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Optimal seismic retrofit design for residential structures using CLT panel and FEMA P-807 methodology

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ABSTRACT

Earthquake are devastating and one of the most ruthless natural hazards due to its effects on life and property. Recent earthquakes, the 1989 Loma Prieta and the 1994 Northridge earthquakes, resulted in severe damages and fatalities to multi-family residential buildings in the San Francisco Bay Area. Many researchers have studied and developed methods to better understand the mechanisms of earthquakes for mitigating losses and fatalities. FEMA P-807 guidelines provides a methodology for engineers to determine a retrofit design for existing buildings. Optimization techniques have been applied to determine the retrofit design under given hazard conditions such as performance drift criteria, seismic capacity, hazard level, etc. Cross-laminated timber is a form of engineered wood that is suitable for use in walls, floors, and roofs. It is selected as a retrofit component for existing buildings. Finally, the optimal seismic retrofit design using cross-laminated timber panel has been achieved and its performance satisfies the FEMA P-807 performance criteria under given hazard conditions.

1. INTRODUCTION

Earthquakes are devastating hazards due to its effect on life and property. They have a power being capable to destroy whole cities and kill thousands of people. The 1989 Loma Prieta earthquake occurred in Northern California on October 17 and its effects extended well to the north into the San Francisco Bay Area. There were approximately 4,000 injuries as a result of the earthquake. Five year later, the 1994

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Northridge earthquake, having a magnitude of 6.7 which produced the highest recorded in urban area in North America, occurred and caused more than 5,000 injuries and 57 fatalities. These two earthquakes caused severely damages on a large number of multi-family light-frame wood buildings throughout the San Francisco Bay Area (FEMA, 2012).

Wood-frame construction have the majority of the building market in North America. Multi-family wood-frame building are quite common in urban areas of the U.S. and Canada. Approximately 4,400 older, pre-seismic-code, wood-frame residential buildings have been identified in the city of San Francisco. These older buildings have parking garages or large openings on the first level and residential units in the upper stories. Unfortunately, these mixed-use construction caused the buildings to have distinct lateral stiffness and strength differences between its first story and the upper stories due to their different column grids or wall layouts. Such a change in these old buildings results in them being vulnerable to collapse during earthquake events (FEMA, 2012).

In May 2012, the FEMA P-807 “Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories” guidelines were published. It provides a guideline for engineers to select a retrofit design when it is needed. Theoretically, there are large number of retrofit options for each building. Optimization techniques, Genetic Algorithms (GAs) in this study, were introduced to help identify the best retrofit options for the building. During the process, various constraints are applied to seek the optimum. Cross-laminated timber (CLT) is an engineering wood product having good structural properties and is capable of being used as robust wall and floor structures in construction. Therefore, it is being nominated as a retrofit material for wood-frame residential structures in this study.

The objective of this study is to develop a retrofit methodology for wood-frame residential construction by means of the FEMA P-807 guidelines combining with CLT and GAs. Initially, a numerical model of the CLT is needed and introduced based on an experimental test. Then, the model has been implemented into the FEMA P-807 guidelines. A probability of failure under given hazard conditions, i.e., a spectral acceleration, is considered as a criterion for the retrofit options.

2. OVERVIEW OF THE PROPOSED METHODOLOGY

FEMA P-807 is a guideline and a simplified procedure focusing on cost-effective evaluation and retrofit for wood-frame buildings with soft first story. It provides cumulative probability of exceeding a performance drift criteria in terms of site specified seismic capacity obtained from the results of multiple nonlinear time history analysis. Initially, hundreds of surrogate structures were generated from the combinations of five parameters, i.e., ground story strength, upper structure strength, ground to upper story strength ratio, ductility, and torsional imbalance. Nonlinear behaviors of structural and non-structural walls were considered during the nonlinear time history analysis. Then, empirical design equations were constructed and proposed based on the results.

Finally, a seismic performance was qualified as a means of the median spectral capacity and was modified considering the presence of torsional irregularity and ground story height by applying adjusting factors. Figure 1 shows the overall procedure of the FEMA P-807 guidelines. More detailed information of the FEMA P-807 guidelines is available in the full document (FEMA, 2012; Park and van de Lindt, 2014).

