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FRAGILITY ANALYSIS OF STRUCTURES WITH CONTROLLED ROCKING BEAM-COLUMN CONNECTIONS AND VISCOUS DAMPERS

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ABSTRACT

Controlled rocking system has been proposed as an alternative design method to improve the structural performance of buildings. The rocking systems allow vertical and horizontal components to rotate freely at boundaries. When integrated in a frame system, rocking columns may reduce the yielding strength of the entire system. The acceleration response of yielding structure is proportional to its own weight, but it is limited by the yield strength. Thus using a rocking system, a limited acceleration response can be achieved. However, the displacements of a structure may become undesirably large due to lower strength, but they can be controlled adding damping. A simplified model of the rocking column was developed and verified through experimental tests conducted at the University at Buffalo. As a case study in this paper, the response of an analytical model of a scaled reinforced concrete frame structure is considered. Synthetic ground motions developed using the Barrier model are used as seismic input of the nonlinear dynamic analysis. Fragility analyses are performed to show the seismic performance of the original structures and the retrofitted structure with the rocking beam-column connections and viscous dampers. The analysis shows that the story accelerations can be limited by using rocking columns, while the story displacements can be controlled by using viscous dampers.

Introduction

The objective of retrofit techniques is to improve the performance of the structure, maintaining the response below their performance limits. The structural response of inelastic structures is usually measured in terms of displacements and accelerations. These are the main causes of damage in structural and non-structural components. In the performance based design, the target of the displacement and strength is dependent on the damage level of the structures. However, it is very important to protect the contents and non-structural systems, particularly in critical facilities such as hospitals, laboratories, advanced technology centers, where the secondary systems representing contents and non-structural components can be more expensive

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than the structure itself. Therefore, in order to improve the performance of a structure, both displacements and acceleration should be kept below acceptable limits. Current retrofit methods such as those employing supplemental bracing lead to an increase in the global strength of the structure. In such cases, although the displacements and the ductility demands decrease, there is an increase in the floor accelerations. Reducing the strength of a structure primarily reduces its structural accelerations and associated forces when subjected to seismic excitation. Recent works conducted by Viti et al. (2006) and Cimellaro et al. (2009) has conceptually shown that it would be more beneficial to reduce the strength of structures defined as "weakening" in order to reduce accelerations and to control the displacement response by adding damping property. This paper deals with the actual practical method to weaken the structure and adding viscous dampers by conducting fragility analyses of a selected model structure.

Weakening and Damping (WeD) retrofit technique

The presented retrofit procedure consists of *weakening the structure* by cutting the ends of the lateral resisting columns to reduce the lateral strength. However, this strength reduction is often accompanied by increased displacements, which can be solved by *adding damping* devices to reduce and control the deformations and displacements. This method has some similarities with the base isolation method when used together with damping, since it reduces both the acceleration and the displacement. However, the base isolation method is unable to avoid a large displacement because technically it is difficult to provide damping at the base of the structure.

Design of weakening and damping retrofit technique

In this study weakening of structures is obtained by using "rocking columns" as a practical technique to reduce structural strength. The technique is developed by Roh (2007) and also presented in Roh and Reinhorn (2008, 2009). It has been implemented in IDARC2D (Reinhorn et al., 2009). The rocking column is a type of double hinged column or cracked base and top column, which resists vertical loads with minimum lateral strength. A simplified relationship moment vs. curvature is developed from principles of mechanics and verified through experiments. The rocking column is shown in Figure 1 and it is modeled using the multi-linear behavior.

