*New Developments in Structural Engineering and Construction*
Yazdani, S. and Singh, A. (Eds.)
ISEC-7, Honolulu, June 18 –23, 2013

# SEISMIC RETROFIT OF SOFT-STORY WOODFRAME BUILDINGS USING CROSS LAMINATED TIMBER

JOHN W. VAN DE LINDT[1], POURIA BAHMANI[1], MIKHAIL GERSHFELD[2], GIRAJ KUMAR KANDUKURI[3], DOUG RAMMER[4], and SHILING PEI[5]

[1]*Civil and Env. Engineering, Colorado State University, Fort Collins, Colorado, USA*
[2]*Civil and Env. Engineering, Cal Poly-Pomona, Pomona, California, USA*
[3]*Civil, Construct., and Env. Eng., University of Alabama, Tuscaloosa, Alabama, USA*
[4]*U.S. Forest Products Laboratory, Madison, Wisconsin, USA*
[5]*Civil and Env. Engineering, South Dakota State University, Brookings, South Dakota, USA*

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 system deficiencies, referred to as a “soft story”. Thus, many multi-story woodframe buildings are susceptible to collapse at the first story during earthquakes. The majority of these older 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. As part of the five-university multi-industry, U.S. National Science Foundation – funded NEES-Soft project, a performance-based retrofit method has been developed for these types of buildings. This paper presents the first generation of this method and resulting retrofit design using an engineered wood technology that is just being introduced in the United States. Cross laminated timber (CLT) panels are used to strengthen and stiffen the soft stories of the building in order to achieve the performance level desired by the stakeholders under a specified seismic intensity. The performance-based seismic retrofit (PBSR) method is summarized and focus in the paper is placed on the retrofit achieving a target drift 50% of the time under a prescribed seismic intensity. The numerical model is developed based on full-scale experiments, which will also be presented, and performance is validated using a state-of-the-art nonlinear time history analysis model.

*Keywords*: Woodframe, Light-frame wood, Seismic retrofit, earthquake engineering, performance-based seismic design, nonlinear time history analysis, direct displacement design.

## 1 Introduction

Woodframe construction in the United States has, by and large, performed well with regard to life-safety over the decades. However, older woodframe buildings, typically two- to four-stories in Northern and Southern California (as well as elsewhere), may have a soft and weak story which makes them susceptible to collapse during even moderate shaking. These buildings often have parking and/or open fronts and very few interior walls resulting in first story stiffness that is sometimes as low as 30% to 40% of the story above. Figure 1 shows a photo of a soft-story building undergoing retrofit in San Francisco. Most local jurisdictions recognize this as a disaster preparedness problem and have been actively developing various ordinances and mitigation plans to address this threat. Some of the most visible efforts are taking place in San Francisco, Los Angeles, San Jose and other major metropolitan areas in the United States that have high seismic vulnerability. In 2008, the San Francisco Department of Building Inspection and the Applied Technology Council initiated the Community Action Plan for Seismic Safety (CAPSS) project with the main goal of identifying possible action plans for reducing earthquake risks in existing buildings. According to the CAPSS study, 43 to 80 percent of the multi-story woodframe buildings in San Francisco will be deemed unsafe after a magnitude 7.2 earthquake and a quarter of these buildings would be expected to collapse.

Figure 1. Soft-story woodframe building in San Francisco, California undergoing voluntary retrofit.

In this paper a performance-based seismic retrofit procedure developed as part of a five-university NSF-funded project entitled NEES-Soft is summarized and its application illustrated using CLT based on a full-scale test building. The method has been preliminarily developed and is being refined for application to a four-story shake table test at NEES@UCSD.

## 2 Performance-based seismic retrofit procedure

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.

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 DDD method developed in the previous studies was demonstrated to be a reliable procedure for designing structures. In performance-based seismic retrofit (PBSR), which is a subset of 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.

