Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories

A report published this January provides guidance to advance the understanding of the behavior of SWOF buildings and encourage improved practice in the design of retrofits. **By Justin Moresco, PE, and David Mar, SE**

Older, multi-unit wood-frame buildings with brittle, weak, and torsionally irregular stories have collapsed in past earthquakes. Often designated as soft, weak, or open-front (SWOF) buildings, many were constructed in the 1950s through 1970s and can be found across the United States, most notably along the West Coast. The lateral systems consist of non-engineered sheathing and architectural finish materials, such as diagonal and 1x lumber sheathing, cement stucco, plaster, and gypsum wallboard. SWOF buildings often house significant numbers of people.

The Federal Emergency Management Agency (FEMA) originally addressed the risk from SWOF buildings by developing and, in May 2012, publishing "FEMA P-807, Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories." This guideline introduced a methodology to focus the retrofit on the first story to protect the building from collapse without transmitting excessive additional seismic forces into the upper stories. This approach accounted for the strength provided by the nonstructural walls and resulted in retrofits that balance performance with economics.

Since that time, California municipalities increasingly have enacted mandatory or voluntary seismic retrofit ordinances for SWOF buildings. The ordinances reflect regional differences in their approaches, including the engineering design requirements for retrofits. These ordinances have increased retrofit experience and highlighted regionally based information regarding the configuration and construction materials used in these types of buildings. Many cities in Northern California require that the entire first story be considered and addressed, whereas many cities in Southern California allow retrofits to directly mitigate the open-front (or open-line) vulnerability without considering or strengthening the entire first story.

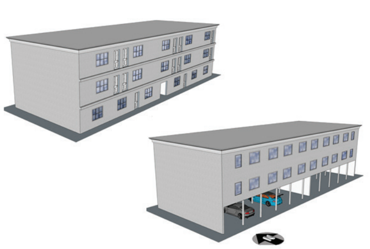
In 2020, FEMA NEHRP launched a project managed by the Applied Technology Council (ATC) that led to the publication of FEMA P-807-1, Guidance and Recommendations for the Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories. The purpose of this report, which was published this January, is to advance the understanding of the behavior of SWOF buildings and to encourage improved practice in the design of retrofits. The report provides technical information about the expected seismic collapse performance of common SWOF building configurations, both in their unretrofitted (or original) and retrofitted conditions. It also presents retrofit design examples. The report is intended to be used by jurisdictions and their consultants to inform decisions regarding ordinance scope and retrofit methods. Throughout FEMA P-807-1, both prevalent methods—full story and open-front retrofits—are analyzed and discussed, and much of the content, in particular the retrofit recommendations, is relevant to all types of SWOF building retrofits.

Archetypes Studied

Two basic forms of archetype buildings were studied. They are rectangular in plan, two and three stories tall above ground, and with an open front on either a long or short elevation, designated as LO (long-side-open) and SO (short-side-open), respectively (Figures 1 and 2). The wall materials are cement stucco exterior siding and either gypsum wallboard or lath-and-plaster interior finishes. The diaphragms are either straight or diagonal sheathing. The selection of these materials was informed by an evaluation of common SWOF characteristics using Northern and Southern California datasets.

The archetype buildings have two material combinations for the walls—strong wall (SW) and weak wall (WW). The strong wall set, which is representative of buildings constructed from the 1920s through early 1960s, has cement stucco exterior finishes and gypsum plaster interior finishes. The weak wall set, which is representative of buildings constructed from the 1950s through 1970s, has cement stucco exterior finishes and gypsum wallboard interior finishes. Two types of diaphragms were investigated—a strong diaphragm (SD) representing diagonal-lumber sheathing and a weak diaphragm (WD) representing straight-lumber sheathing. These different materials were combined with one another to create the "primary study" archetype building options (Table 1). They consist of long-side-open and short-side-open forms of two and three stories, with both the strong wall/weak diaphragm (SW-WD) and weak wall/strong diaphragm (WW-SD) material configurations.

