Performance-Based Seismic Retrofit Procedure for Soft-Story Woodframe Buildings with Excessive Torsion

P. Bahmani & J. W. van de Lindt
Colorado State University, Fort Collins, Colorado, USA

T. N. Dao
University of Alabama, Tuscaloosa, Alabama, USA

15 WCEE
LISBOA 2012

SUMMARY:
In soft-story buildings the relative stiffness of the soft-story, typically the bottom story, is significantly less than upper stories due to the presence of large openings which reduce the available space for lateral force resisting system components such as shear walls. In many cases, the distance between the center of rigidity and center of mass (i.e. eccentricity) of the soft-story is significant which produces a torsional moment in addition to the lateral force caused by the earthquake. This paper presents the development and application of the Direct Displacement Retrofit (DDR) procedure to ensure a specified performance level for retrofitted soft-story buildings under lateral forces and excessive torsional moments. The approach is validated using detailed finite element models of asymmetric buildings under a suite of earthquake ground motions and found to accurately reproduce the desired dynamic structural response. Steel frames and wood shearwalls are the two retrofit techniques considered in this study.

Keywords: Soft-story building; Torsion; Retrofit; Direct displacement design; earthquake

1. INTRODUCTION

A soft-story building, in general, is a building that has a story with low relative stiffness compared to its upper stories. In other words, a soft-story building is a building with discontinuity in its lateral stiffness resisting system at the level of the soft story. Insufficient lateral stiffness or strength (i.e. discontinuity) of the building can result in failure of the building under a moderate to large earthquake due to large inter-story drift at the level of the soft story. In order to improve the seismic performance of soft-story buildings, several retrofit techniques can be employed by applying a Performance Based Seismic Retrofit (PBSR) method based on direct displacement design, termed a direct displacement retrofit (DDR) procedure.

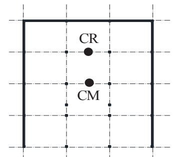
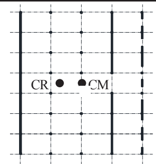
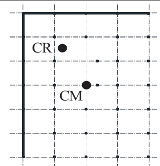
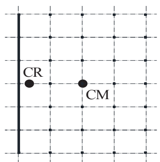
In PBSR, the inter-story drift due to lateral forces is reduced by increasing the lateral stiffness of the weak story; whereas, the inter-story drift due to torsional moments is reduced by increasing the torsional stiffness of the story which leads to lower displacements due to torsional moments. The first step in PBSR is identifying the target inter-story drift and corresponding seismic intensity at which that drift is not to be exceeded for the specific building; then, in the second step, the direct displacement design method (Bahmani et al, 2012) is used to determine the contribution of translational and torsional displacement in the overall story drift; then, in the third step, the DDR procedure is employed to determine the distribution of both lateral and torsional stiffness for each story such that the target performance requirements are satisfied for 50% of earthquakes (i.e. a non-exceedance probability of 50%). Finally, the most economical multi-story retrofit technique is selected for the building and may be different for each story.

2. SOFT STORY CLASSIFICATIONS

Soft stories can be classified into two major categories with regard to vertical irregularity criteria: (1)

stiffness-soft story and (2) stiffness-extreme soft story. According to ASCE7-10, ”Stiffness-soft story is a story in which the lateral stiffness is less than 70% of that in the above story or less than 80% of the average stiffness of the three stories above. Stiffness-extreme soft story is a story whose lateral stiffness is less than 60% of that in the above story or less than 70% of the average stiffness of the three stories above” (ASCE7-10, 2010). Soft stories can also be classified with regard to in plan irregularities (i.e., story eccentricity). Table 2.1 presents soft story classifications based on the location of the line of resistance and the story eccentricity for each category. It can be seen from the floor plan configurations that a soft story may not only lack stiffness in translation, but may also lack enough torsional stiffness. Thus, in order to retrofit a soft-story building, both lateral stiffness and torsional stiffness of the story should be taken into consideration.

Table 2.1. Soft story classifications

Soft Story Classification	Structural Description		Soft-story Configuration
	Resistance against lateral force	Resistance against torsional moment	
A	Three lines of resistance; Soft in one direction	Eccentricity in one direction; Soft in torsion	
B	Two parallel lines of resistance; Soft in one direction	Eccentricity in one direction; Soft in torsion	
C	Two perpendicular lines of resistance; Soft in both directions	Eccentricity in both directions; Soft in torsion (excessive torsion)	
D	One line of resistance; Soft in both directions	Eccentricity in both directions; Soft in torsion (excessive torsion)	