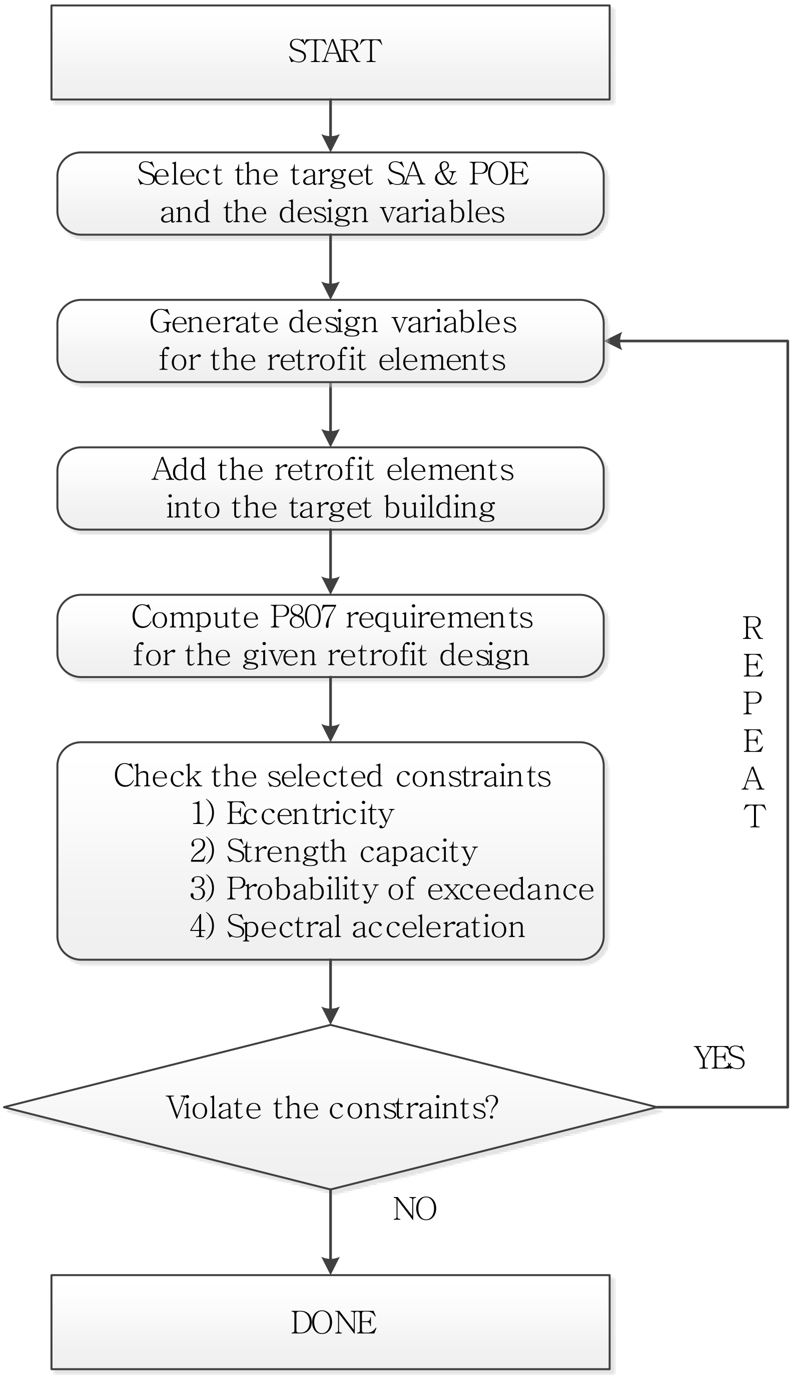


Figure 1: Overall procedure of the FEMA P-807 guidelines (Park and van de Lindt, 2014).

GAs have been applied widely in optimization problem to seek useful solutions for over 40 years due to the robustness and simplicity. Initially, GAs were proposed by

Holland and were developed by Goldberg. GAs are a heuristic search procedure based on the mechanics of natural selection and genetics, and do not require the gradient of the objective function nor the existence of derivatives to find solution. It consists of mainly four operators such as selection, reproduction, crossover, and mutation (Goldberg, 1989). Figure 2 shows the flowchart of GAs.

