $e_y$  is greater than  $e_x$  and the excitation components in X direction are stronger than those in Y direction, most peak relative displacement responses in Y direction are lower

than those in X direction. This means that the effect of structural asymmetry is reduced and, consequently, the torsional responses are lowered under simultaneous bidirectional ground motions in X and Y directions. It seems that whether the asymmetric structure is fixed-base or RNC-isolated, a bidirectional excitation counteracts its twist and reduces its torsional response, compared to a unidirectional excitation at a time. Therefore, a bidirectional excitation might not be suitable to fairly judge the proposed anti-torsion RNC isolation technique. However, Fig. 7(c) shows that the improved RNC isolation is able to reduce the peak structural displacements, at topmost floors, more than the case of

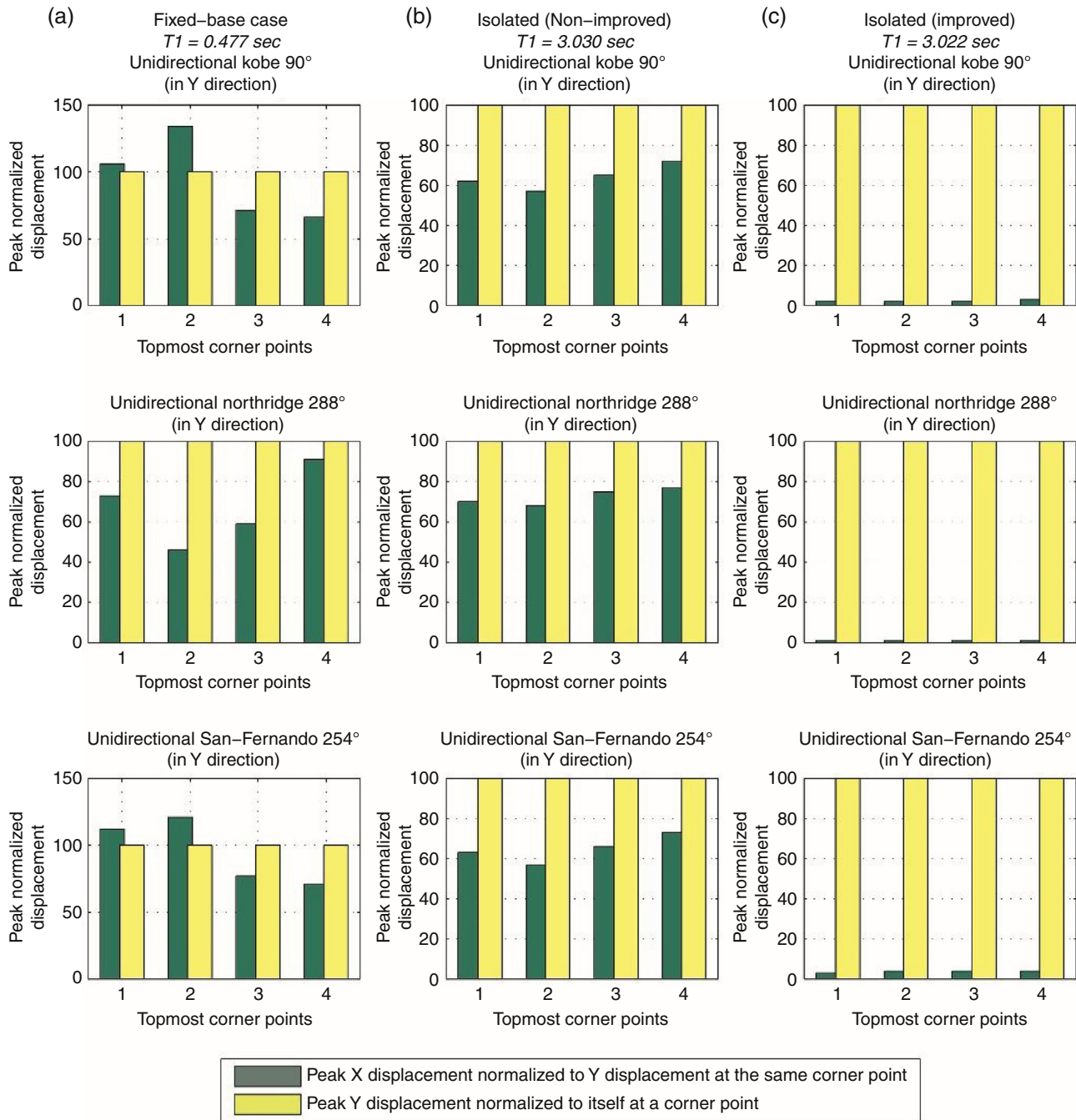


Figure 6. Normalized peak displacements in X and Y directions at the topmost corner points of the asymmetric structure under the unidirectional components Kobe 90°, Northridge 288° and San Fernando 254° earthquakes in Y direction: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

non-improved RNC isolation, which is obvious under Kobe and Northridge earthquakes. This can be particularly useful under relatively limited seismic gaps between adjacent structures to mitigate or even to avoid direct structural pounding. Moreover, the peak structural displacement responses at the four corner points in Figure 7(c) are almost the same under each earthquake in X and Y directions, which emphasizes the nearly-perfect translational rigid body behavior of the improved RNC-isolated structure, without exhibiting rotation about a vertical axis, contrary to the cases of Fig. 7(a and b).

### 2.2. RNC isolation efficiency

This section investigates the influence of improved RNC isolation on the isolation efficiency compared to the non-improved RNC isolation and the fixed-base cases. Figs. 8–10 display the corresponding peak absolute structural accelerations, at the same topmost four corner points, to the displacement responses of Figs. 5–7, respectively. Under unidirectional X ground motion components, Fig. 8(b and c) show that the RNC isolation has reduced significantly the acceleration responses relative to the

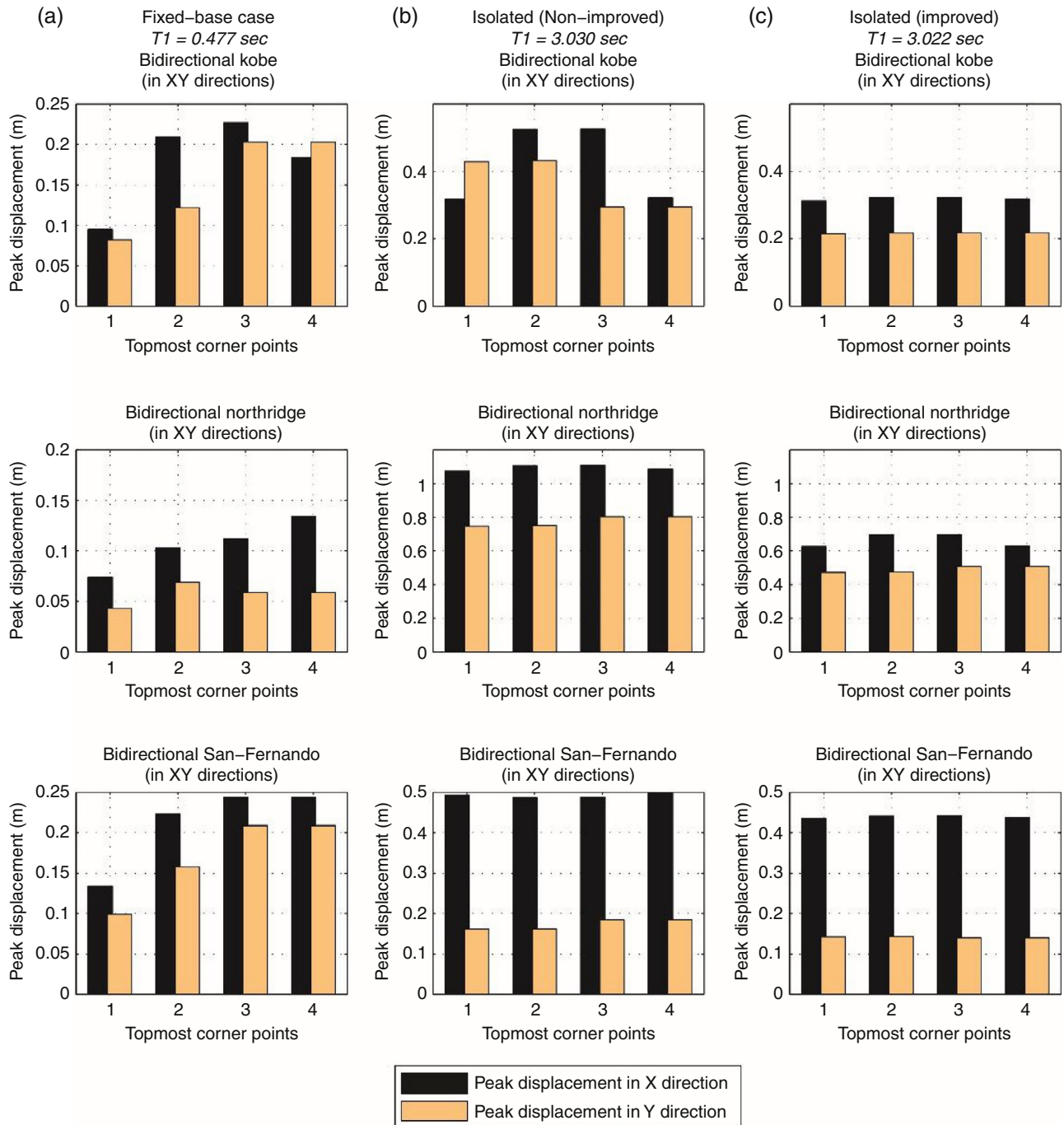


Figure 7. Peak displacements in X and Y directions at the topmost corner points of the asymmetric structure under simultaneous bidirectional components of Kobe, Northridge and San Fernando earthquakes in X and Y directions, respectively: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

fixed-base case of Fig. 8(a), especially the out-of-plan accelerations in Fig. 8(c), due to the improved RNC isolation.