The current DDD methodology (Pang et al., 2009) only determines the required lateral stiffnesses over the height of the building such that the building meets the target displacement. This method serves as the basis for a direct displacement retrofit (DDR) procedure and can be used to retrofit symmetric buildings (i.e., no torsional moment due to seismic force induces during earthquake), or buildings that havenegligible torsional moment after retrofit (eliminating torsion by reducing the in-plane eccentricity) (Bahmani and van de Lindt, 2012).

In-plane torsional moments and consequently rotational displacements can be induced when the center of rigidity (i.e. point where seismic force is resisted) of a story does not coincide with the center of mass (i.e. point where seismic force is applied). In this case, the current DDD and DDR methods are not applicable anymore since the additional displacements due to torsion are not taken into account which leads to underestimation of the response of the structure. The DDD method proposed in this paper can be used to design and retrofit torsionally unbalanced buildings. Figure 2 presents an N-story building with lumped masses of $M_j$ and $d_j$ for the $j^{th}$ story. It can be seen that the total displacement at 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 ($\Delta_j^{Tor.}$). Since the total displacement is a linear combination of translational and torsional displacements, it is the design engineer's decision to select a proportion between these two displacements (e.g., 80% of the total displacement is due to inter-story translation and 20% is due to inter-story rotation). At this point in the PBSR development this decision is arbitrary but should not exceed 50% $\Delta_j^{Tor.}$.

In order to simplify the DDR procedure, an equivalent single degree of freedom system can be used. The effective mass ($W_{eff}$) and lateral force distribution factors ($C_v$) can be calculated based on NEES-Wood report-05 (2009). The fundamental translational period of the building can be found from the intersection of the response spectral acceleration using ASCE7-10 (2010) design maps and response of the structure at the target drift (Figure 3). Having the period of the building, the effective lateral effective stiffness and consequently lateral stiffness of at each story can be found. The last step is locating the lateral load resisting systems (i.e., shearwalls or other retrofit assemblies in woodframe buildings), such that it satisfies the initial assumption of the contribution of torsion in the total displacement. The required lateral stiffness can be provided by using the secant stiffness of standard wood shearwalls and CLT panel at the target displacements (assuming that all walls experience the same displacement).

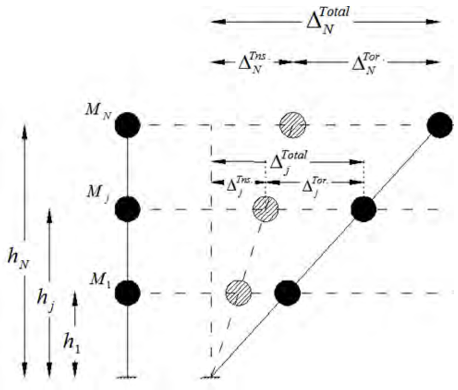

Figure 2. Translational and torsional displacements in a torsionally unbalanced building.

