Performance-Based Seismic Retrofit of Soft-Story Woodframe Buildings

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Abstract

Soft-story woodframe buildings are recognizable by their large garage openings at the bottom story which are typically for parking and storage. In soft-story buildings the relative stiffness and strength of the soft-story, usually the bottom story, is significantly less than the upper stories due to the presence of large openings which reduce the available space for lateral force resisting system components such as shearwalls. This leads to large inter-story drifts and potential collapse at the ground floor, before the upper stories inter-story experience significant drifts. In many cases the ground floor eccentricity, the distance between the center of rigidity and center of mass, of the soft-story is significant enough to develop considerable in-plane torsional moment in addition to the lateral force caused by the earthquake. A Performance Based Seismic Retrofit (PBSR) procedure can be used to effectively design retrofits that improve the performance of these at-risk buildings. This paper focuses on the PBSR methodology and the application and validation of this retrofit technique to a 4,000 sq. ft. full-scale four-story woodframe building tested at the University of California San Diego (UCSD) Network for Earthquake Engineering Simulation (NEES) outdoor shake table. The structure was retrofitted with various systems including a system that combined wood structural panel sheathing and Simpson Strong-Tie® Strong Frame® steel special moment frames. These types of retrofit techniques improve the performance of the soft-story building while accommodating existing architectural constraints of the building.

Introduction

As early as 1970, the structural engineering and building safety community recognized that a large number of two-, three- and four-story woodframe buildings designed with the first floor used either for parking or commercial space were built with readily identifiable structural deficiencies, referred to as a "soft story". Often these buildings also have a strength deficiency when compared to the stories above, in which case they are also classified as "weak". The majority of these multi-story woodframe buildings have large openings and few partition walls at the ground level. This open space condition results in the earthquake resistance of the first story being significantly lower than the upper stories. Thus, many of these multi-story woodframe buildings are susceptible to collapse at the first story during earthquakes. Furthermore, in-plane torsional moments and consequently rotational displacements can be induced when the center of rigidity (i.e. the point where seismic force is resisted) of a story does not coincide with the center of mass (i.e. the point where seismic force is applied). In this case, the building experiences additional displacement due to torsional moment, which causes more damage and increases the chances of collapse.

This paper presents the first generation of Performance-based seismic retrofit (PBSR) and resulting retrofit design using a combination of wood structural panel sheathing and Simpson Strong-Tie® Strong Frame® steel special moment frames. 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 the PBSR, retrofits were installed such that the building meets the performance criteria at the DBE and MCE level and its torsional response reduces to an acceptable range. In this retrofit design methodology, retrofits are not limited to the bottom story (like those of the FEMA P-807 retrofit methodology). They can also be applied to the upper stories to increase the strength of the building, leading better overall performance of the structure.

The seismic performance of the retrofitted building with PBSR procedure was evaluated numerically and validated by a full-scale four-story wood-frame building that was tested in summer 2013 at the NEES at UC San Diego outdoor shake table facility as part of the NEES-Soft project. The NEES-Soft project consists of a number of tasks including extensive numerical analysis, development of a performance-based seismic retrofit methodology, and a major testing program with testing at five university-based laboratories to better understand the behavior of these at-risk structures and the retrofit techniques. The listing of all the phases within the project can be found in the WDF article by Pryor et al in this issue. A full Journal paper from the WDF authors is forthcoming and a project report will be available at www.nees.org .

Performance-based Seismic Retrofit (PBSR)

In performance-based seismic retrofit (PBSR), which is a subset of performance-based seismic design (PBSD), the stiffness of the structure is distributed along its height and in the plane of each story such that a target displacement can be achieved under a specific seismic intensity, taking into account nonlinear behavior of the structure. 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.

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. (2009) to allow correction as a function of building height. This design methodology determines the required lateral stiffnesses over the height of the building such that the building meets the target displacement defined by the building code. This method serves as the basis for a PBSR procedure by distributing the required in-plane stiffness of each story to eliminate the torsional response of the structure (i.e., reducing the in-plane eccentricity) (Bahmani and van de Lindt, 2012). However, for cases in which eliminating torsion cannot be achieved, PBSD that allows some level of torsional response can be used as the basis for design of retrofits for such buildings (Bahmani et al., 2013).