Similarly, Figs. 9(b and c) and 10(b and c) under unidirectional Y and bidirectional XY ground motions, respectively, demonstrate the RNC isolator’s ability for efficient protection against severe NF ground motions compared to Figs. 9(a) and 10(a). However, the variations between acceleration responses of improved and non-improved RNC isolation cases in Figs. 9 and 10 seem to be insignificant, if compared to the fixed-base case

in each figure, as they depend mainly on the excitation characteristics.

### 3. Torsional pounding elimination with adjacent structures

#### 3.1. Efficiency of the RNC isolator’s buffer mechanism

This section addresses the problem of seismic pounding between a RNC-isolated asymmetric structure with adjacent

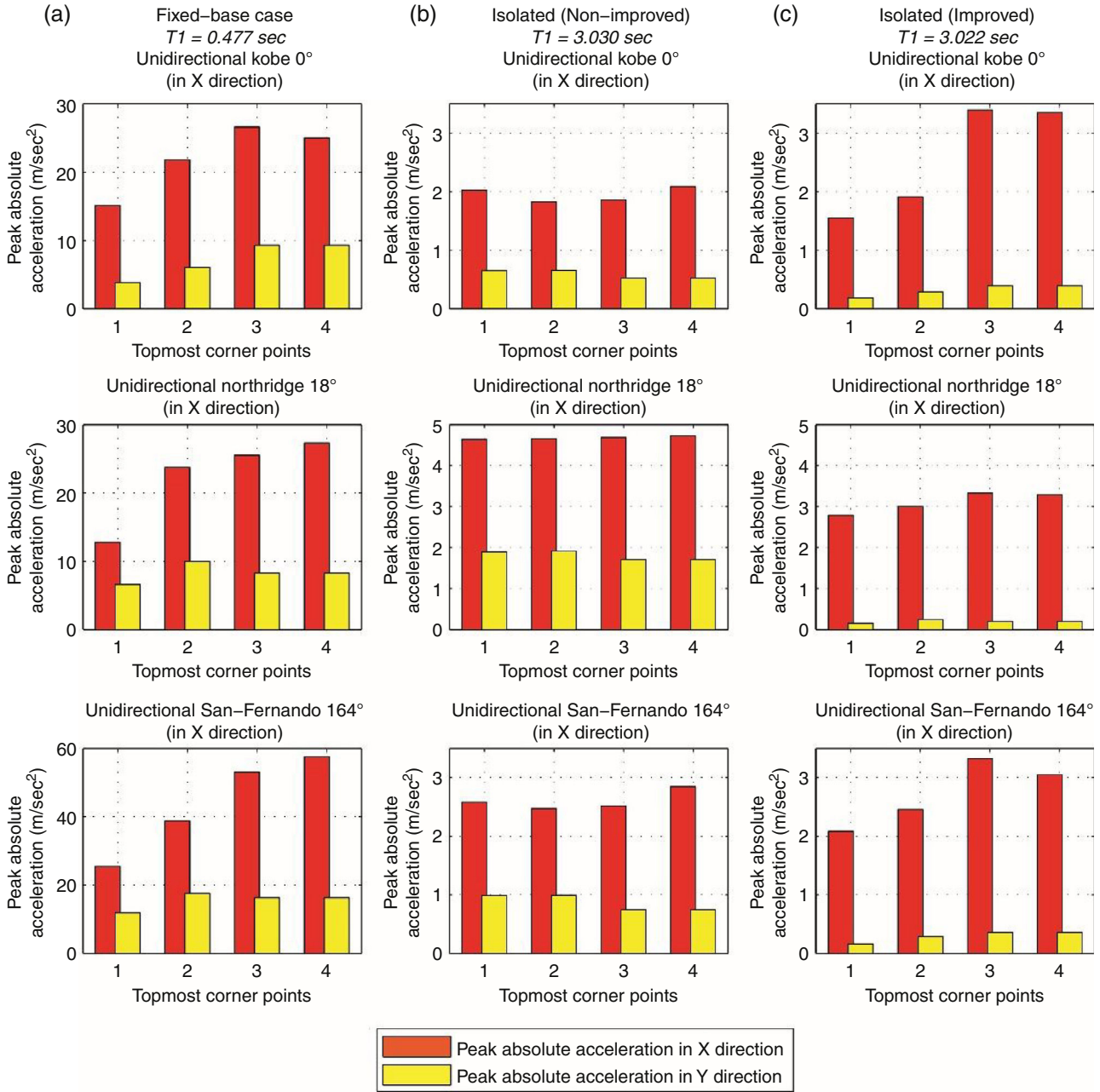


Figure 8. Peak absolute accelerations in X and Y directions at the topmost corner points of the asymmetric structure under the unidirectional components Kobe 0°, Northridge 18° and San Fernando 164° earthquakes in X direction: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

structures and its mitigation, or even elimination, under severe NF earthquakes considering limited seismic gaps. Then, the influence of such mitigation or elimination of seismic pounding on the RNC-isolated structural responses is investigated, considering the three cases of fixed-base, non-improved RNC isolation and improved RNC isolation, which aims at significant reduction of torsional effects. Particularly, the impact of improved RNC isolation on seismic pounding mitigation or elimination is highlighted.

Figure 3 (companion paper, part I) shows the considered RNC-isolated asymmetric structure surrounded from two sides by an L-shape rigid structure, of the same height, to consider pounding in X and Y directions. The topmost floor edge points

of the RNC-isolated structure are connected to their corresponding points on the adjacent rigid structure through unidirectional nonlinear gap elements, which are available in SAP2000, to output pounding force intensity if the selected gap is insufficient to prevent direct structural pounding at the uppermost sides of the seismic gap. Along the rest of this paper, the expression of “structural pounding” will refer to direct pounding of RNC-isolated structure with the adjacent rigid structure, while the inner developed pounding inside the RNC isolator due to the activation of its inherent buffer mechanism is referred to as “RNC isolator pounding”. The RNC-isolator is provided with an inherent self-stopping or buffer mechanism to prevent uncontrolled bearing displacements under ground motions stronger than the design



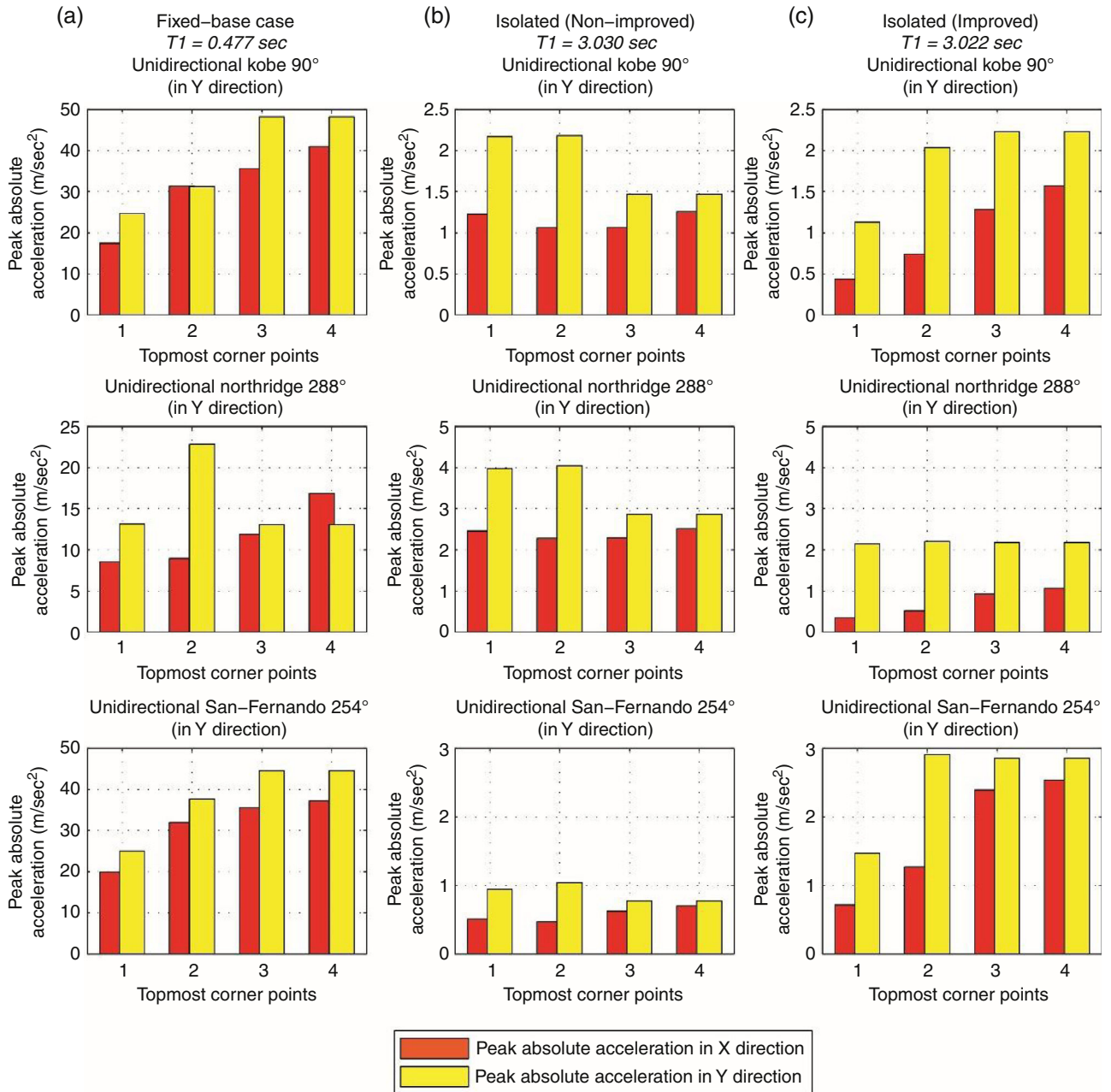


Figure 9. Peak absolute accelerations in X and Y directions at the topmost corner points of the asymmetric structure under the unidirectional components Kobe 90°, Northridge 288° and San Fernando 254° earthquakes in Y direction: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

earthquakes. In addition, the RNC-isolator’s buffer aims at minimizing or preventing structural pounding as it draws down any possible pounding of the superstructure to be only within the solid boundary of the RNC isolator’s metallic body. This could be particularly useful for seismic isolation under insufficient or limited seismic gaps that may result in severe structural and nonstructural damage due to structural pounding under strong earthquakes.