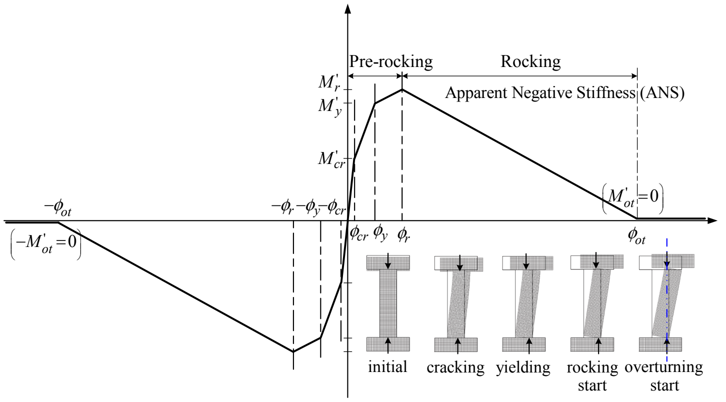

Figure 1. Modeling of rocking columns

There are several sequences in the lateral behavior such as a *base opening*, *yielding at edge*, *rocking start point*, and *overturning start point*. Details of these definitions are given in Roh (2007). When a lateral force is applied, one side of the element separates from the base. This state is defined as an *opening (cracking) state*. Once the partial separation occurs, the contact area at the base of the column is smaller than the area of the section. The *yielding state* is defined by the yield stress or strain developed at the edge of the compressive side. At the onset of rotation, the lateral force resistance no longer increases and remains at its maximum value, that is the strength of the rocking column and defined as a rocking point. The *overturning point* is determined from geometric considerations as shown in the right corner of Figure 1. When the rocking column reaches the overturning point, it has zero lateral resistance. The rocking columns behave nonlinear elastically if the rectangular edges are designed with a spherical edge shape where no stress concentration and crushing are developed. The spread plasticity or nonlinearity model captures the length of the nonlinear stress zone which is developed due to the absence of tensile resistance at the column base. For the rocking phase simulation that shows an Apparent Negative Stiffness (ANS), the stepwise strength reduction scheme is used. More details are described in the reference (Roh and Reinhorn, 2009).

For adding damping force, viscous dampers are used. The viscous dampers are modeled using Maxwell model with a high spring stiffness to activate the viscous property only (Reinhorn et al., 2009).

Simulated ground motion

The seismic input is one of the most uncertain quantities involved in the evaluation of the structural response under seismic excitation, because the magnitude of the ground motion as well as its frequency content and its duration are very difficult to predict. Such parameters are usually assumed statistically, and they are characterized by a relevant dispersion. A set of ground motions have been used in this study called MCEER series (Wanitkorkul and Filiatrault, 2005). The MCEER series consist of 100 synthetic near fault ground motions divided in fours subsets corresponding to 4 hazard levels 20%, 10%, 5% and 2% of the probability of exceedance in 50 years, respectively. Records have been generated using a physical model called Barrier model (Papargeogiu et al., 1983), which was calibrated using actual near fault records. Details about this set of ground can be found in Wanitkorkul and Filiatrault (2005).

Case study

As an illustration of the proposed retrofit technique, a structure designed only for gravity loads and that has been previously studied (Bracci et al., 1995), has been used. The 1/3 scaled model is shown in Figure 2.

Structural model

The scaled model consists of two frames and the weakening strategies are applied to *frame B only* as shown in Figure 2. Two types of structural columns are considered depending on the end shape of the rocking columns. (i) If all rocking columns have fixed ends (FE), the frame B provides full lateral resistance, which is defined as Type A corresponding to the original structure. (ii) If the columns are allowed to rock, having a flat contact with spherical edges

(FCSE) at the ends, then the lateral resistance of frame B is decreased. Two cases are considered depending on the rocking column locations. Type BA corresponds to the case when all columns at the first floor of frame B are allowed to rock, while Type SA corresponds to the case when all columns at all stories of frame B are allowed to rock. Type BA investigates the structural response with a weak-first story and Type SA investigates the effect of weakening at all stories. Nodal weights are considered to model the moment-curvature capacity of rocking column which is presented in right corner of Figure 2. The viscous dampers for the damped configurations are applied to *frame A* only. The dampers are installed for every story and every bay, thus total of 9 dampers are used. The viscous coefficient used for all dampers is 0.143 kip-sec/in.