In torsionally unbalanced buildings, in-plane torsional moments, and consequently rotational displacements, can be induced when the center of rigidity of a story does not coincide with the center of mass. In this case, additional rotational displacements due to torsional imbalance should be taken into account whenever they occur. Figure 1(a) presents an N-story building with lumped masses of M_j for the j^{th} story. The total displacement of the center of mass of the j^{th} story is a summation of displacement due to lateral force ($\Delta_j^{Tns.}$) and displacement due to torsional moment ($\Delta_j^{Tor.}$). Eliminate of the torsional response of the structure can be achieved by distributing the retrofit in the plane of each story such that the retrofitted building becomes a structurally symmetric building (i.e., $\Delta_j^{Tor.} \approx 0$). However, if the torsion cannot be feasibly eliminated, the PBSR approach can be applied by assuming a ratio between the displacement caused by lateral force and torsional moments and then satisfying the assumption while applying the retrofit. A three-story torsionally unbalanced wood-frame building was retrofitted using PBSR methodology without eliminating torsion by van de Lindt et al. (2013).

In order to simplify the PBSR procedure, the structure can be modeled by an equivalent single degree of freedom system (Figure 1(b)). The effective weight (W_{Eff}) and lateral force distribution factors (C_v) can be calculated based on the approach outlined in NEESWood Report-05 (2009). The fundamental translational period of the building can be obtained from the displacement response spectrum which is developed based on the design spectral acceleration maps of ASCE7-10 (2010) and should be modified to take into account the effect of equivalent damping. The next step is to obtain the effective lateral stiffness, and consequently the distribution of the stiffness for lateral load resisting elements at each story. The last step is locating the lateral load resisting systems (i.e., shearwalls or other retrofit assemblies) such that the design satisfies the initial assumption

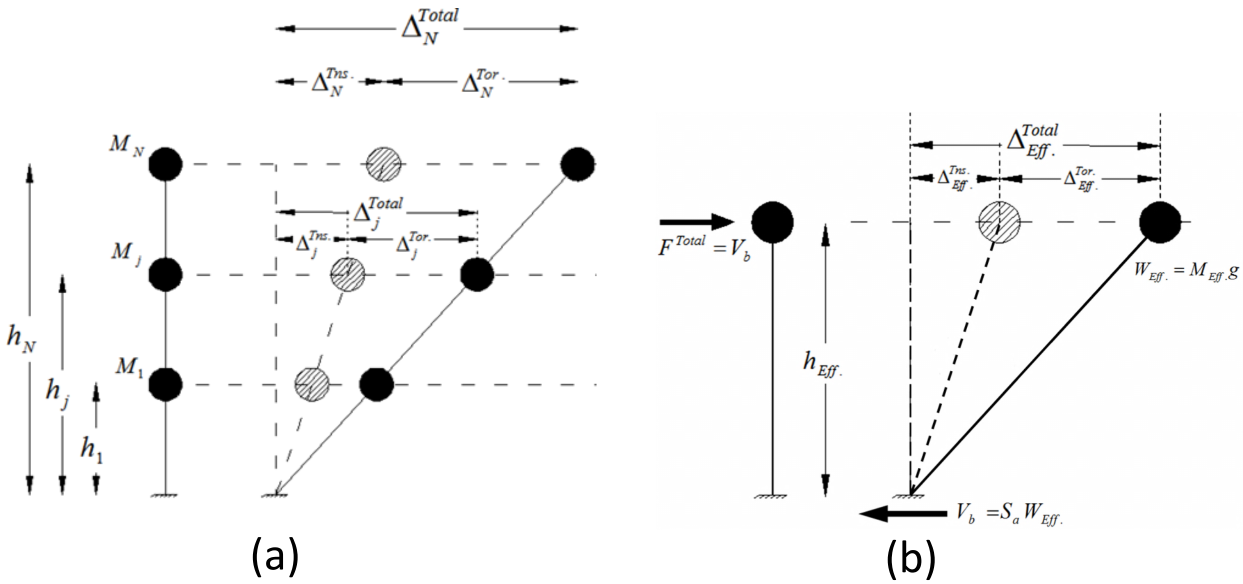


Figure 1. Translational and Torsional Displacements in a Torsionally Unbalanced Building (a) Multi-Story Building, (b) Equivalent SDOF Model of Multi-Story Building

that is made regarding the contribution of torsional response to the total displacement. If the contribution of torsional response is assumed to be close to zero (i.e., eliminating the torsion), then the lateral force resisting elements should be placed such that the CR and CM at each story become very close to each other at the target displacement. The required lateral stiffness can be provided by using the secant stiffness (at the target displacement) of the lateral force resisting elements (i.e., standard wood shearwall, steel moment frame, etc.).