Fig. 11 demonstrates the ability of the RNC isolator to eliminate, or at least to minimize, structural pounding under nine cases of loading regarding both non-improved and improved RNC isolation at a seismic gap of 45.0 cm, a RNC design displacement of 40.0 cm and an isolation period of 3.0 s. Each load case is

named after its earthquake component followed by X, Y or XY characters. The X and Y notations refer to a unidirectional ground motion component in X or Y at a time, while the XY denotes a simultaneous application of bidirectional ground motion components in X and Y. Fig. 11(a) shows the direct pounding force intensity of the RNC-isolated asymmetric structure with the adjacent rigid structures in X and Y directions considering the non-improved RNC-isolation. Structural pounding appears to develop under six cases of loading with a maximum intensity of  $3.70 \times 105$  kN in Y direction under unidirectional Y Northridge seismic component. On the other hand, the improved RNC isolation has eliminated structural pounding under four of the six cases as demonstrated by Fig. 11(b). The remained structural

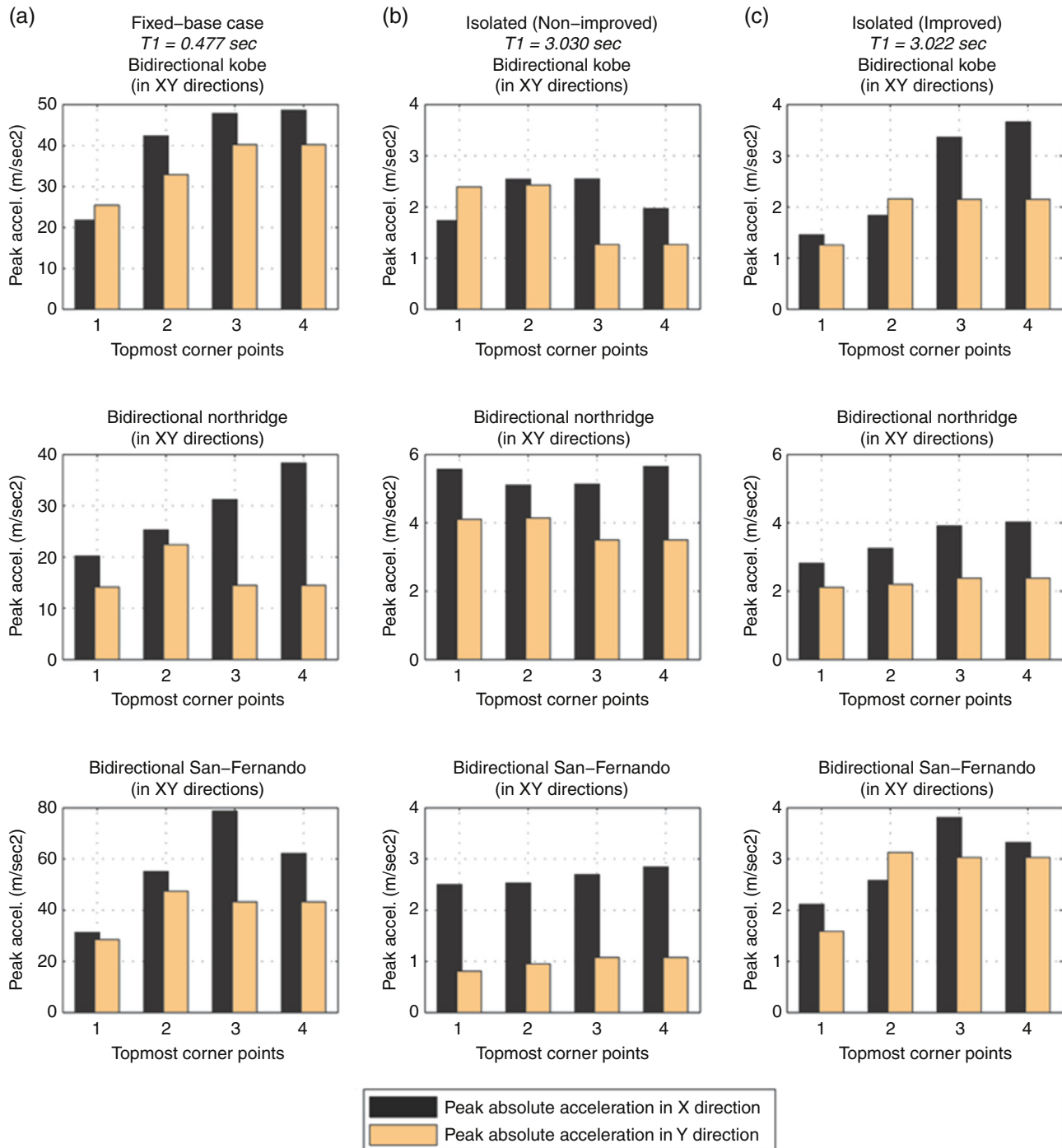


Figure 10. Peak absolute accelerations in X and Y directions at the topmost corner points of the asymmetric structure under simultaneous bidirectional components of Kobe, Northridge and San Fernando earthquakes in X and Y directions, respectively: (a) fixed-base case; (b) non-improved base-isolated case; (c) improved base-isolated case.

pounding is minimized to a maximum intensity of  $1.46 \times 10^4$  kN in X direction under unidirectional X Northridge ground motion component.

Approximately, the peak structural pounding ratio after and before the application of improved RNC isolation is 3.95%, which means significant structural pounding reduction under the same loading and structural conditions, disregarding the absolute structural pounding elimination under two thirds of the six cases of pounding. Moreover, Fig. 11(a) shows significant

out-of-plan pounding under unidirectional ground motions, which is not the case under improved RNC isolation case in Fig. 11(b).

The corresponding developed inner pounding within each RNC isolator, due to activation of its buffer mechanism at bearing displacement higher than its selected design displacement, is shown in Fig. 12 considering non-improved and improved RNC isolation under the same nine cases of loading. Under non-improved RNC isolation, Fig. 12(a) shows the resulting RNC

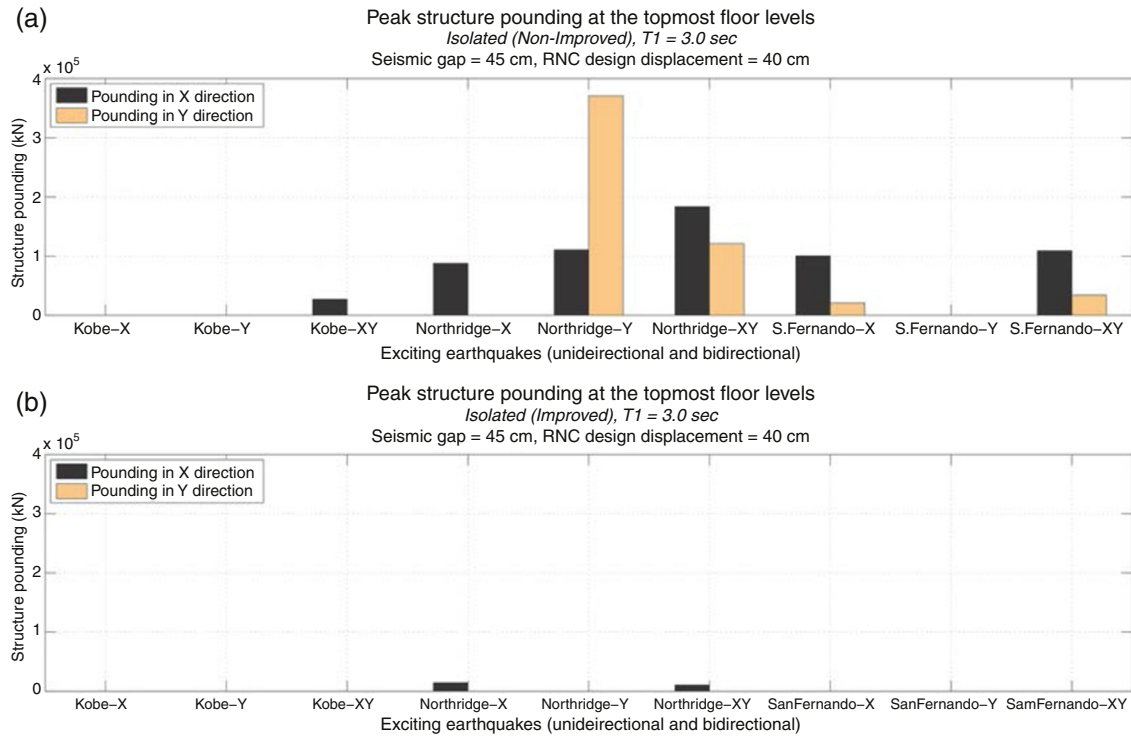


Figure 11. Peak structure pounding with adjacent structures at the topmost floors in X and Y directions under uni- and bidirectional near-fault ground motions: (a) non-improved RNC-isolated case; (b) improved RNC-isolated case.

