impractical. However, the lower strength retrofit may still be worthwhile since it substantially mitigates the risk of collapse when compared to the as-built weak building.

THREE- AND FOUR-STORY BUILDINGS

Next considered was the effect of having a mix of 3- and 4-story buildings with a 4-story building having twice the weight and mass of a 3-story building. Conclusions based on the analyses follow:

• When all the buildings in a series have similar relative strengths (Vu / W, where Vu = ultimate lateral strength, and W = building weight), variation in building weights have very little effect on collapse risk, independent of gap size.

• When the buildings in the series have differing relative strengths, variation in building weights influence the collapse risk. The pounding rates are biased toward the no-pounding risk of the heavier buildings in the series.

LARGE GAPS

Larger gaps led to higher collapse rates in many pounding cases above, and considered next was the effect of pounding on 3-story buildings having relatively large 15 inch gaps. Analyses were conducted and the conclusions follow:

• Should all building in a series be retrofitted, thus having similar relative strengths (Vu/W), the collapse risk is likely to be similar to the no-pounding situation, independent of gap size. For this case, code mandated gap sizes may be superfluous since they have no effect on collapse risk.

• With large gaps, weak buildings may collapse onto their strong neighbors thereby negating much of the intended benefits provided by retrofitting adjacent buildings.

• It is probably not possible to define a generic safe separation distance that mitigates the hazard posed by weak buildings that may collapse.

HILLSIDE BUILDINGS

The study also addressed pounding of hillside buildings for the type shown in Figure 1d. These are basically the same as those on flat terrain except that the hillside could provide lateral bearing support to the first story, and the floor elevations in adjacent buildings do not coincide. When a building deflects into the hillside, its cross-walls that butt-up against the hillside foundation can have their strength increased via diagonal compression strut action. This leads to asymmetrical lateral strength depending on whether the displacements are toward or away from the hill. The as-built spring used in the analyses was modified to have asymmetrical strength. Conclusions based on the analyses follow:

• Under no-pounding conditions, a building located on a hillside has similar collapse risk to that of the same building located on flat terrain, although the hillside building will have its direction of collapse biased toward the downhill direction.

• Pounding has little effect on the collapse risk of a building within a series of similar buildings having nearly the same relative strength.

• The collapse risk of a retrofitted building may be aggravated more when it is located near the downhill position within a series of weak buildings.
• A weak building may receive little to no beneficial support from a retrofitted building when it is located downhill from the retrofitted building

FINDINGS

Several key factors based on trends observed across the different pounding scenarios are discussed below. Though the study was limited to a group of five adjacent buildings, it is reasonable to assume that trends from the analyses of these situations hold for other cases having different numbers of buildings including corner buildings.

Relative building strengths. This was the most important factor affecting the collapse risk of a building within a series of buildings that pound. The relative strength is expressed as the ratio of building ultimate lateral strength divided by building weight (Vu / W).
• When all the buildings in the series had similar relative strengths, pounding had very little effect on collapse risk, independent of gap size. The risk was virtually the same as the no-pounding condition.
• When the relative strengths differed, collapse risk increased in the stronger buildings and decreased in the weaker ones.

Relative building weights. The pounding collapse risk of a particular building was biased toward the no-pounding risk of the heavier buildings in the series. If the heavier buildings had relatively high no-pounding collapse rates (indicating low strengths), then the pounding rates shifted upward toward the no-pounding rates; and vice versa for heavier buildings with low no-pounding rates. However, the influence may be considered modest in view of the large weight differences for the 3- and 4-story building combinations studied here (4-story had twice the weight and mass of a 3-story).

Building gap size. Larger gaps generally led to increased collapse risk, but there were exceptions. First, when all buildings had similar relative strengths, gap size had virtually no effect. Second, for a building located at the series exterior (end) with the neighboring buildings having greater relative strengths, smaller gaps increased the collapse risk of the end building. In addition, very large gaps may lead to a situation in which a weak building is in a state of collapse prior to pounding, thereby collapsing onto an adjacent strong or retrofitted building, causing it to collapse as well.

POLICY IMPLICATIONS

1. For typical situations, the potential for pounding does not appreciably change the collapse risk of weak buildings. Buildings having high risk under no-pounding conditions are likely to have similar risk under pounding. Hence, collapse prevention

performance evaluations may be conducted as if they are in a no-pounding condition as is the usual case now.