The PBSR procedure described in this paper was applied to a four-story multi-family soft-story wood frame building with a soft-story at the ground level and was tested at the outdoor shake table at NEES at UC-San Diego. The building was designed to have less than 2% inter-story drift with 50% probability of non-exceedance (PNE) at all stories using PBSR methodology subjected to MCE level by eliminating torsional response of the building.

Shake Table Testing of a Full-Scale Four-Story Wood-frame Building

A full scale four-story building was constructed at the outdoor shake table facility at NEES at UC San Diego. On the ground floor, there was a large laundry room, a storage room, and a light well. The light well was included since many of these buildings are surrounded by other buildings on two sides and therefore have two essentially solid sides and two open sides. The test building was designed to replicate these conditions, thus making it, in many ways, a worst case scenario. The interior wall den-

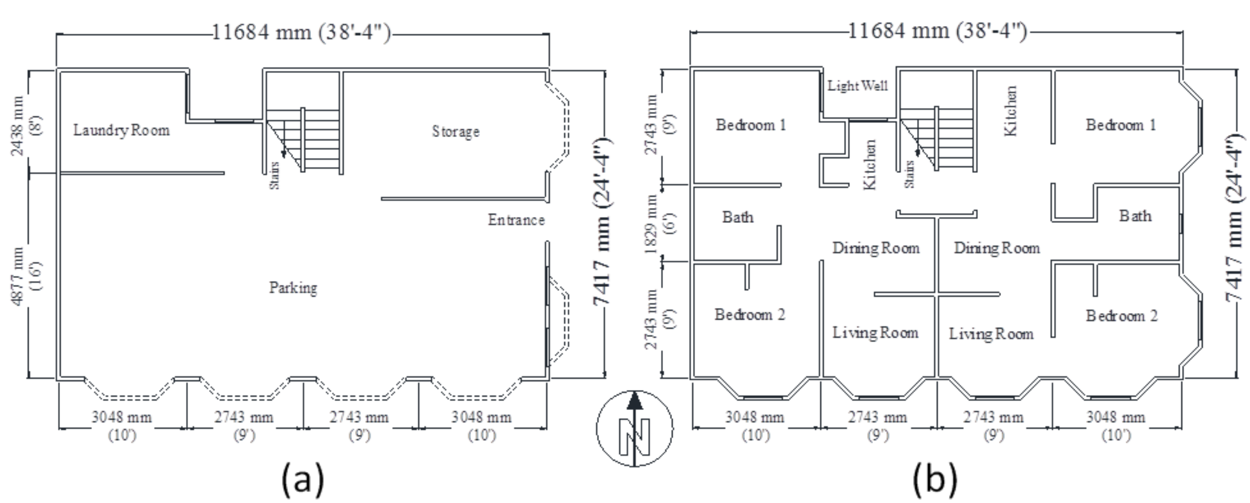


Figure 2. Floor Plans for the Four-Story Building: (a) Ground Story, (b) Upper Stories

Figure 3. (a) Completed 4-story 4000 sq-ft Building, (b) Isometric View of the Building.

sity in the upper stories was high, but this is in line with many soft-story woodframe buildings of that era. The outside was covered with horizontal wood siding (1x8 in. Douglas-Fir grade No 2 or BTR) with two 8d common nails connected to each vertical wall stud. The inside walls were covered with gypsum wall board instead of plaster. Figure 2 shows the ground floor and upper story floor plans for the building (plan dimensions are 24 ft x 38 ft). Each of the upper three stories had two two-bedroom apartment units as can be seen in Figure 2 (b). Figure 3 shows the finished building ready for shake table testing at the UCSD NEES laboratory.

Steel Special Moment Frame (SSMF) and Wood Structural Panel (WSP) Retrofits

In the PBSR procedure the objective was to design the building such that all the stories experience the same level of peak inter-story drift. This utilized the capacity of the upper stories to resist seismic loads and increases the probability of survival of the building under higher earthquake intensities. To achieve this goal, the four-story test building was retrofitted with a Simpson Strong-Tie Strong Frame steel special moment frame (SMF) at the ground level and 15/32" thick sheathing-rated plywood shear wall panels with different nail schedules and tie downs on the selected walls of the upper stories. The steel frames were designed and located such that they did not interfere with the intended use of the space (i.e. vehicle parking), or conflicted with any other architectural aspect of the building. Figure 4 presents the location of Strong Frames and wood shearwalls (SW) that were installed to retrofit the building. Simpson-Strong-Tie Anchor Tie-Down System (ATS) rods were used to transfer uplift forces, induced in the wood shear walls during the earthquake, to the foundation or in case of shear walls above the SSMF to the frame, (i.e. to provide overturning restraint). It should be noted that both the Strong Frame and wood shearwalls were placed such that the center of rigidity moved toward the center of mass at each story which effectively eliminated the concerns associated with torsional response of the structure. Figure 5 shows the Strong Frame, plywood panels, and ATS rods used to retrofit the building.