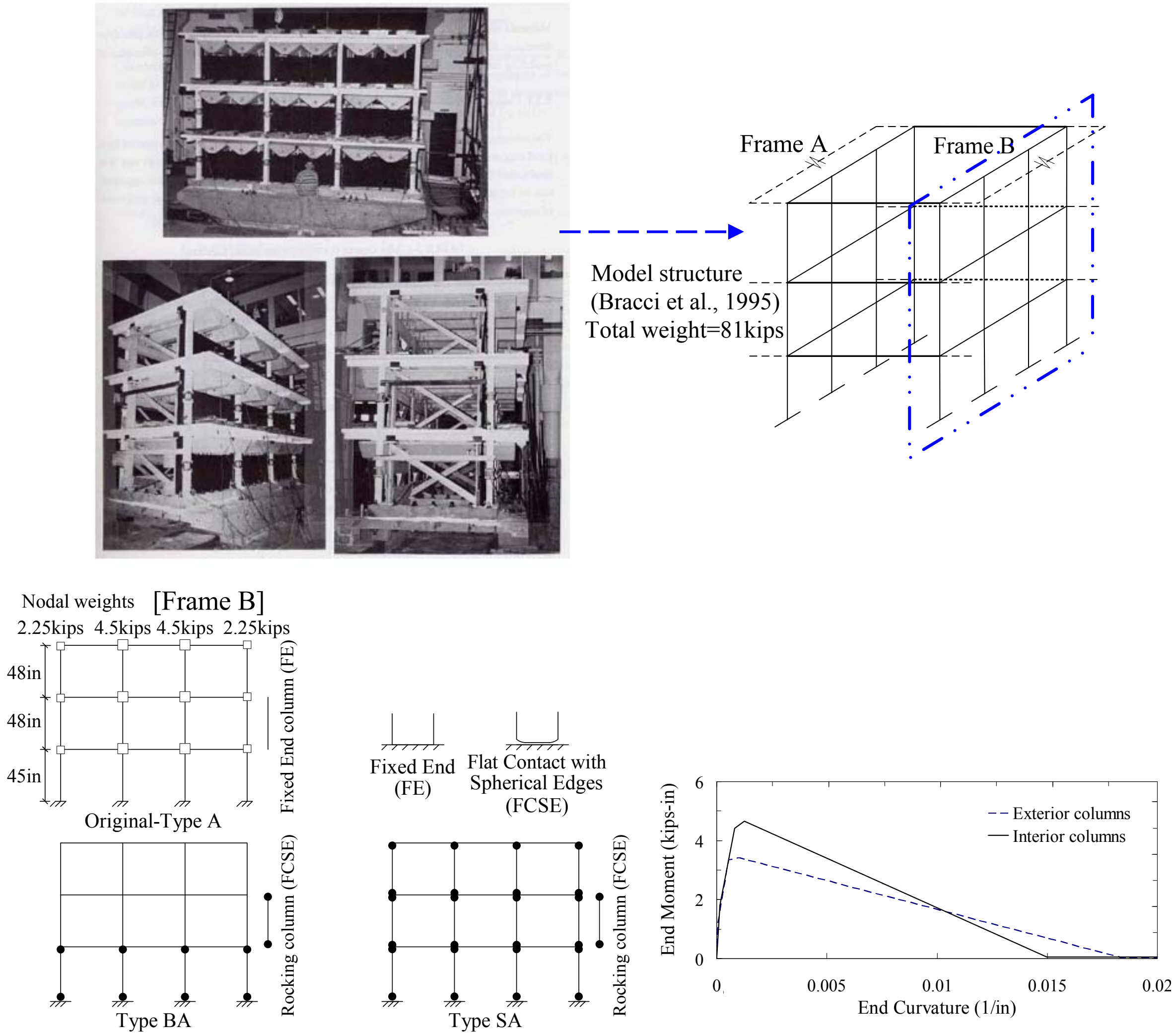

Figure 2. Model structure and alternatives for weakening

The described model undergoes 100 earthquake records of different intensity. The simulations are performed in IDARC2D (Reinhorn et al., 2009). Because the structure is a scaled model, the time scale of the simulated earthquakes is compressed of a factor $\tau=\sqrt{\lambda}=0.577$ where $\lambda=0.33$ in the 1/3 scale model, therefore final earthquake records duration is 23.65sec.