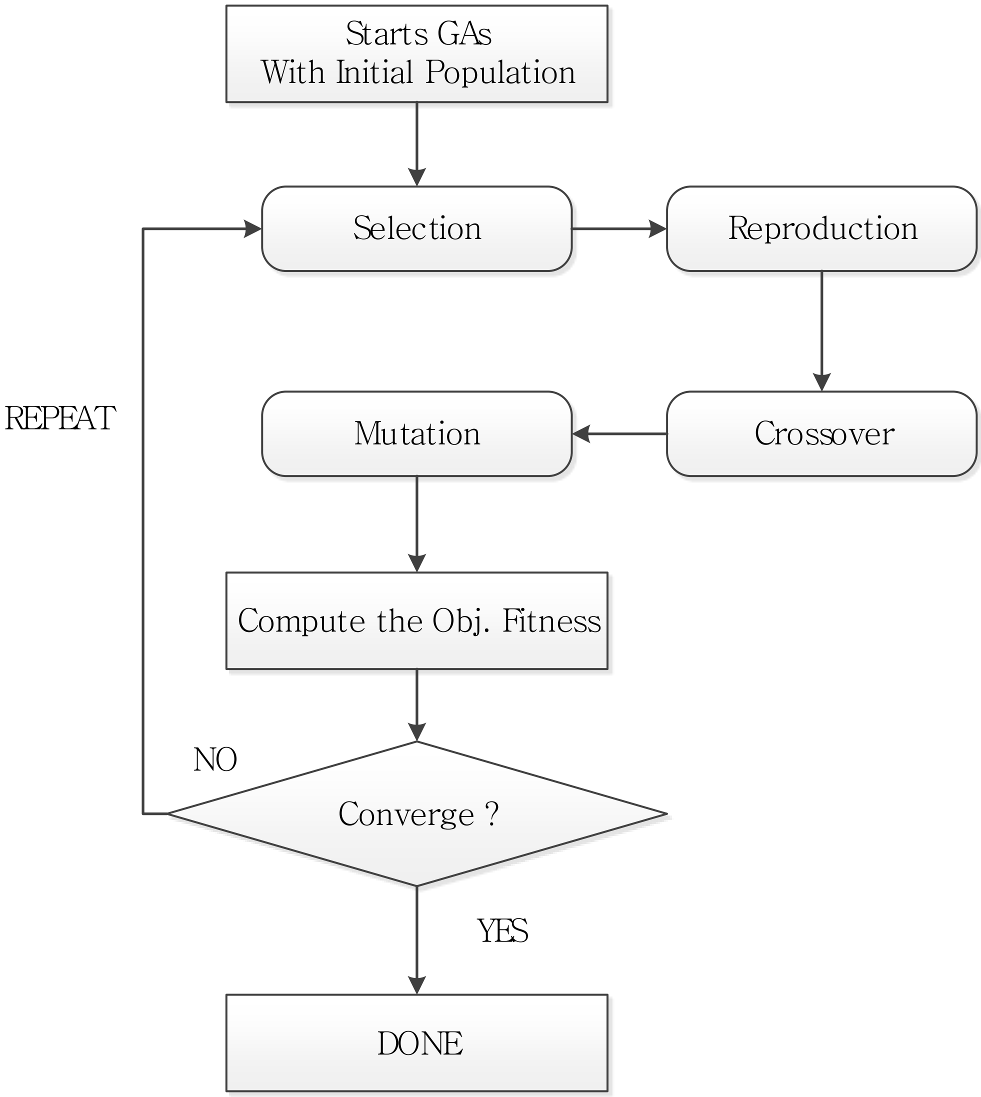


Figure 2. Schematic procedure for GAs.

Typically, an optimization problem having constraints can be written as:

$$\text{Minimize } f(x) \tag{1}$$

$$\text{Subjected to} \begin{cases} g_i(x) \le 0 & : \quad i = 1, 2, ...q \\ h_j(x) = 0 & : \quad j = q+1, q+2, ...\text{m} \end{cases} \tag{2}$$

where *f(x)* is an objective function that depends on the specifics of the problem, *g(x)* are the inequality constraints, *q* is the number of inequality constrains, *h(x)* are the equality constraints, and *m–q* provides the number of equality constraints (Park and van de

Figure 3. Schematic overview of CLT layer configuration (Laguarda Mallo and Espinoza, 2014)

Table 1 Selected Data Point

ID	Drift Ratio[1)] (%)	Force (kN)	Force[2)] (kips)
1	0	0	0
2	0.5	2.6860	0.6038
3	1.0	6.5505	1.4726
4	1.5	10.2792	2.3109
5	2.0	13.1567	2.9582
6	3.0	20.5209	4.6133
7	4.5	24.3207	5.4675
8	6.0	25.4211	5.7149
9	7.53	25.2402	5.6742
10	8.0	17.6791	3.9744

1) Displacement ratio is defined as actual displacement over the height of the floor (i.e., 2.44meter, 96inch)
2) 1 kN = 0.22481kip

Lindt, 2014).

Three constraints have been selected from FEMA P-807 methodology: 1) eccentricity limits; 2) strength capacity limits; and 3) the specified drift limits for a given hazard conditions. Solution must not violate these constraints and GAs can be helpful to seek the best one. The design variables for the problem are structural configurations of the retrofit wall element(s), so they are expressed as a vector for each element. Coordinates, length, stiffness, available material types for the elements, and their combinations can be possible. Materials for retrofit element can be various such as W-shape, gypsum wall board, horizontal wood sheathing, plywood panel, CLT, etc. In this study, CLT is adopted as the retrofit element.

CLT has the potential to change the building construction in a considerable way. CLT was developed in Austria and Germany in the early 1990's and is an engineering wood product which is glued or fasten together to form a solid panel with mechanical fastenings alternating 90 degrees (Figure 3). Many studies shows that this configuration helps to achieve rigidity, stability, and mechanical properties in the two directions (Laguarda Mallo and Espinoza, 2014).