3. PERFORMANCE-BASED SEISMIC RETROFIT (PBSR)

Performance-based seismic retrofit (PBSR) is essentially the same as performance-based seismic design (PBSD) with the obvious exception of the additional constraints on the design due to existing structural and non-structural assemblies. The PBSD method is a design methodology that seeks to ensure that structures meet prescribed performance criteria under seismic loads. In displacement-based design which is a subset of PBSD, the stiffness of the structure is distributed along its height such that a target displacement can be achieved under a specific seismic intensity. Displacement-based design was originally proposed by Priestley (1998) and later modified by Filiatrault and Folz (2002) to be applied to wood structures. Pang and Rosowsky (2009) proposed the direct displacement design (DDD) method using modal analysis and later, Pang et al (2009) proposed a simplified procedure for applying the DDD method which was eventually applied to a six-story light-frame wood building and tested in Miki, Japan (van de Lindt et al., 2010) validating the simplified DDD procedure. Finally Wang et al (2010) extended the work of Pang et al to allow correction as function of building height. The PBSR method presented herein can be used to retrofit existing buildings such that all stories meet the performance criteria; and it can be used to retrofit buildings that are weak under both translational forces and torsional moments.

The DDD method developed in the previous studies is a reliable procedure for designing structures, but in its present form it can only be employed for structures which have negligible in-plane torsional moments. In this paper, an approach to decouple the torsional and translational mode shapes that was formulated by Kan and Chopra (1977) is applied in order to find the contribution of translational and torsional mode shapes for the overall lateral displacement at each story. In this approach, vibration periods and mode shapes of a torsionally coupled building were approximated as a linear combination of three uncoupled mode shapes resulting from modal analysis of the corresponding torsionally uncoupled system. This method leads to a simpler procedure for application of the DDD method which serves as the basis for the direct displacement retrofit (DDR) procedure proposed.

The DDD and DDR methods proposed herein can be employed to either design or retrofit buildings with any level of in-plane and vertical irregularity in order to meet the desired performance criteria and have been verified using a detailed 3-D finite element model. The performance criterion in this paper is defined by an inter-story drift ratio calculated at the center of mass of each story.

3.1. DDD procedure for buildings under excessive torsion

The objective of this paper is to find the distribution of the stiffness of lateral load resisting system of a torsionally unbalanced building to ensure the maximum inter-story drift experienced by the structure is less than the inter-story drift expectation. For a symmetrical building (i.e., no torsion), only the distribution of the lateral stiffness over the height of the building must be determined; whereas, in an unsymmetrical building (i.e. torsionally coupled building) the lateral stiffness must be defined both in-plane of each story and over the height of the building.

In order to find the contribution of translational and torsional mode shapes to the overall lateral displacement, modal analysis with the aid of response spectrum analysis is used to evaluate the maximum response of a torsionally uncoupled building. The global stiffness matrix has to be defined prior to conduct the modal analysis; however, in the DDD procedure the stiffnesses of lateral load resisting systems are being sought which eventually leads to an iteration process to calculate the stiffness matrices during the design. In order to eliminate the iteration process in conducting modal analysis, the vibrational mode shapes of the building should be standardized in such a way that their shape (but not their amplitude) are independent of the stiffness matrix of the building. In other words, the mode shapes should remain constant regardless of the actual stiffness of the building. This can be achieved by assuming that mass-to-stiffness ratio over the height of the building and stiffness ratios of lateral load resisting elements at each floor remain constant during the analysis. The optimal design (or retrofit) of the building can be achieved by selecting the appropriate mass-to-stiffness ratios such that all stories experience almost the same inter-story drifts.

3.1.1. Modal Analysis for torsionally coupled buildings

Modal analysis, which is a simple alternate method to time-history analysis, can be employed in order to calculate the displacements of a building due to lateral forces and torsional moments under ground excitation. The advantage of modal analysis over time-history analysis is that it can be conducted by determining the global mass and stiffness matrices of the structure, without the need for integration of the equation of motion. The maximum responses, then, can be obtained by means of the pseudo-acceleration response spectrum which is easily generated for the building location. However, for a torsionally coupled system, calculating the global stiffness matrix is cumbersome which leads to the need to solve a high order eigenvalue problem; and therefore, weakens the advantages of using modal analysis (i.e. simplicity and time efficiency) over a detailed finite element time-history analysis.

For a torsionally coupled N-story building as shown in Figure 3.1 the circular vibration frequencies (i.e., ω) and mode shapes (i.e., Φ) of the building can be determined by solving the following eigenvalue problem:

$$\left([K]-\omega^2[M]\right)[\Phi]=[0] \tag{3.1}$$

where, $[K]$ and $[M]$ are global stiffness and mass matrices of the building, respectively. After decoupling translational and torsional mode shapes, the eigenvalue problem can be expressed as

$$\left([K]_l - \omega^2 [M]_l\right)[\Phi]_l = [0] \tag{3.2}$$

where, $[K]_l$ and $[M]_l$ are stiffness and mass matrices in the l direction which can be substituted by x, y or θ.

