Submitted to the Journal of Earthquake Engineering

Implementation of Plan Irregularity Rapid Visual Screening Tool for Wood-Frame, Single-Family Dwellings

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ABSTRACT:

A plan irregularity rapid visual screening method for seismic performance assessment of wood-frame, single-family dwellings is presented. Results from 124 samples were compared with (i) building-specific, non-linear time-history analysis, and (ii) FEMA 154 and ASCE 31 Tier 1. Verification using two houses damaged in the 1994 Northridge Earthquake is presented. The method includes effects of shape, torsional forces from eccentricity, and is based on conservative values of shear wall capacities and a non-linear time-history analysis. The method is relatively more conservative than ASCE 31 Tier 1 and FEMA 154, and provides conservative but reasonable predictions of actual earthquake damage.

Short Title: Case Study for Plan Irregularity Screening Tool

CE Database subject headings: seismic analysis; wood structures; rapid visual screening

1. Introduction

Economic losses due to major earthquakes have been extensive, including to residential buildings or single family dwellings (SFD). For example, the dollar loss to SFD from the 1994 Northridge Earthquake was at least $20 billion [Kircher et al. 1997]. In the City of Los Angeles, a total of 40,010 (of the existing 442,994) SFD were damaged [Schierle 2000]. Damage was observed on different elements such as garage doors, chimneys, cripple walls, partition walls, and shear walls. The total repair cost for SFD was estimated to be more than $414 million, and for those with shear walls damaged, the estimated average shear wall repair cost was as much as $ 11,819 per building. Damage to shear walls demonstrates the load path is reasonably defined but shear capacity to resist ground motion forces is lacking in many of these SFD. Many existing wood-frame SFD were non-engineered in their design. Some were code-prescribed but the level of damage from a major earthquake is unknown. For engineered structures, they are designed to provide life safety, and not damage control. The inherent torsion due to eccentricity is also not typically included in the design practice of SFD due to the non-engineer designer. The adequacy of shear walls in existing wood-frame SFD to resist both direct shear and torsional shear (due to eccentricity) from future earthquakes thus should be evaluated.

This paper presents the method and results of the third and final phase of a project whose objective was to develop a rapid visual screening (RVS) tool for evaluating seismic performance of wood-frame SFD. The first phase [Lucksiri et al., 2012a] introduced an approach to classify wood-frame SFD based on shape parameters including the number of floors, plan shape, base area, percent cutoff area, and percent openings, as shown in Figure 1 for L-shape buildings. That study showed that, when neglecting contributions from interior walls, seismic performance of wood-frame SFD of the same size (base area), shape, and percent openings, is strongly dependent on the overall plan proportions (shape ratio) and amount of reduction in area from the base rectangle (percent cutoff). The second phase [Lucksiri et al., 2012b] developed a plan irregularity rapid visual screening (piRVS) method which takes into consideration the shape of the floor plan, number of stories, base-rectangular area, percent cutoff, and openings from doors/windows and garage doors. It was found that plan shape and plan irregularity were important features especially in houses located in high 1 (S_a= 1.00g) and high 2 (S_a= 1.50g) seismicity regions. For low and moderate seismicity, the performance ranges from satisfying the collapse prevention limit to the immediate occupancy limit. This third phase is on piRVS implementation with three study objectives as follows:

i. To determine uncertainties inherent in piRVS scores that result from configuration differences between piRVS index models and an actual house population.
ii. To compare prediction results from piRVS [Lucksiri et al., 2012b] to FEMA 154 [FEMA 2002a] and ASCE 31 Tier 1 [ASCE, 2003].
iii. To compare the prediction results from piRVS, Tier 1 of ASCE 31, and FEMA 154 to examples of 1994 Northridge Earthquake house damage.

2. Evaluation methods

Fast and qualitative methods for building seismic hazard evaluation were mainly developed to preliminary identify the inherent sources of seismic deficiencies in buildings and to obtain a recommendation of whether a more detailed analysis should be performed. The assessment generally involves building inspection and/or simple calculations. This study focuses on three methods that can be applied to SFD building types including:

2.1 FEMA 154 (Rapid Visual Screening of Buildings for Potential Seismic Hazards)

FEMA 154 [FEMA, 2002a] was developed by the Federal Emergency Management Agency to identify, inventory, and rank buildings that are potentially seismically hazardous. FEMA 154 methodology is based on a “sidewalk survey” of a building. A simple data collection form is provided for each seismicity area which was classified as low-, moderate-, and high-seismicity based on the expected response acceleration. The process starts by the determination of a basic structural hazard (BSH) score based on the primary lateral load resisting system. Score modifiers (SMs) are selected to incorporate effects of height, plan irregularity, vertical irregularity, year built, and soil types. For plan irregularity, just one SM was provided for each structural type and each seismicity regardless of level of irregularity severity (e.g. size of reentrant corners). A final score (S) is obtained by summation of the BSH and all applicable SMs. FEMA 154 performance scores were based on spectral displacements of representative models and predictions from nonlinear static analysis. The properties of representative models, i.e. building capacity curves and fragility curves, were obtained from HAZUS 99 [NIBS, 1999]. The suggested cutoff score (S= 2) is related to 1% probability of collapse. Buildings with final scores of 2 or less are suggested to have more detailed evaluation.

2.2 Tier 1 of ASCE 31-03 (Seismic Evaluation of Existing Buildings)

ASCE 31 [ASCE, 2003] is a three-tiered evaluation process. Tier 1 summarizes potential deficiencies through the provided checklists and simple calculations. The checklist is a compliant/non-compliant evaluation system, with no performance scoring. For light wood frames, a simple procedure for demand-capacity checking of shear walls is provided. With an appropriate ductility related m-factor, shear stresses are checked against the suggested shear wall capacity. Tier 2 and 3 provide more detailed evaluation guidelines focusing on the potential deficiencies as indentified in Tier 1. ASCE 31 evaluates buildings at immediate occupancy (IO) and life safety (LS) performance limits.