To use CLT as the retrofit element in FEMA P-807, a numerical model of CLT is needed. The model were developed based on experimental test and has been implemented into FEMA P-807 guideline. To do this, several cyclic testing were carried out and the data were averaged. Then, minimum data point to simulate the behavior of CLT has been selected. Finally, the model has been implemented into the FEMA P-807. It should be noted that the number of data points to simulate the behavior of CLT in guide is limited (FEMA, 2012).

Table 1 shows the selected data points. Figure 4 shows that the behavior of CLT and its fitted data.

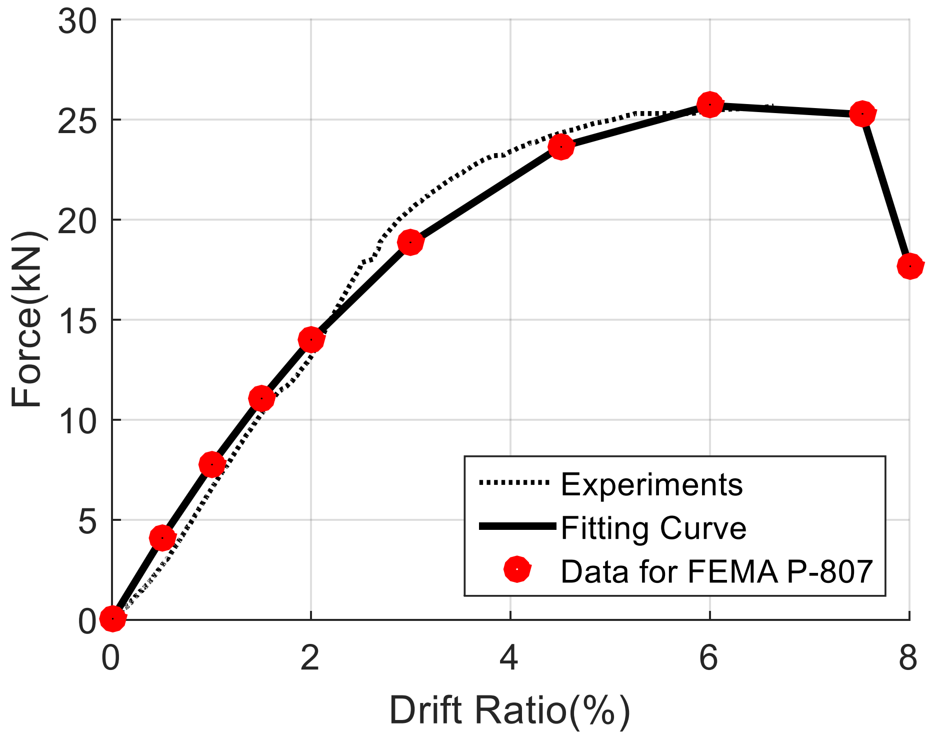


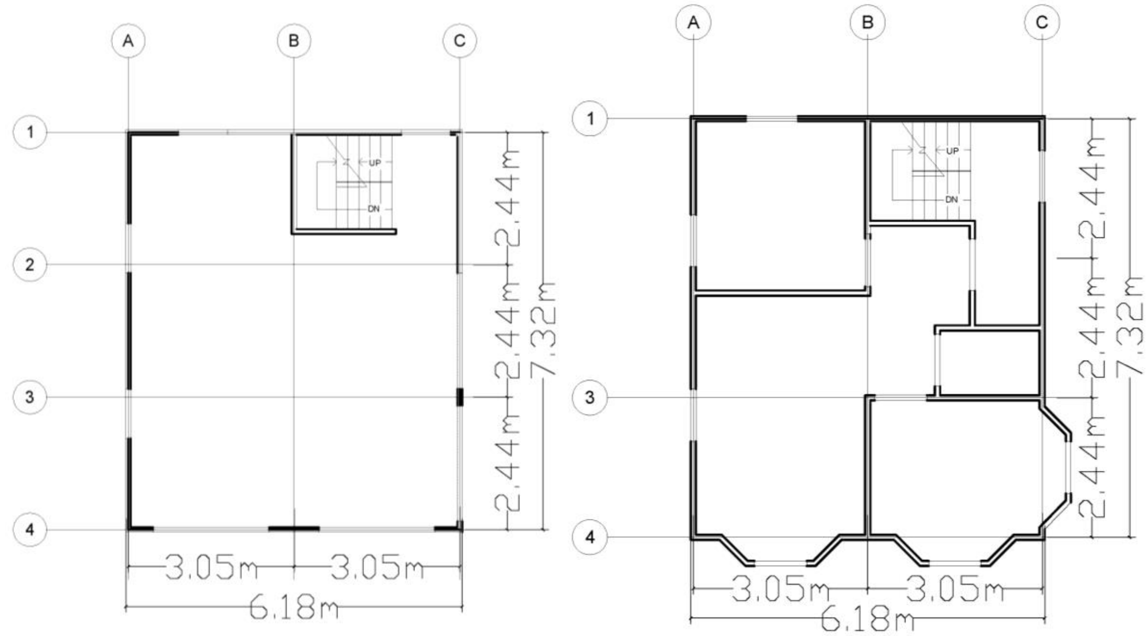
Figure 4. Testing data and numerical model of CLT

