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Comparing the Seismic Collapse Performance of Cantilever Column and Moment Frame Retrofits for Woodframe Structures using Los Angeles Soft-Story Basic Ordinance Guidelines

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1 Introduction

The 1994 Northridge Earthquake highlighted the dangers of multi-unit wood-frame structures with soft, weak, and open-front wall lines (SWOF). These buildings, which are constructed with adjacent stories having large differences in strength, can lead to the formation of a single-story mechanism during earthquake shaking. The Los Angeles Ordinance was enacted in 2015 with the aim of reducing the collapse risk for the estimated 13,500 SWOF Buildings in Los Angeles today (SEAOSC 2017).

1.1 Previous research on seismic collapse performance of soft story woodframe buildings using Los Angeles Basic Ordinance (BO) Design Procedures

Burton et al. 2019 evaluated the seismic collapse performance of Los Angeles SWOF structures retrofitted using various procedures permitted under the Ordinance. In addition to the "SWOF-wall-line-only" retrofit methodology prescribed in the LADBS Strucutral Design Guidelines (Basic Ordinance retrofit), the study also considered "full-story" retrofits based on Appendix A4 of the 2012 IEBC (International Existing Building Code), ASCE 41-13 (Seismic Evaluation and Retrofit of Existing Buildings) and FEMA P807 (Seismic Evaluation and Retrofit of Multi-Unit Woodframe Buildings with Weak First Stories). A comparative assessment of the increase in collapse safety provided by all four retrofit methods was performed using dynamic analyses on a set of archetypical structural models developed based on an extensive survey of Los Angeles SWOF buildings. The study found that the number of stories demonstrated the greatest effect on the relative collapse safety benefits derived from each method. The number of SWOF wall lines and the ductility of the upper stores also impacted the extent to which the retrofits improved collapse safety.

1.2 Objectives of current study

Under the Los Angeles Ordinance, several lateral force resisting systems are permissible, with moment frames and cantilever columns being among the most common. As a “SWOF-wall-line-only” retrofit, the Basic Ordinance (BO) procedure only requires the SWOF wall lines to be retrofitted, leaving the selected lateral system as the sole retrofitting element. Given that a large portion of retrofits approved by the LADBS are designed using cantilever columns under the Basic Ordinance, there are concerns within the design community that these designs do not yield the same seismic collapse performance benefit as other systems, such as moment frames. While it is recommended that there be at least 2 cantilever columns on the retrofitted SWOF wall line to achieve proper redundancy (SEAOSC 2017), this is not enforced.

The assessment of seismic collapse performance using the Basic Ordinance retrofit performed in Burton et al. 2019 was based on designs which incorporate the use of ordinary moment frames (OMFs). There is no available quantitative information on the relative improvement in collapse performance when cantilever columns are used as the retrofit elements.

This study conducts a performance-based assessment of the retrofitted SWOF woodframe building archetypes to compare the seismic collapse performance between steel special cantilever columns (SCCs) and OMF retrofits in accordance with Basic Ordinance design procedures. The set of archetypes used in this study are identical to those used in Burton et al. 2019. Nonlinear structural models of the retrofitted (using moment frames and cantilever columns) archetypes are constructed in *OpenSees* (Mazzoni et al. 2013) and their collapse performance is assessed using incremental dynamic analyses (IDAs). The results from this study can be used to inform the selection of an appropriate lateral force system by owners and practicing engineers based on the implications to collapse risk reduction.

2 Retrofit Designs for SWOF Archetype Buildings

A total of thirty-two archetype buildings were developed and used to represent the inventory of SWOF woodframe buildings in the City of Los Angeles (Burton et al. 2019). Among the 12000 buildings surveyed, approximately 17%, 2%, 61%, and 20% had layouts L1, L2, L3, and L4, respectively (Fig. 1). Archetype exterior walls were constructed with a combination of stucco on the outside and either gypsum wall board (GWB) or horizontal wood siding (HWS) on the inside. Each model is developed using a small and large building aspect ratio. Details regarding each archetype can be found in Burton et al. 2019, Table 1.