Besides the "primary study" archetypes, "variant study" archetypes were developed in FEMA P-807-1 to investigate the impact of wing walls, no open-front vulnerability, and relatively weaker and more brittle diaphragm properties. This article focuses on the "primary study" archetype results due to space limitations.



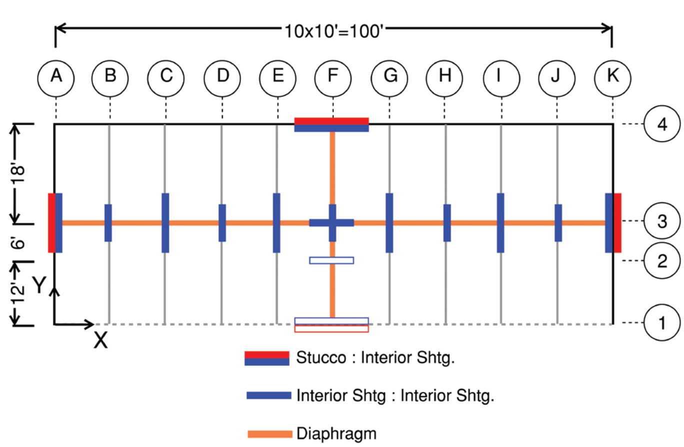


Figure 1. Shown is isometric renderings of a long-side-open archetype building above. Right: The plan view model diagram is shown.

Analytical Models

The buildings were modeled in three dimensions with OpenSees using an assemblage of non-linear shear springs to represent the walls, diaphragms, and retrofit frames when present. The non-linear springs are placed along a single line in each principal building direction (e.g., Grid Line 3 in Figure 1b or Grid Line C in Figure 2b), and tributary masses are assigned at grid points. The springs were calibrated to physical tests of the representative wall and diaphragm materials. The springs have appropriate non-linear behavior for in-plane shear, high elastic stiffness for in-plane flexural and axial modes, and negligible stiffness for out-of-plane modes. The retrofit frames were modeled as point springs at the second-floor elevation, centered in the open line. The X direction is parallel to the open side and the Y direction is perpendicular.

The archetype buildings were subjected to seismic shaking per the FEMA P-695 protocol. The seismic input for the incremental dynamic analysis (IDA) was 22 bi-directional, far-field records. Each set of records was rotated 90 degrees to expand the set to 44 inputs. The records were scaled with increasing intensities until the models were identified to have collapsed. The peak inputs usually corresponded to walls reaching between 5%-10% drift, while collapse typically resembled an explicitly modeled P-delta collapse, primarily driven by the P-delta effects in the hysteretic wall spring models along with P-delta columns at the open front. Within the IDA results, collapse is seen as an infinite increase in drift without increase in spectral acceleration (Figure 3). As shown in Figure 3, spectral acceleration (Sa) values at each increment of the analysis are taken at a period, T = 0.25 seconds, consistent with the FEMA P-695 protocol.

Unretrofitted Building Behavior

The seismic resistance of the archetype buildings is limited by multiple vulnerabilities. These are the lateral strengths in each direction, the diaphragm strength, and the torsional imbalance of the structure. A useful analogy is that of a chain with several potential weak links, where the resistance to collapse is controlled by the weakest link. The buildings were found to have multiple vulnerabilities with similar capacities. As such, mitigating one vulnerability without improving the rest often resulted in little improvement to building collapse risk. A seismic retrofit of SWOF buildings usually needs to address several or all the vulnerabilities in the weak story to substantially improve safety.