Numerical results

The seismic response of the case study was evaluated by performing nonlinear dynamic analysis. The response of the original structure (Type A), of the weakened structure (Type BA and Type SA) are plotted in Figure 3, while the response of the same configurations, but with added viscous dampers are plotted in Figure 4. Responses for the 100 earthquake records considered are plotted in the plane drift-acceleration where the peak drift and acceleration at each story level and for each earthquake record are plotted in Figure 3 and Figure 4 for all the configurations described above.

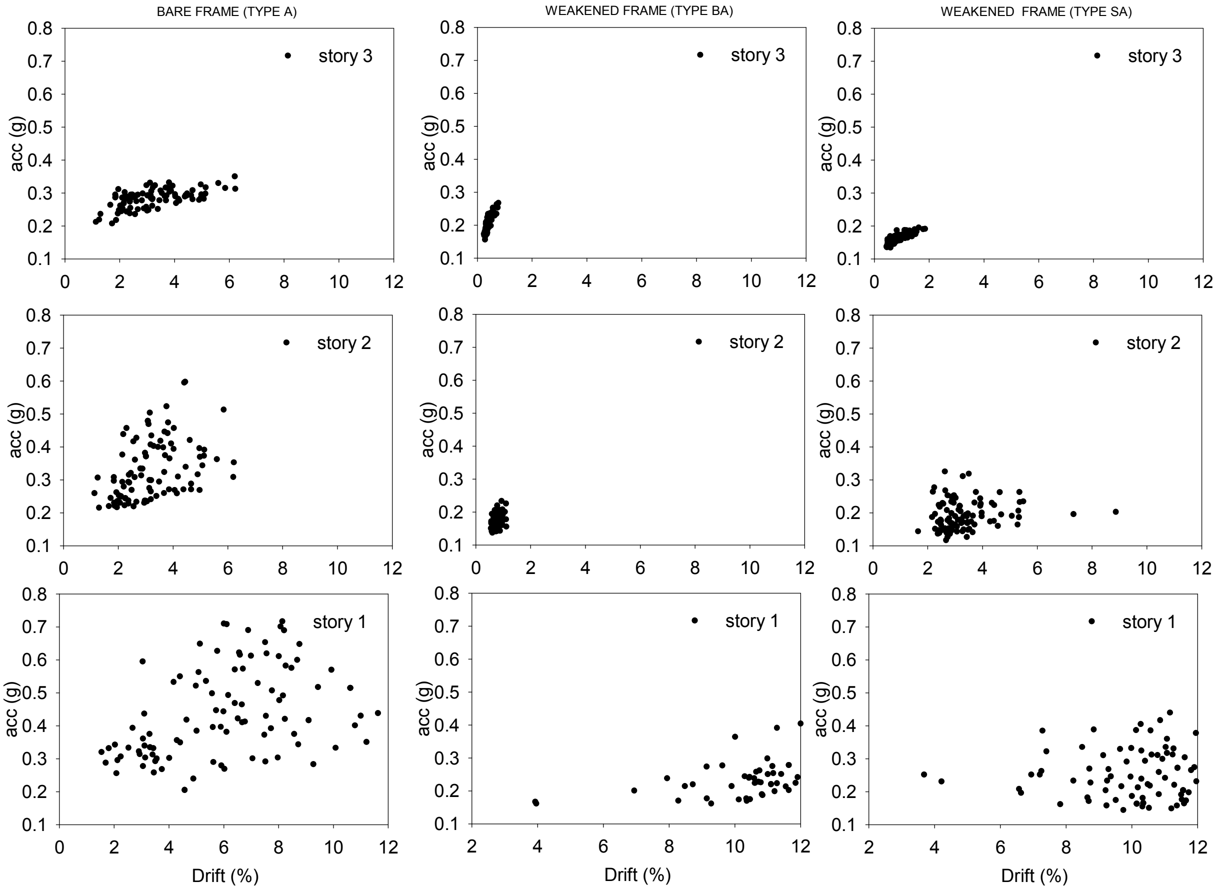

Figure 3. Effects of weakened retrofitting

As shown in Figure 3 the weakening generates acceleration reduction at all story levels, and it also narrows the band of response. The building response consequentially is more predictable. If we focus on the drift response in Figure 3 it is possible to observe an increment of drift at the first story, but a drift and acceleration reduction at the upper stories. In Figure 4 is shown the effect of damping on the same structural configurations described in Figure 3. Damping generates a reduction of drift at the first story for the weakened configurations, while maintaining the same performances at the upper stories.