2.3 piRVS (Plan Irregularity Rapid Visual Screening)

piRVS [Lucksiri et al., 2012b] was developed for seismic performance evaluation of wood-frame SFD, with plan irregularity. The tool examines the adequacy of the structure's exterior shear walls to resist lateral forces resulting from ground motions, including torsional forces induced from plan irregularity but does not cover other sources of seismic deficiencies such as cripple walls, anchor bolts, chimneys, and vertical irregularities. It uses the concept of a sidewalk survey with a similar scoring procedure to FEMA 154. Selection of the BSH score is based on the number of floors, plan shape, base area, shape ratio, and percent cutoff area. Selection of the SMs is based on percent openings along short and long directions, and garage doors. A final score (S) is obtained by summation of the BSH score and all applicable SMs. Performance scores were based on spectral displacements from a set of representative models and predictions using nonlinear time-history analysis. piRVS supports evaluation at immediate occupancy (IO), life safety (LS), and collapse prevention (CP) performance targets with the suggested cutoff scores of 3.5, 2.5, and 1.5, respectively.

3. Methodology

3.1 Study Samples

There are two sets of samples studied. The first set includes 124 wood-frame SFD in Oregon; 95 one-story houses from Corvallis (Table 1) and 29 two-story from Salem and Portland (Table 2). Observation was performed through image data of Google Earth, with the limitation that not all wall sides can be observed. It was assumed that the percent openings on the unobserved sides are equal to the weighted average (by length) of the percent openings of the observed walls along the same direction. The second set of samples was selected from 530 buildings damaged in the 1994 Northridge Earthquake

[ATC, 2000]. Applicable buildings were W1 type (light-frame) with floor area less than 464 m^2 (5,000 ft^2), and having damage on the exterior walls. Eleven houses qualified but only two were usable. Exclusion of the other nine buildings was due to one of the following: having complex plan shapes, ground motions were not recorded, unable to locate/observe on Google Earth, no reference photo, and roofing material unclear. Image from Google Earth permitted a simulated sidewalk-survey. An assumption was made for percent openings on the unobservable side, as discussed.

3.2 Modeling assumption

Simplified models were used to represent these structures. The following assumptions were used in this study. Building structural system was assumed to be made of vertical shear walls, and horizontal diaphragm elements including roof, ceiling, and floor. Exterior shear walls are structural-sheathed on one side and gypsum wallboard-sheathed on the other. Lateral loads were resisted by exterior shear walls only. Story height is at 2.44 m (8 ft). A dead load of 527 N/m^2 (11 psf) was assumed, based on ASCE 7-05 [ASCE, 2005], for shear walls and a uniformly distributed load per floor area of 718 N/m^2 (15 psf) for partition walls. Seismic masses for roof, ceiling, and floor, were 478 N/m^2 (10 psf), 191 N/m^2 (4 psf), and 383 N/m^2 (8 psf), respectively. Sample buildings were assumed to have no vertical irregularity and built before 1976, in other words, before the initial adoption of seismic codes such as the 1976 UBC [ICBO, 1976] for engineered structures, and also before the first editions of the current International Residential Code (IRC) [ICC, 2012] for prescribed designs of houses.

3.3 Level of Seismicity and Soil Types

Level of seismicity was classified as low, moderate, or high based on design spectral acceleration (Table 3) at short period (0.2 sec) and 1.0 sec. In piRVS, the high seismicity was separated into 2 ranges to increase the resolution. As defined in ASCE 31 [ASCE, 2003], the design spectral acceleration is a function of the expected MCE and the site adjustment factors. The site adjustment factor covers five different site classes from class A (hard rock) to class E (soft clay). The seismicity level for ASCE 31 and piRVS thus depends on site class. Differently, FEMA 154 defines seismicity based on site class "B" which refers to rock with an average shear wave velocity between 762 to 1,524 m/s (2,500 to 5000 ft/sec).

In this study, comparisons between piRVS and ASCE 31 Tier 1 were made at the upper limits of each seismicity, i.e. at 0.167g, 0.500g, 1.000g, and 1.500g. For comparisons between piRVS and FEMA 154, site class B was assumed. Since the site adjustment factor for site class B equals 1.0, the level of seismicity for a building comparison for FEMA 154 and piRVS is always the same.

3.4 Evaluation Methods and Assumptions

FEMA 154

Study samples were considered to be the W1 building type, defined as light wood-frame residential and commercial buildings smaller than or equal to 464 m^2 (5,000 ft^2). Three BSH scores were obtained, one for each seismicity. SMs for plan irregularity were applied for L-, T, U, and Z-shape samples due to reentrant corners. Since all dwellings were assumed to be built before 1976, the post-benchmark SMs were not applied. Samples with final scores of 2 or greater were tagged as "Pass", otherwise, as "Fail".

FEMA 154's cutoff level (at S= 2.0) is related to 1% probability of collapse. ASCE 31 and piRVS use different performance limits including immediate occupancy (1% drift for piRVS, IO), life safety (2% drift for piRVS, LS), and collapse prevention (3% drift for piRVS, CP). Additional back-calculation was performed for the FEMA 154 S = 2 cutoff score to obtain percent lateral drifts that correspond to such a level of probability of collapse. Based on the BSH definition [FEMA, 2002b] and default values for building capacity curves and fragility curves [NIBS, 1999], percent lateral drifts at the S = 2 cutoff score for high-, moderate- and low-seismicity are 4.8%, 4.8%, and 3.8%, respectively. The percent lateral drifts for high and moderate seismicity regions are equal because they share the same values of drift ratio [NIBS, 1999] that define a damage state. Although the drift limits are different, evaluation results were compared between FEMA 154 and the piRVS at the CP limit.