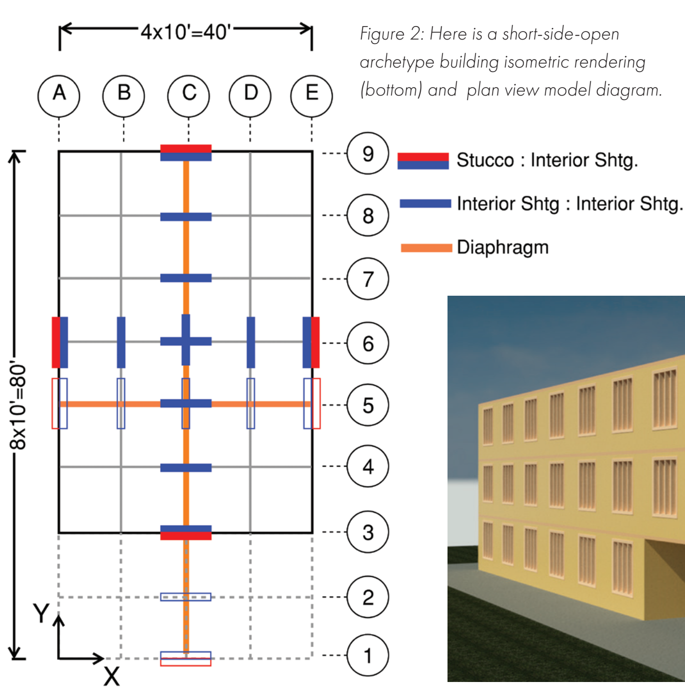


Figure 2: Here is a short-side-open archetype building isometric rendering (bottom) and plan view model diagram.

Table 1. The Primary Study Archetype Building Descriptions

		Material Types	
		WW-SD	SW-WD
Long Side Open	2-Story	LO2-WW-SD	LO2-SW-WD
	3-Story	LO3-WW-SD	LO3-SW-WD
Short Side Open	2-Story	SO2-WW-SD	SO2-SW-WD
	3-Story	SO3-WW-SD	SO3-SW-WD

The most direct way to assess the building's lateral capacity is to examine the first-story strength-to-weight ratio (V/W). Pushover studies were made of the "primary study" archetypes (Figure 5), and key results are:

- Archetype buildings with weak walls have slightly higher controlling strength-to-weight ratios than buildings with strong walls . This is because the buildings with strong walls are heavier.
- The archetypes are brittle, with very limited ductility. Most pushover curves have a steep strength loss after reaching the peak strength.
- The LO archetypes have similar strength-to-weight ratios in the X and Y directions for both the strong and weak wall conditions. The presence of an open side does not lead to appreciable weakness in the open direction. This is because the walls adjacent to the tuck-under parking are solid, without windows, unlike the typical exterior elevations.
- The SO archetypes are weaker parallel to the open front (X direction) for both wall types. The strength-to-weight ratio difference is greater with the strong walls.
- The controlling strength-to-weight ratios of the two-story buildings (not shown in Figure 5) are typically more than 40%, which is significantly greater than their three-story counterparts. This is because the first-story wall layout is the same, but the two-story building carries significantly less mass because there is one fewer floor.

Retrofits: Line, Optimized Line, and FEMA P-807

Three types of retrofits were designed for each archetype: line, optimized line, and FEMA P-807. The line retrofits follow the requirements of the Los Angeles SWOF ordinance and associated city guidelines. The optimized line retrofits also conform to the Los Angeles SWOF ordinance except that the prescribed deflection limits on frames at the open front are ignored, making the frames controlled by strength requirements. The FEMA P-807 retrofits are in accordance with the FEMA P-807 report and are based on output of the Weak Story-Tool assuming default material property values. The Weak-Story Tool is a freely available electronic resource that was developed to help users apply the rules and perform the calculations described in FEMA P-807.

A site in downtown Los Angeles was selected for determining seismic demands, corresponding to a horizontal spectral acceleration of 1.0g for all three retrofits. This seismic demand reflects use of 75% of new building design spectral acceleration, which is permitted by the Los Angeles SWOF ordinance. The ordinance also specifies that acceptable performance for FEMA P-807 retrofits is based on drifts corresponding to onset of strength loss

Table 2. Selected Seismic Retrofit Parameters for 3-Story Archetype Building

Archetype	Building Seismic Weight, W (kips)	Response Modification Coefficient, R	Seismic Response Coefficient C_s (g)	Deflection Amplification Factor, C_d	Retrofit Elements		
					Frame	Plywood X (feet)	Plywood Y (feet)
LO3-WW-SD-L	303.4	3.5	0.376	3	(4) W12x26	NA	NA
LO3-WW-SD-OL	303.4	3.5	0.376	1	(4) W10x22	NA	NA
LO3-WW-SD-P807	303.4	NA	NA	NA	(4) W10x22	20	72

and that the maximum drift limit probability of exceedance is 20% at the specific hazard. These FEMA P-807 design criteria were input into the Weak Story-Tool.