Earthquake forces reduction on the structure are more evident if base shear is considered as shown in Figure 5. The base shear is plotted for the 4 different hazard levels considered in the nonlinear dynamic analysis and for the four different structural configurations. The maximum base shears appear in their inelastic ranges. It means that the peak acceleration responses are obtained from the strength reduction. Both weakened configurations of Type BA and Type SA achieve a reduction of base shear of about 30%. The weakening configurations have a narrow band effect on the building response as shown in the acceleration response of the case study in Figure 6. In fact, the histograms of the acceleration response of the weakened configurations shift to the left with respect to the bare frame and provide a more predictable response.

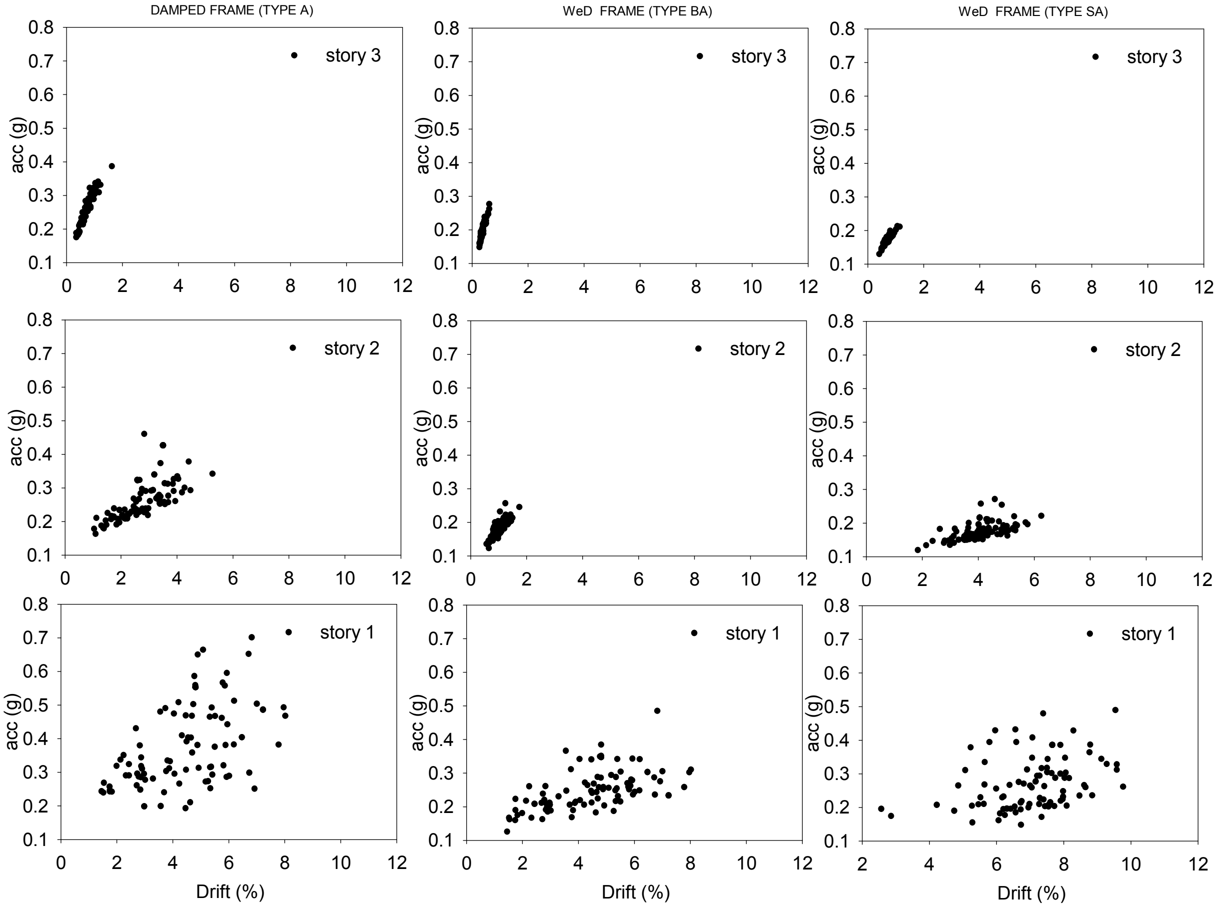

Figure 4. Effects of weakened and damped retrofitting

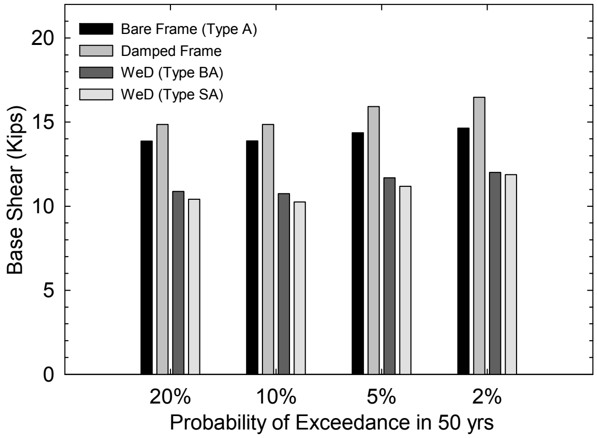

Figure 5. Average base shear vs. hazard level for different configurations

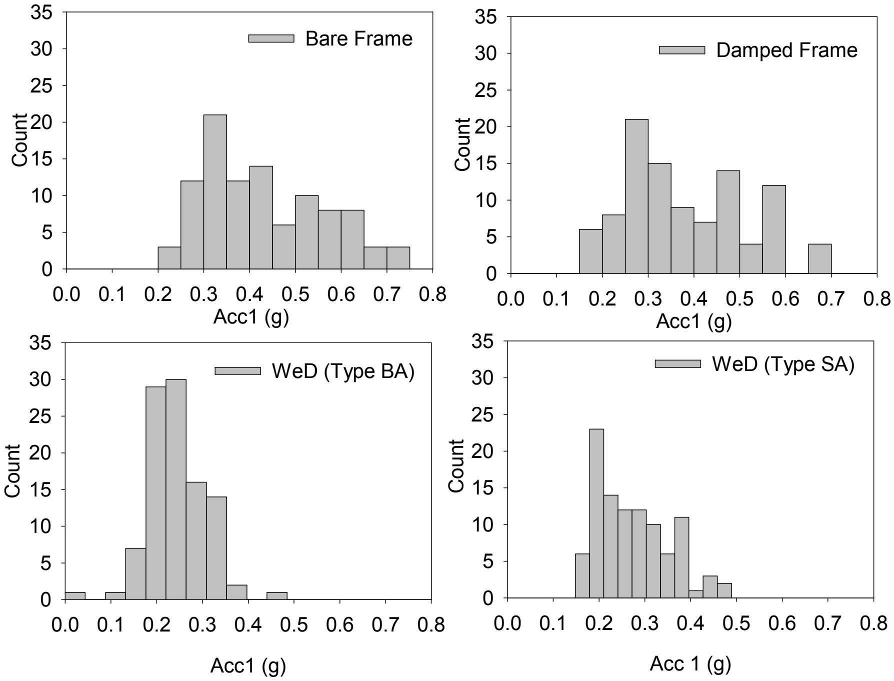

Figure 6. Histograms of accelerations for different configurations

Fragility analysis

Fragility *F* represents the probability that the response of a specific structure (or family of structures) exceeds a given threshold associated with a limit state, conditional on earthquake intensity parameter. In mathematical form, this is a conditional probability (Cimellaro et al., 2006):