Moment frame and cantilever column retrofits are designed for each SWOF archetype using the Basic Ordinance procedure, for a total of 64 retrofitted archetypes. All retrofits are developed based on S_{MS} = 2.2g and S_{M1}= 1.2g, which represent median values from a distribution of surveyed sites (Burton et al. 2019). For all designs, Risk Category II, importance factor I=1.0 and soil site class D is assumed. The seismic weight of each building is calculated using 35 psf as the typical floor dead load, 25 psf for roof dead loads, 10psf for the weight of interior partitions and 15psf for the exterior wall weight per square foot of wall (LADBS 2015). The seismic weight and empirical period (ASCE 7-16 Eq. 12.8-7) of each archetype are tabulated in Burton et al. 2019, Table 2. The locations and types of retrofitting elements (cantilever columns and moment frames) used for each archetype is shown in Fig. 2.

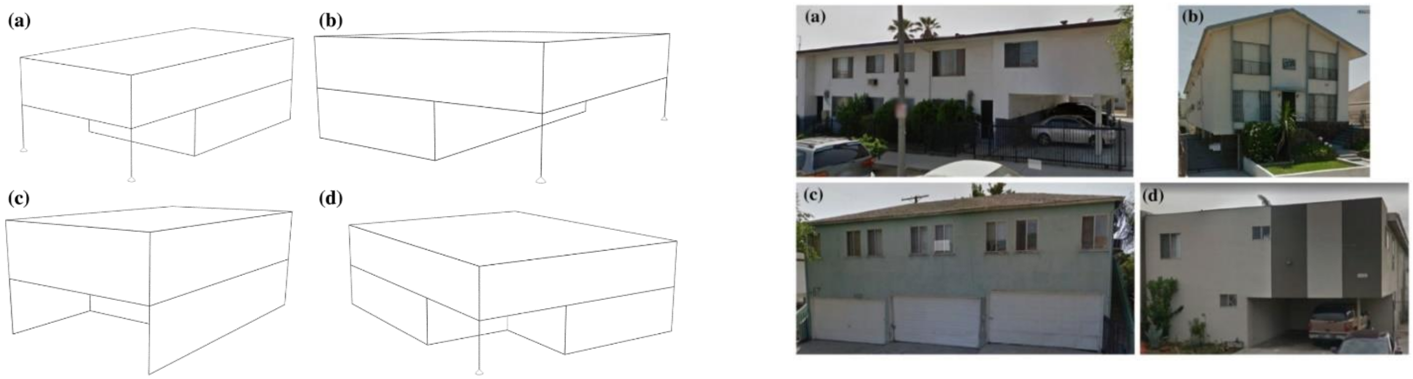


Fig. 1 Schematic isometric views of typical SWOF woodframe building configurations (Burton et al. 2019) identified from survey (left), along with photos of typical SWOF woodframe building configurations (right): **a** L1, **b** L2, **c** L3 and **d** L4

Moment frame retrofits each utilize a 15’-0” one-bay steel OMF in the open wall line. While ordinary moment frames are generally not permitted in seismic design categories D, E, and F (ASCE 7-10 Table 12.2-1), an exception is made in cases where (a) the building height does not exceed 35 feet, (b) the roof and floor dead loads no not exceed 35 psf, and (c) the wall dead loads do not exceed 20 psf. Force demands used to design these elements are computed using a seismic response modification coefficient and deflection amplification factor of R=3.5 and C_D = 3.0, respectively. Since ordinary cantilever columns are only permitted in seismic design categories A and B, steel special cantilever columns (SCCs) were designed using values of R=2.5 and C_D = 2.5 (ASCE 7-16, Table 12.2-1), which are permitted in all categories. Each column is designed in accordance with AISC 341 (Seismic Provisions for Steel Buildings), and a single section is placed at the center of each open wall line. For each archetype, OMF and SCC retrofits are designed to achieve similar demand to capacity ratios (DCR) (Table 1).

Table 1: Summary of retrofit DCRs for building archetypes L1 through L4.

Layout	Number of Stories	Aspect Ratio	**X-Direction SWOF Line**		**Y-direction SWOF Line**	
			SCC DCR	OMF DCR	SCC DCR	OMF DCR
L1	2	small and large	0.93	0.95	0.82	0.86
L1	3	small and large	0.97	0.92	0.96	0.95
L2	2	large	0.94	0.92	0.93	0.95
L2	3	small	0.94	0.92	0.93	0.95
L2	2	small	0.86	0.92	0.93	0.88
L2	3	large	0.94	0.92	0.92	0.90
L3	2	small and large	n/a	n/a	0.99	0.93
L3	3	small and large	n/a	n/a	0.89	0.95
L4	2	small and large	0.93	0.88	0.93	0.88
L4	3	small and large	0.98	0.95	0.98	0.95