The line retrofits consist of cantilever columns cast into reinforced concrete grade beams along the open front. This system acts as an inverted moment frame, where the grade beam is strong and stiff enough to develop the capacities of the columns in flexure. The optimized line retrofits are similar to the line retrofits except that the removal of the deflection limits results in lighter and more flexible frames. The FEMA P-807 retrofits also use cantilever columns along the open front, as well as new plywood shear walls in both orthogonal directions applied to the inside of existing wood-frame walls. Table 2 provides selected seismic retrofit parameters for the three-story LO archetype building with weak walls and strong diaphragms, where "L", "OL", and "P807" corresponds to line retrofit, optimized line retrofit, and FEMA P-807 retrofit, respectively.

Primary Study Performance Summary

Figure 6 presents results of the IDAs for the "primary study" archetype buildings in terms of probability of collapse (POC) at spectral acceleration of 1.0g. The following trends are noted:

- FEMA P-807 retrofits are effective with results better than 20% POC.
- Line and optimized line retrofits do not consistently improve safety. Three-story LO archetypes show moderate improvements. SO archetypes show limited improvements.
- Line and optimized line retrofits provided similar results for a given archetype.
- Three-story archetypes are more vulnerable than their two-story counterparts.
- SO archetypes are usually more vulnerable than their LO counterparts.

Recommendations for Seismic Retrofit Ordinances

FEMA P-807-1 presents a series of recommendations related to seismic retrofit ordinances that are based on the results of the aforementioned analytical studies. These recommendations include:

Importance of Retrofit: In high-seismic-hazard regions, it is recommended that seismic retrofit ordinances be considered for SWOF buildings as part of a program to identify and address seismically vulnerable buildings. Based on the archetypes studied, high POCs were identified for unretrofitted SWOF buildings. This is consistent with observed collapses and near collapses of SWOF buildings in the 1989 Loma Prieta and 1994 Northridge earthquakes. The POCs can be reduced through seismic retrofits. In moderate and low seismic regions, the need for seismic retrofit ordinances for SWOF buildings is less clear because unretrofitted POCs can be significantly lower.

Type of Retrofit, Part 1: It is recommended that full first-story retrofits be required, where practicable. For the archetypes studied, FEMA P-807 retrofits consistency provided notably better performance than line or optimized line retrofits, with POCs averaging about 10%. Published studies by others suggest that, in general, full-story retrofits in accordance with IEBC Chapter A4 or ASCE/SEI 41 will provide similar or improved performance of the first story relative to the requirements of FEMA P-807 (Buckalew et al., 2015; Burton et al., 2019).

Type of Retrofit, Part 2: Where it is not possible to require a FEMA P-807 or other full-story retrofit, it is recommended that screening occur for open-front wall lines on all exterior walls of the building, including those perpendicular to the evident open-front wall. Where suggested by screening criteria, retrofits should be provided for all applicable exterior walls, including those perpendicular to the evident open front.

Building Prioritization: Where prioritization of SWOF building retrofits is desired, it is recommended that SWOF buildings three stories or more be given higher priority than two-story SWOF buildings. The three-story archetypes generally have higher unretrofitted POCs and greater benefit of retrofit reduction in POC than two-story archetypes.