2. The goal should be to retrofit all weak buildings so these all have similar relative strengths (*Vu / W*) thereby minimizing the collapse risk of all buildings in a series. Pounding can help protect weak buildings in certain situations, but the collapse risks of neighboring retrofitted buildings are likely to be increased, perhaps beyond the performance objective intended by building codes or retrofit ordinances, which typically are premised on isolated building performance. Conscientious building owners undergoing retrofit would be unfairly and perhaps unknowingly sacrificing some of their building's retrofit safety margin to marginally protect neighboring weak buildings. This effect may be amplified for retrofitted buildings located toward the downhill side of a series of building.

3. It is probably not practical to expect an enhanced retrofit of one building to buttress weak neighboring buildings that are yet to be upgraded. The collapse risk of the retrofitted building will progressively decrease as more neighboring buildings are retrofitted. Hence, it should be recognized that during the early stages of a retrofit program, when only few buildings are upgraded, pounding diminishes the effectiveness of the upgrades.

4. Relatively weak buildings with large gaps can be very dangerous because these can collapse onto their neighbors with devastating outcomes. Retrofitting these should be given high priority since they can largely negate the retrofits in neighboring buildings. Weak buildings having small gaps also adversely affect their retrofitted neighbors, but to a lesser degree.

CONCLUSION

Pounding of buildings can change the collapse risk when compared to the risk of the same buildings in a no-pounding situation (i.e. having no adjacent buildings). The risk of a particular building may increase, decrease, or remain about the same, depending on the neighboring buildings' properties. There is a myriad of possible building pounding scenarios, but it is believed this study has captured most of the important aspects governing collapse of midblock buildings. Specific conclusions are presented above in each section addressing particular pounding aspects. These can help inform design office practice and public policy.

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herein are solely those of the authors, and do not represent an official opinion of the EBC or SEAONC in general.

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Example Case Studies of Soft-Story Retrofits Using the San Francisco Ordinance

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ABSTRACT

San Francisco's mandatory soft-story building retrofit program names three alternative design criteria for the retrofits: FEMA P-807, ASCE 41, and IEBC Appendix Chapter A4. This paper presents example case studies on the retrofit of two buildings using the three alternative design criteria according to the San Francisco ordinance (total six example retrofits). The objectives are to provide design professionals with insights about:

- how the P-807 performance-based guideline differs from more traditional methods such as ASCE 41 and IEBC A4,
- the different retrofit outcomes that result from using the alternative criteria, and
- which criteria can best serve client needs.

INTRODUCTION

San Francisco's Ordinance 66-13 mandates retrofit of the "soft-story" of certain multi-unit buildings. The ordinance performance objectives can be met by conformance to the requirements of either: FEMA P-807 (2012) *Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories*, ASCE 41-13 (2013) *Seismic Evaluation and Retrofit of Existing Buildings*, or IEBC *International Existing Buildings Code* Appendix Chapter A4-12 (ICC 2012b). Unfortunately, it is not practical to evaluate the merits of each approach within the scope of a typical retrofit design project. Hence, the engineer finds himself advising his client on which criteria best satisfies the building owner's needs without knowing *a priori* how the outcomes could differ.

This paper presents case studies of two building retrofits using three alternative design criteria in the San Francisco ordinance (total six example retrofits). They are typical San Francisco buildings constructed prior to the Second World War (pre-1940). Building 1 is a three-story *midblock* building, and Building 2 is a four-story *corner* building similar to those that collapsed in the Marina District of San Francisco during the 1989 Loma Prieta Earthquake. This paper is derived from a 2013 Special Projects Initiative funded by the Structural Engineers Association of Northern California (SEAONC), but opinions herein are those of the authors alone.

ALTERNATIVE CRITERIA

The following tables summarize key aspects of the three criteria as used in this study consistent with Ordinance 66-13. All comparisons below are based on the linear static methods used to retrofit the example buildings.

Table 1. Guideline overview

ASCE 41-13	ASCE 41-13 is a comprehensive standard used to evaluate and retrofit existing structures. It is intended for all building sizes and types.
IEBC A4-12	IEBC A4-12 is a prescriptive retrofit code created specifically for wood-frame buildings with a soft, weak, or open front. Vertical elements not conforming to current code are presumed to have zero capacity.
FEMA P-807	FEMA P-807 is a new retrofit guideline created specifically for wood-frame buildings with weak first stories. It utilizes a performance-based engineering approach, and uses regression analyses of numerous nonlinear earthquake simulations to predict soft-story drift as onset of strength loss.