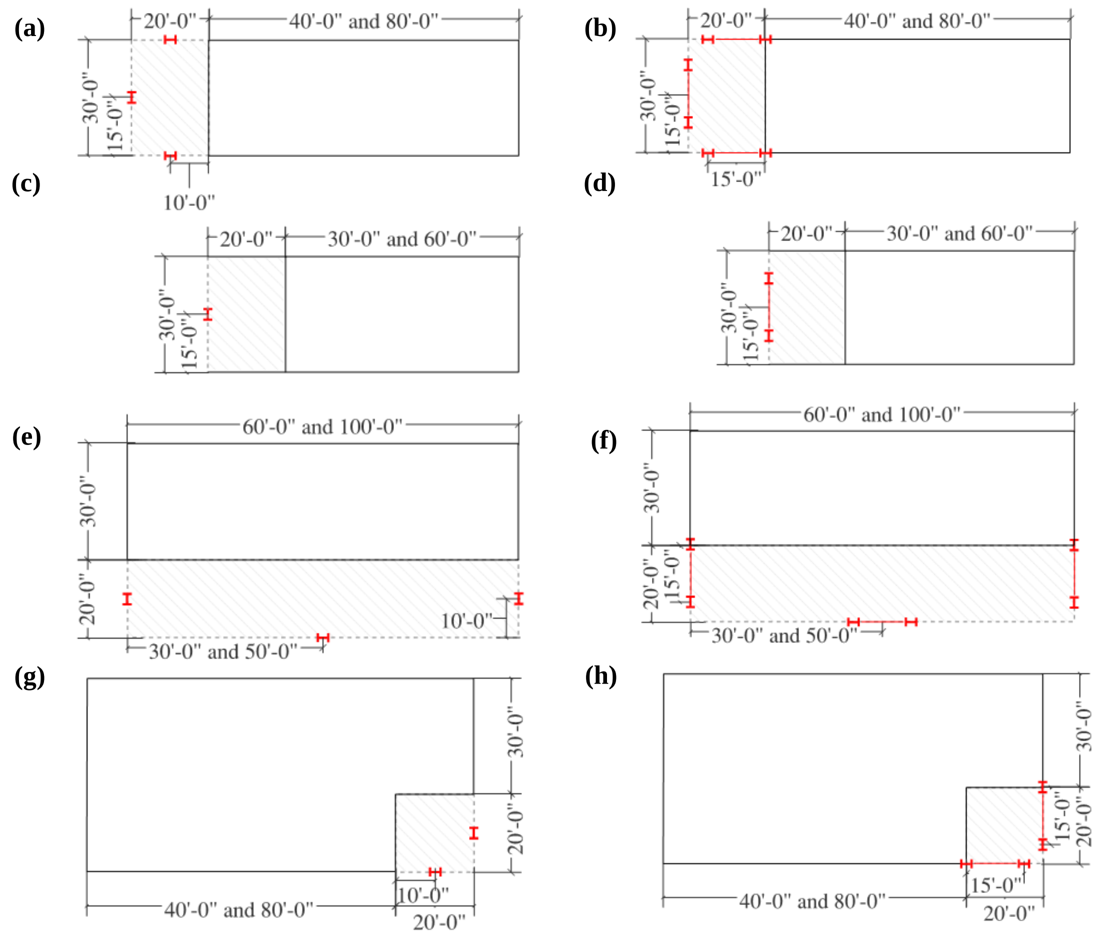
3 Structural Modelling, Nonlinear Static Analysis, and Collapse Performance Assessment

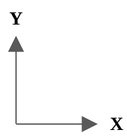
3.1 Structural Modelling

Thirty-two three-dimensional numerical models of both the SCC and OMF retrofitted archetypes are developed in OpenSees. This is done by applying the SCC and OMF retrofits directly to the existing building models developed in Burton et al. 2019. The SCCs and OMF beams and columns are modeled using elastic elements with concentrated plastic hinges, which incorporate the Modified Ibarra-Krawinkler deterioration model (Ibarra et al. 2015). The model parameters for the hinges are obtained from the empirical equations developed by Lignos and Krawinkler (2013). To capture the spatial distribution of masses and P-Δ effects, nine leaning columns (one in each corner, one at mid-length and one at the center of mass) are placed in each model. A rigid diaphragm constraint is applied at all suspended floor levels. Rayleigh damping corresponding to 1% of critical damping in the first and third modes is also applied (Folz and Filiatrault 2001). Wood panels in each archetype are modelled using the parameters outlined in Burton et al. 2019, Section 5.1.