Local Seismic Hazard: When considering adoption of a seismic retrofit

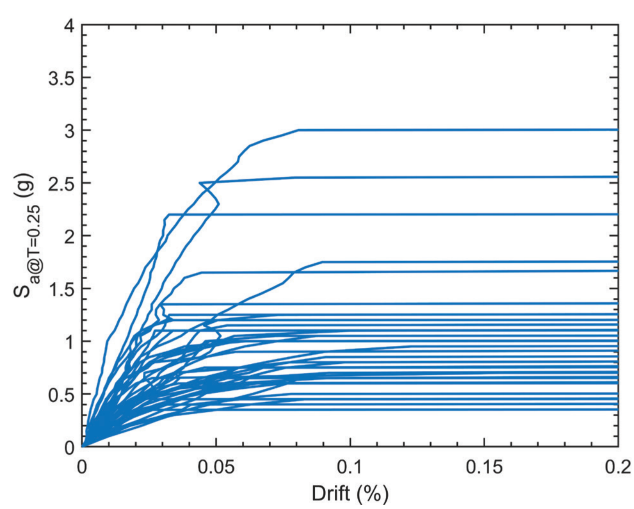


Figure 3. IDA results for a three-story, short-side-open archetype building show that collapse is seen as an infinite increase in drift without increase in spectral acceleration.

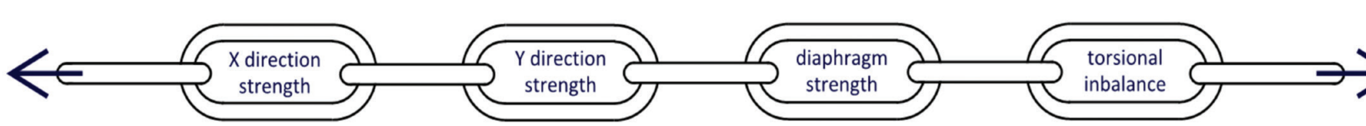


Figure 4. Like links in a chain, a building's lateral capacity is controlled by the weakest of several potential vulnerabilities.

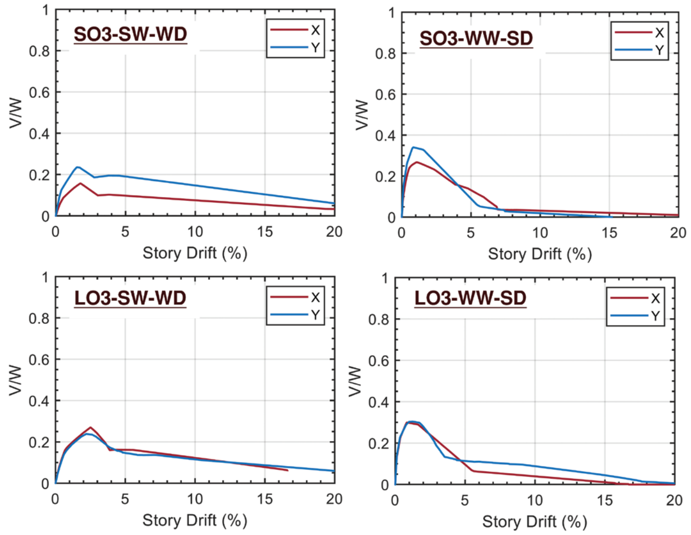


Figure 5. Pushover curves of the unretrofitted conditions for the LO and SO primary study three-story archetypes.

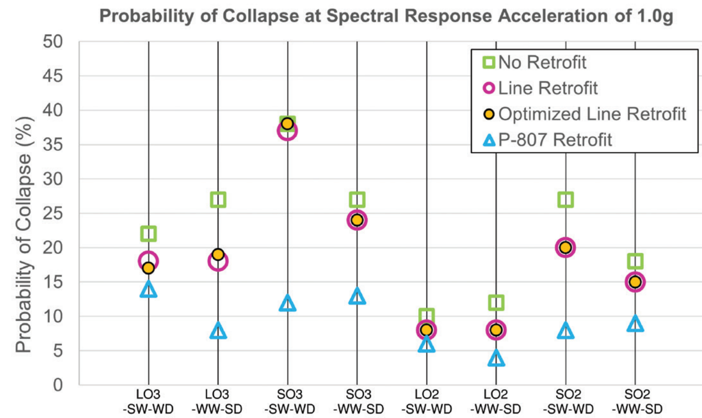


Figure 6. Comparison of probabilities of collapse (%) at spectral acceleration of 1.0g for the primary study archetype buildings.