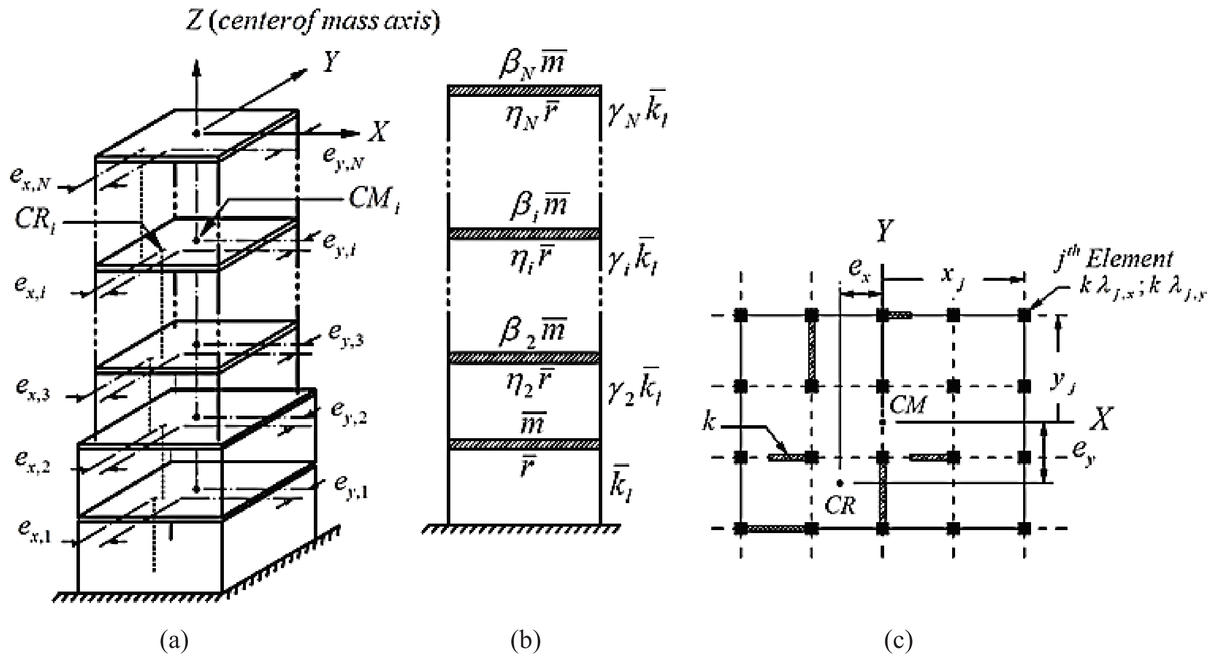


Figure 3.1. (a) N-story building (after Kan & Chopra,1977) ; (b) Elevation view; (c) Plan view of i^{th} floor

Decoupling mode shapes can be conducted using the method that was proposed by Kan and Chopra (1977). By decoupling torsional modes from translational modes, the size of the stiffness matrices reduces from $3N \times 3N$ to $N \times N$ (N= number of stories). In addition, there will be no need to define the coupled stiffness terms in the global stiffness matrix. After determining the decoupled mode shapes and the modal coupling parameters of the building, the response due to each mode can be calculated with the aid of the pseudo- acceleration response spectra. Finally, the maximum response can be obtained by combining the response due to each mode shape using the well-known square-root-of-the-sum-of-the-squares (SRSS) or complete-quadratic-combination (CQC) methods.

3.1.2. Normalized mass and stiffness matrices

In order to simplify the modal analysis and eliminate the iteration process during modal analysis, the mass and stiffness matrices in Equation (3.2) should be defined such that the vibrational mode shapes of the building become independent of the actual stiffness and mass of each story. In order to overcome this problem, standard mass and stiffness matrices can be defined as follows:

$$[M] = \bar{m}\left[\tilde{\beta}\right] \tag{3.3}$$

where, $[M]$ is the total mass matrix, $\bar{m}$ is the total lumped mass of the first floor, and $\left[\tilde{\beta}\right]$ is total mass-ratio matrix. Since the unit mass and area of each floor is constant during the analysis, $\left[\tilde{\beta}\right]$ remains unchanged.