Table 2. Performance objectives

ASCE 41-13	Life safety in the BSE-1E event (20%/50yr earthquake). The short period spectral acceleration was taken as S_a = 0.85g for this study (Pekelnicky and Poland 2012). Evaluation and design performed for the first floor only.
IEBC A4-12	Prescriptive retrofit based on 75% of current code forces for new construction. This results with S_a = 0.75g for this study.
FEMA P-807	30% probability of exceedance at $0.5S_{MS}$. Probability of exceedance refers to the chance the building story drift will exceed a value defining near-collapse. This results with S_a = 0.75g for this study.

Table 3. Material strengths

ASCE 41-13	Material tables provided for lateral system elements, diaphragms, foundations, and connections. Dissimilar materials were combined using FEMA P-807 rules.
IEBC A4-12	Material strengths taken as those for new construction. Per Section 403.9.1, gypsum and plaster shear walls are presumed to have zero capacity.
FEMA P-807	Material tables provided for wall elements. P-807 has no material tables for diaphragms, connections, or foundations. However, the Ordinance provides guidance for diaphragms.

Table 4. Strength checks

ASCE 41-13 (1st story)	Local (component) strength check [7.5.2.2.1]
	$mkQ_{CE} > Q_{UD}$, where
	m = component ductility factor = ~3 to 4 for plywood, gypsum, wood sheathing [Table 12-3];
	m = 6 for steel moment frame flexure [Table 9-5];
	k = knowledge factor = 1.0;
	Q_{CE} = expected component strength (deformation controlled);
	Q_{UD} = component demand (deformation controlled); and
	Check that DCR = $Q_{UD}/Q_{CE} < 3.0$ to allow for use of linear analysis procedures [7.3.1.1]

IEBC A4-12	Local (component) strength check using response modification factor applied to component forces, R = 6.5 for wood panel shear walls [Table 12.2.1]: $\varphi V_n > V_u$; and $\varphi M_n > M_u$ where, φV_n and φM_n = component capacities, and V_u and M_u = component demand per ASCE 7-10 at 75% code.
FEMA P-807	Global spectral capacity check: [FEMA P-807, 5-6; AB-107, B1.2.6.1] $S_c > S_a$, where S_c is the short period spectral capacity, and S_a is the spectral demand taken as $0.5S_{MS}$ per ASCE 7-10. This check is deemed satisfied with a 30% probability of exceedance on drift criteria associated with onset of strength loss.

Table 5. Drift checks

ASCE 41-13	No explicit limit on drift for linear static analysis
IEBC A4-12	2.5% maximum inelastic story drift [A403.4]
FEMA P-807	No explicit drift check (drift limits from 1.25% to 4% implicit to methodology). This implicit check is deemed satisfied with a 30% probability of exceedance on drift criteria (AB-107, B1.2.6.1).

Key points from the above tables follow.
• The performance objectives (Table 2) are set by Ordinance 66-13. It is important to recognize that each design criteria has different objectives resulting in different retrofits that are not equivalent in terms of seismic safety. The engineer should confer with their clients to select a criteria that best suits the client's needs.
• ASCE 41-13 and P-807 deal with expected ultimate strength using *all* components, and the strengths provided differ in the criteria. IEBC A4-12 deals with code values for new construction that are not necessarily ultimate strength; it does not permit the use of gypsum or plaster products to resist lateral loads and does not recognize nonconforming code materials at the first floor (Table 3).
• ASCE 41-13 and IEBC A4-12 perform strength checks on a *local* component-by-component basis whereas P-807 checks the *global* spectral demand and capacity in a probabilistic sense (Table 4).
• For this study, ASCE 41-13 retrofits were "over-designed" to keep demand-to-capacity ratios (DCR) below 3.0 in order to use linear analysis methods (Table 4). This would reflect expected practice in a design office based on project budgetary constraints.
• It turns out that IEBC A4-12 retrofits were controlled by drift checks, meaning components were proportioned to provide required stiffness, and this added capacity beyond that necessary to meet the required minimum strength (Table 5). Note that the computed drift used in the check is conservative given that existing materials are not considered.

ASSUMPTIONS

The following features were inherent to the study.
• The buildings were assumed to be located in San Francisco on stiff soil (site class D) with an ASCE 7-10 MCE spectral acceleration of S_{MS} = 1.5g.

