# USAGE OF SEISMIC BASE ISOLATION TO REDUCE THE DUCTILITY DEMAND FROM PREFABRICATED CONCRETE STRUCTURES

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## 1 Introduction

Seismic Base Isolation is a technology utilized to improve the seismic performance of buildings and bridges, and for the seismic retrofitting of existing structures. The technology was first proposed at the end of the 19th century and its applications began in the 1970s. Today, seismic isolation is a mature technology with growing recognition and application around the world.

When utilized in prefabricated structures, seismic base isolation has the potential to reduce the ductility demand from these structures under seismic loading, thus making it possible to design and build prefabricated concrete structures with superior seismic performance.

In this work, the effectiveness of seismic base isolation in controlling the deformations in prefabricated concrete structures was studied. A typical multi-story prefabricated concrete frame was modeled with and without a base isolation system. The dynamic behavior of the two structures was analyzed using computer simulations. Material non-linearity was incorporated into the models in order to properly analyze the effect of past yielding deformations in the structural members.

## 2 SEISMIC BASE ISOLATION

### 2.1 CONCEPT

The underlying concept of Seismic Base Isolation is to decouple the superstructure (above the foundation section) of a structure from its foundation. During an earthquake the foundation moves with the ground and the structure is subjected to seismic excitation. With the utilization of a seismic base isolation system, the response of the superstructure to the dynamic seismic loading is altered favorably and the seismic dynamic energy transferred to the superstructure is reduced. Thus seismic inertial loads are reduced and the seismic damage the structure acquires is drastically reduced. Many innovative devices and systems were developed for the purpose of seismic base isolation of buildings and bridges. The most widely used base isolation devices are described below.

### 2.2 TECHNOLOGY AND DEVICES

LAMINATED ELASTOMERIC BEARINGSElastomeric bearings laminated with steel plates were developed for the base isolation of buildings and bridges. These bearings consist of numerous steel plates vulcanized with layers of rubber/neoprene (Figure 1). Seismic performance, especially the shear strain capacity (up to 200%), of laminated steel-

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rubber/neoprene bearings are far superior to rubber/neoprene bridge pads. Rubber or Neoprene based elastomeric bearings have been utilized for the shrinkage protection of bridge decks for over 50 years. Although there are numerous companies producing bridge pads globally, only a few specialized companies are able to produce laminated bearings to the quality levels required for seismic base isolation systems.

LEAD CORE LAMINATED ELASTOMERIC BEARINGS

Natural rubber or neoprene laminated seismic bearings naturally have little inherent dynamic damping. Damping is crucial to minimize the seismic energy flow to the superstructure and to limit the horizontal (shear) displacements of the bearings. Improved damping characteristics are achieved by placing a lead core inside a steel laminated rubber bearing (Figure 1). The lead core deforms plastically at a predetermined flow stress and thus dissipates energy through hysteretic damping.

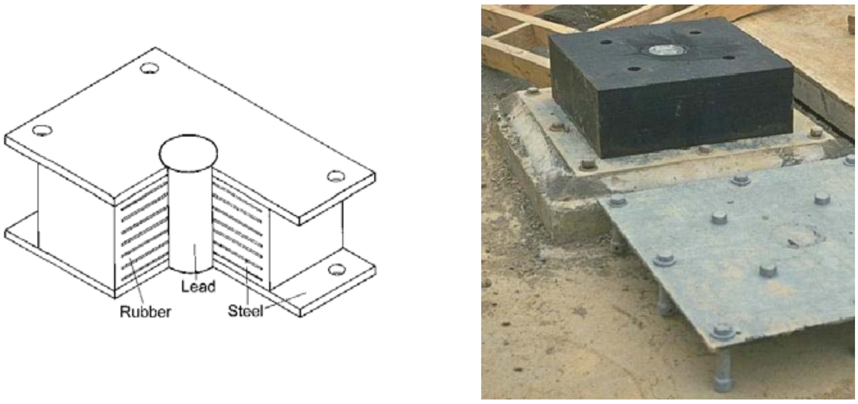


Figure 1, Lead Core Steel Laminated Elastomeric Isolation Bearing

HIGH DAMPING NATURAL RUBBER BEARINGS

In 1982, the Malaysian Rubber Producers' Research Association first achieved high damping characteristics in laminated rubber seismic bearings by incorporating special additives in the rubber [1]. Thus, the necessity for external damping devices can be eliminated.