Accordingly, it can be assumed that the radius of gyration of the i^{th} story about a vertical axis through the center of mass of the floor can be defined as

$$[R] = \bar{r}\,[\tilde{\eta}] \tag{3.4}$$

where, $\bar{r}$ is the radius of gyration of the first floor and $[\tilde{\eta}]$ is the global radius of gyration matrix. Since the geometric properties of the floors do not change during the analysis, $[R]$ and $[\tilde{\eta}]$ remain constant. Thus, the mass matrix in Equation (3.2) for determining torsional mode shapes can be calculated as

$$[M]_\theta = \bar{m}\bar{r}\,[\tilde{\beta}][\tilde{\eta}] \tag{3.5}$$

The uncoupled lateral stiffness matrices of the i^{th} story along the principal axes of resistance x and y can be expressed as

$$K_{i,x} = \sum_j k\,\lambda_{j,x} \;\; ; \;\; K_{i,y} = \sum_j k\,\lambda_{j,y} \tag{3.6}$$

where, $K_{i,x}$ and $K_{i,y}$ are the total lateral stiffness of the i^{th} story along x and y directions, respectively; $\lambda_{j,x}$ and $\lambda_{j,y}$ are the stiffness ratio of the j^{th} lateral load resisting element in the x and y directions, respectively, to the stiffness of the weakest resisting element of the first story (i.e., k) (Figure 3.1). The uncoupled torsional stiffness matrix defined at the center of mass of the i^{th} floor can be expressed as

$$K_{i,\theta} = \sum_j (k\,\lambda_{j,x})\,y_j^2 + \sum_j (k\,\lambda_{j,y})\,x_j^2 \tag{3.7}$$

where, $K_{i,\theta}$ is the torsional stiffness about the center of mass of the i^{th} floor; and, x_j and y_j are the distances between the center of mass of the floor to the centroid of the resisting element in x and y directions, respectively. Thus, the uncoupled stiffness matrices can be defined as

$$[K]_l = \bar{k}_l\,[\tilde{\gamma}]_l \tag{3.8}$$

where, $[\tilde{\gamma}]_l$ is the global stiffness ratio matrix of the building along the l direction. $\bar{k}_l$ is the total stiffness of resisting elements in l direction at the first story. Therefore, the eigenvalue problem for a torsionally decoupled system can be reformulated as

$$\left(k \left(\sum_j \lambda_j \right)_1 [\tilde{\gamma}] - \omega^2 \bar{m} [\tilde{\beta}] \right)_{x,y} [\Phi]_{x,y} = [0] \tag{3.9}$$

$$\left(k \left(\sum_j (\lambda_{j,x})\,y_j^2 + \sum_j (\lambda_{j,y})\,x_j^2 \right)_1 [\tilde{\gamma}] - \omega^2 \bar{m}\bar{r} [\tilde{\beta}][\tilde{\eta}] \right)_\theta [\Phi]_\theta = [0] \tag{3.10}$$

Equations (3.9) and (3.10) can be used to find the uncoupled translational and torsional mode shapes, respectively. It can be seen from the above equations that the only variables are k and $\bar{m}$ and all other terms are assumed to be constant during the analysis; therefore, it can be concluded that the mode shapes and their corresponding frequencies only depend on the value of k and $\bar{m}$. The mass of each story can be estimated to a good level of accuracy before the design; thus, the response of the structure depends only on the secant stiffness of the weakest element at the target drift in the first floor. If the maximum response of the structure is plotted against the period of the first story (i.e. $T_1 = 2\pi / \sqrt{\bar{k}_l / M}$), then the $\bar{k}_l$ and consequently k can be determined. By knowing k and the secant stiffness of the retrofitting elements or sub-assemblies at the target drift, the retrofits can be designed.

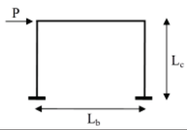
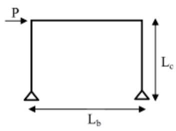
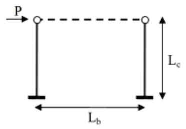
4. RETROFIT TECHNIQUES

During a moderate to large earthquake, a soft-story building can experience a large inter-story drift at the soft-story level due to translation, rotation, or a combination of translation and rotation, while the stories above behave almost rigidly. In order to improve the performance of a soft-story building, the translational and torsional stiffness (and strength) of the soft story should be increased to prevent the excessive inter-story drift. Translational forces can be reduced by increasing the stiffness of the building in both directions, or the soft and weak direction if only one exists. For torsional moments, there are two retrofit options: (1) Option A: eliminating the torsional moment by adding the retrofits such that the in-plane eccentricity of the soft-story diaphragm decreases which consequently reduces the torsional moment; or (2) Option B: designing for torsion (accommodating the design for the contribution to displacement from the torsional moments) by increasing the torsional stiffness of the soft story which is used to retrofit buildings in this study. In this study, Steel Frame and Columns and wood shearwalls with different nailing patterns are selected as retrofit design options for the existing woodframe building. These retrofit options are quite practical and can be implemented for a large number of woodframe buildings. Steel frames can be added over the garage door opening of the building and wood shearwalls can be added where there are non-structural walls or nail patterns altered to provide stronger and stiffer walls.