$$F = P\left\{R \geq r_{\text{lim}} / I\right\} \tag{1}$$

where R is the response parameter (deformation, force, velocity, etc.), r_{lim} is the response threshold parameter that is correlated with damage, and I is the earthquake intensity (represented by either return period, or PGA, or Modified Mercalli Intensities, etc.). In this paper the maximum likelihood method is used to generate the fragility curves like in the approach proposed by Shinozuka et al (2003). This method assumes that the fragility curves are expressed by the cumulative lognormal distribution function given by the following equation

$$F_Y\left(y\right) = \Phi\left[\frac{1}{\beta}\ln\left(y/\theta_Y\right)\right] \quad y \geq 0 \tag{2}$$

where Φ is the standardized cumulative normal distribution function, θ_y is the median of y, and β is the standard deviation of the natural logarithm of y. The two parameters are determined by the method of maximum likelihood (MLE) (Soong, 2004; Shinozuka et al., 2003). The likelihood function L for the present purpose is expressed as

$$L=\prod_{j=1}^{k}\left[F_Y\left(a_j\right)\right]^{x_j}\left[1-F_Y\left(a_j\right)\right]^{1-x_j} \tag{3}$$

where $F_Y()$ represents the fragility curve for a specific state of damage; $a_j=PGA$ value to which the building is subjected; $x_j=1$ or 0 depending on whether or not the structure sustains the state of damage under $PGA=a_j$; k = total number of earthquake records considered. The two parameters θ_y and β are computed in such a way so as to satisfy the following equation that maximizes ln(L), and hence L

$$\frac{d\ln L}{d\theta_y}=\frac{d\ln L}{d\beta}=0 \tag{4}$$

Fragility curves obtained with the Maximum Likelihood method (MLE) at different story level of the structure are shown in Figure 7, Figure 8, and Figure 9.

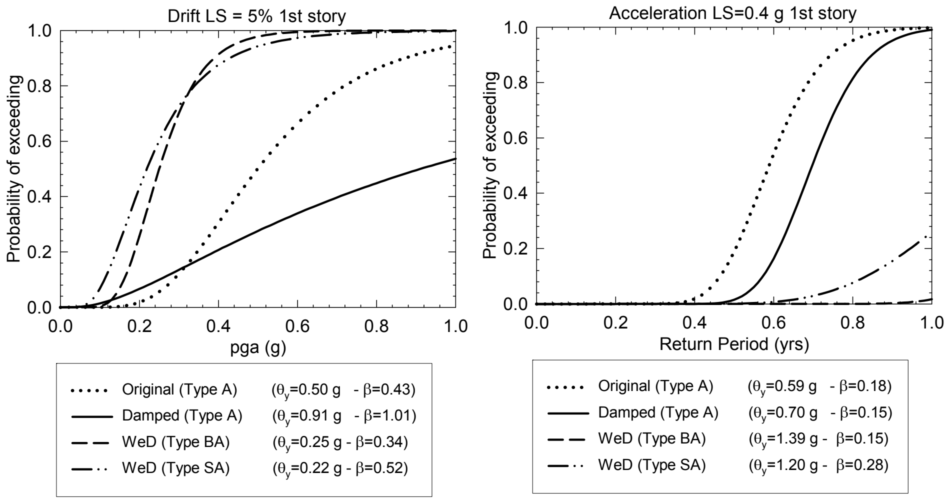

Figure 7. Fragility curves at the 1st story level using drift and acceleration limit states