ASCE 31 Tier 1

The shear wall shear stress check in ASCE 31 Tier 1 is based on a performance-based methodology using pseudo lateral forces. This means that a pseudo lateral force was applied to a structure to obtain an "actual" displacement during a design earthquake. The pseudo lateral force was calculated using Equation (1).

$$V = C\,S_a\,W \qquad (1)$$

where C= modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response; S_a= spectral acceleration (g's); and W= effective seismic weight. Modification factor is based on the number of stories. For wood frames, C equals 1.3 and 1.1 for one-story and two-story buildings, respectively.

The pseudo lateral force (Eq. 1) is distributed vertically to determine story shear at each floor level using the prescribed methods in Section 3.5.2.2 [ASCE, 2003]. The story shear was then used to calculate average the shear stress in shear walls (Eq. 2). Since the analysis is linear, the (pseudo lateral) force to reach the expected displacement is unrealistically high. The ductility-related m-factor was used to reduce the pseudo lateral force to a more realistic level.

$$v_{avg} = (V_j/L_w)/m \qquad (2)$$

where V_j= story shear at level j (in accordance with Section 3.5.2.2 of ASCE 31); m = component modification factor: m = 4.0 for life safety limit, m = 2.0 for immediate occupancy limit; L_w= summation of shear wall length in the direction of loading.

For evaluations at both life safety and immediate occupancy limits, the shear stresses in shear walls calculated from equation (2) were checked against the 14.6 kN/m (1,000 plf) capacity limits for structural panel sheathing shear walls, as specified in Section 4.4.2.7.1 of ASCE 31. Sample models with maximum shear stress lower than this limit were tagged as "Pass", otherwise, tagged as "Fail".

piRVS

Modifications were made in the piRVS scoring tables [Lucksiri et al., 2012b] to reduce performance score variations due to inspectors. The modification rules were selected in such a way to minimize the overall score differences (of all study models) between the piRVS and building-specific case analyses using SAPWood [Pei and van de Lindt, 2009], a nonlinear time history analysis software developed specifically for light frame wood structures. These rules could be adjusted and would affect the level of conservatism of piRVS relative to FEMA 154 and ASCE 31 Tier 1. For BSH, more specific ranges were specified for base area, shape ratio, and percent cutoff area. For example, in the unmodified tables, users would have to select the percent cutoff areas for single-story L-shape houses to be either 10% or 30%. The new tables modified these numbers to ≤20%

and > 20%, respectively. An example of the updated scoring table for one-story, L, T, Z shape buildings at high 1 seismicity is as shown in Figure 2. In addition, a flowchart was developed to assist selection of SMs for percent openings (Figure 3).

The observed configuration details were used directly as piRVS input except for percent openings in which two average values, one along each major direction, were used. For garage doors, the SMs are included only when a garage is parallel to the short direction of a building. This is because the development of piRVS assumed a garage door to be on the most critical side, a wall side where maximum drift tends to occur most often (see, for example, Filiatrault et al, 2010, van de Lindt et al, 2010), and which is usually one of the walls on the short direction. The cutoff scores for piRVS for IO, LS, and CP limits are 3.5, 2.5 and 1.5, respectively.

Building-Specific Case Analysis using SAPWood

Building-specific case analysis follows the same procedures as in the piRVS development [Lucksiri et al., 2012b]. In general, the analysis is based on nonlinear time-history analysis using the SAPWood software. The evolutionary parameter hysteresis model (EPHM) [Pei et al., 2006] was used to represent the load-displacement relationship of structural panel-sheathed shear walls. Values of the EPHM parameters are from a SAPWood database [Pei 2007] and linear interpolation was used to obtain parameters for different wall lengths. The assumed nail spacing values for edge and field are 150 mm (6 in.) and 300 mm (12 in.), respectively, with a stud spacing of 406 mm (16 in.). A ten parameter CUREE hysteresis model [Folz and Filiatrault, 2004] was used to represent the load-displacement relationship for gypsum wallboard-sheathed walls. The "pancake" model [Folz and Filiatrault, 2002] was used for structural modeling. Ten pairs of ground motion time histories developed for Seattle [Somerville et al. 1997], having probabilities of exceedance of 2% in 50 years were used. The analysis results, i.e. maximum shear wall drifts, were converted to performance grade from 0 (worst) to 4 (best). Conceptually, grades of 4, 3, 2, 1, and 0 are associated with the 1% immediate occupancy (IO) drift limit, 2% life safety (LS) limit, 3% collapse prevention (CP) limit, drifts greater than 3% up to 10%, and drifts greater than 10%, respectively.