3. ILLUSTRATIVE EXAMPLES

The three-story residential structures was selected as an illustrative examples. Its total living area is approximately 75 m^2 (808 ft^2) and has a first story parking garage.

The height of the building from the first floor slab to the roof eaves was 8.92 m (29.25 ft) and its total weight was approximately 20.8 tons (41.6 kips). The floor plan for this example, shown in Figure 5, is from the NEES-Soft project (van de Lindt et al., 2013).

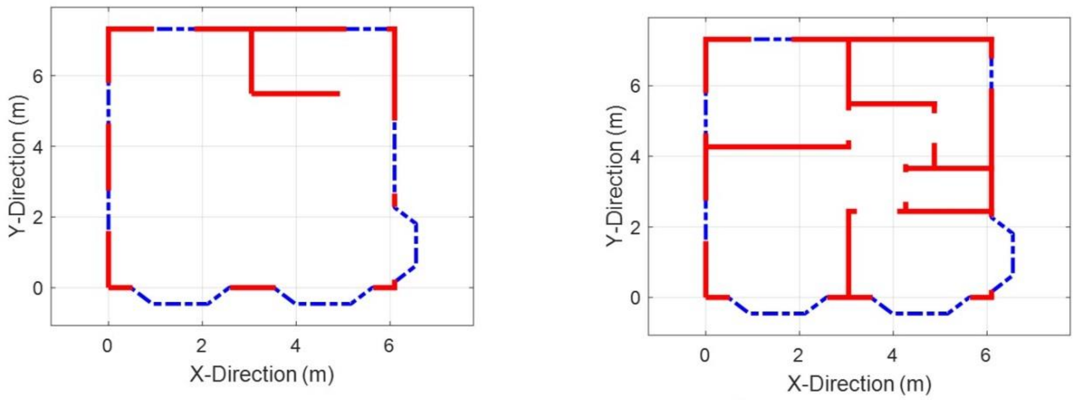
As mentioned earlier, CLT was adopted for the retrofit element type. Two CLTs for each direction are considered and they can be located anywhere inside the building. Coordinates and stiffness are the design variables for each CLT. Figure 6 shows the schematic overview of the model for the example building.



1st Story: Garage Level 2nd & 3rd Story: Living Area

Figure 5: Floor plan for the three-story residential structure with first story parking garage (van de Lindt et al., 2013).

Two seismic performance levels, i.e., BSE-1E and BSE-2E, are selected from ASCE41-13, Seismic Evaluation and Retrofit of Existing Buildings (ASCE, 2013). According to the United State Geological Survey (USGS 2015), the Basic Safety Earthquake-1, which is 20% probability of exceedance in 50 years in ASCE 41-13, for the San Francisco Bay Area, CA, U.S.A have the seismic intensity of 0.892g spectral acceleration at 0.2sec, ζ =5%. Additionally, the Basic Safety Earthquake-2, which is 5% probability of exceedance in 50 years, for the San Francisco Bay Area, CA, U.S.A have the seismic intensity of 1.542g spectral acceleration at 0.2sec, ζ =5%. It should be noted that there are several options for determining seismic performance in USGS and ASCE 41-13 Retrofit Standard is adopted as the Building Code reference document in this study.



1st Story: Garage Level 2nd & 3rd Story: Living Area

Figure 6: Schematic overview of the model for the example building.

The location of the two retrofit walls and their length were considered as the design variables, so there are 6 design variables. Table 2 shows the detailed information for the design variables.

Table 2: Detailed information for the design variables.

Design Variable ID	Low value	Upper value	Type	Comments
1 & 3	0	240	X coordinate, Integer	Wall 1 & 2
2 & 4	0	288	Y coordinate, Integer	Wall 1 & 2
5 & 6	0	6	Length of the Wall, Integer	Wall 1 & 2

The optimum retrofit solution for 0.9g spectral acceleration with the 20% drift limit probability of exceedance has been sought. Optimization problem was solved successfully under the given conditions and was summarized in Table 3. Figure 7 shows the solution for the three-story example building with 0.9g spectral acceleration, 20% probability of exceedance (POE).