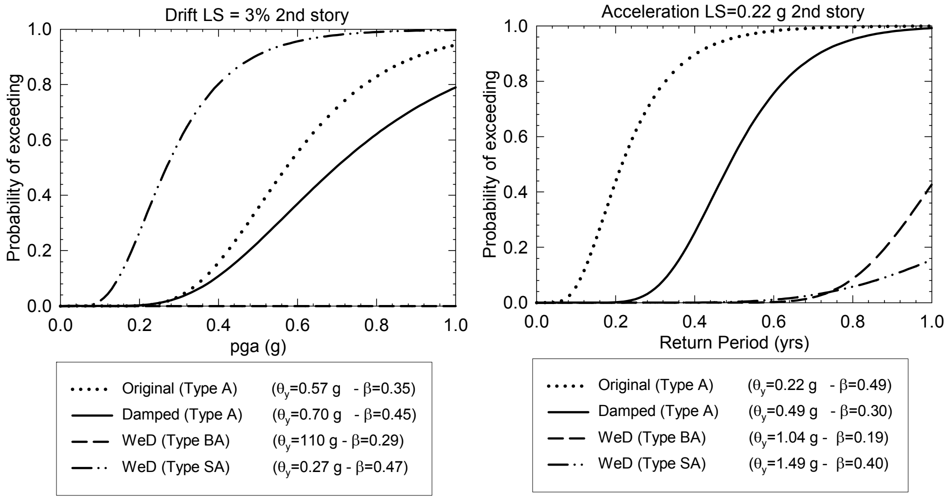

Figure 8. Fragility curves at the 2nd story level using drift and acceleration limit states

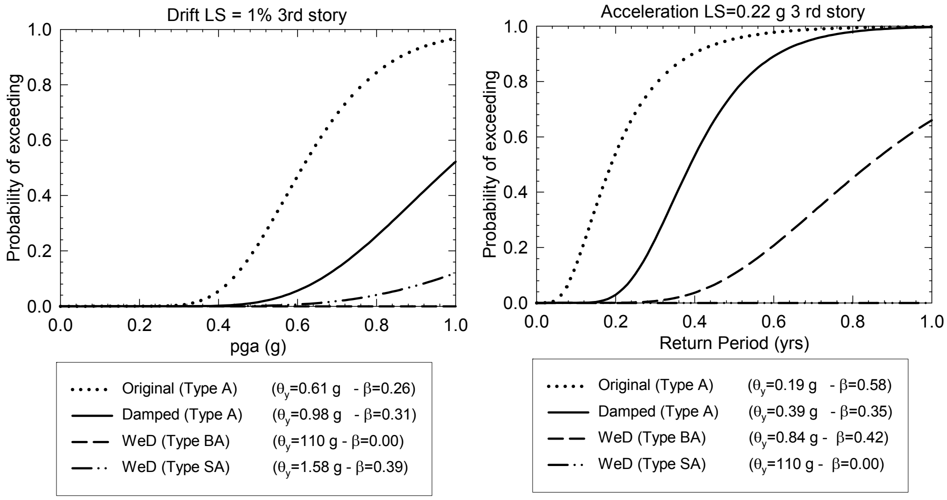

Figure 9. Fragility curves at the 3rd story level using drift and acceleration limit states

In probabilistic term, the weakened configurations have higher probability of exceedance the drift limit threshold at the first story level, while it reduces at the second and third story level. On the contrary the weakened configurations have always at all story levels a lower probability of exceedance the acceleration threshold with respect to the damped structure. In summary the weakened configurations always perform better with respect to the building only damped, with the exception of the drift at the first and second story level. These considerations lead to the conclusion that the proposed retrofit method is more effective in buildings where acceleration sensitive nonstructural components are equipped (e.g., hospitals, libraries, storage racks, physics laboratories, etc.).

Conclusions

This paper presents the performance of a weakened and damped (WeD) structure subjected to seismic excitations. The WeD retrofit technique reduces both structural accelerations and displacements. The benefits of the retrofitting procedure are shown in detail in a three story scaled model by using nonlinear dynamic analysis. Fragility analyses are conducted to show the seismic performance of the original structures and the retrofitted structures with the rocking beam-column connections and viscous dampers using the 100 earthquake records selected. The analysis shows that the story accelerations can be limited by using rocking columns, while the story displacements can be controlled by using viscous dampers. In particular the WeD retrofit technique is able to reduce acceleration and base shear with respect to the damped structure, for both weakened configurations. If optimal damping is provided to the weakened structures, the drift reduction will be more effective.

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