• The second floor diaphragm was assumed to be rigid across all of the guidelines/standards. This assumption is implicit to P-807.
• IEBC A4-12 and ASCE 41-13 retrofit designs did not take advantage of the Ordinance allowance that the retrofitted story strength need not exceed 1.3 times the expected strength of the story immediately above in a three or more story building. This would have only a slight effect for the buildings studied here (discussed below).
• The additional loads due to accidental (i.e., artificial 5% mass offsets) and inherent (actual) torsion were considered in the ASCE 41-13 and IEBC A4-12 retrofits [ASCE 41-13, Section 7.2.3.2.1; ASCE 7-10, Section 12.8.4.2]. The increase in demand on certain components due to combined torsion (inherent and accidental) was on the order of 5 to 7%. Only inherent torsion was considered in P-807.
• P-delta effects were considered in the ASCE 41-13 and IEBC A4-12 retrofits. To avoid analysis iterations (since P-delta lateral forces depend on story drifts), a simplified factor was used based on the IEBC A4-12 drift limit of 2.5%. The global base shear demand was increased by $0.025W$ to account for P-delta effects. This assumes the first story reaches 2.5% drift and imposes an additional lateral load equal to 0.025 times the gravity load. This is conservative when the final story drifts are less than 2.5%.
• Only the vertical elements associated with the first story retrofits (shearwalls and moment frames) using the different criteria were designed (due to time and budget constraints). Other parts of the load path were not checked. Hence, it was assumed that the diaphragm, connections, collectors, and foundation elements could develop the required forces of the first floor vertical elements.
• Retrofits were designed assuming wood shear walls (nailing of 10d@4" O.C.) and steel special moment frames pinned at the base. Note that the decision to use special moment frames versus say intermediate, ordinary moment frames, or cantilever columns can dramatically impact the ASCE 41-13 and IEBC A4-12 retrofits by reducing the 'R' and 'm' factors. The Ordinance also allows use of inverted moment frames with concrete grade beams.
• The retrofit elements were located to maintain existing wall layout and openings. Hence, it was assumed that existing conditions would not restrict placement or sizing of new elements. In actual buildings, aspects such as ceiling space, wall cavity size, space above garage doors, and location of utility meters could significantly affect the retrofit design.
• The existing wall elements were assumed to be of good quality construction and not having environmental deterioration (e.g. decay or fastener corrosion). No ASCE 41-13 reduction factors were applied to material strengths specified in the different guidelines (i.e., knowledge factor = 1.0).

MIDBLOCK BUILDING

Figure 1 shows the building elevation. Figures 2, 3 and 4 show the retrofits meeting P-807, IEBC A4-12 and ASCE 41-13 guidelines, respectively. It should be recognized that there are a myriad of retrofits satisfying each criteria, and some consistency in retrofit layouts was used here to make comparisons across criteria appropriate. Key points follow.

• Retrofit using P-807 was less extensive than that from IEBC A4-12 and ASCE 41-13. Note that P-807 did not require any retrofit in the building longitudinal direction.
• The P-807 retrofit had a global DCR of 0.92 in the transverse (Y) direction. This DCR is the component ultimate strength ratio and *not* explicitly part of the design. The DCR would vary depending on the probability of exceedance used in the design as this affects the amount of upgrades required.
• The IEBC A4-12 retrofit had to rely on the new elements to resist all the lateral force since all existing materials were either gypsum or plaster or nonconforming materials. Most of the new walls in the transverse (Y) direction were narrow and the 2.5% drift limit controlled the design of the retrofit. The design (not ultimate) strength DCRs of the retrofitted structure was about 0.80 in the transverse direction implying about 25% additional strength was added to meet drift requirements.
• The ASCE 41-13 retrofit was affected by limiting the DCR so linear analysis procedures (LSP) could be used. The ultimate strength DCR (including m factors) were around 0.80 implying about 25% extra ultimate strength was added to the retrofit to justify the use of LSP.
• IEBC A4-12 and ASCE 41-13 retrofits had about 25% additional strength as a result of drift and LSP requirements, respectively. However, even without these additional requirements, the P-807 retrofit would still be less extensive. ASCE 41-13 and IEBC A4-12 would each require about 40% of the walls in the transverse direction to be upgraded as opposed to P-807, which would require only about 24%.

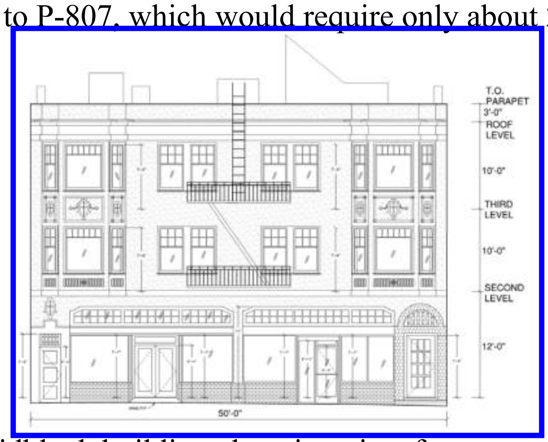

Figure 1. Midblock building elevation view from street (Building 1).