4.1. Steel Frame and Columns

Steel frames and columns can be used to retrofit stories especially at the soft-story level, i.e. the first story. The steel frame can be modelled as a bilinear spring with initial stiffness, K_1 (Figure 4.1.a). The stiffness for three types of steel frame with different end supports has been evaluated in this paper. For each type of steel moment frames, it is assumed that the stiffness is constant (i.e. initial stiffness K_1) up to the yield force, F_y, associated with the yield drift of Δ_y at which point it reduces to K_2. In this study, the drift at the yield point is set equal to 1% and the ratio of the secondary stiffness to the initial stiffness is assumed to be 0.125. Table 4.1 presents the relationship between lateral force, displacement, and initial stiffness of three different types of steel frames.

Table 4.1. Lateral stiffness and displacement for steel frames – (after Silvia and Badie, 2008)

Support Condition	Steel Frame Type	Lateral Displacement*	Lateral Stiffness*
Fixed Support		$\Delta = \left(\frac{6\alpha+4\kappa}{6\alpha+\kappa}\right)\frac{P L_c^3}{24 E I_c}$	$K_1 = \left(\frac{6\alpha+\kappa}{6\alpha+4\kappa}\right)\frac{24 E I_c}{L_c^3}$
Pinned Support		$\Delta = \left(4+\frac{2\kappa}{\alpha}\right)\frac{P L_c^3}{24 E I_c}$	$K_1 = \left(\frac{\alpha}{4\alpha+2\kappa}\right)\frac{24 E I_c}{L_c^3}$
Inverted Moment Frame (cantilevered columns)		$\Delta = \frac{P L_c^3}{6 E I_c}$	$K_1 = \frac{6 E I_c}{L_c^3}$

* I_c , L_c = moment of inertial and height of column; I_b , L_b = moment of inertial and length of beam

$\alpha = \frac{I_b}{I_c}$ *and* $\kappa = \frac{L_b}{L_c}$

In order to design the retrofits, the secant stiffness is known based on the PBSR analysis and the initial stiffness are being sought. Having assumed the bilinear spring for steel frame, the secant stiffness of a single steel frame can be calculated using Equation 4.1. Then, the section properties of beam and columns can be calculated using equations presented in Table 4.1. It should be noted that the frames with horizontal beam can be used only if the beams are braced against lateral torsional buckling. Since it is difficult to provide lateral bracing for steel beams in a woodframe building, an inverted moment frame (IMF) (termed a cantilevered column) is the only practical option for retrofitting woodframe buildings using steel frames as this time.

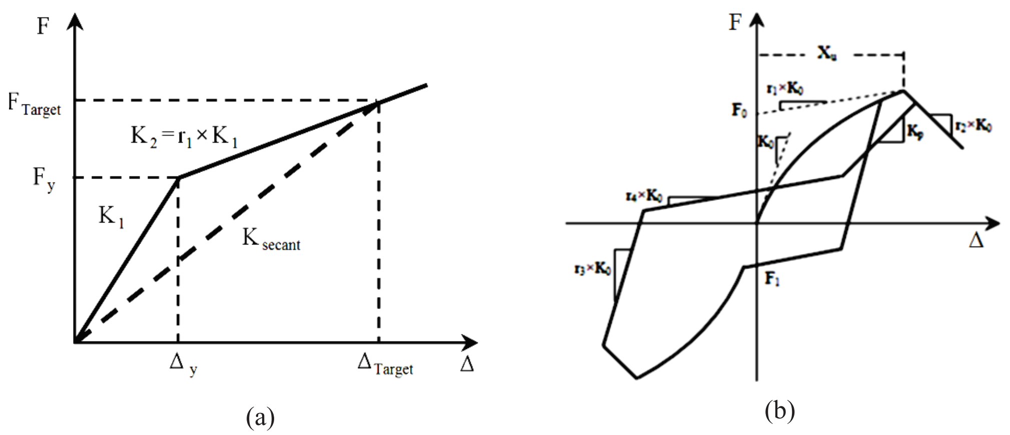
$$K_{secant} = \frac{(1-r_1)\Delta_Y + r_1 \Delta_{Target}}{\Delta_{Target}} K_1 \tag{4.1}$$

4.2. Wood Shearwall

In this paper, wood shearwalls are selected as a retrofit design option for the upper stories. The wood shearwalls can be substituted for non-structural walls or existing shearwalls can be modified to have a denser nail schedule, i.e. closer nail pattern. Wood shearwall modelling is based on a well-known ten-parameter hysteretic model (Folz and Filiatrault, 2001). Figure 4.1.b presents the ten-parameter hysteretic spring for wood shearwalls. The required secant stiffness at the target drift can be determined from the wood shearwall backbone. Table 4.2 presents the secant stiffness corresponding to different levels of drift ratio for 2.44 meter (8 ft) tall standard wood shearwalls.