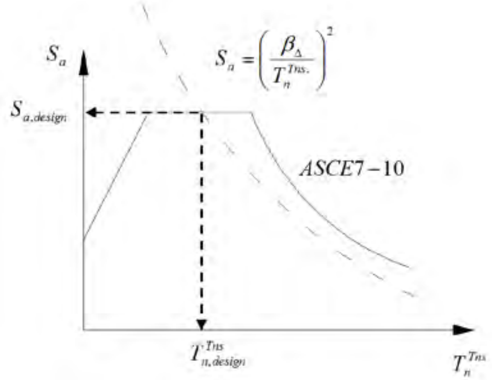

Figure 3. Fundamental translational period of the retrofitted building

## 3 NEES-Soft Retrofit Building

The NEES-soft retrofit building (scheduled to be tested at NEES@UB beginning in spring, 2012) was designed to be representative of a variety of three to four-story wood-frame buildings built in the greater San Francisco, California, area during the early and mid 20th century, presently classified as soft/weak story structures. A number of site visits to examine existing buildings under retrofit construction and the review of the retrofit drawings were undertaken to assist in developing the test structure. The visual observations confirmed a number of known deficiencies associated with early 20th century construction practices. For example, the lack of steel hardware in the connections, lack of connections to foundations, and the use of diagonal block bracing for the lateral load resisting system were confirmed. It was also confirmed that architectural layouts featured relatively open ground floors used as either tenant parking or leasable commercial office space, while upper levels were used as residential space and had a large number of interior walls. The architectural finishes for exterior walls included stucco, plaster on wood lath, and wood siding. Based on the site visits, and considering the constraints imposed by available space in the laboratory, the test structure was specified as a three-story building with a 6 m x 7 m (20 ft x 24 ft) footprint and 2.44 m (8 ft) typical wall height and is shown without wall finish materials in Figure 4.

(a) (b)

Figure 4. NEES-Soft project retrofit building to be tested at NEES@Buffalo and used as the illustrative example in this paper; (a) Elevation view showing soft-story; (b) Solid model of full-scale experimental setup with first story numerically reproduced during hybrid experiment.

## 4 Cross laminated timber (CLT) retrofit

Cross laminated timber is an engineered structural panel made up of cross-oriented layers of dimension lumber and is either glued or mechanically connected. The panels themselves behave almost rigidly and the hysteresis developed using metal connectors, brackets, and hold downs (Popovski et al, 2010; Pei et al, 2013). The technology was invented in Europe approximately 20 years ago but is only beginning to be used in North America. No seismic provisions for CLT in the U.S. are available yet, but a project to develop seismic response factors is recently underway. Recall from the summary of the PBSR procedure outlined earlier that all that is needed to include the CLT garage wall section into the retrofit procedure is the hysteretic backbone. Test of a garage wall return was conducted at the University of Alabama structural engineering laboratory. The test setup is shown in Figure 5 and the hysteresis curves for a 2-ft long CLT panel are presented in Figure 6.

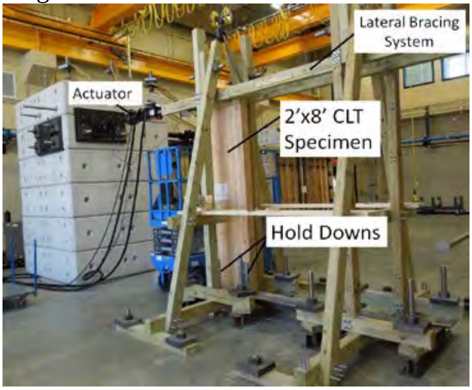

Figure 5. Cyclic testing 2-ft long CLT panel.

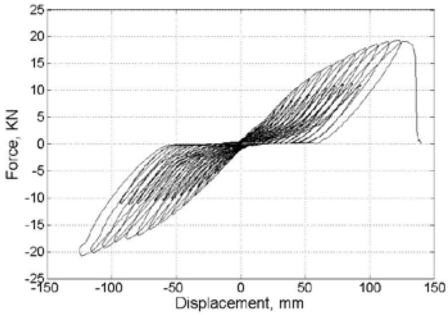

Figure 6. 2-ft long CLT panel hysteresis curve

Multi-incremental dynamic analysis (MIDA) was conducted for suites of 22 earthquake ground motions (FEMA, 2009) before and after retrofitting the NEES-Soft test building in both X and Y directions. A number of 2-ft long CLT panels were added next to the openings of the first floor (soft story level) in X- and Y-directions. The upper stories were retrofitted using standard wood shearwalls mostly with 4/12 and 6/12 nail pattern, i.e. GWB was replaced with OSB sheathed shear walls for several walls. It can be seen from Figures 7 and 8 that the inter-story drift for the retrofitted building at a spectral acceleration of 1.5g (MCE level for many locations in CA) is less than the 3% target inter-story drift in both directions; whereas, the Sa corresponding to 3% drift for the original building occurred near only 0.15g.