4. RESULTS AND DISCUSSION

4.1 Uncertainties inherent in piRVS Performance Scores

The performance scores from piRVS were compared against the reference scores from building-specific analysis using SAPWood. Figure 4 shows comparisons for 40 one-story L-shape models (out of all 95 one-story models) at high 1 seismicity. The higher score implies better performance (i.e. less drift). An ideal piRVS would provide the same score for each model and thus give the same plots. Using piRVS, although not perfectly matched, the plots are similar and the scores scatter about the same level (approximately S= 2.5, for this case). Cases with large score differences were partly due to limitations of piRVS to cover some extreme configurations, and insufficient resolution of piRVS shape parameters. For example, the score difference for model number 9 (Fig. 4) is -1.7. The piRVS final score was based on a SM for 30%|15% openings (30% along long direction and 15% along short direction) while the actual openings are 72%|16%. The provided SM thus does not support this extreme case well where the percent openings on the long direction of the observed building is much higher than that of the index models. Large percent openings along the length can also change the critical direction of a building since the long direction may become weaker than the short direction. Another example related to the resolution of shape parameter is for model number 27. Note that the piRVS for L-shape models was developed based on two levels of shape ratio; 0.50 (for rectangle-like) and 1.00 (for square-like). The assumed shape ratio range for square-like shapes in this study is from 0.85 to 1.00, Model 27 (shape ratio= 0.84) was thus considered as rectangular-like and its piRVS score is 1.8. With a SAPWood score of 3.4, the score difference is 1.6. The difference would reduce to 0.8 if the model was considered as square-like and the piRVS score improves to 2.6. Increasing the piRVS shape ratio resolution could be a benefit for this case.

Figure 5 summarizes the score differences (SAPWood - piRVS) for all models in a box plot format. Box widths show the middle 50% of the data. A line within each box shows the median. Whiskers show the 10^{th} to 90^{th} percentile range. For single-story dwellings, medians are generally within ± 0.10 ranges, except for moderate seismicity where the median equals 0.50. The overall score differences are within the ± 0.80 range; minimal at low, peaked at high 1, and reduced at high 2 seismicity. At low seismicity, the difference is minimal due to low seismic demand. All models are subject to small drifts as illustrated in Fig. 6 with all one-story L-shape models at low seismicity at scores of 4.0.

At moderate seismicity, the range of the score difference increases. Most of the models remain at a SAPWood score of 4.0 (Fig. 6). The piRVS scores decrease earlier, thus the score differences initiate on the positive side. For high 1 seismicity, the range of score difference is peaked as the buildings behave more nonlinearly. Figure 6 shows that the majority of SAPWood scores reduce to 2.0 to 3.5. Unlike moderate seismicity, the score differences are now on both positive and negative sides. A possible reason is that the effect of nonlinearity, torsional moment due to eccentricity, and load redistribution, become more obvious. The range of score difference decreases at high 2 seismicity since the performance score of 1.0 covers a wider range of percent drifts from more than 3% up to 10%.

For two-story dwellings, medians of the difference are also within ± 0.10 ranges. The overall score differences are within a ± 0.50 range, thus relatively less variation than for a one-story. This is partly because the set of two-story models have less configuration variations than for one-story models. For example, from Table 1 and 2, two-story samples generally cover narrower ranges of base area as well as overall width to length ratio. There are also less two-story sample models (N= 29) than one-story models (N= 95).

4.2 Prediction Results between piRVS, ASCE 31 Tier 1, and FEMA 154

piRVS vs ASCE 31 Tier 1

Table 4 shows comparison results in terms of percent "Fail" and "Pass" agreement. The percent agreement ranges from as low as 7% up to 100%. The perfect (100%) agreements are observed for low seismicity where the seismic demand is very low. The percentages tend to, but not always, reduce at the moderate and high 1 seismicities before increasing again at high 2 seismicity. piRVS is seen to be relatively more conservative than ASCE 31 Tier 1. It predicts failures roughly 1 step (in seismicity level) ahead of ASCE 31.

The conservatism of piRVS is partly because the effects of torsional forces from eccentricity, dynamic loadings, nonlinearity, and force redistribution were included. The difference in shear wall capacity can also be a major factor. piRVS assumed shear walls with 8d nails and a nail spacing for the edge and field of 150 mm (6 in.) and 300 mm (12 in.), respectively. Stud spacing was assumed at 406 mm (16 in.). The ultimate capacity used in piRVS development for a 2.40 x 2.40-m (8 x 8-ft) shear wall is approximately 8.90 kN/m (610 plf). ASCE 31 does not specify configuration details of a shear wall but suggests a shear capacity of 14.6 kN/m (1,000 plf). References such as Report 154 [Tissell, 1993] and Pardoen et al. [2000] show that typical 2.40 x 2.40-m (8 x 8-ft) shear walls using 8d nails, with 150 mm (6 in.) nail spacing value for the edge and 300 mm (12 in.) for the field, generally have a shear capacity within this range, i.e. from 8.76 kN/m (600 plf) to 14.6 kN/m (1,000 plf). Variations in shear capacity depend on factors such as blocked and unblocked conditions, and sheathing material and thickness. Shear wall capacity used in piRVS is thus closer to the lower bound while the ASCE 31 value is closer to the upper bound.

The last column of Table 4, percent agreement (2), shows the re-calculated percent agreement after revising the ASCE 31 shear capacity to 10.2 kN/m (700 plf). Selection of the 10.2 kN/m (700 plf) is somewhat arbitrary but is within the 8.76 kN/m (600 plf) to 14.6 kN/m (1,000 plf) range, and closer to the value used in piRVS. While this revision improves the overall agreement, a more careful study is recommended.

piRVS vs FEMA 154

The piRVS is sensitive to plan configuration as can be seen from Fig. 4 where the piRVS scores for one-story L-shape models at high 1 seismicity vary across the group models. Differently, the FEMA 154 scores (Fig. 4) are at a constant value since all models use the same FEMA 154 basic score of 4.4 with the same SM for plan irregularity of -0.5. As a result, their final scores are 3.9 (S= 4.4 – 0.5).