Table 3: Retrofit design for two CLT walls with 0.9g, 20% POE

No.	Location (m/inch)		Length (m/ft)
	X-Direction	Y-Direction	
Wall #1	2.77 (109)	4.04 (159)	0.61 (2)
Wall #2	3.30 (130)	2.31 (91)	0.61 (2)

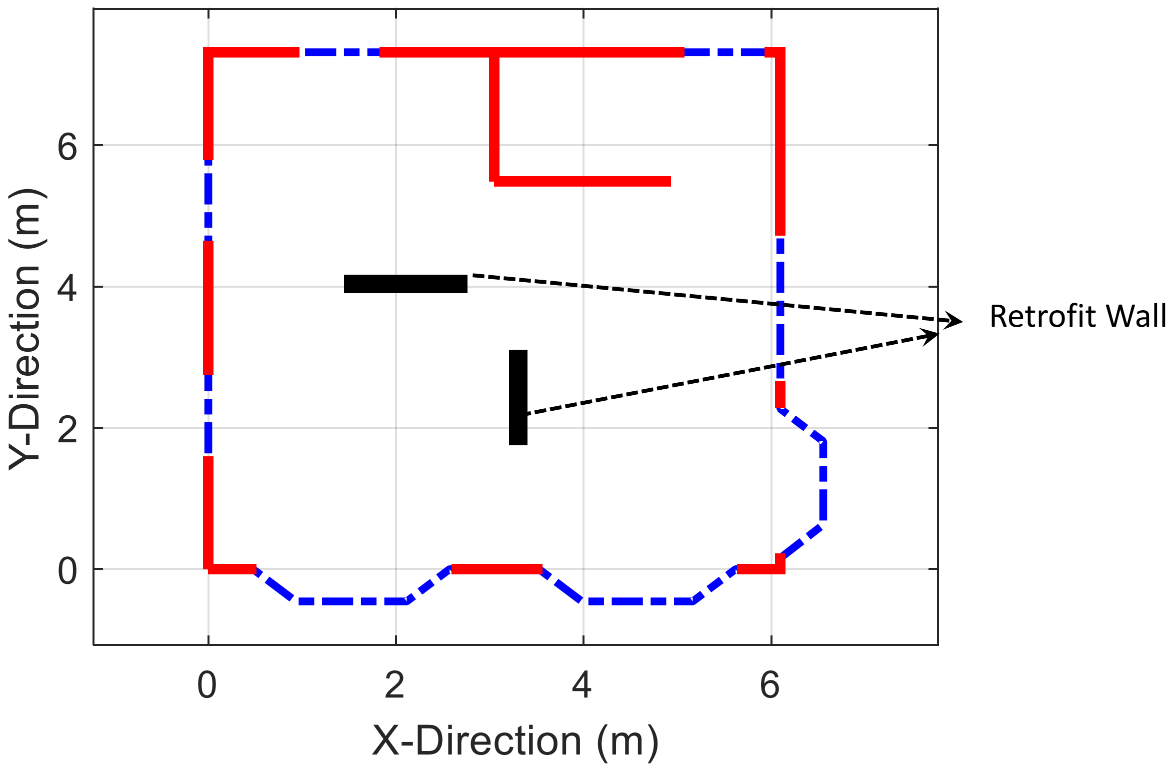


Figure 7: Retrofit Design for the example building with 0.9g, 20% POE.

Probabilistic relationships between spectral acceleration and structural damage are commonly expressed as fragilities (Park and van de Lindt, 2014). The fragility curves for the x- and y-direction were presented and can be expressed by a lognormal distribution function:

$$F(x) = \Phi\left(\frac{\ln(x_{sa}) - x_m}{\beta}\right) \tag{3}$$

where, $\Phi(\bullet)$ denotes the value of the standard normal cumulative distribution function, x_{sa} is the spectral acceleration, x_m denotes the median value of the distribution, and β denotes the logarithmic standard deviation (Park and van de Lindt, 2014).

Figure 8 shows that the example building meets the FEMA P-807 retrofit requirements for 0.9g spectral acceleration with 20% POE limits. The failure probability of the building was decreased from 88.6% to 16.4% and 84.3% to 13% for each direction, respectively. Therefore, a seismic risk was reduced and its performance has been improved. Additional simulations are performed up to 1.5g spectral acceleration with 0.1g increments. Over 1.2g spectral acceleration, retrofit solutions could not be found. It can be explained that finding proper solutions under the given constraints, e.g., restricted retrofit wall locations, limited wall length, a high spectral accelerations demand, etc., may not be possible to obtain.