SLIDING BASE ISOLATION DEVICES

The initial concepts of seismic base isolation proposed at the end of the 19th and the beginning of the 20th centuries were based on placing the superstructure on sand or talc [1]. This concept is realized through the usage of modern materials; stainless steel on Teflon. There has been extensive testing work done on sliding bearings. A main disadvantage of the sliding bearings is that these devices are not self-centering due to the lack of a restoring force. To overcome this deficiency friction pendulum systems were developed where the bearing has a curved surface to provide the necessary restoring forces. Due to the corrosion problems of metals, sliding type bearings require regular maintenance.

## 2.3 ADVANTAGES

In a base isolated structure the displacements are concentrated in the isolation bearings during a seismic event. The vertical distribution of the absolute inertial forces is relatively even compared to a fixed base structure. As a result, the relative displacements of the floors (inter-story drift) and consequently the element forces are significantly reduced.

The design forces used for the dimensioning and detailing of the structural elements in a base isolated structure may not always be significantly lower compared to a fixed base structure. This is mainly due to the low force reduction factors, R, assigned to base isolated structures in design codes compared to the R factors used for fixed base structures (R=5-8 for ductile fixed base structures against R=1.4-2 for base isolated structures) [2]. Considering that high R factors will result in extensive plastic deformations in the structural elements to dissipate seismic energy during a major seismic event, the low R factors used for seismic base isolated structures assure minimal plastic deformation, hence reduced ductility demand from elements and connections, and consequently minimal seismic damage. The reduced ductility demand is a significant improvement of performance to be taken advantage of in prefabricated structural systems. The difference between the R factors for fixed base and isolated structures also creates a necessary vibration frequency separation between the superstructure and the base isolation system

Reduced seismic structural damage makes operability possible immediately following a major seismic event. Continuous operability is required for essential facilities such as health care centers, fire stations, and emergency centers. Of the 10 hospitals affected by the 1994 Los Angeles Earthquake, only the base isolated hospital (University of Southern California Teaching Hospital) was able to operate immediately following the event [3].

Another important benefit provided by seismic base isolation is reduced floor accelerations due to the low frequency first mode behavior of the base isolated structure. The relatively lower floor accelerations reduce the inertial loads on the contents of the structure, installations and non-ductile architectural elements such as facade coverings. Thus, seismic isolation provides a good solution for structures with valuable contents such as museums and facilities housing high value machinery.

## 2.4 LIMITATIONS OF THE TECHNOLOGY

Although seismic base isolation is an effective technology for improving the seismic performance of a structure, there are certain limitations on its usage.

Seismic base isolation improves the performance of a structure under seismic loading partially by changing (increasing) the fundamental (first mode) vibration period of the structure. Thus the vibration period of the structure is moved away from the high-energy seismic ground period and seismic energy transfer to the structure is minimized. Therefore usage of seismic base isolation on soft or weak soil conditions, where high period ground motion is dominant, reduces the benefits offered by the technology.

The base isolation system has a relatively high vibration period compared to a conventional structure. Due to the principle of dynamic resonance, a larger difference between the dynamic vibration frequencies of the isolation system and the superstructure results in a minimized seismic energy transfer to the superstructure. Therefore, seismic base isolation is most effective in relatively rigid structural systems and will provide limited benefits for highly flexible superstructures.

During a major seismic event, very large deformations occur in the seismic isolation bearings; in the range of 500mm depending on the characteristics of the system [1] [4]. The large deformations in the bearings result in large displacements of the superstructure. This motion requires sufficient clearance from surrounding buildings and possible obstructions. Furthermore precaution must be taken in the external electrical and mechanical installations connected to the building to accommodate for these large displacements.

## 2.5 COST EFFECTIVENESS

Seismic base isolation significantly reduces the plastic deformations in a structure, and hence reduces the ductility demand from the structural system. Consequently, the necessary detailing for ductility in the members and connections of the structure will be less "conservative" compared to a fixed base structure, facilitating significant reductions in detailing costs.