Table 5 shows a summary of percent agreement between FEMA 154 and piRVS for all models. FEMA 154 does not predict any failures at all seismicities. piRVS is more conservative as it starts to provide warnings at high 1. The results show very good agreement (100%) between the two methods for low and moderate seismicity. Percent agreement starts to reduce at high 1 and becomes worse at high 2 where the agreement drops to 20% and 0% for one-story and two-story buildings, respectively. Conservatism of piRVS may due to two reasons. First, the drift limits were different. piRVS collapse prevention limit is associated with 3% drift while the FEMA 154 cutoff score is associated with 4.8% drift for high- and moderate-, and 3.8% drift for low-seismicity. Second, their index models, assumptions, and analysis approach are different. FEMA 154 was developed based on standard build capacity curves (NIBS, 1999) representing load-displacement properties of typical W1 type buildings. For piRVS, the load-displacement properties of buildings depend on different combinations of shape parameters. Effects of torsional moment due to eccentricity, nonlinearity, load redistribution, and dynamic loadings are included. Lateral load resistance contribution from interior wall is excluded.

4.3 1994 Northridge Damage Predictions

Selected houses from ATC 38, "USC021-GTZ-21" and "USC053-ER-01", are designated house 1 and house 2, respectively. Comparisons were qualitatively made between the observed conditions and the predictions from piRVS, ASCE 31 Tier 1, and FEMA 154.

Observed Damage Conditions

The observed damage conditions for both houses can be summarized as follows:

House 1: The overall damage condition is moderate meaning that repairable structural damage has occurred. Existing elements can be repaired in-place without substantial demolition or replacement. Percent structural element damage was estimated to be 1% to 10%. Diagonal cracks were found in the north wall.

House 2: The overall damage condition is moderate. Percent structural element damage was approximate 1% to 10%. Moderate damage was on exterior walls.

The damage description above was used to describe both houses in terms of the ASCE 41-06 [ASCE, 2007] performance scale (i.e. IO, LS, and CP limits). Since shear wall damage is present but repairable, both houses were considered to “fail” the IO limit but “pass” the LS limit. Figure 7 shows the ASCE 41-06 performance scale, the corresponding damage description, and the seismic performance for both sample houses.

Predicted Damage Conditions

The overall configuration details, natural periods, and spectral accelerations for both houses are summarized in Table 6. The natural periods were determined using SAPWood based on the observed configuration and an assumption that interior walls were spaced every 4.57 m (15 ft). With the provided response spectra [ATC, 2000], the spectral accelerations for both sample houses were determined.

The obtained spectral accelerations were used directly in the ASCE 31 Tier 1 calculation. Building effective seismic weight was calculated based on the assumed values described earlier. The calculated pseudo lateral force (Eq. 1) for house 1 and house 2 are 511 kN (115.0 kips) and 388 kN (87.3 kips), respectively. The calculated maximum shear stresses (equation 2) for house 1 are 32.8 kN/m (2,246 plf) (at IO) and 16.4 kN/m (1,123 plf) (at LS) which means that house 1 fails both the IO and LS (shear capacity= 14.6 kN/m (1,000 plf) for both performance limits). The prediction is for somewhat more severe damage than observed. The extent of damage beyond the LS limit is unknown. For house 2, the calculated maximum shear stresses are 16.6 kN/m (1,137 plf) (at IO) and 8.29 kN/m (568 plf) (at LS), so it fails the IO but passes the LS limit. This is considered slightly unconservative since the predicted damage level is the same as the observed even though the interior wall contribution has not been included. Tier 1 of ASCE 31 thus provides reasonable predictions although they could be slightly unconservative for some cases.

The FEMA 154 evaluation was performed using the high-seismicity data sheet. The only applicable SM is for plan irregularity. The final score for house 1 is 4.4 (S= 4.4 – 0), and for house 2 is 3.9 (S= 4.4 – 0.5). Both houses thus pass the cutoff score. FEMA 154 provides correct predictions in that neither collapsed. However, how well these houses would perform at the higher performance limits (i.e. at IO, LS, and CP) is unidentified.

The piRVS evaluation was made at high 1 seismicity. Based on their configuration details (Table 6), the BSH scores are 2.9 and 3.0 for house 1 and house 2, respectively. The SMs for both houses are equal at 1.1. The garage door score modifier is not included since it is not in the short direction. As a result, the performance scores for house 1 and house 2 are 1.8 (S= 2.9 – 1.1) and 1.9 (S= 3.0 – 1.1), respectively. Both houses fail the IO (cutoff score= 3.5) and LS (cutoff score= 2.5), but pass the CP limit (cutoff score= 1.5). For these two buildings, the piRVS prediction is conservative as it predicts somewhat more severe damage (one performance level difference) than observed.

CONCLUSIONS

Plan Irregularity Rapid Visual Screening (piRVS) is a new method to predict the expected seismic performance level of wood-frame, single family dwellings with plan irregularity with regards to the Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The method is able to reasonably evaluate seismic performance for building-specific cases as the variation in final scores, relative to building-specific nonlinear time history analyses, is generally within the ± 0.80 range for 1-story (N= 95) models and ± 0.50 range for 2-story (N= 29) models.

piRVS is relatively more conservative than ASCE 31 Tier 1. It predicts failures earlier than ASCE 31 Tier 1, roughly one step in seismicity level ahead. In other words, for a particular performance level, ASCE 31 Tier 1 allows a building to withstand a more severe seismic intensity than the piRVS. The benefits of piRVS over ASCE 31 are (i) the effects of torsional forces from eccentricity, dynamic loadings, nonlinearity, and force redistribution are included, and (ii) piRVS shear wall capacity is closer to the lower bound.