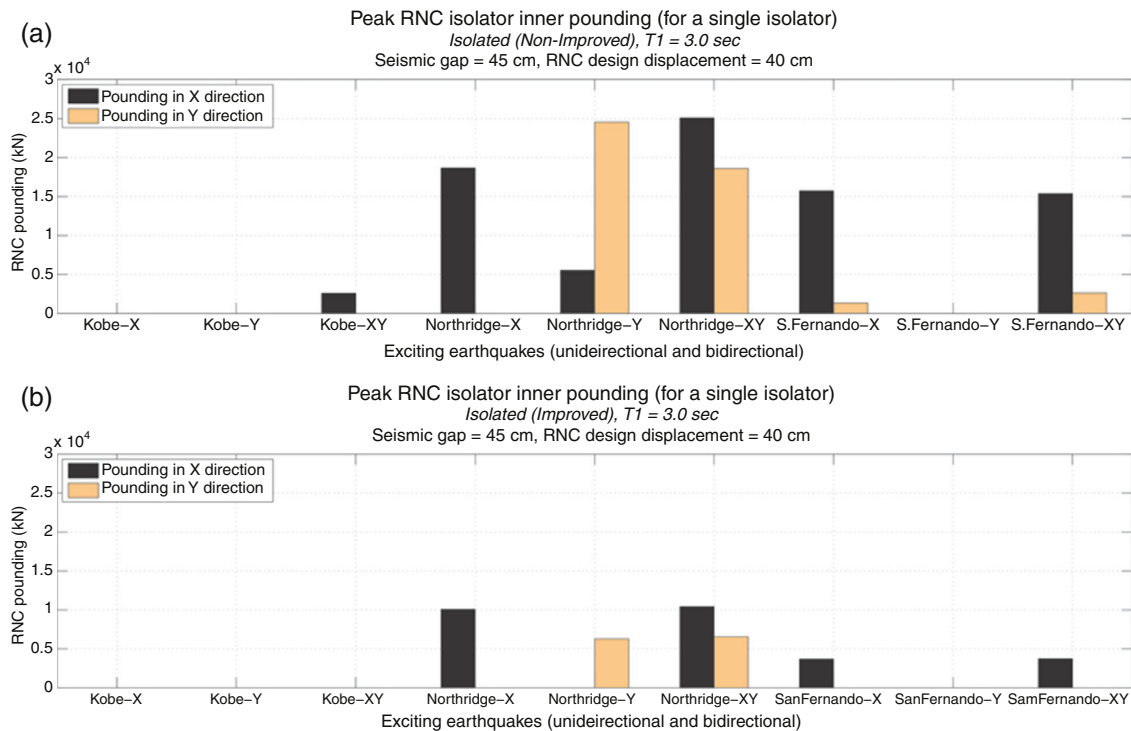


Figure 12. Peak inner pounding of a RNC isolator in X and Y directions under uni- and bidirectional near-fault ground motions: (a) non-improved RNC-isolated case; (b) improved RNC-isolated case.

isolator pounding under the same previous six load cases having pounding. Such pounding is proportional to the amount of bearing displacement beyond the chosen RNC isolator’s design displacement at the same considered value of buffer stiffness,

which is  $2.50 \times 10^6$  kN/m. The ratio of peak RNC isolator pounding, Fig. 12(a), to that of structural pounding, Fig. 11(a), is 6.76% considering non-improved RNC isolation. Although the peak RNC isolator pounding might be of considerable amount

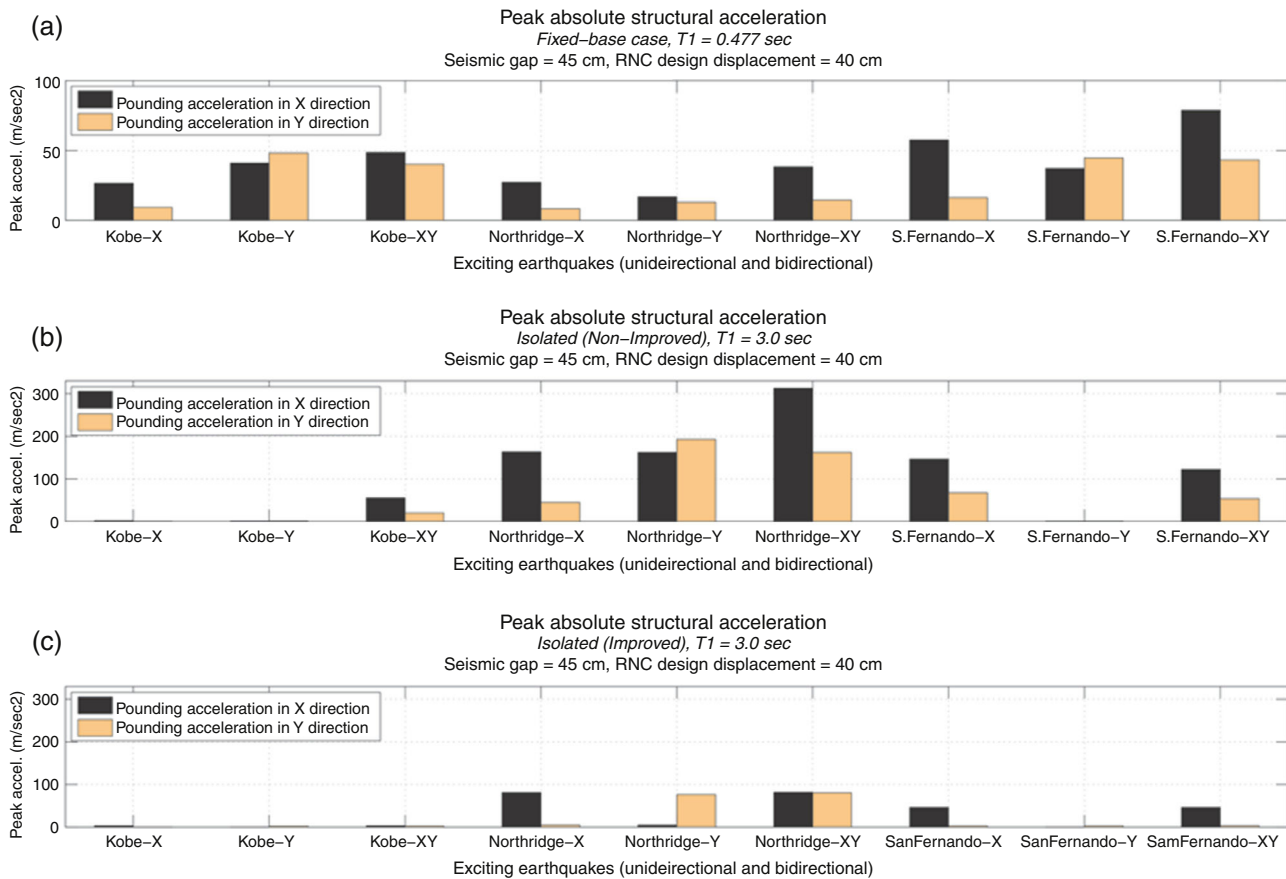


Figure 13. Peak absolute structural acceleration in X and Y directions under uni- and bidirectional near-fault ground motions: (a) fixed-base case; (b) non-improved RNC-isolated case; (c) improved RNC-isolated case.

compared to the overall structure pounding of some cases in Fig. 11(a), the activation of the RNC isolator's buffer offers more critical advantages. For example, it is not only able to minimize or even prevent structural pounding, and consequently prevents the possibly resulting severe local or global structural and non-structural damages, but it also distributes pounding regularly on the isolated base floor's in-plan area and keeps pounding always within the solid metallic body of the RNC isolator. Therefore, the RNC isolator's buffer could prevent structural pounding contact with no severe concentration of pounding forces at a local point or zone anywhere in the RNC-isolated structure, which is generally translated into less arising negative effects. According to Fig. 12(b), the improved RNC isolation has significantly reduced the RNC isolator pounding under five cases and eliminated pounding entirely under the sixth case of loading. Additionally, there is no out-of-plan pounding generated from a unidirectional ground motion. Such improvements could be attributed to the reduced in-plan and out-of-plan peak structural displacement responses, by means of the improved RNC isolation.

The corresponding influence of RNC isolator pounding on the isolation efficiency is shown in Fig. 13 regarding the peak absolute structural acceleration at the topmost floor as a performance measure. Although the peak acceleration responses of the fixed-base asymmetric structure are actually high, as in Fig. 13(a), they are even amplified significantly if structural or

RNC isolator pounding exists. The load cases that exhibit no pounding show minimal peak structural acceleration responses. The amplified structural accelerations due to pounding are worse (more amplified) in the case of non-improved RNC isolation, as shown by Fig. 13(b). In other respects, the improved RNC isolation has put an end to bidirectional RNC isolator pounding for all load cases, except under bidirectional Northridge earthquake, as in Fig. 12. Therefore, it has minimized the corresponding peak structural acceleration responses as demonstrated by Fig. 13. The remaining amplified accelerations, except under bidirectional San Fernando earthquake, are still higher than the fixed-base case but are significantly lower than those due to the non-improved RNC isolation. In other words, instead of having eleven peak acceleration responses in Fig. 13(b) higher than their corresponding values in the fixed-base case, Fig. 13(a), only four acceleration response quantities remain unacceptable due to the improved RNC isolation, Fig. 13(c), with a reduction percentage of around 64.0%.

According to Table 3 (companion paper Part I), the bidirectional San Fernando ground motions represent the most severe seismic excitation considered in this paper regarding the PGA. This excitation is used herein to show the effect of pounding on the peak absolute structural acceleration, at the topmost floor, along the excitation time history, as shown in Fig. 14. The peak response values of Fig. 14 are plotted in Fig. 13(a–c) as the ninth load case of San Fernando XY. A sudden stopping of