Considering the minimal or lack of structural damage acquired by a seismically base isolated structure during even a major seismic event, seismic base isolation offers a significant reduction in the operational costs of the structure. Moreover significant business (operation) interruption losses are prevented due to the continuous operation capability of seismic base isolated structures. Therefore seismic base isolation offers cost effective solutions when the seismic performance criterion is more than life saving and operational costs are considered.

## 2.6 APPLICATIONS

Seismic Base Isolation is enjoying growing popularity worldwide due to both the innovative devices invented which increased feasibility of the technology, and the extensive research and development work done globally which has developed confidence in the concept. Japan, New Zealand and U.S.A. are the countries where the technology has received widest acceptance [1] [4].

One of the early and most notable applications of seismic base isolation is the William Clayton Building in Wellington New Zealand. The 17000-m2 structure completed in 1982, was isolated with lead core rubber bearings. A notable retrofitting project realized with seismic base isolation is the Old Parliament Building also in Wellington. This historical building, built in 1922, was retrofitted in 1996 with 514 lead core rubber bearings. In the Te Papa - Museum of New Zealand base isolation was utilized to minimize floor accelerations for the protection of valuable contents (Figure 2).

Figure 2, Te Papa – Museum of New Zealand

The first structure in the world to be isolated with high damping rubber bearings is the Foothill Communities Law and Justice Center in California U.S.A. The Los Angeles City Hall, a 28 story steel frame structure, is the tallest building with seismic base isolation. Built in 1928, this building was retrofitted with 475 high damping bearings, 60 sliding bearing and numerous viscous dampers.

The largest base isolated building in the world (47000 m2) is the West Japan Postal Computer Center located in Kobe. The superior performance of this structure during the 1995 Kobe Earthquake has highly popularized the usage of seismic base isolation in Japan, especially for residential buildings. There are also many applications of seismic base isolation in China, Europe (especially Italy and France), Chile and Armenia.

## 3 DUCTILITY DEMAND IN PRECAST CONCRETE STRUCTURES

Prefabricated industrial production of concrete structural elements has many advantages compared to cast-in-situ concrete. Among these are superior quality control, speed in production and erection. Due to these advantages utilization of structural (load bearing) and architectural (non-load bearing) prefabricated concrete elements is common around the world.

Structures built in high seismic zones are generally designed to withstand strong earthquakes by absorbing energy through plastic deformations; ductility. Ductile behavior is achieved through special design and detailing of structural elements and connections.

Most national design codes require the connections of prefabricated structures to be designed, detailed and constructed such that the structure behaves like cast-in-situ reinforced concrete. This concept is called "cast-in place emulation". For example, the Turkish Seismic Code requires seismic design forces for connections to be increased by 50% for welded (dry) connections and 20% for cast-in-situ (wet) connections [5]. The over design of the connections is prescribed to facilitate plastic hinge formation in the elements away from the connections.

There is ongoing research worldwide, following an alternative path, to develop ductile and energy absorbing connections for prefabricated structures [6] [7] [8] [9]. This new design philosophy is known as "jointed construction". In these kinds of connections, the deformations are concentrated at the joints, while the beams, columns and panels are protected.

Seismic base isolation, whenever feasible, has the potential to minimize and even eliminate plastic deformations in connections and elements of structures, minimizing the ductility demand from the structural system.

## 4 SIMULATIONS

A computer model of a typical prefabricated moment frame structure was utilized to run computer simulations. The objective of the simulations was to compare the performance (deformations and displacements) of the fixed base structure with the base isolated structure. The load deformation characteristics of the elements were modeled to incorporate material non-linearity into the model.

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### 4.1 STRUCTURAL MODEL

A four story, 4x5 bay typical prefabricated concrete moment frame was modeled for the computer simulations (Figure 4). The bays are 8.750 m in each direction. The building consists of square section columns and I section beams. The columns are 80 cm square and the I beams 40 cm wide by 115 cm deep in the X direction and 95 cm deep in the Z direction.