The piRVS is also relatively more conservative than FEMA 154. This is felt to be reasonable because the piRVS evaluation uses the CP limit while FEMA 154 uses 1% probability of collapse (higher drift limits). The benefits of piRVS are that (i) effects of plan configurations and eccentricities are directly included, (ii) contributions from interior walls are neglected which is conservative for sidewalk-survey-based evaluations, and (iii) its non-linear dynamic analysis background is more rigorous.

The piRVS provides reasonable damage predictions for Northridge Earthquake damage samples. By excluding shear resistance from interior walls, the piRVS predicts slightly more damage (one performance level difference) than observed. Among the three methods, it is the only one that provides a seismic performance assessment for all of the ASCE 41 performance levels (IO, LS, and CP).

Overall, piRVS is an engineering-based rapid visual screening method for wood-frame SFD with plan irregularity. While the piRVS covers many different combinations of shape parameters, the evaluation method is simple and thus suitable for rapid visual screening. It provides reasonable and conservative predictions. It is believed that the piRVS is an effective tool for use in rapid visual screening of wood-frame SFD.

ACKNOWLEDGMENTS

The authors are grateful for the financial support of this project by the Royal Thai Government, the School of Civil and Construction Engineering, and the Department of Wood Science and Engineering, Oregon State University.

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Table Captions

TABLE 1 Summary of 1-story sample models

TABLE 2 Summary of 2-story sample models

TABLE 3 Levels of Seismicity Definitions

TABLE 4 Summary of percent agreement between ASCE 31 Tier 1 and piRVS for all models

TABLE 5 Summary of percent agreement between FEMA 154 and piRVS for all models

TABLE 6 Configuration details and dynamic properties of sample models from ATC38

TABLE 1 Summary of 1-story sample models

1-Story Dwellings (Corvallis, OR)					
	Rect.	L	T	U	Z
No. of Samples	20	40	16	7	12
Avg. Base Area, m^2 (ft^2)	157 (1,693)	239 (2,569)	276 (2,974)	245 (2,642)	283 (3,049)
Base Area Ranges, m^2 (ft^2)	89 (960) to 259 (2,788)	84 (900) to 361 (3,888)	98 (1,050) to 438 (4,712)	190 (2,040) to 301 (3,240)	202 (2,176) to 357 (3,848)
Overall Width to Length Ratio	0.41 to 0.95	0.45 to 1.00	0.43 to 0.96	0.57 to 0.96	0.53 to 1.00

TABLE 2 Summary of 2-story sample models

2-Story Dwellings (Salem and Portland, OR)					
	Rect.	L	T	U	Z
No. of Samples	15	10	2	N/A	2
Average Based Area, m^2 (ft^2) (per floor)	116 (1,253)	136 (1,459)	196 (2,108)	N/A	207 (2,224)
Based Area Ranges, m^2 (ft^2) (per floor)	61 (660) to 184 (1,976)	85 (912) to 241 (2,592)	171 (1,840) to 221 (2,376)	N/A	172 (1,848) to 242 (2,600)
Overall Width to Length Ratio	0.43 to 1.00	0.62 to 1.00	0.81 to 0.87	N/A	0.95 to 0.96

TABLE 3 Levels of Seismicity Definitions

Level of seismicity	Design short-period spectral response acceleration parameter, S_{DS}			Design spectral response acceleration parameter at a one-second period, S_{D1}
	ASCE 31	FEMA 154	piRVS	
Z1: Low	< 0.167g	< 0.167g	< 0.167g	< 0.067g
Z2: Moderate	≥ 0.167g < 0.500g	≥ 0.167g < 0.500g	≥ 0.167g < 0.500g	≥ 0.067g < 0.200g
High	≥ 0.500g	≥ 0.500g	-	≥ 0.200g
Z3: High 1	-	-	≥ 0.500g < 1.000g	≥ 0.200g
Z4: High 2	-	-	≥ 1.000g < 1.500g	≥ 0.200g

TABLE 4 Summary of percent agreement between ASCE 31 Tier 1 and piRVS for all models

No. of Floors	Performance Level	Seismicity Level	No. of Samples	No. of Failures		Percent Agreement	Percent Agreement (2)
				ASCE 31	piRVS		
1	Immediate Occupancy	Low	95	0	0	100%	100%
		Moderate	95	0	45	53%	52%
		High 1	95	40	95	42%	93%
		High 2	95	90	95	95%	100%
	Life Safety	Low	95	0	0	100%	100%
		Moderate	95	0	0	100%	100%
		High 1	95	0	21	78%	77%
		High 2	95	3	91	7%	58%
2	Immediate Occupancy	Low	29	0	0	100%	100%
		Moderate	29	3	25	24%	62%
		High 1	29	28	29	97%	100%
		High 2	29	29	29	100%	100%
	Life Safety	Low	29	0	0	100%	100%
		Moderate	29	0	1	97%	55%
		High 1	29	3	29	10%	100%
		High 2	29	18	29	62%	100%

Note: Percent agreement (2) was determined after revising ASCE 31 shear capacity to 10.2 kN/m (700 plf)

TABLE 5 Summary of percent agreement between FEMA 154 and piRVS for all models

No. of Floors	Performance Level	Seismicity Level	No. of Samples	No. of Failures		Percent Agreement
				FEMA 154	piRVS	
1	Collapse Prevention	Low	95	0	0	100%
		Moderate	95	0	0	100%
		High 1	95	0	4	96%
		High 2	95	0	76	20%
2	Collapse Prevention	Low	29	0	0	100%
		Moderate	29	0	0	100%
		High 1	29	0	18	38%
		High 2	29	0	29	0%