Fig 2. Archetype floor plans (not to scale) showing locations of retrofit elements for each configuration:

a Layout 1, SCC
b Layout 1, OMF
c Layout 2, SCC
d Layout 2, OMF
e Layout 3, SCC
f Layout 3, OMF
g Layout 4, SCC
h Layout 4, OMF





3.2 Nonlinear Structural Analysis

Nonlinear Static (pushover) analyses are performed on the numerical models to investigate the effect of each retrofit on the strength and overall drift capacity of each SWOF building. Using the load pattern from ASCE 7-16, Section 12.8-3 (ASCE 7-16), the pushover analyses are performed on each OMF and SCC retrofitted archetype. The ratio of maximum base shear for each OMF retrofit compared to that of each SCC retrofit is presented in Fig. 3.

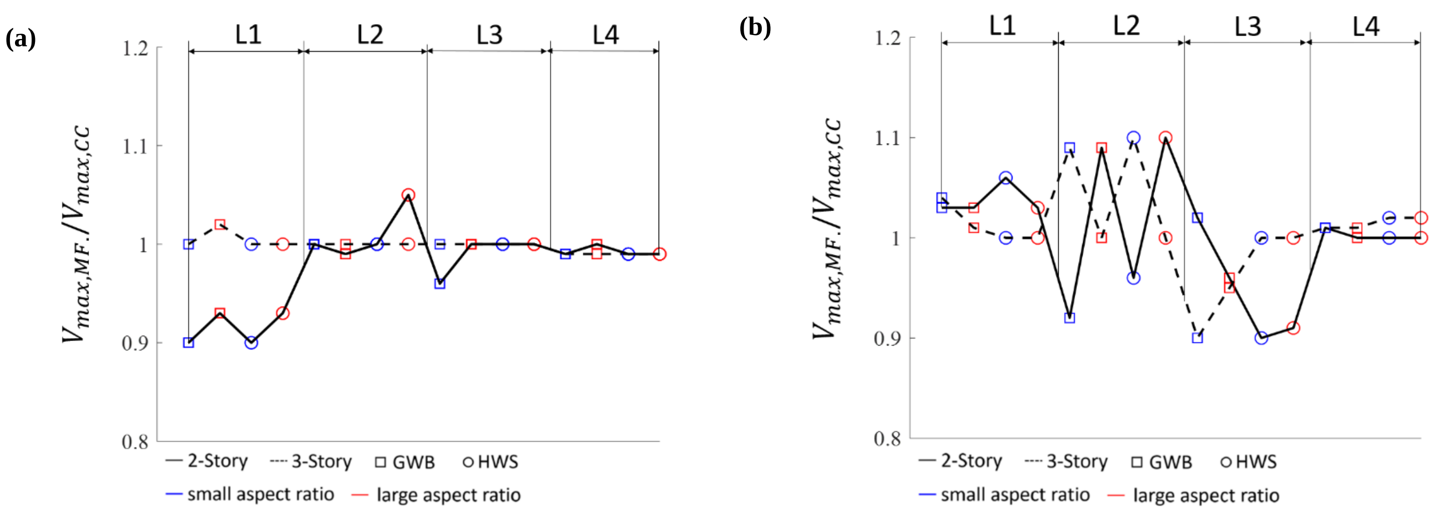


Fig. 3 Ratio of maximum base shear from pushover response between OMF-retrofitted archetypes and SCC-retrofitted archetypes is presented for the X-direction (a) and Y-direction (b).

From Fig. 3, it can be deduced that the maximum difference in pushover strength between the OMF and SCC retrofitted archetypes is approximately 10% in both the X- and Z-directions for the 2-story archetypes. The maximum difference in pushover strength for the 3-story archetypes is 2% and 10% in the X- and Z-direction, respectively. The average ratio of $V_{max,MF}/V_{max,CC}$ for all archetypes is 0.99 in the X-direction and 1.01 in the Y-direction.

3.3 Collapse Performance Assessment

The collapse safety of the SCC and OMF retrofitted building cases is assessed using incremental dynamic analyses in OpenSees. The collapse analysis is performed using the far-field record set of 22 component pairs of the ground motions specified in the FEMA P695 (FEMA 2009) guidelines using bi-directional loading. The ground motions are scaled using a single factor such that the median spectra for the set matches the target intensity level at the period of interest. Two analyses are conducted for each record-pair, generating a total of 44 total collapse intensities. Fig. 4 plots the ratio of median collapse intensity between SCC and OMF-retrofitted SWOF buildings ($\hat{S}a_{col,MF.}/\hat{S}a_{col,CC}$) for the complete set of archetypes.