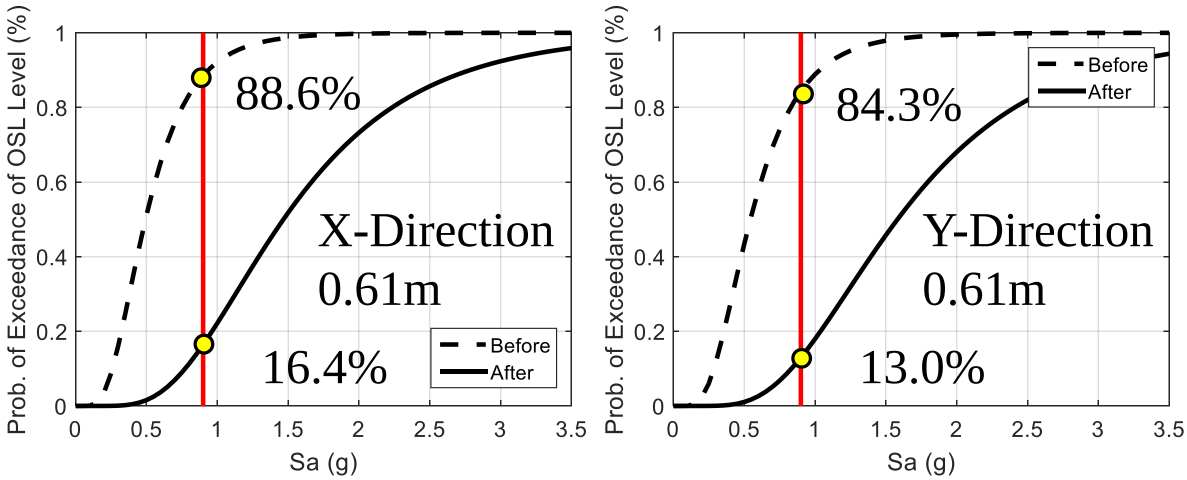


Figure 8: Fragility curves for the x- and y-direction of the three-story example building.

A solution for 1.2g spectral acceleration and 20% POE was successfully found and is summarized in Table 4. Fragility curve for the solution is depicted in Figure 9. Figure 10 shows the solution for the three-story example building with 1.2g spectral acceleration, 20% probability of exceedance (POE).

Table 4: Retrofit design for two CLT walls with 1.2g, 20% POE

No.	Location (m/inch)		Length (m/ft)
	X-Direction	Y-Direction	
Wall #1	2.77 (109)	4.04 (159)	0.61 (2)
Wall #2	3.30 (130)	2.31 (91)	0.61 (2)

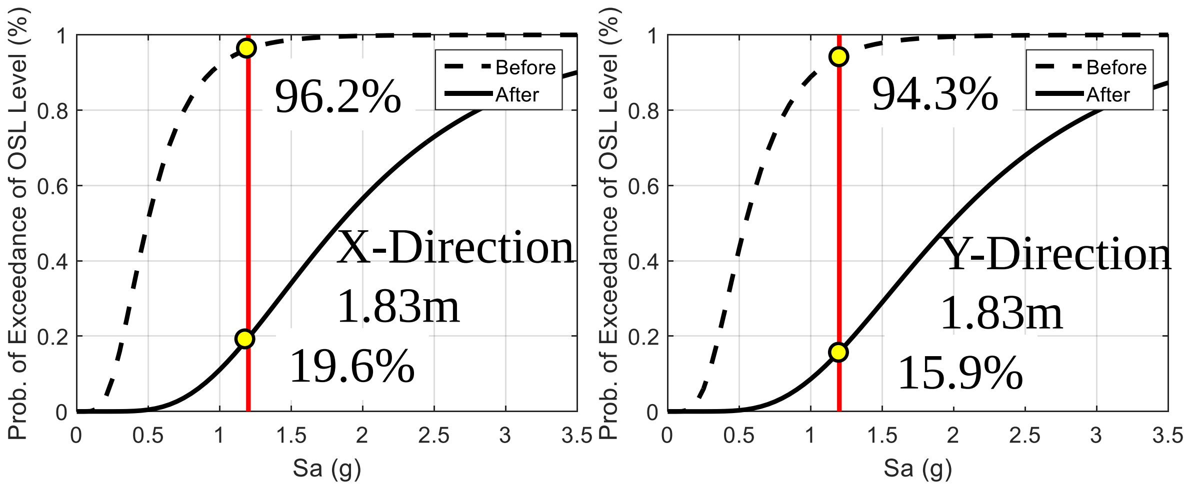


Figure 9: Fragility curves for each direction of the example building with 1.2g, 20% POE.