TABLE 6 Configuration details and dynamic properties of sample models from ATC38

Model	Plan Shape	Base Area, m^2, (ft^2)	Shape Ratio	Percent Cutoff	Percent Openings (Long | Short)	Garage Door	Ground Motion Station ID	Natural Period (sec)	Spectral Acc. (g)
House 1	Rect. (1-story)	291 (3,136)	0.33	N/A	75 | 60	Yes (on long dir.)	USC-21	0.132	0.91
House 2	L (1-story)	285 (3,072)	0.75	8	60 | 60	Yes (on long dir.)	USC-53	0.114	0.75

Figure Captions

FIGURE 1 Basic shape parameters for L-shape buildings

FIGURE 2 Example of a scoring table for one-story, L, T, Z shape buildings at high 1 seismicity

FIGURE 3 A flowchart for selection of percent opening score modifiers

FIGURE 4 Comparisons of performance scores between piRVS, SAPWood, and FEMA 154 for 40 one-story L-shape models at high 1 seismicity

FIGURE 5 Ranges of score difference between piRVS and SAPWood for all models

FIGURE 6 SAPWood performance scores for 40 one-story L-shape models at each seismicity level

FIGURE 7 Seismic performance of sample houses on ASCE 41-06 performance scale

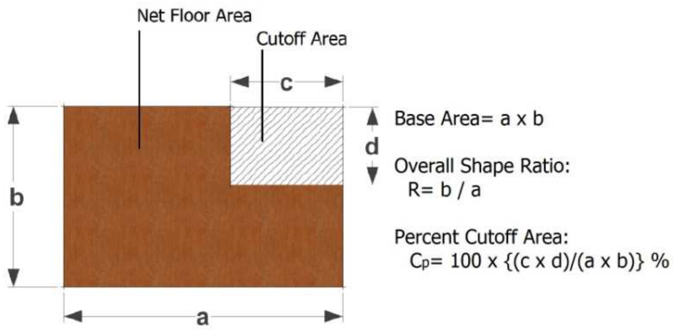
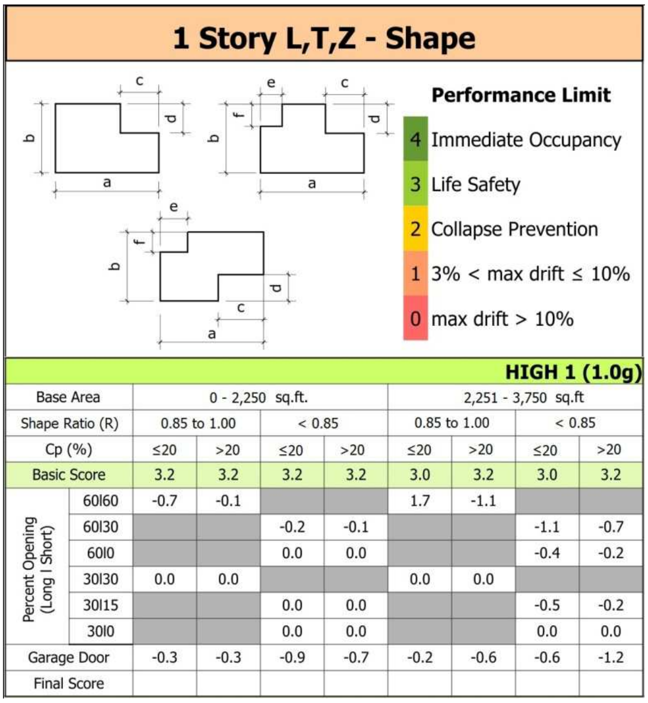


FIGURE 1 Basic shape parameters for L-shape buildings



Base Area		0 - 2,250 sq.ft.				2,251 - 3,750 sq.ft			
Shape Ratio (R)		0.85 to 1.00		< 0.85		0.85 to 1.00		< 0.85	
Cp (%)		≤20	>20	≤20	>20	≤20	>20	≤20	>20
Basic Score		3.2	3.2	3.2	3.2	3.0	3.2	3.0	3.2
Percent Opening (Long I Short)	60I60	-0.7	-0.1			1.7	-1.1		
	60I30			-0.2	-0.1			-1.1	-0.7
	60I0			0.0	0.0			-0.4	-0.2
	30I30	0.0	0.0			0.0	0.0		
	30I15			0.0	0.0			-0.5	-0.2
	30I0			0.0	0.0			0.0	0.0
Garage Door		-0.3	-0.3	-0.9	-0.7	-0.2	-0.6	-0.6	-1.2
Final Score									

FIGURE 2 Example of a scoring table for one-story, L, T, Z shape buildings at high 1 seismicity