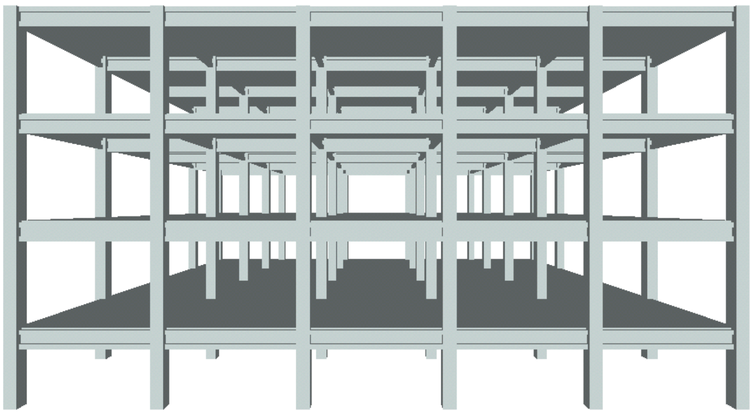

Figure 4, Analysis Model of Non-Isolated Building

The calculated periods of the structure, based on gross section properties, are 0.93 seconds in the X direction and 1.08 seconds in the Z direction, where the beams are shallower.

The structure was intended for illustrative purposes only and so a full design to a specific seismic load level was not performed, rather typical reinforcing contents were assumed for the elements. At the beam ends, the beams were assumed to have 1% top steel and 0.75% top steel. The columns were assumed to have 2% reinforcing throughout.

The strength of the building with this reinforcing was assessed by performing a pushover analysis, where a lateral load proportional to the 1$^{st}$ mode shape is applied until a mechanism forms. Figure 5 shows the force-displacement curves for the two directions.

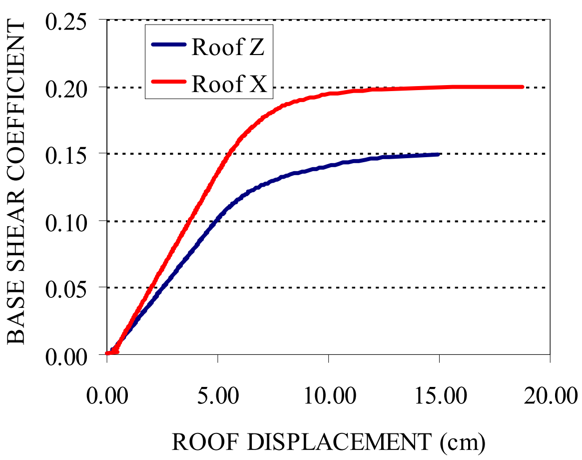


Figure 5, Pushover Curve for Non-Isolated Building

In the X directions, where the beams are deeper, the maximum strength corresponds to 20% of the structure weight, with maximum roof displacements of approximately 20 cm. In the Z direction the maximum base shear force of 15% of weight occurs at a displacement of 15 cm.

## 4.2 STRUCTURAL MODEL WITH BASE ISOLATION

The model was adapted to a base isolated configuration by adding a floor diaphragm at ground level with isolator elements beneath (Figure 6). The isolation system was based on lead-rubber bearings, 100 cm diameter x 30 cm high with lead cores sized to provide a yield level of approximately 5% of the seismic weight.

The isolators were designed to provide an effective period of 2.5 seconds under an earthquake corresponding to Seismic Zone 1, site Class Z2. At this period, the calculated displacement was 24 cm, the base shear coefficient 0.15 and the effective damping 20%.