Table 4.2. Secant stiffness for standard 2.44 meter tall (8 ft) wood shearwall (NEESWood – Report 5)

		Secant Stiffness, K_s (KN/mm per m)				
	Edge/Field Nail Spacing (mm)	Wall Drift				
		0.50%	1.0%	2.0%	3.0%	4.0%
Standard Wood Shearwall	51/304	1.570	1.100	0.657	0.385	0.244
	76/304	1.214	0.786	0.448	0.256	0.159
	102/304	0.955	0.611	0.340	0.194	0.121
	152/304	0.684	0.422	0.231	0.132	0.082



(a) (b)

Figure 4.1. (a) Bilinear spring, (b) Ten-parameter hysteresis spring (after Folz and Filiatrault, 2001)

5. EXAMPLE: PBSR OF A THREE-STORY BUILDING

A three-story building with excessive torsion at all stories was retrofitted based on the proposed PBSR method. The floor plans of the building were designed such that the first story behaved as a soft-story during an earthquake. The ratio of the secant stiffness of the first story to the second story at the target drift of 2% (i.e. target drift corresponding to DBE level earthquake) is 50% in the X direction. Therefore, the building fell into the stiffness-extreme soft-story category. The in-plane eccentricity ratio in X and Y directions for all stories were 12.5% and 16.7%, respectively. Figure 5.1 presents the floor plan and elevation of the building. The secant stiffness of the walls in bold were assumed to be twice of other walls. This led to move the center of rigidity (i.e. CR) toward the stiffer part of the building which consequently increased the in-plane eccentricity.

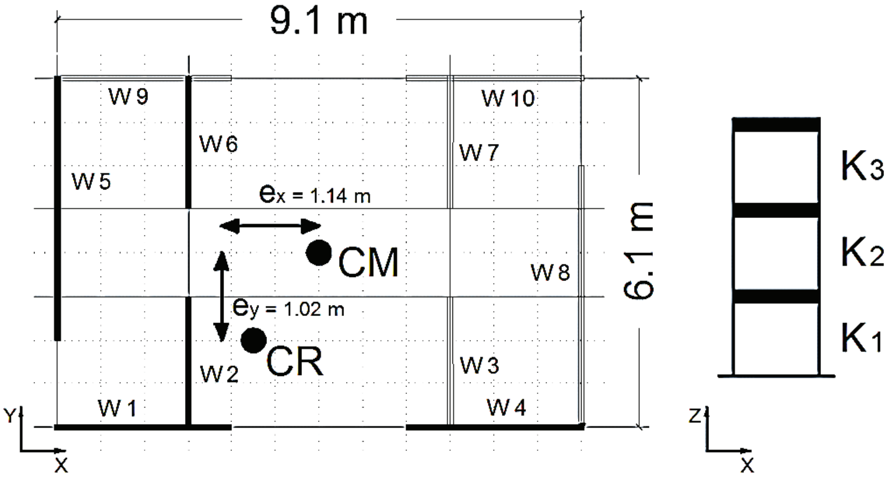
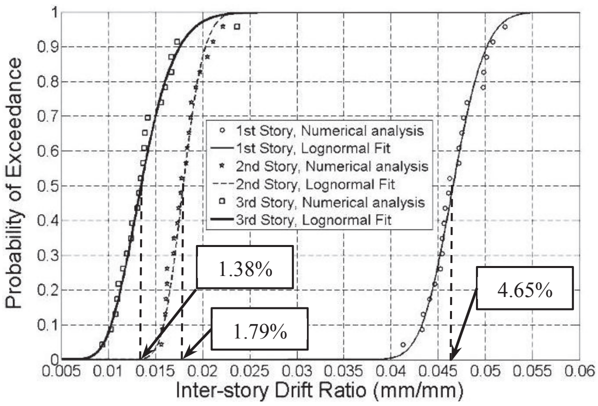