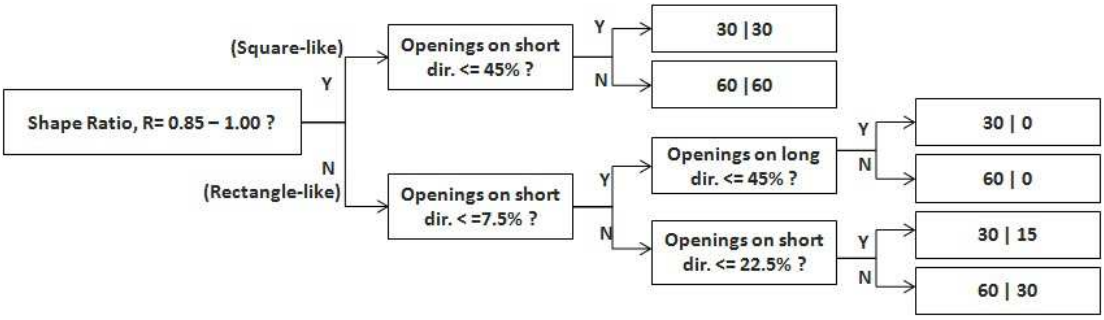


FIGURE 3 A flowchart for selection of percent opening score modifiers

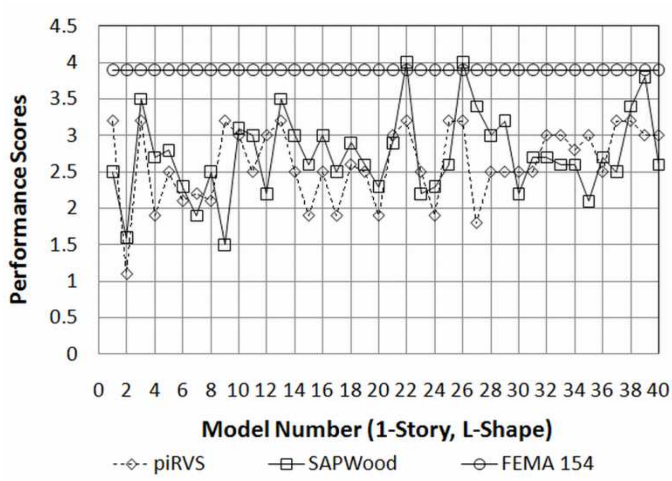


FIGURE 4 Comparisons of performance scores
between piRVS, SAPWood, and FEMA 154
for 40 one-story L-shape models at high 1 seismicity

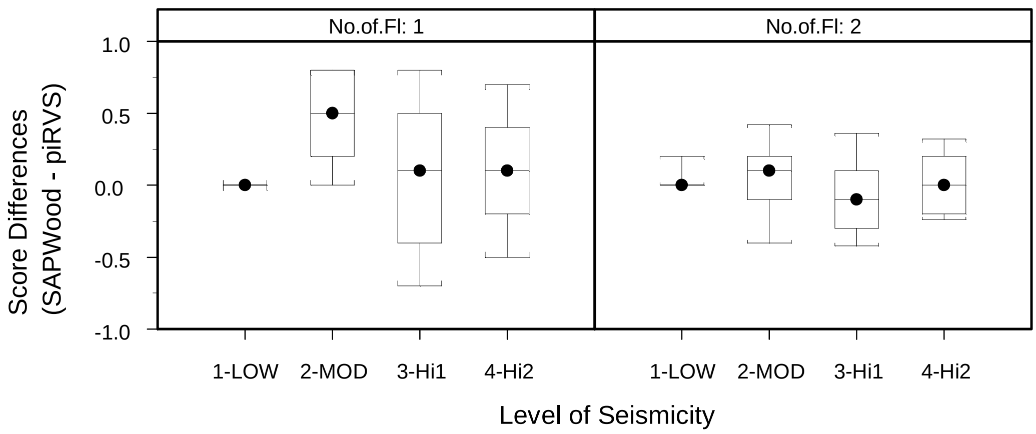


FIGURE 5 Ranges of score difference between piRVS and SAPWood for all models

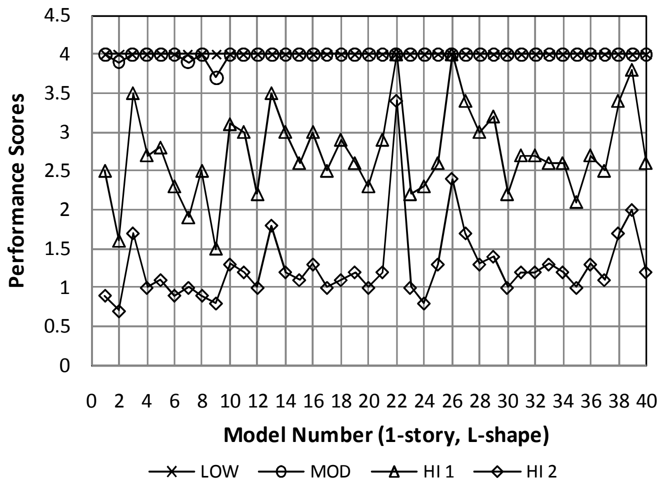


FIGURE 6 SAPWood performance scores for
40 one-story L-shape models at each seismicity level

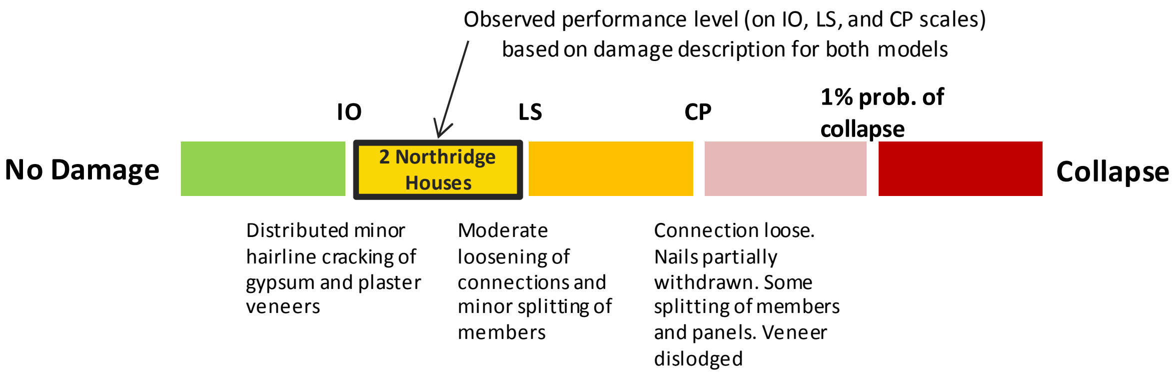


FIGURE 7 Seismic performance of sample houses on ASCE 41-06 performance scale