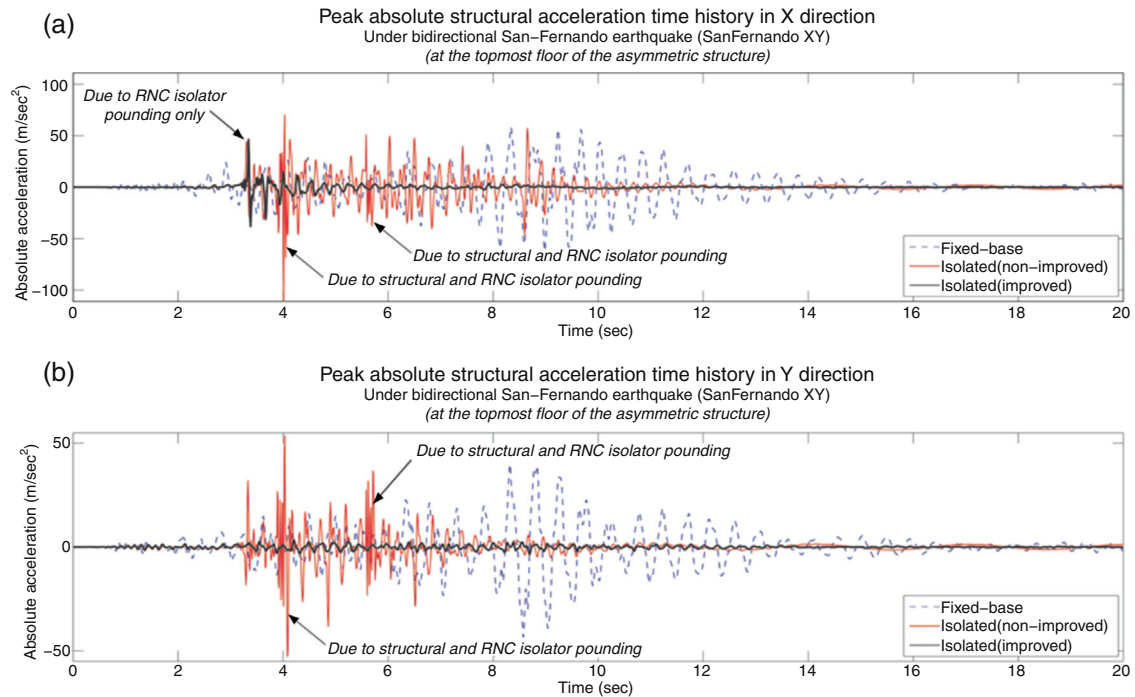


Figure 14. Peak absolute structural acceleration time history in X and Y directions under and bidirectional San-Fernando earthquake considering fixed-base, non-improved isolated and improved isolated cases: (a) structure pounding exists, considering the improved RNC isolation; (b) structure pounding does not exist, considering the improved RNC isolation.

displacement at the pounding level results in large and quick acceleration pulses in the opposite direction, which seems evident as a result of structural pounding at the topmost floor, as indicated in Fig. 14(a and b), where the acceleration responses are amplified and have significantly higher frequency in the case of non-improved RNC isolation. On the other side, the RNC isolator pounding gives no such rise to the acceleration peak value and frequency, as shown in Figure 14(a) by the solid black line representing the improved RNC isolation, which suffers only RNC isolator pounding in X direction. This might be seen as an advantage of inevitable RNC isolator pounding. Because of both structural and RNC isolator pounding in X direction, the corresponding isolation efficiency is severely deteriorated under non-improved RNC isolation as shown in Fig. 14(a), where the RNC-isolated peak structural acceleration is higher than that of the fixed-base case. Under the same conditions, the improved RNC isolation shows a reasonably good efficiency except at the instant of pounding, where the resulting peak acceleration is still even lower than that of the fixed base case with a ratio of 74.40%. Fig. 14(b) shows the acceleration responses in Y direction, where both structural and RNC isolator pounding are considerably less than those in X direction, as in Figs. 11(a) and 19(a), considering the non-improved RNC isolation case. Although, the peak acceleration response of that case is remarkably lowered but is still higher than the fixed-base case. On the other hand, both sources of pounding are nonexistent in the case of improved RNC isolation. As a result, the peak absolute structural acceleration is greatly reduced to represent a ratio of 8.0% to that of the fixed-base case.

### 3.2. Minimum Safe Seismic Gap (MSSG) using the RNC isolator

In this section, the term Minimum Safe Seismic Gap (MSSG) is introduced to express the smallest sufficient separation distance, between two adjacent structures, that permits no structural pounding. The MSSG is used herein as a performance measure for the RNC isolator's ability to limit the peak displacements of a RNC-isolated structure to mitigate or even to entirely avoid or eliminate structural pounding consequently. All the nine cases of loading, considered in Figs. 11–13, are reconsidered. Then, the worst, highest, single result under them all is recorded for each case study, regardless of the excitation. Forty-five different cases are studied considering the variation of both isolation period and the RNC isolator's design displacement. The peak response quantities of interest in this section are the structural pounding at the top-most floor, the corresponding RNC isolator pounding and the corresponding structural story drift in both X and Y directions considering the two methods of non-improved and improved RNC isolation. The buffer stiffness is the same as previous, which is  $2.50 \times 106 \text{ kN/m}$ .

Fig. 15 shows the MSSG in X direction and the corresponding RNC isolator pounding under non-improved and improved RNC isolation. From Fig. 15(a and b), it appears that the improved RNC isolation produces more regular variation of the MSSG against the isolation period and the RNC isolator's design displacement. In addition, the MSSGs are remarkably lower in Fig. 15(b), because of the improved RNC isolation, than in Fig. 15(a). As a result, the corresponding peak RNC isolator pounding in the case of improved RNC isolation, Fig. 15(d),

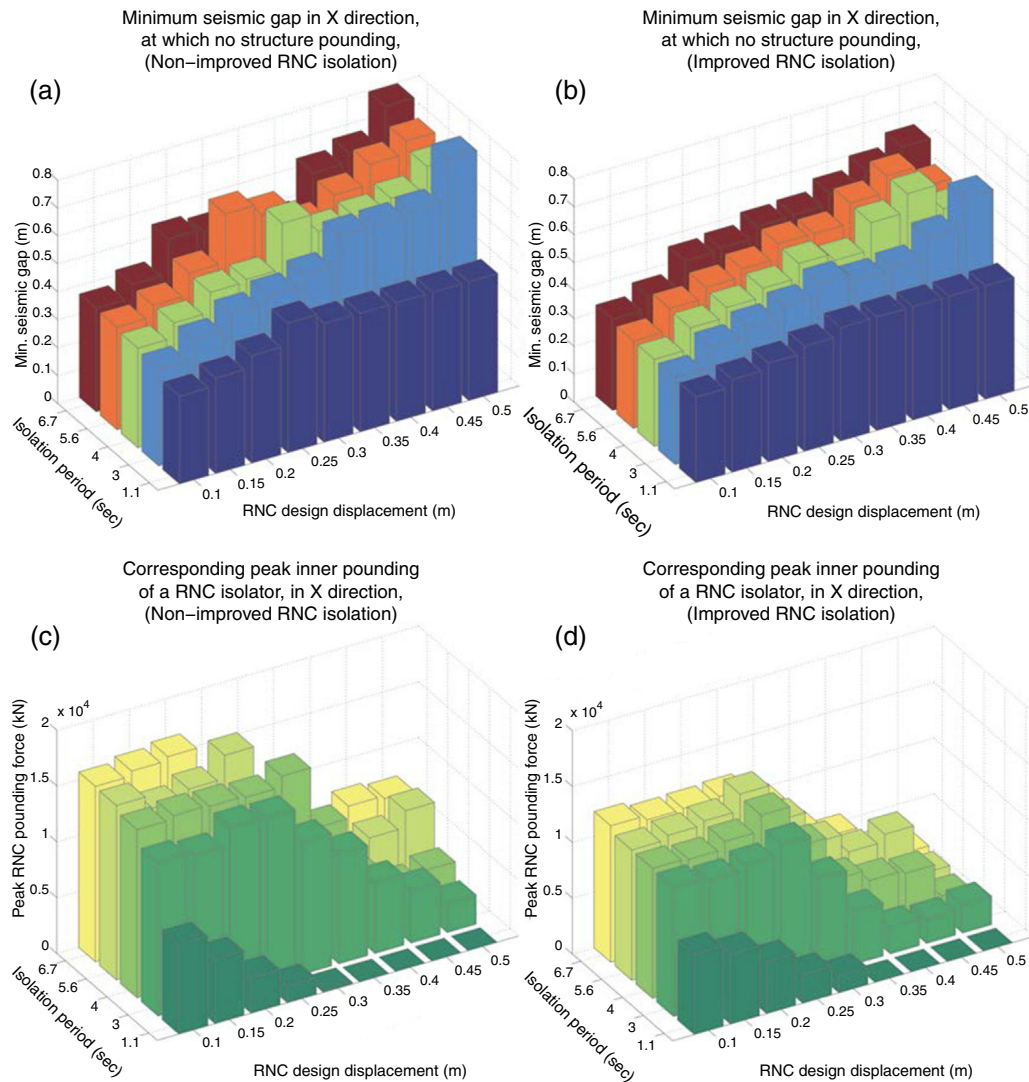


Figure 15. Minimum safe seismic gap in X direction, at which no structural pounding occurs, and the corresponding peak RNC isolator pounding considering the worst of the nine cases of loading: (a) minimum safe seismic gap, non-improved RNC isolation; (b) minimum safe seismic gap, improved RNC isolation; (c) corresponding peak RNC isolator pounding, non-improved RNC isolation; (d) corresponding peak RNC isolator pounding, improved RNC isolation.

is lower than that of the non-improved RNC isolation case, Fig. 15(c). Additionally, Fig. 15(a and b) shows that the variation of the RNC isolator's design displacement affects the MSSG more than the isolation period. This is attributed to the activation of the buffer mechanism after a certain pre-determined bearing design displacement; regardless of how much flexible is the bearing. Such buffer activation cancels the effect of added isolator flexibility to provide higher isolation period. Therefore, the MSSG increases substantially with the increase of RNC isolator's design displacement and increases slightly with the increase of the isolation period, as illustrated by Fig. 15(a and b). Regarding the RNC isolator pounding of Fig. 15(c and d), it seems to be almost invariable at lower design displacements and higher isolation period, then it starts to remarkably decrease after a design displacement of around 30.0 cm as the RNC isolator's design displacement gets bigger. This decrease of the RNC isolator pounding may be attributed to the relatively low kinetic energy of the isolated structure just

before hitting the buffer at those high RNC isolator's design displacements.

Fig. 16 shows the same response quantities of Fig. 15 but in Y direction under the same conditions. Similar to Fig. 15, Fig. 16 shows a superior behavior of the improved RNC isolation to the non-improved one regarding MSSG and RNC isolator pounding, which are significantly less under the improved RNC isolation, as demonstrated by Fig. 16(b and d). Moreover, the variation of the MSSG and the corresponding RNC isolator in Y direction against the isolation period and the bearing design displacement is similar to that in X direction. The only difference is that the improved RNC isolation has lowered significantly the peak structural displacements in Y direction to a degree that has not only prevented structural pounding at relatively lower seismic gaps, but also the RNC isolator pounding is reduced considerably and became nonexistent in many cases.