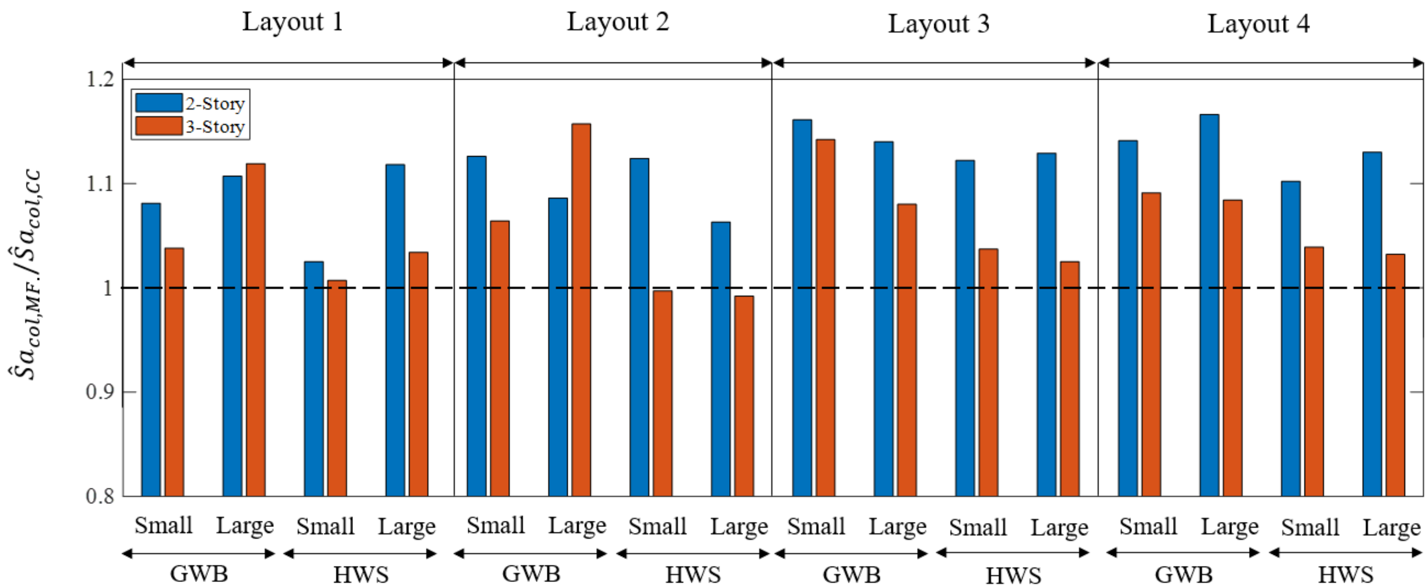


Fig 4. Ratio of median collapse capacity between OMF and SCC-retrofitted SWOF buildings.

From Fig. 4, several conclusions can be drawn. The percentage increase in median collapse capacity by selecting the OMF retrofit is 8.69% higher than the SCC retrofit on average when considering all archetypes. Two-story structures see an average of 11.38% higher collapse capacity when retrofitted using an OMF compared to the SCC. However, this average decreases to 5.84% for the 3-story structures.

4 Conclusion and Future Direction

The Los Angeles Basic Ordinance is a prescriptive retrofit method developed by LADBS in accordance with the Los Angeles Soft Story Ordinance. A comparison of the seismic collapse performance of two permitted lateral systems, namely, ordinary moment frame (OMF) and special cantilevered column (SCC), was conducted using incremental dynamic analyses (IDAs). The pushover strength for each method varied between 2-10% but the average difference was only 1% across all models. The IDA results revealed that the 2- story archetypes derived the greatest benefit from selecting an OMF retrofit over an SCC retrofit, with an 11% average increase in median collapse capacity. The 3-story archetypes achieved average collapse capacity improvements equal to approximately 6%. Of the four archetype configurations, Layouts 3 and 4 experienced the greatest improvements using OMFs on 2-story 3-story structures, respectively. These results demonstrate that on average, OMF retrofits under the Ordinance provide higher collapse capacities than SCC retrofits and that the number of stories and configuration determine the extent to which this is true.

5 Acknowledgements

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