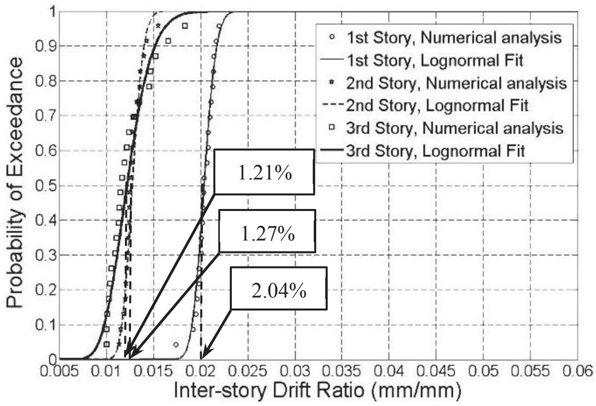
Figure 5.1. Plan view and elevation of the soft-story building with excessive torsion

In order to evaluate the seismic performance of the building before and after applying the retrofits, the probability of exceedance of the building for the prescribed inter-story drift was calculated under twenty-two far-field earthquake records (FEMA P695, 2009) scaled for the seismic intensity corresponding to spectral acceleration for DBE level earthquake in San Francisco, California. Figure 5.2 presents the probability of exceedance versus inter-story drift ratio before and after adding retrofits to the building. It can be seen from Figure 5.2.a that the inter-story drift ratio corresponding to 50% non-exceedance at the first story is 4.65%; whereas, the inter-story drifts for the upper stories are both less than 2%. It can be concluded that the first story behaves as a soft-story and the two upper stories move almost as a rigid body thereby only moderately contributing to the lateral resistance of the building against seismic loads. Further, this lack of contribution would only be exacerbated for more intense earthquake level. Thus, the building needs to be retrofitted. As mentioned earlier, there are two approaches for retrofitting soft-story buildings with excessive torsion; (1) retrofitting buildings such that it meets the performance criteria without completely eliminating the soft-story, or (2) retrofitting buildings such that all stories experience the same drift (eliminating the soft-story behavior).

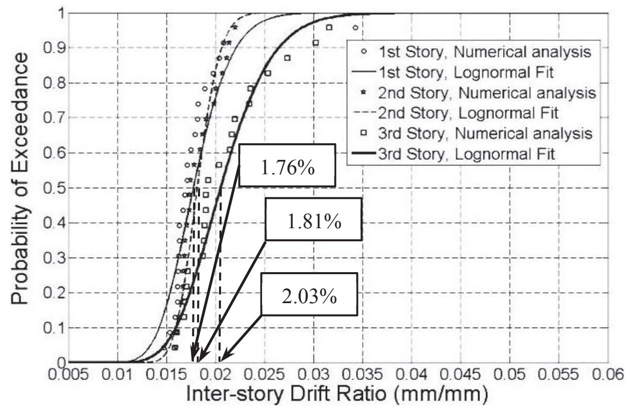
Figure 5.2.b and Figure 5.2.c present the probability of exceedance versus inter-story drift ratio for the same building using the first and second approaches in PBSR methodology, respectively. The figures show that the retrofitted building meets the performance criteria (i.e., 50% probability of non-exceedance for a 2% inter-story drift at the DBE level earthquake). Table 5.1 presents the inter-story drift and stiffness ratios of the stories over the height of the building. It can be seen that the both retrofit designs limit the maximum inter-story drift of the building to 2%. In the retrofitted building using PBSR Method 1, the building after applying the retrofit is still soft at the first story; however, the PBSR method in this study meets the performance criteria. The building that is retrofitted using PBSR Method 2 has no soft story since the stiffness ratios over the height of the building were calculated such that all stories experience almost the same drift (i.e. 2% drift in this case) under earthquake excitation, and is thus consistent with current design code regulations in the U.S. such as ASCE 7-10 (2010).



(a) Original building without retrofit



(b) Retrofitted building - PBSR Method 1



(c) Retrofitted building - PBSR Method 2 (elimination of soft story)

Figure 5.2. Probability of failure of building before and after retrofit

Table 5.1. Stiffness and drift ratios before and after applying PBSR retrofits – 2% target drift at DBE level

			Retrofitted buildings			
	Original Building		PBSR - Method 1		PBSR - Method 2	
Story	Stiffness	Drift (%)	Stiffness	Drift (%)	Stiffness	Drift (%)
1	K	4.65	K*	2.04	K**	1.76
2	2.0 K	1.79	1.3 K*	1.27	0.89 K**	1.81
3	1.8 K	1.38	0.9 K*	1.21	0.70 K**	2.03

K = Translational stiffness of the first story in X-direction in the original building
K* = Translational stiffness of the first story in X-direction in the retrofitted building - PBSR Method 1
K** = Translational stiffness of the first story in X-direction in the retrofitted building - PBSR Method 2