The corresponding peak story drift ratios in X and Y directions are plotted in Fig. 17 against the isolation period and the

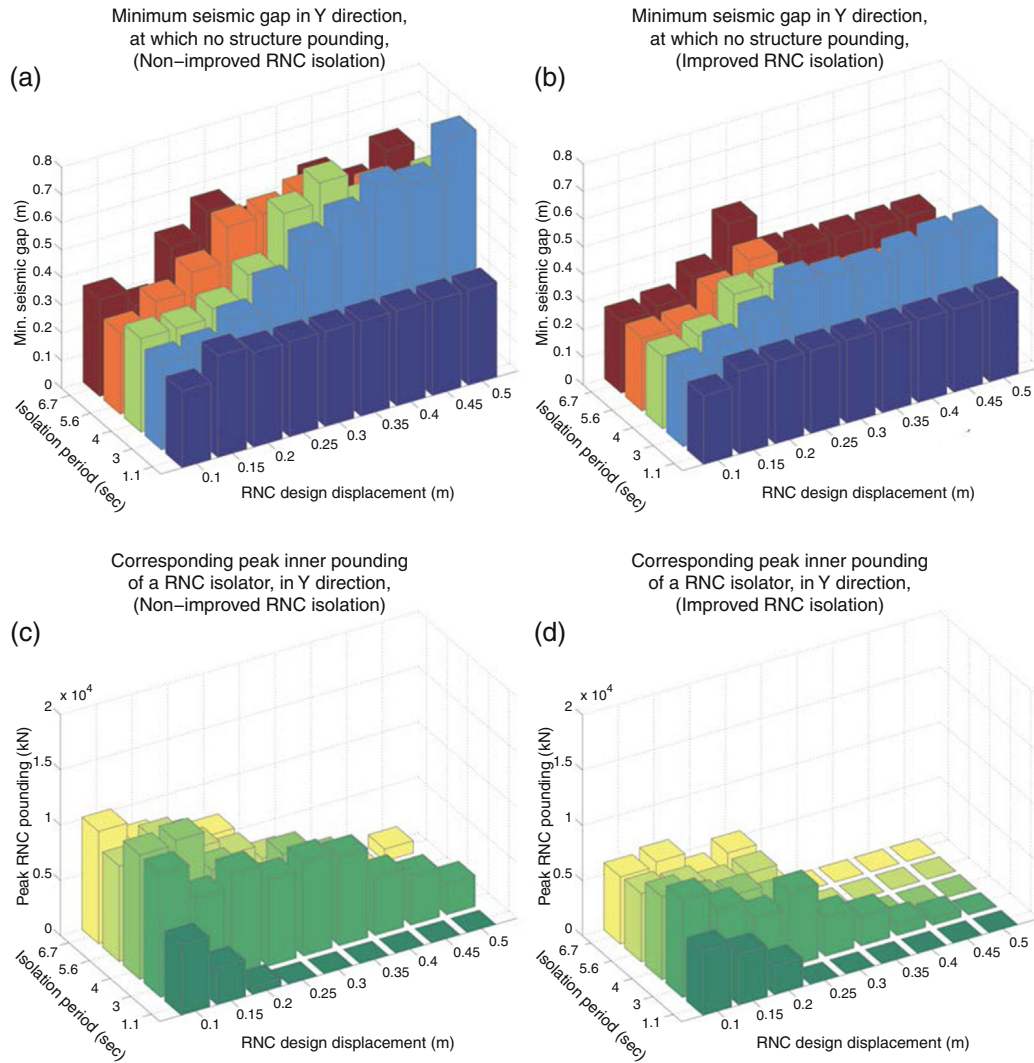


Figure 16. Minimum safe seismic gap in Y direction, at which no structural pounding occurs, and the corresponding peak RNC isolator pounding considering the worst of the nine cases of loading: (a) minimum safe seismic gap, non-improved RNC isolation; (b) minimum safe seismic gap, improved RNC isolation; (c) corresponding peak RNC isolator pounding, non-improved RNC isolation; (d) corresponding peak RNC isolator pounding, improved RNC isolation.

RNC isolator's design displacement considering non-improved and improved RNC isolation methods. Once more, Fig. 17(b and d) show that the structural behavior is better using the improved RNC isolation, especially, the peak drift ratios in Y direction, Fig. 17(d), where the RNC-isolated asymmetric structure behaves almost as a rigid body, as a result of entire elimination of both structural and RNC isolator pounding, in many cases at higher design displacements of the RNC isolator. However, the importance of peak drift ratio is to be used as a measure of possible future structural damage under earthquakes [1]. Reference [1] specified four seismic performance levels SP1 (negligible damage), SP2 (minor to moderate damage), SP3 (moderate to major damage) and SP4 (major damage). Those four seismic performance levels are associated to maximum drift ratios of 0.5%, 1.5%, 2.5% and 3.8%, respectively. Accordingly, the highest two, odd, peak drift ratios of Fig. 17 are 0.74% under non-improved RNC isolation, Fig. 17(a), and 0.50% in case of improved RNC isolation, Fig. 17(b). The earlier is less than half the limit of SP2 to predict minor structural

damage, while the latter of 0.50% means negligible structural damage of the worst, highest, case study under improved RNC isolation. Certainly, the remaining lower peak drift ratios should exhibit less structural damage theoretically. The main outcome of this section is that the RNC isolator could efficiently mitigate (or entirely) eliminate possible structural pounding with adjacent structures, under severe NF ground motions considering limited or insufficient seismic gaps, with minor or negligible negative influence on structural damage.

### 3.3. Appropriate RNC isolator characteristics for no pounding

This section attempts to present a more practical study, where a relatively limited seismic gap is selected based on the available literature [2,3]. Then, a RNC isolator is designed to accommodate with the selected limited gap producing neither structural nor RNC isolator pounding under any of the nine cases of loading. Finally, the peak absolute structural

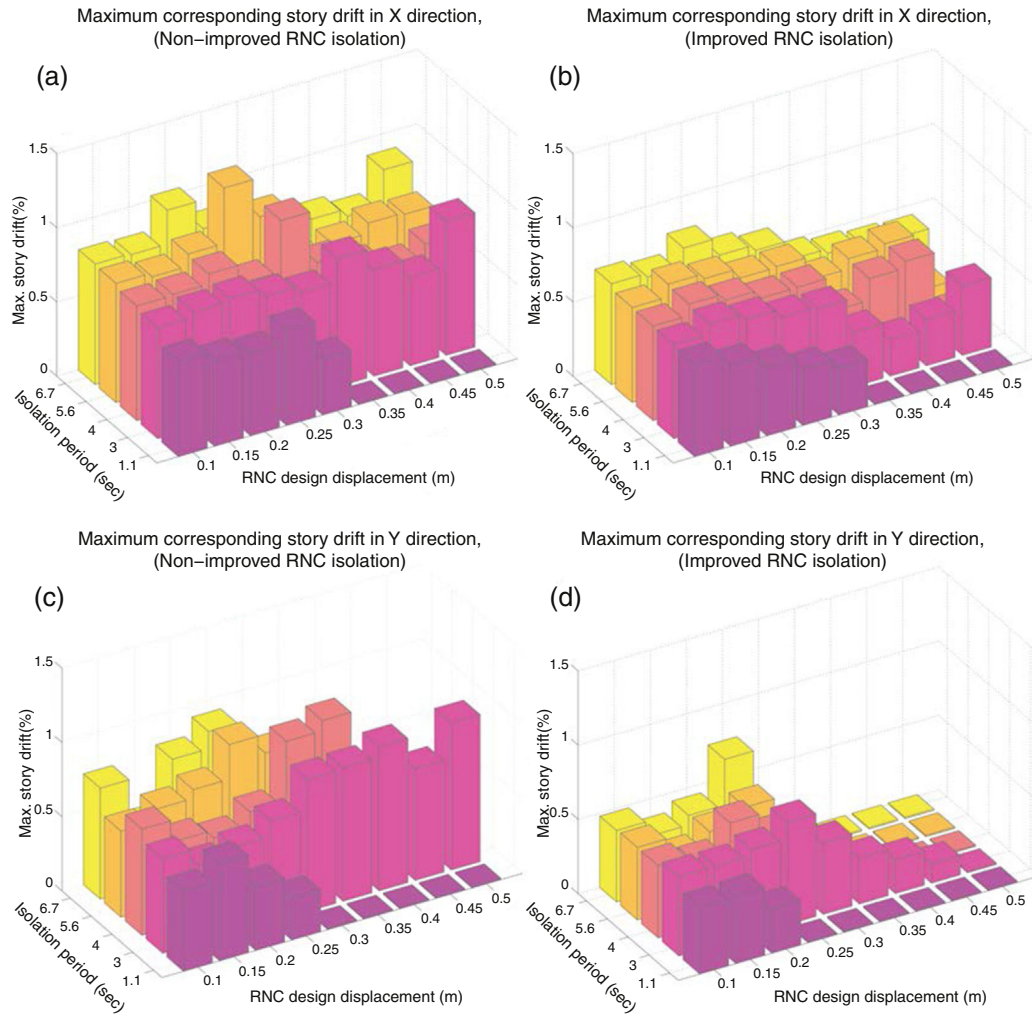


Figure 17. Corresponding peak story drift: (a) in X direction considering non-improved RNC isolation; (b) in X direction considering improved RNC isolation; (c) in Y direction considering non-improved RNC isolation; (d) in Y direction considering improved RNC isolation.

accelerations and structural base shear reactions are employed as performance measures to assess the RNC isolation efficiency. The solution key under such conditions is through reducing the horizontal flexibility of the RNC isolator to a degree that allows for some reasonable structure-ground decoupling and prevents any pounding contact of the RNC-isolated structure with adjacent structures within the selected limited gap. In addition, the resulting peak bearing displacement will be lower than a chosen relatively small design displacement of the RNC isolator. This could achieve reasonably efficient isolation with no pounding at all. Moreover, the choice of a less flexible RNC isolator with a relatively small design displacement imposes constraints upon the peak bearing displacement and velocity. Constraining the bearing displacement decreases the probability of activating the buffer mechanism, while constraining its velocity allows the RNC-isolated structure to hit the buffer with significantly low kinetic energy to produce reasonably low inner RNC isolator pounding with less arising unwanted effects on the other structural responses, compared to the case of highly flexible RNC isolator design.