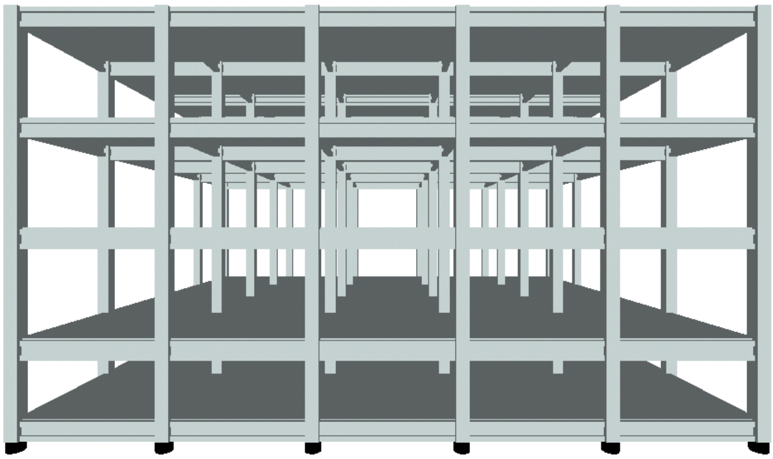

Figure 6, Analysis Model of Isolated Building

## 4.3 STRUCTURAL RESPONSE AND COMPARISON

The models were analyzed using the ANSR-L computer program, a version of the ANSR-II program originally developed at the University of California, Berkeley [10]. The program has been modified to suit modern Performance Based Design practices [11]. The evaluations used the time history method of analysis, incorporating the non-linear behavior of the frame elements and the base isolators.

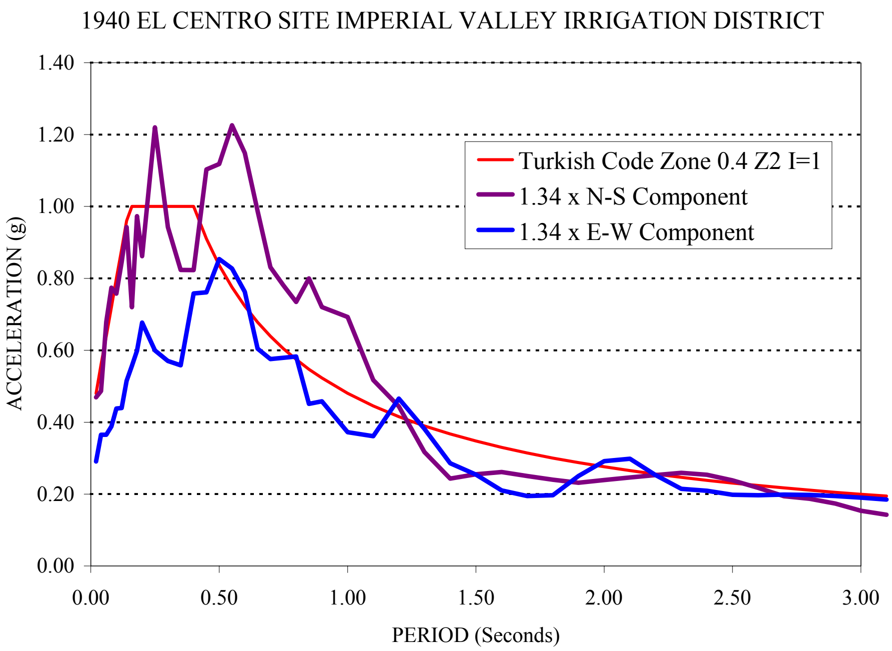


Figure 7, 5% Damped Spectrum of Time History Used for Analysis

The selected time history utilized for the simulations used the two horizontal components of the 1940 El Centro earthquake, applied simultaneously along the two horizontal axes. The record was applied first with the N-S component along the X-axis and then with the N-S component along the Z-axis.

A scale factor of 1.34 was applied to both components so as to provide a reasonable match to the Seismic Zone 1, site Class Z2 seismic load level assumed for isolation system design (Figure 7). A duration of 30 seconds was used, applied at a time step of 0.01 seconds, with 5% viscous damping.

The frame elements non-linearity was modeled with flexural hinges at each end of the element. The moment strength was based on the nominal ultimate strength and the yield function was bi-linear with zero strain hardening. The column strength was based on a yield surface, which was a function of the axial load and bending moments about each axis. The lead rubber isolators were modeled as yielding flexural elements with stiffness and strength set to match the design properties of the devices.

### 4.3.1 Base Shears

Table 1 lists the maximum base shear coefficients from each analysis and the maximum displacements in the isolation system.

| | Base Shear $V_x$ / W | Base Shear $V_z$ / W | Base Disp. X (cm) | Base Displ. Z (cm) |
|---|---|---|---|---|
| Non-Isolated EQ 1 | 0.222 | 0.181 | | |
| Non-Isolated EQ 2 | 0.221 | 0.186 | | |
| Isolated EQ 1 | 0.078 | 0.116 | 13.6 | 19.9 |
| Isolated EQ 2 | 0.105 | 0.078 | 20.8 | 13.7 |

Table 1 Maximum Response Quantities

The maximum base shear coefficients in the non-isolated frame were 0.22 in the X direction and 0.19 in the Z direction. The elastic coefficient at a period of 1 second is approximately 0.50g and the reduction is the effect of ductility in the structural system.