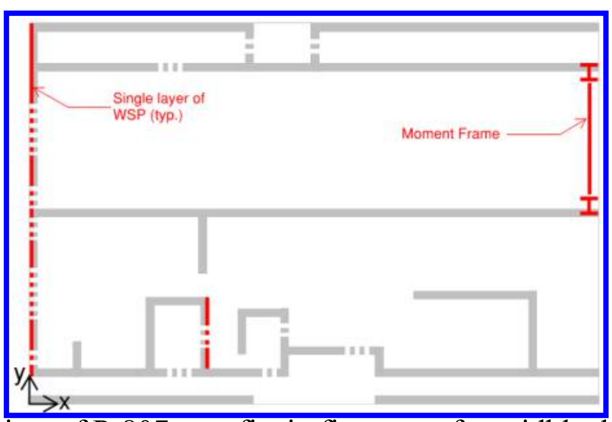

Figure 2. Plan view of P-807 retrofits in first story for midblock building. Street side is on left (new elements in red (or black, if grayscale) and existing walls in gray).

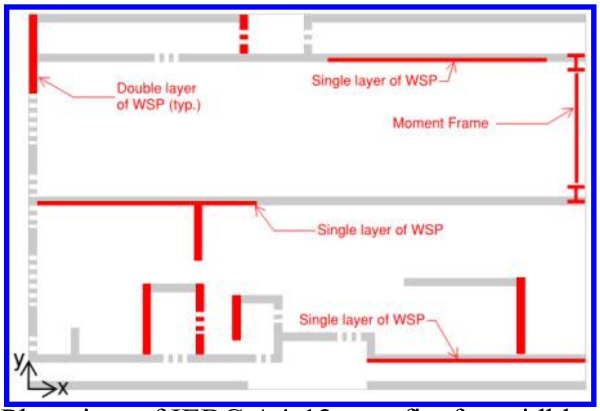

Figure 3. Plan view of IEBC A4-12 retrofits for midblock building.

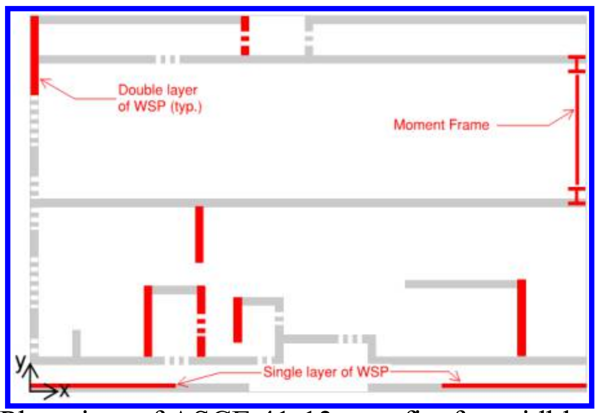

Figure 4. Plan view of ASCE 41-13 retrofits for midblock building.

Figure 5 shows the push-over curves for the transverse (Y) direction based on the P-807 material curves. The curves were created in an Excel spreadsheet as the sum of the individual component backbone curves (P-807 software can do this internally for the P-807 retrofit). Note that the P-delta effect is not reflected in the graphs (including the P-delta would progressively reduce the curves with increasing drift ratio). Key points follow.

• IEBC A4-12 and ASCE 41-13 retrofits have more than twice the lateral strength of the P-807 retrofit. This is due to several reasons. First, P-807 retrofit is based on limiting expected drifts and *not* (directly) on component or story strength. Second, ASCE 41-13 and IEBC A4-12 were controlled by aspects other than strength as mentioned above. Third, IEBC A4-12 does not account for existing materials (gypsum or plaster or nonconforming) whereas they are included in the push-over curve calculations. Fourth, ASCE 41-13 was designed to a larger spectral acceleration as required by the performance objective (Table 2).

• The dashed line shows 1.3 times the strength of the second story, and represents the "need-not-exceed" cap that is in the Ordinance. The IEBC A4-12 and ASCE 41-13 retrofits have peak strengths slightly exceeding the peak "need-not-exceed" value thus indicating the retrofits could be economized slightly.

• The existing building is clearly identified as being inadequate in the transverse direction by having very low strength. As a result of using the P-807 material data,