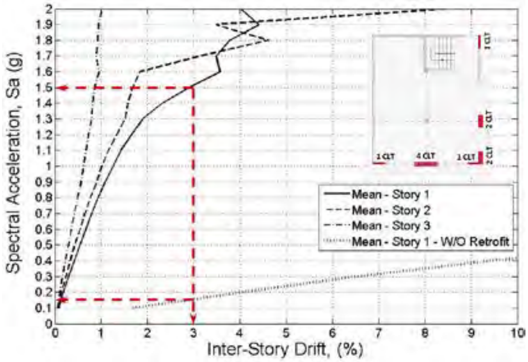

Figure 7. MIDA in X-direction.

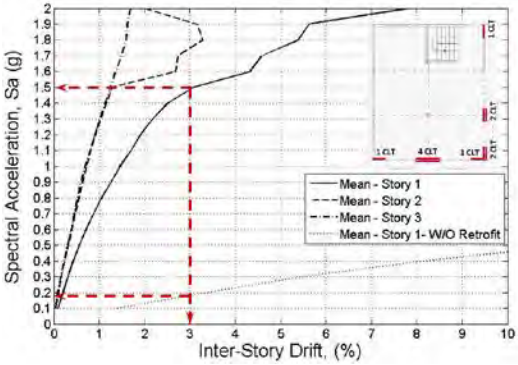

Figure 8. MIDA in Y-direction.

From this, CLT hytersteric parameters were developed for use in dynamic analysis, with existing sheathing parameters (Table 1)

Table 1. Hysteresis parameters for existing sheathings and CLT panel

| **Sheathing Type** | **$K_0$ (N/mm)** | **$F_0$ (N)** | **$F_1$ (N)** | **$r_1$** | **$r_2$** | **$r_3$** | **$r_4$** | **$X_u$ (mm)** | **α** | **β** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Horizontal Wood Siding (per ft)** | 19 | 245 | 71 | 0.099 | -0.050 | 1.050 | 0.004 | 208.3 | 0.72 | 1.1 |
| **Gypsum Wall Board (per ft)** | 77 | 467 | 28 | 0.020 | -0.050 | 1.000 | 0.010 | 25.9 | 0.75 | 1.1 |
| **2-ft CLT Panel (per panel)** | 473 | 13500 | 445 | 0.010 | -0.080 | 1.000 | 0.010 | 122.9 | 0.50 | 1.1 |

## 5 Summary and conclusions

The philosophy behind the DDR retrofit procedure developed as part of the NEES-Soft project was summarized and applied to a soft-story building that is to be tested beginning in Spring 2013. A new wood technology known as cross laminated timber, which is a sustainable construction alternative, was selected for retrofit. The IDA results show that using several panels at the garage front combined with the addition of OSB sheathed shear walls in the upper stories ensures that the building meets the performance objectives outlined for the retrofit. It should be noted that the foundation was assumed to be able to resist the CLT shear wall loading. Foundation retrofit was not part of this study and may be required if existing foundation capacity is exceeded. While some modifications to the procedure are underway, it is concluded that the new approach for DDR, which can be applied to building with torsion, is viable, and significantly improves the safety of the building in moderate and strong earthquakes.

## Acknowledgments

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 additional members of the NEES-Soft project team: David V. Rosowsky at Rensselaer Polytechnic Institute, Andre Filiatrault at University at Buffalo, Gary Mochizuki at Structural Solutions Inc., David Mar at Tipping Mar, and Charles Chadwell and the practitioner advisory committee: Laurence Kornfield, Steve Pryor, Tom Van Dorpe, Doug Thompson, Kelly Cobeen, Janiele Maffei, and Rose Grant.

## References

Bahmani, P., and van de Lindt, J.W. (2012) Numerical Modeling of Soft-Story Woodframe Retrofit Techniques for Design, *Proceeding of Structures Congress*, Chicago.

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.

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.

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.