ordinance, it is recommended that local seismic hazard levels be taken into consideration. Unretrofitted collapse potential of SWOF buildings varies significantly with seismic hazard, thereby varying the need for and benefit of retrofit. For example, the unretrofitted POC is less than 10% at a spectral acceleration of 0.5g for all primary study archetypes and is less than 20% at a spectral acceleration of 0.75g for all but one of the primary study archetypes.

Recommendations for Retrofit Designs

FEMA P-807-1 includes a series of recommendations related to design and construction of SWOF retrofits. The objective of these recommendations is to assist engineering designers and building officials in avoiding common pitfalls and applying proven strategies for strengthening SWOF buildings. The recommendations address the following categories:

New Seismic-Force-Resisting Systems: Common retrofit options include adding new steel moment frames, steel cantilevered columns, wood-structural-panel shear walls, proprietary systems or, in some cases, a combination of these systems. FEMA P-807-1 discusses each of these options and provides recommendations related to more general topics including redundancy, compatibility, and optimal location of new systems.

Protection of Existing Structural Systems: SWOF buildings do not have engineered lateral systems and are constructed using nonductile materials, making it essential that engineers pay special attention to the impact of their designs on the existing building. For example, local demolition of stucco at the second floor is often necessary to install new retrofit elements, such as collectors, that tie the existing structure directly to new vertical seismic-force-resisting elements. But exterior stucco walls in SWOF buildings often are a major contributor to lateral strength. Several examples are provided in FEMA P-807-1 for how to protect the existing lateral and gravity systems.

Foundations: It is recommended that the foundation system of a new seismic-force-resisting system be tied to the existing foundation system to minimize the possible negative effects of sliding, uplift, and overturning. Other topics covered in FEMA P-807-1 include recommended detailing for fixed-base retrofits, weak-axis implications for fixed-base retrofits, and protecting existing foundations.

Besides the categories noted above, FEMA P-807-1 also provides recommendations related to load paths to new retrofit elements; collectors, moment frame beams, and columns; and quality assurance. Two design examples are presented—an optimized line and a FEMA P-807 retrofit. The design examples include conceptual construction details and illustrate implementation of the design recommendations.

Conclusions

SWOF buildings can be found across the U.S., and their structural vulnerabilities make them prone to collapse during earthquakes. Municipalities in California increasingly have enacted seismic retrofit ordinances for SWOF buildings, with the ordinances reflecting regional differences in their approaches. The purpose of FEMA P-807-1 is to advance the understanding of the behavior of SWOF buildings and to encourage improved practice in retrofit designs. The report is also intended to be used by jurisdictions and their consultants to inform decisions regarding ordinance scope and retrofit methods.

FEMA P-807 was shown to generate full-story retrofit designs that provide significant benefits in terms of reducing probabilities of collapse for SWOF buildings. A few suggestions for future FEMA P-807 enhancements are given, but no major shortcomings with the method were identified. Both line and optimized line retrofits were shown to provide mixed benefits in terms of reducing probabilities of collapse. For some archetypes, the reductions were moderate, whereas for other archetypes the reductions were negligible. ▪

Similar to other ATC-managed projects, the project team included a Project Technical Committee and Working Groups who collectively conducted the technical work and authored FEMA P-807-1. In addition, a Project Review Panel provided technical review at key milestones in the development of the report. The work forming the basis for this publication was conducted pursuant to a contract with FEMA. The substance of such work is dedicated to the public. The authors are solely responsible for the accuracy of statements or interpretations contained in this publication. No warranty is offered with regard to the results, findings and recommendations contained herein, either by FEMA, ATC, its directors, members, or employees. These organizations and individuals do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any of the information, products, or processed included in this publication.

Full references are included in the online version of the article at **STRUCTUREmag.org**.

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