The isolated structure had a maximum base shear coefficient of 0.12 and a maximum displacement of 20.8 cm. These values are slightly lower than the design estimates of 0.15 and 24 cm, demonstrating the effect of a flexible structure above the isolation system. The design procedure assumes a rigid superstructure.

### 4.3.2 Displacements

Figure 8 shows the envelope displacement profiles for the isolated and non-isolated structures. The isolated structure has higher total displacements because of the effect of the base displacement. However, the net structural displacements, the difference between base and roof displacements, are significantly smaller.

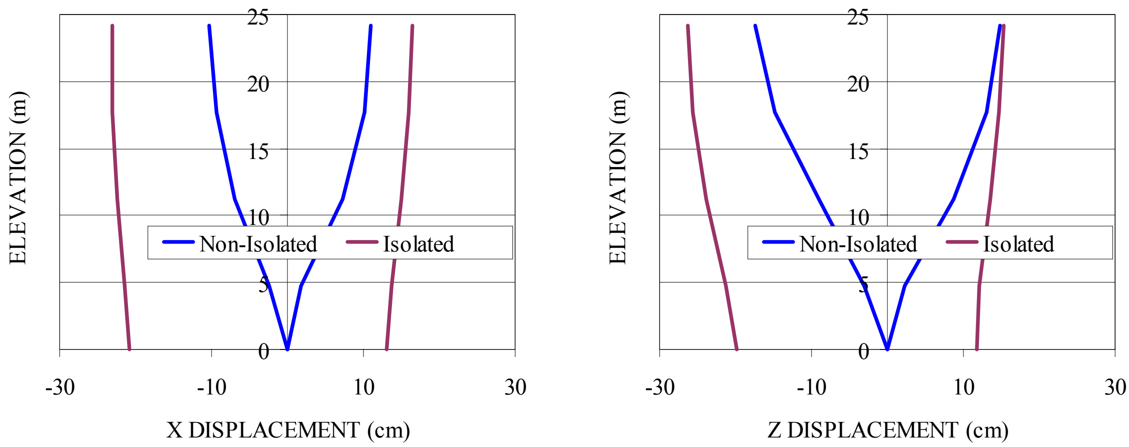


Figure 8 : Maximum Displacement Profiles

Figure 9 plots the Z displacements for the non-isolated and isolated configurations. The isolated displacements plotted are the net structural displacements, calculated as the difference between the roof and ground floor at each time step.