In this section, the seismic gap between the RNC-isolated asymmetric structure and the surrounding adjacent one, in both X and Y directions, is taken less than or equal to:

$$\text{Seismic gap of a RNC – isolated structure} \leq x_{\text{des}} + \frac{S_{AB}}{4} \quad (1)$$

where  $x_{\text{des}}$  is the RNC isolator’s design displacement, and  $S$  is the horizontal separation distance, between two fixed-base structures A and B, which is obviously equal to the peak relative displacement response  $x_{\text{rel}}$  between those adjacent fixed-base structures. The separation distance  $S$  is given by [2,3] as:

$$S_{AB} = x_{\text{rel}} = \sqrt{x_A^2 + x_B^2 - 2\rho_{AB}x_Ax_B} \quad (2)$$

where  $x_A$ ,  $x_B$  and  $x_{\text{rel}}$  are the mean peak displacement values of the two adjacent structures and their relative displacement, respectively. Based on the period ratio  $r = T_b/T_a$ , the correlation coefficient  $\rho$  is given by [4,5] for a two adjacent structures with equal damping ratio  $\theta$  as:

$$\rho_{AB} = \frac{8\xi^2(1+r)r^{3/2}}{(1-r^2)^2 + 4\xi^2r(1+r)^2} \quad (3)$$



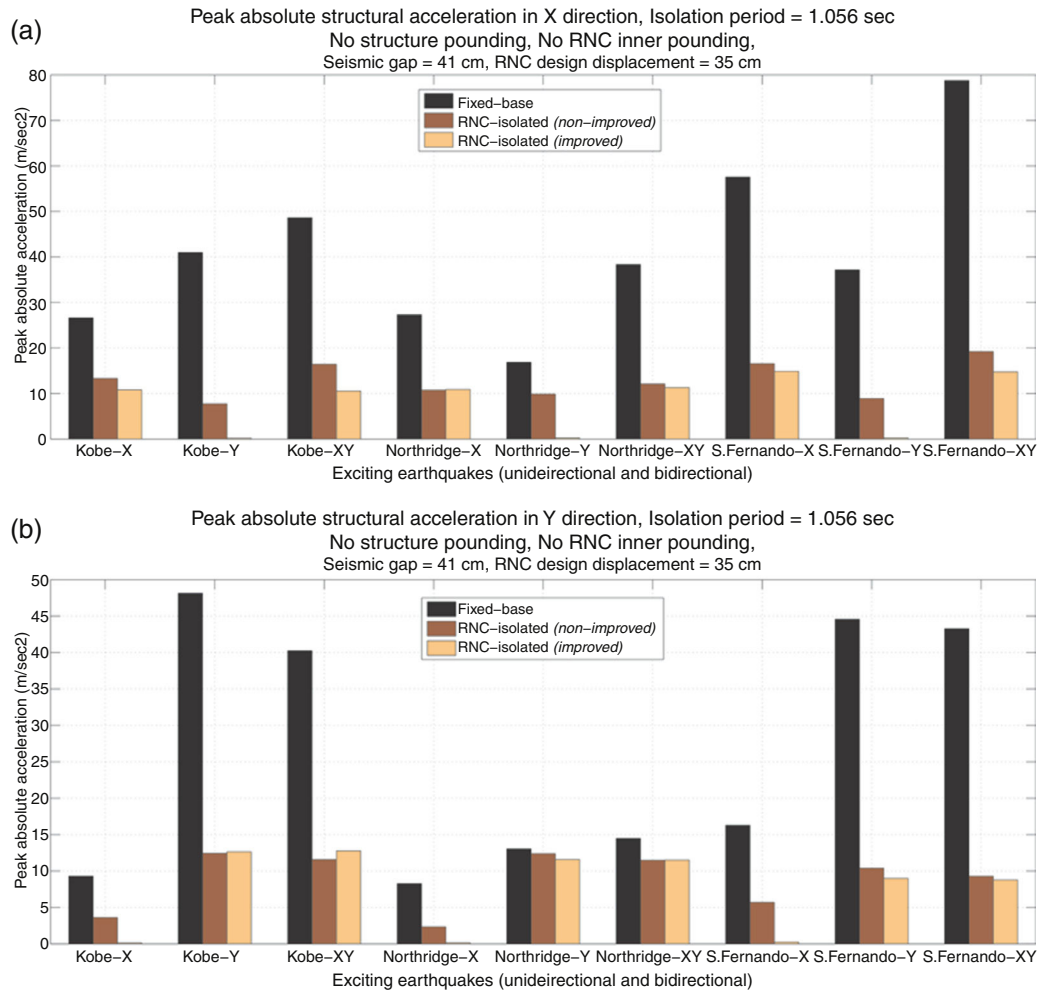


Figure 18. Peak absolute structural acceleration considering low isolation period and a limited seismic gap, at which there is no structure pounding nor inner RNC pounding: (a) in X direction; (b) in Y direction.

In this section, the design displacement of the RNC isolator is taken as 35.0 cm, while the calculated separation distance according to Eqs. (2) and (3) is found to be 27.15 cm. Therefore, and according to Eq. (1), a relatively small seismic gap is considered in this section as 40.0 cm.

Considering a small isolation period of 1.056 s, chosen by trial and error method to fulfill the above conditions, Fig. 18 compares the peak absolute structural accelerations of the non-improved and improved RNC-isolated asymmetric structure with their corresponding values in the fixed-base case in X and Y directions. In addition to the nearly zero out-of-plan acceleration responses under unidirectional excitations using the improved RNC isolation, the other main observation is that the RNC-isolator is able to significantly reduce the peak structural accelerations under most of the severe NF ground motion cases, at low isolation period with no pounding, regardless being non-improved or improved RNC isolation. Although, it was noted that the peak structural and bearing displacements are still lower than their chosen limits under some excitations. Therefore, a trial and error method is used to obtain the most appropriate isolation period of only the improved RNC isolation under simultaneous bidirectional excitations of each of the three considered NF

earthquakes, such that the resulting peak structural and RNC isolator displacements are just below their chosen limits. The resulting structural responses of the RNC-isolated asymmetric structure should be the lowest possible under the bidirectional excitations within those limits. Therefore, they may lead to a fair assessment of the RNC isolator's efficiency under the specified limited conditions.

Figs. 19–21 demonstrate those obtained results under the simultaneous bidirectional components of Kobe, Northridge and San Fernando, respectively, in X and Y directions. Under bidirectional Kobe earthquake, the appropriate isolation period is found to be 1.393 s, where the controlling parameters were both the peak structural and RNC isolator displacements in Y direction, Fig. 19(b). The RNC isolator has reduced the frequency and amplitude of the peak absolute structural acceleration to a reasonably satisfying degree in X and Y directions under the specified restrictions, as shown in Figure 19(a). Other peak response quantities are listed in Fig. 19(b). The base shear reaction, which is a measure for the seismic force transfer into the structure, is reduced to 49.0% of its value in the fixed-base case in Y direction. Similarly, the main controlling parameter was found to be the peak RNC isolator's displacement in X direc-

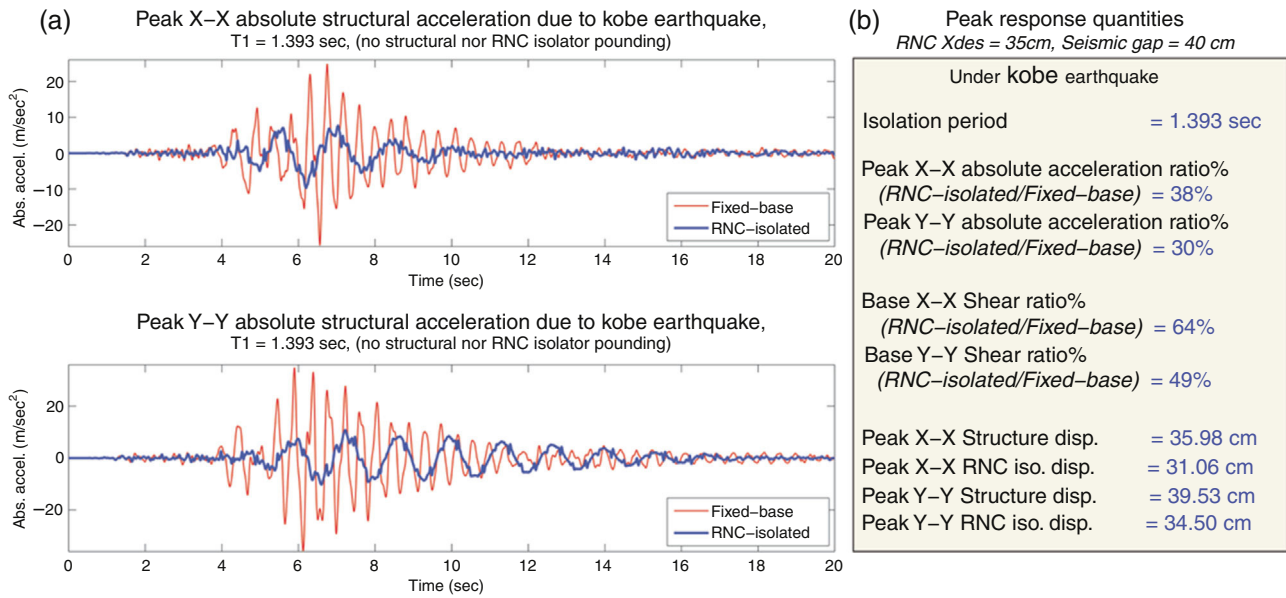


Figure 19. Lowest response quantities considering the appropriate RNC isolator characteristics to achieve isolation without any pounding at a seismic gap of 40 cm and a RNC isolator design displacement of 35 cm: (a) peak absolute structural acceleration under Kobe earthquake; (b) peak response quantities under Kobe earthquake.