6. SUMMARY AND CONCLUSION

The proposed PBSR method, which is based on the direct displacement design methodology, can be used for retrofitting buildings that are weak in both torsion and translation by providing a simple yet accurate way for engineers and practitioners to design retrofits for soft-story buildings. In this study, a logical retrofit option for soft-story buildings with excessive torsion was evaluated. It was shown that the seismic performance of a soft-story building under both lateral forces and torsional moments due to earthquakes can be systematically improved by using a multi-story performance-based retrofit technique. Direct displacement design (DDD) was modified to design the retrofits not only along the height of the building, but also in-plane by including the effect of torsional moments into the inter-story drifts. It was shown that PBSR can be used to retrofit soft-story buildings by completely and partially eliminating the soft story behavior such that the building meets the desired performance criteria. It should be noted that if the stiffness of the soft story is much greater than the stories above after adding retrofits, the soft-story behavior will be transferred to the upper stories of the building. The PBSR method assures that the soft-story behavior does not transfer to the upper stories by providing help to distribute stiffness both along the height of the building and in the plane of each story.

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1041631 (NEES Research) and NEES Operations. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the investigators and do not necessarily reflect the views of the National Science Foundation. The authors kindly acknowledge the Co-Principal Investigators of the NEES-Soft project: Michael D. Symans at Rensselaer Polytechnic Institute, WeiChiang Pang at Clemson University, Xiaoyun Shao at Western Michigan University, Mikhail Gershfeld at Cal Poly – Pomona, and senior personnel David V. Rosowsky at Rensselaer Polytechnic Institute, Andre Filiatrault at University of Buffalo, Gary Mochizuki at Structural Solutions Inc., Shiling Pei at South Dakota State University, Douglas Rammer at U.S. Forest Products Lab., David Mar at Tipping Mar, and Charles Chadwell at Cal Poly – SLO.

REFERENCES

ASCE (2010). Minimum Design Loads for Buildings and other Structures. American Society of Civil Engineering; Structural Engineering Institute 7-05, Reston, VA.

Bahmani, P., van de Lindt, J.W. and Dao, T.N. (2012). Direct Displacement Design of Buildings with Torsion I: Theory and Verification, *ASCE Journal of Structural Engineering,* Submitted in May 2012.

FEMA, Federal Emergency Management Agency. (2009). Quantification of Building Seismic Performance Factors, FEMA P695. Washington (DC).

Filiatrault A. and Folz B. (2002). Performance-based seismic design of wood framed buildings, *ASCE Journal of Structural Engineering,* **128(1)**: 39-47.

Folz, B. and Filiatrault, A. (2001). Cyclic Analysis of Wood Shear Walls. *ASCE Journal of Structural Engineering*, **Vol. 127(4**), 433-441.

Kan, C.L., and Chopra, A.K. (1977). Elastic Earthquake Analysis of Trosionally Coupled Multistorey Buildings. *Earthquake Engineering and Structural Dynamics*, **Vol. 5,** 395-412.

Pang, W.C., and Rosowsky, D.V. (2009). Direct Displacement Procedure for Performance-based Seismic Design of Mid-rise Woodframe Structures, Earthquake Spectra, **25(3), 583**–605.

Pang, W.C., Rosowsky, D. V., van de Lindt, J.W. and Pei, S. (2009), Simplified Direct Displacement Design of Six-story NEESWood Capstone Building and Pre-Test Seismic Performance Assessment., *NEESWood Report NW-05*.

Priestley, M.J.N. (1998). Displacement-based approaches to rational limit states design of new structures. Keynote Address, *Proc*., *11th European Conference on Earthquake Engineering*, Paris, France.

Silvia, P., and Badie, S. S. (2008). Optimum Beam-to-Column Stiffness Ratio of Portal Frames under Lateral Loads. *Structure Magazine*, March 2008.

van de Lindt, J.W., Pei, S., Pryor, S.E., Shimizu, H. and Isoda, H. (2010). Experimental Seismic Response of a Full-Scale Six-Story Light-frame Wood Building, *ASCE Journal of Structural Engineering,* **136(10)**: 1262-1272.

van de Lindt, J.W., Pryor, S.E. and Pei, S. (2009). Shake Table Testing of a Seven-Story Mixed-Use Condominium at Japan's E-Defense. *2009 SEAOC Annual Convention*, San Diego, CA, September 23-26.

Wang, Y., Rosowsky, D. V., Pang W. C. (2010). Performance-Based Procedure for Direct Displacement Design of Engineered Wood-Frame Structures. *ASCE Journal of Structural Engineering*, **Vol. 136(8),** 978-988.