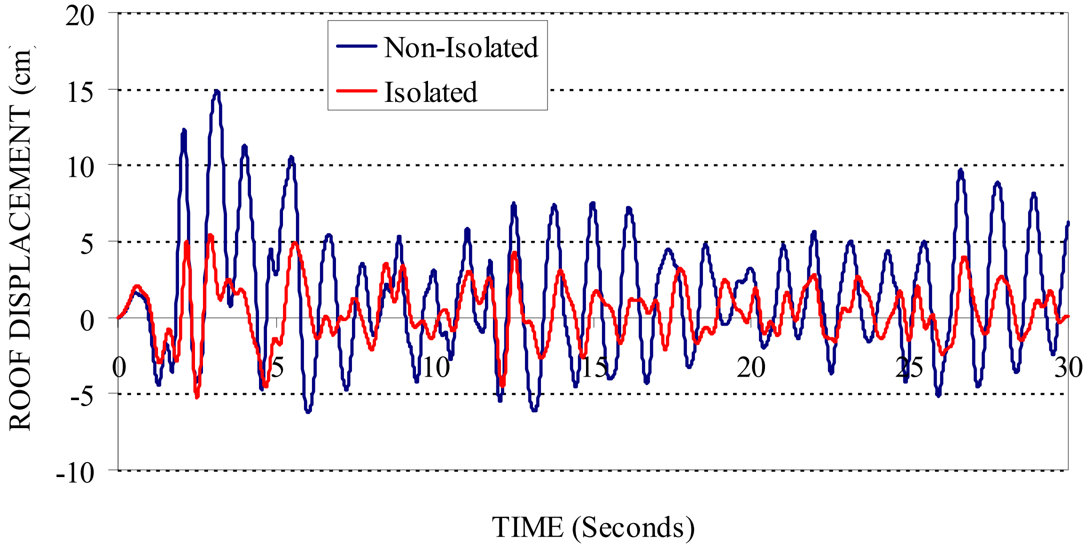


Figure 9 : Time History of Displacements

### 4.3.3 Accelerations

Figure 10 plots the peak floor acceleration profiles for the two configurations in each direction. The isolation system de-amplifies the ground accelerations for all levels except the roof, that is, the intermediate floors have peak accelerations lower than the peak ground acceleration which is 0.47 for the scaled earthquake record used.

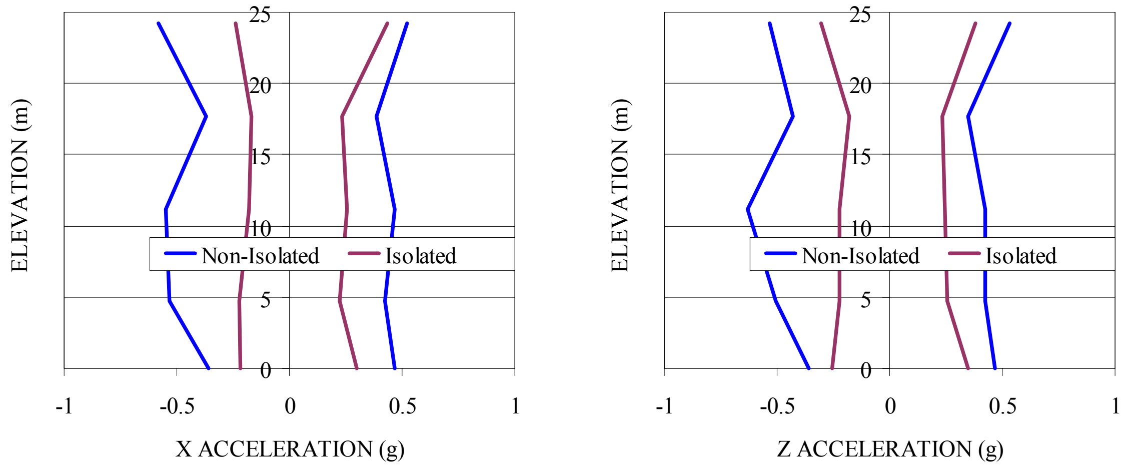


Figure 10 : Maximum Acceleration Profiles

The floor accelerations in the non-isolated building are higher than those for the isolated building. However, the margin is not as great a margin as would be expected. This is because non-linear actions in the frames act to limit the maximum accelerations transmitted into the building, in a similar manner to the isolation system but in a less effective and less controlled manner.

### 4.3.4 Drifts

Figure 11 plots the maximum drifts that occurred at each story during any time in the analyses. The isolation system reduced the drifts by a factor of more than 2, with the peak non-isolated drift of 1.00% reducing to 0.46% when the isolation system was incorporated in the model.