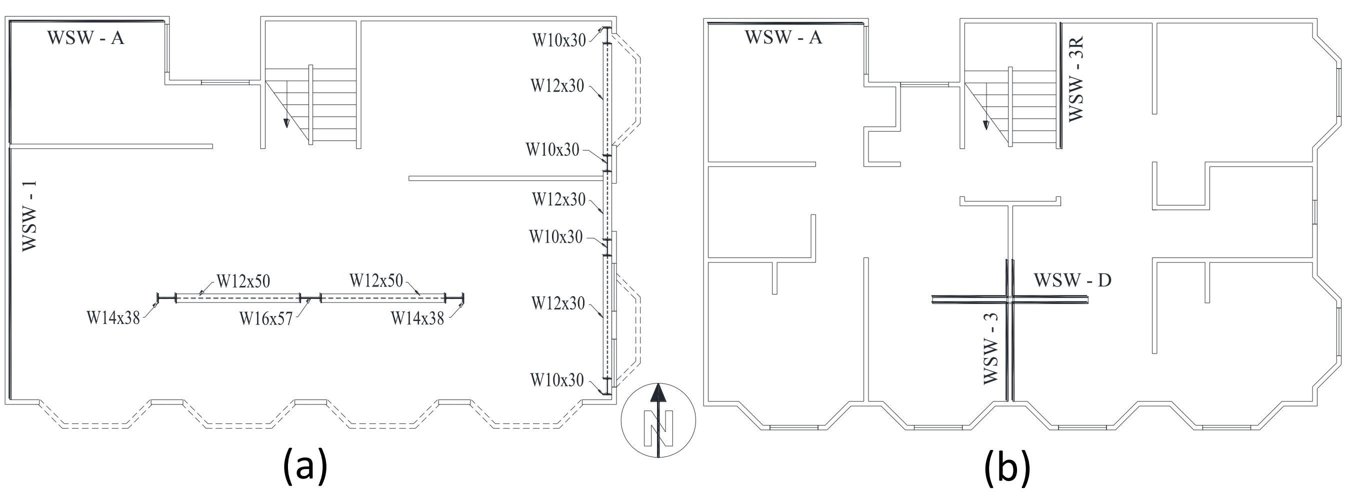


Figure 4. Location of the PBSR Retrofits: (a) Ground Level, and (b) Upper Stories

(a) (b) (c)

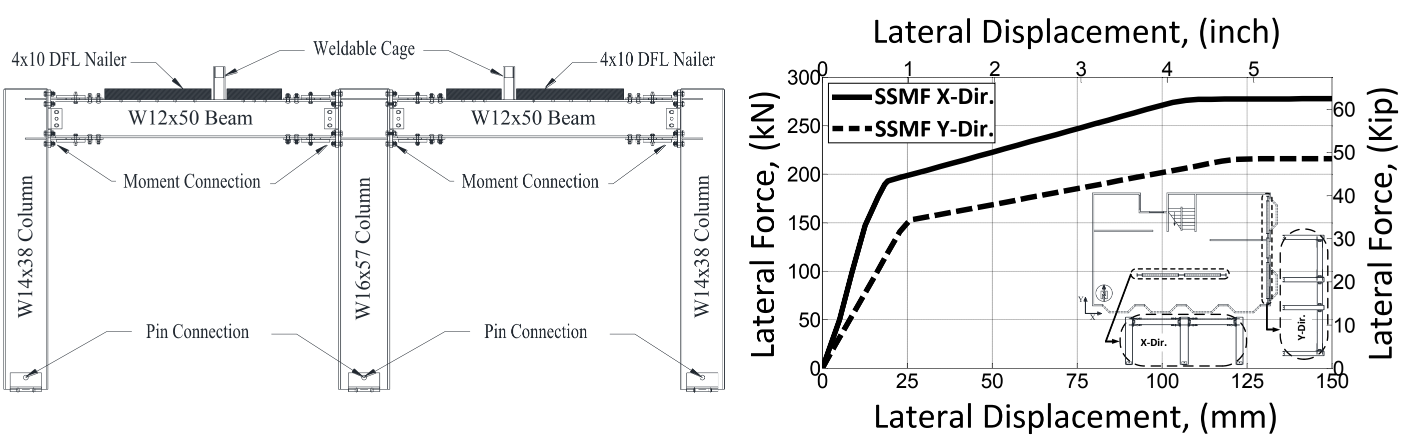
Figure 5. (a) East Span of Strong Frame Installed Parallel to the Motion of Shake Table, (b) ATS Rods and Stud Pack Inside Wood Shearwall, (c) Plywood Panels at Upper Stories

Figure 6 (a) shows the Simpson Strong Frame SMF that was installed at the ground floor parallel to the motion of the shake table and Figure 6 (b) presents backbone curves obtained from numerical pushover analysis for frames installed at the ground floor.