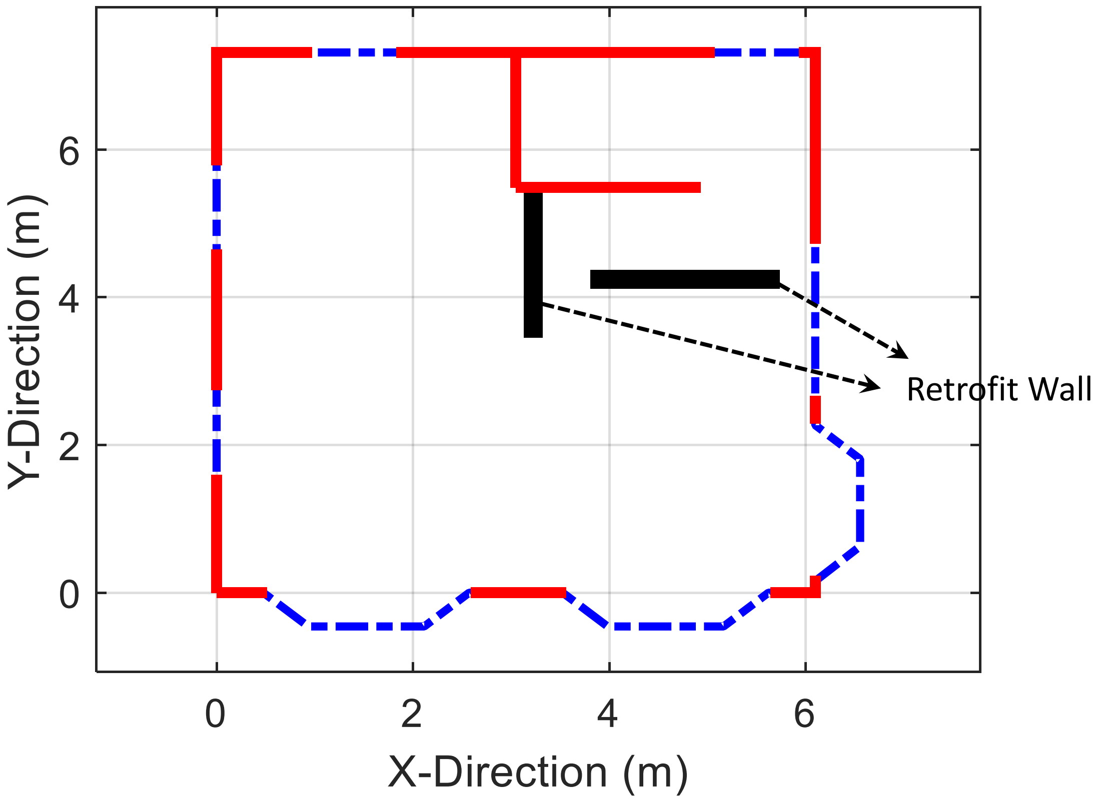


Figure 10: Retrofit Design for the example building with 1.2g, 20% POE.

4. CONCLUSIONS

The main goal of this study was to develop an optimization approach for the FEMA P-807 guidelines for wood-framed residential structures using CLT. The methodology was successfully developed and presented in this study. During optimization, various constraints were applied to fine the solution. Three-story building were used to demonstrate the proposed methodology. Simulations, ranged from 0.9g to 1.2g for 20% probability of exceedance, were completed. The methodology presented in this study can provide helpful information to make decisions for stakeholders, homeowners, etc.

ACKNOWLEDGMENTS

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REFERENCES

American Society of Civil Engineers (ASCE). (2013). “Seismic Evaluation and Retrofit of Existing Buildings.” *ASCE/SEI 41-13*, Reston, VA.

Federal Emergency Management Agency(FEMA) (2012). “Seismic evaluation and retrofit of multi-unit wood-frame buildings with weak first stories.” *FEMA P-807*, Washington. D.C.

Goldberg, D. E. (1989). “Genetic algorithms in search, optimization, and machine learning”, pp. 1-215, Addison-Wesley Publishing Co., Boston, MA, USA.

Laguarda Mallo, Maria Fernanda and Espinoza, Omar (2014), “Outlook for Cross-Laminated Timber in the United States”, *Bioresources*, 19(4), 7427-7443

Park, S. and van de Lindt, J.W. (2014), “Genetic Optimization for Seismic Retrofit of Soft-Story Woodframe Buildings Using FEMA P-807 Methodology”, *ASCE Journal of Performance of Constructed Facilities*, 10.1061/(ASCE)CF.1943-5509.0000637

USGS (2015). "U.S. Seismic Design Map ". Retrieved June, 2015, from https:// http://earthquake.usgs.gov/designmaps/us/application.php.

van de Lindt, J.W., P. Bahmani, M. Gershfeld, X. Shao, W. Pang, M.D. Symans, and G. Mochizuki. (2013). “Performance-based seismic retrofit of soft-story light-frame wood buildings.”, Proc. *10th International Conference on Urban Earthquake Engineering*, March 1-2, Tokyo, Japan.