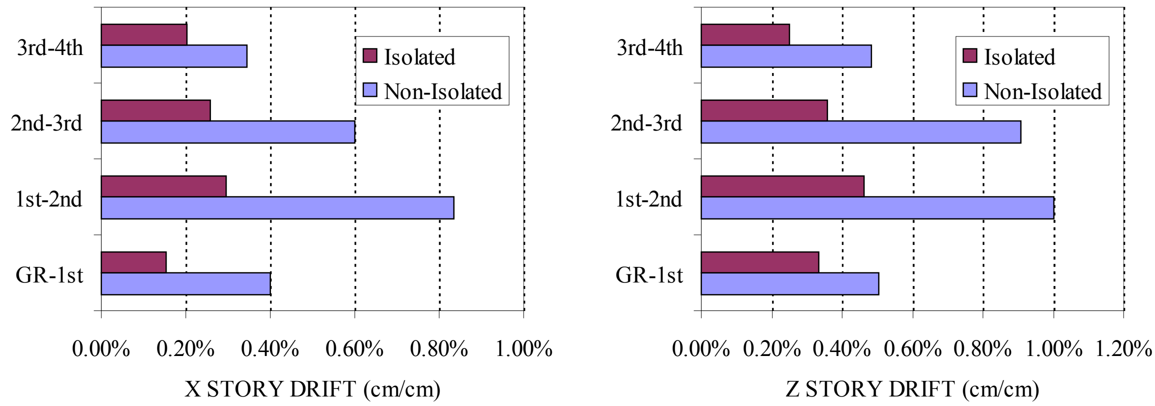


Figure 11 : Maximum Story Drifts

### 4.3.5 Plastic Rotations

Table 2 lists the maximum plastic rotations for the non-isolated and the isolated structures. The plastic rotations are measured in radians and are peak values reached at any time in the analysis.

Some column hinging occurred in the non-isolated structure, with maximum plastic rotations of 0.0062 and 0.0050 radians in the X and Z directions respectively. When the base isolation system was included in the model, yielding did not occur in the columns at any time.

Plastic hinging occurred in beams at all levels for the non-isolated frame, with a peak value of 0.0104 r, and at all levels but the roof for the isolated configuration, with a peak value of 0.0029 r. The non-isolated hinging was reversing at most locations, indicated by both positive and negative plastic rotations. For the isolated frame, hinging in most case was non-reversing, with positive plastic rotations but no negative plastic rotations. Plastic rotations for both structures were higher in the Z direction, where the beams are shallower and have a lower yield strength.

| **X Non-Isolated** | | **X Isolated** | | **Z Non-Isolated** | | **Z Isolated** | |
|---|---|---|---|---|---|---|---|
| Column Plastic Rotation (rads) | Beam Plastic Rotation (rads) | Column Plastic Rotation (rads) | Beam Plastic Rotation (rads) | Column Plastic Rotation (rad) | Beam Plastic Rotation (rad) | Column Plastic Rotation (rad) | Beam Plastic Rotation (rad) |
| | -0.0000 | | -0.0000 | | -0.0008 | | -0.0000 |
| | 0.0000 | | 0.0000 | | 0.0002 | | 0.0000 |
| 0.0018 | | 0.0000 | | 0.0020 | | 0.0000 | |
| | -0.0023 | | -0.0000 | | -0.0041 | | -0.0000 |
| | 0.0029 | | 0.0000 | | 0.0055 | | 0.0003 |
| 0.0031 | | 0.0000 | | 0.0030 | | 0.0000 | |
| | -0.0067 | | -0.0000 | | -0.0084 | | -0.0000 |
| | 0.0060 | | 0.0004 | | 0.0104 | | 0.0029 |
| 0.0062 | | 0.0000 | | 0.0045 | | 0.0000 | |
| | -0.0029 | | -0.0000 | | -0.0046 | | -0.0000 |
| | 0.0056 | | 0.0000 | | 0.0067 | | 0.0024 |
| 0.0045 | | 0.0000 | | 0.0050 | | 0.0000 | |

Table 2 : Maximum Plastic Rotations in Columns and Beams

## 4.4 DISCUSSION OF SIMULATION RESULTS

The base isolation system has demonstrated capability to significantly reduce the plastic deformations and hence damage in the superstructure. Moreover floor accelerations were also relatively smaller in the base isolated system compared to the non-isolated structure.

The elastic base shear of 0.50g is reduced to 0.22g by structural yielding and to 0.12g by the isolation system. Similarly, peak elastic floor accelerations would be expected to be 1.5 times the base shear coefficient, of 0.75g. Yielding reduced this to 0.63g and the base isolators to 0.44g. Drifts were reduced from 1.00% to 0.46% by the isolation system. Without seismic isolation, the prefabricated frame yields extensively and this acts to limit the earthquake forces which can be transmitted into the structure, in a similar fashion to an isolation system however in an uncontrolled and destructive manner

The extent and amplitude of plastic deformations showed the beneficial effects of isolation most clearly. Without isolation, the frame deformations caused extensive reversing hinges in the columns (up to 0.006 radians) and the beams (up to 0.0104 radians). When the isolation system was installed, the columns did not yield and most beam hinges were non-reversing, with maximum plastic rotations of 0.0029 radians, 28% of the non-isolated values.

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