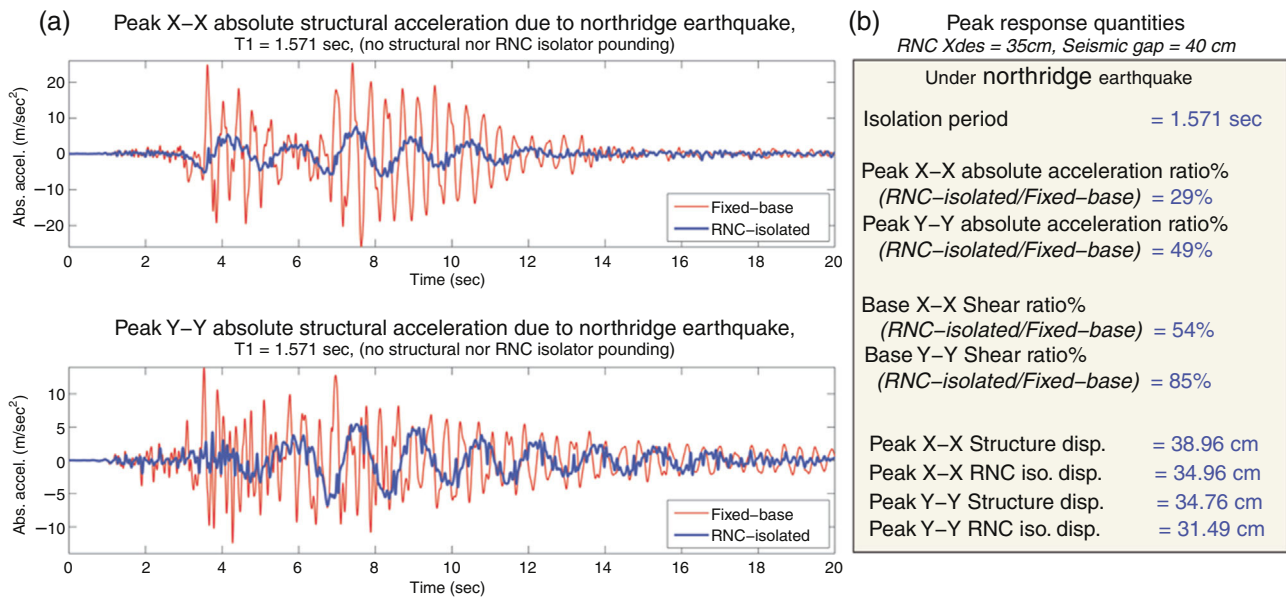


Figure 20. Lowest response quantities considering the appropriate RNC isolator characteristics to achieve isolation without any pounding at a seismic gap of 40 cm and a RNC isolator design displacement of 35 cm: (a) peak absolute structural acceleration under Northridge earthquake; (b) peak response quantities under Northridge earthquake.

tion under bidirectional Northridge earthquake, Fig. 20(b), at an appropriate isolation period of 1.571 s to just avoid pounding. The peak acceleration and base shear are reduced to 29.0% and 54.0% in X direction, respectively. Under such severe NF excitation, the time history plots of peak structural accelerations, Fig. 20(a), show a fairly good behavior of the improved RNC isolation in X direction, while in Y direction the behavior is moderately good. In Fig. 20(a), there are no high frequency acceleration pulses, which indicates nonexistent pounding. Under the severest ground motion in this paper, regarding PGA, the RNC isolator has efficiently reduced the peak structural

accelerations to 25.0% and 15.0% in X and Y directions, respectively, under bidirectional San Fernando earthquake, Fig. 21. In the same way, the structural base shear is reduced to 56.0% and 31.0% in X and Y directions, respectively. Fig. 21(a) confirms the efficient behavior of the improved RNC isolator with no indication of structural or RNC isolator pounding at the lowest isolation period of 1.057 s among the three considered earthquakes, where the controlling parameter was the peak structural displacement in X direction. The main conclusion of this section is proving the ability of the RNC isolator to provide an efficient protection of multistory asymmetric structures,

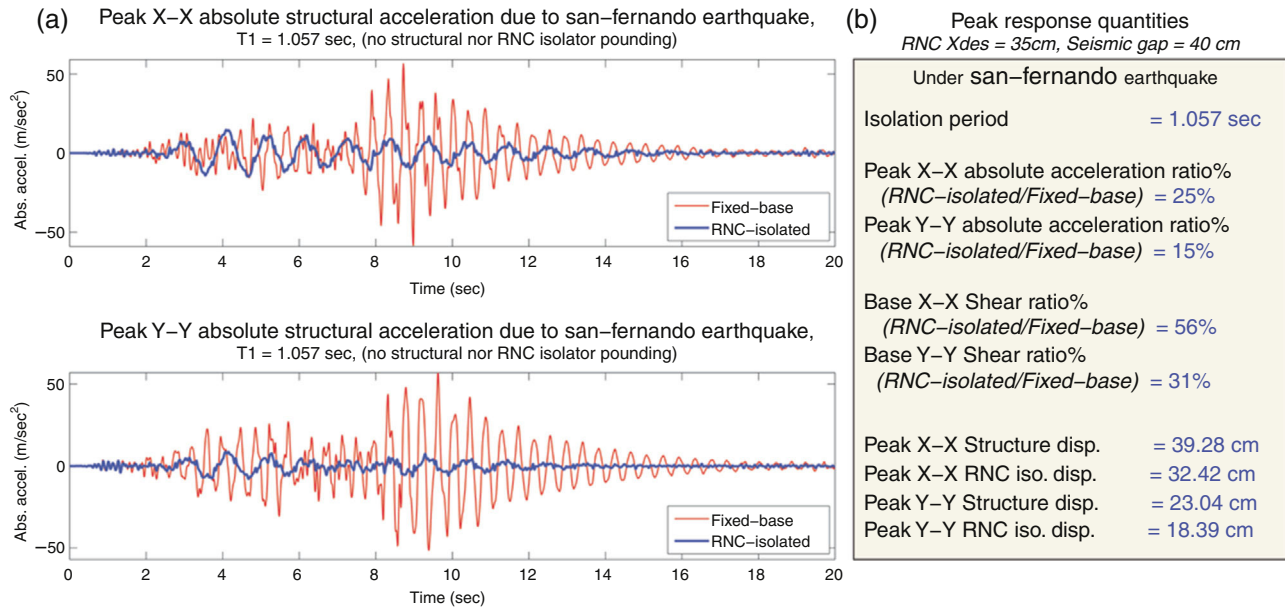


Figure 21. Lowest response quantities considering the appropriate RNC isolator characteristics to achieve isolation without any pounding at a seismic gap of 40 cm and a RNC isolator design displacement of 35 cm: (a) peak absolute structural acceleration under SanFernando earthquake; (b) peak response quantities under SanFernando earthquake.

against bidirectional NF earthquakes considering limited seismic gaps, with absolutely no structural nor RNC isolator pounding.

#### 4. Summary and conclusions

This paper addresses the possibility of nearly eliminating the torsional responses and torsional structural pounding of isolated asymmetric structures using the Roll-in-Cage (RNC) isolator considering near-fault (NF) ground motions.

It was found that the RNC isolator is able to theoretically minimize or to entirely eliminate torsional responses of the RNC-isolated asymmetric superstructures. Therefore, the paper investigated the influence of that torsion minimizing on the isolation efficiency under uni- and bidirectional NF excitations. Then, the paper investigated numerically the efficiency of the RNC isolator's buffer mechanism, especially, its ability to draw downward any possible pounding of the RNC-isolated superstructure to take place only within the solid bearing bounds. Moreover, the ability of RNC isolator's buffer mechanism to limit the peak bearing displacement, has allowed the paper to introduce the concept of minimum safe seismic gap (MSSG). The MSSG is introduced to express the smallest sufficient separation distance, between two adjacent structures, that permits no structural pounding. The MSSG is used herein as a performance measure for the RNC isolator's ability to limit the peak displacements of a RNC-isolated structure to mitigate or even to entirely avoid or eliminate structural pounding consequently. The influence of partial and full elimination of direct seismic pounding, of the RNC-isolated superstructure, on the isolation efficiency is investigated.

It was also found that the generated inner pounding inside the RNC isolator (due to its buffer activation after exceeding a certain design displacement chosen by the designer) has less negative effects on the peak structural responses compared to the direct seismic pounding of the RNC-superstructure itself with adjacent structures. This has motivated the paper to benefit from the ability of the rolling-based RNC isolator to provide efficient seismic isolation, even at low isolation periods, to entirely prevent inner pounding of the RNC isolator together with the direct seismic pounding of the RNC-superstructure under the same seismic gap widths and NF excitations. This was achieved by using relatively stiffer RNC isolators such that they provide efficient seismic isolation with no pounding at all. Finally, it was found that the RNC isolator has achieved significant reductions in peak absolute acceleration responses besides entire elimination of torsion and pounding of RNC-isolated asymmetric structures considering limited seismic gaps and strong uni- and bidirectional NF earthquakes.

#### References

- [1] SEAOC, Recommended lateral force requirements and commentary, Seismology Committee, Structural Engineers, Association of California, Sacramento, CA, 1999.
- [2] V. Jeng, K. Kasai, B.F. Maison, A spectral difference method to estimate building separations to avoid pounding, *Earthq. Spectra* 8 (2) (1992) 201–223.
- [3] j. Penzien, Evaluation of building separation distance required to prevent pounding during strong earthquakes, *Earthq. Eng. Struct. Dyn.* 26 (1997) 849–858.
- [4] A. Der, Kiureghian, Structural response to stationary excitation, *ASCE J. Eng. Mech. Div.* 106 (6) (1980) 1195–1213.
- [5] M. Grigoriu, Mean-square structural response to stationary ground acceleration, *ASCE J. Eng. Mech. Div.* 107 (5) (1981) 969–986.