In order to test the retrofitted building, the building was subjected to the similar ground motions that were recorded during the 1989 Loma Prietaand 1992 Cape Mendocino earthquakes. The earthquakes were scaled to DBE and MCE levels with maximum spectral accelerations of 1.2g and 1.8g, respectively. Before and after each seismic test, a white noise test with a root mean square (RMS) amplitude of 0.05g was conducted to determine the fundamental period of the building and its modes shapes, and to obtain a qualitative feel for damage based on changes in building period. Figure 7 presents the building profile at its maximum deformations for five seismic tests along with a time-history response for the test with the highest response. It can be seen that all the stories experience less than 2% inter-story drift which meets the performance criteria (i.e., under 2% drift with only non-structural damages) and meet.

Conclusion

Overall the PBSR method was validated with the level of accuracy that would be expected for this type of testing. The peak inter-story drift response was approximately 2.5% at story 3 with the average of all stories being well under 2%. Full results will be presented in a forthcoming project report which will be available at www.nees.org in 2014.



(a) (b)

Figure 6. (a) Strong Frame SMF Installed Parallel to the Motion of Shake Table, (b) Backbone Curves of the Strong Frame SMFs Installed Parallel and Perpendicular to the Motion of Shake Table

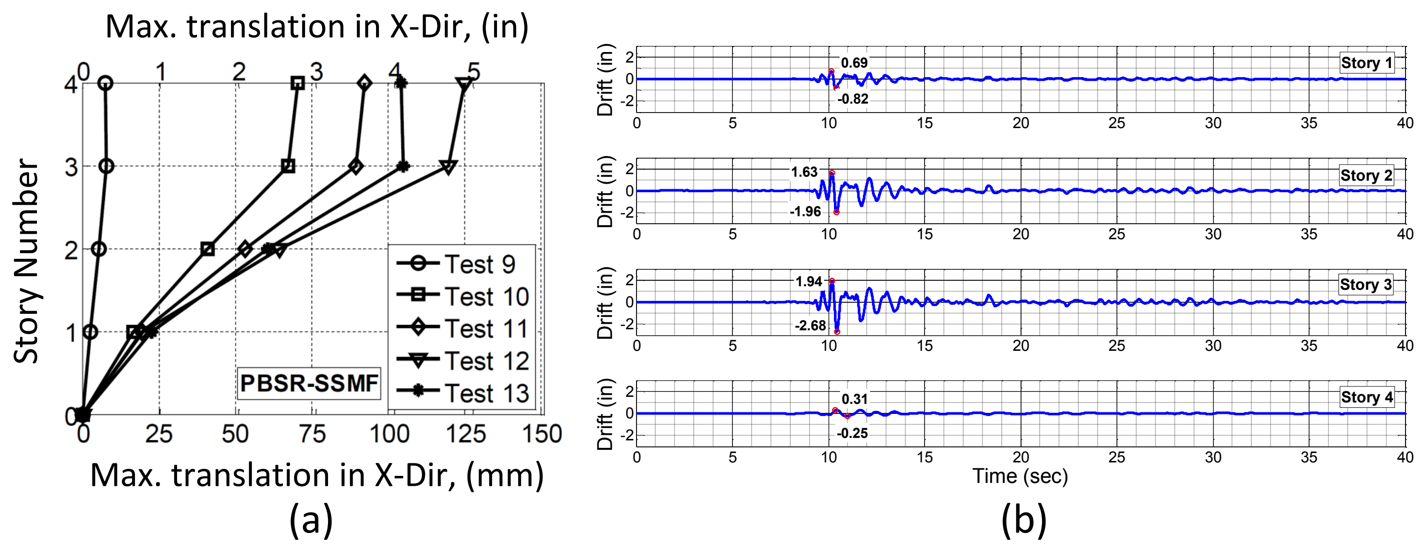


Figure 7. PBSR- Strong Frame SMF Retrofit. (a) Building Maximum Deformation Profile, and (b) Time-History Response to Cape Mendocino Earthquake Record with PGA of 0.89g

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