USE OF PERFORMANCE-BASED ENGINEERING CRITERIA IN MOTIVATING RESIDENTIAL SEISMIC RETROFIT

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Abstract

Performance-based engineering criteria have begun to be incorporated into discussion of objectives for residential construction. One example is the recently published simplified assessment methodology of FEMA P-50 (FEMA, 2012a), which seeks to motivate owners of single family dwellings to undertake seismic retrofit. In the FEMA P-50 assessment, a broad range of structural and site hazard characteristics are evaluated, a resulting Seismic Performance Grade ranging from A to D- is assigned, and vulnerabilities that could be retrofit to increase performance are identified. In the past, discussion of residential retrofit focused on significant and disproportionate damage, however the FEMA P-50 developers believed that a broader range of performance descriptors was needed to motivate homeowners. Performance-based descriptors associated with grades A to D include: overall seismic performance, anticipated level of structural and nonstructural damage, damage cost range, and likelihood of continued occupancy. The implementation of performance based engineering in residential retrofit construction is made challenging by the wide variation of configurations and construction inherent in the residential building stock, and the need for great cost-effectiveness in both retrofit design and construction cost. There is significant further work needed to rigorously support implementation of residential seismic retrofit with performance based engineering objectives. This presentation will provide an overview of the FEMA P-50 assessment, discuss the performance descriptors, steps already taken, and additional work needed.

Introduction

To date, documents identifying seismic vulnerabilities and retrofit methods in smaller residential structures have tended to focus on the most significant vulnerabilities that might cause significant damage and pose a hazard to occupants. Examples include the *International Existing Building Code* (IEBC) (ICC, 2012) Appendix Chapter A3 provisions, with measures to improve bracing of cripple walls and anchorage to the foundation in wood-framed dwellings, and IEBC Appendix Chapter A4 provisions for soft-story multi-family residential buildings. The stated objective of these provisions is hazard reduction, a lower level of performance than required for new buildings. A variety of similar guidelines and provisions exist. To date, however, implementation of these types of seismic retrofits in California and beyond has been limited to a very small portion of affected residential buildings. These provisions have not yet captured the attention and interest of the great number of homeowners with seismically vulnerable dwellings.

The recently published *Simplified Seismic Assessment of Detached, Single-Family Wood-Frame Dwellings* (FEMA P-50) (ATC, 2012), takes a new approach in communicating both the possible consequences of a significant earthquake, and the improved consequences if seismic retrofit is performed. In the forward to FEMA P-50, it is noted that FEMA supported this document in order to provide a tool that communities could use to encourage the seismic retrofitting of residential structures, thereby reducing future earthquake losses. It is hoped that the new approach, through better communication of earthquake consequences using performance-based descriptors, motivates evaluation and retrofit of dwellings by homeowners, communities, and other stakeholders.

The descriptors of seismic performance used in FEMA P-50 require use of performance-based engineering approaches. While performance-based engineering is gaining wider use in other buildings types, there has been little use in dwellings due to the high cost of performance-based approaches relative to the cost of dwelling construction, and due to the wide variation of configuration and construction materials inherent in the residential building stock. There is significant further work needed to rigorously support implementation of residential seismic retrofit with performance-based engineering objectives.

The Simplified Seismic Assessment Methodology (FEMA P-50)

The FEMA P-50 document is an update to the previously published ATC-50 (ATC, 2002a) document, developed by ATC in collaboration with the City of Los Angeles following the 1994 Northridge, California Earthquake. As identified in the title, the scope of the document is detached single-family wood-frame dwellings. The FEMA P-50 document update was funded by the Federal Emergency Management Agency (FEMA).

The concept of both the ATC-50 and FEMA P-50 documents is to provide an assessment form that can be filled out on-site by a person with some knowledge of residential construction in about an hour. The result of the assessment is an assigned Seismic Performance Grade ranging from a low of D- to a high of A, indicating the likely performance of the dwelling under seismic loading, and identifying items that can be retrofit to improve the grade. This is intended to make the seismic assessment of dwellings simple enough that individual homeowners or communities can have seismic assessments performed without prohibitive cost and effort. The ATC-50 document was developed for use in the Los Angeles area. The FEMA P-50 update includes expansion to a national basis, incorporation of web-based consideration of regional seismic hazard, and modifications to the assessment criteria. Two companion documents were developed in conjunction with ATC-50: ATC 50-*1 Seismic Rehabilitation Guidelines for Detached Single-Family Wood-Frame Dwellings* (ATC, 2002b) and ATC-50-2: *Safer at Home in Earthquakes: A Proposed Earthquake Safety Program* (ATC, 2002c). The ATC-50-1 document has been updated and published as FEMA P-50-1 in conjunction with publishing of FEMA P-50.

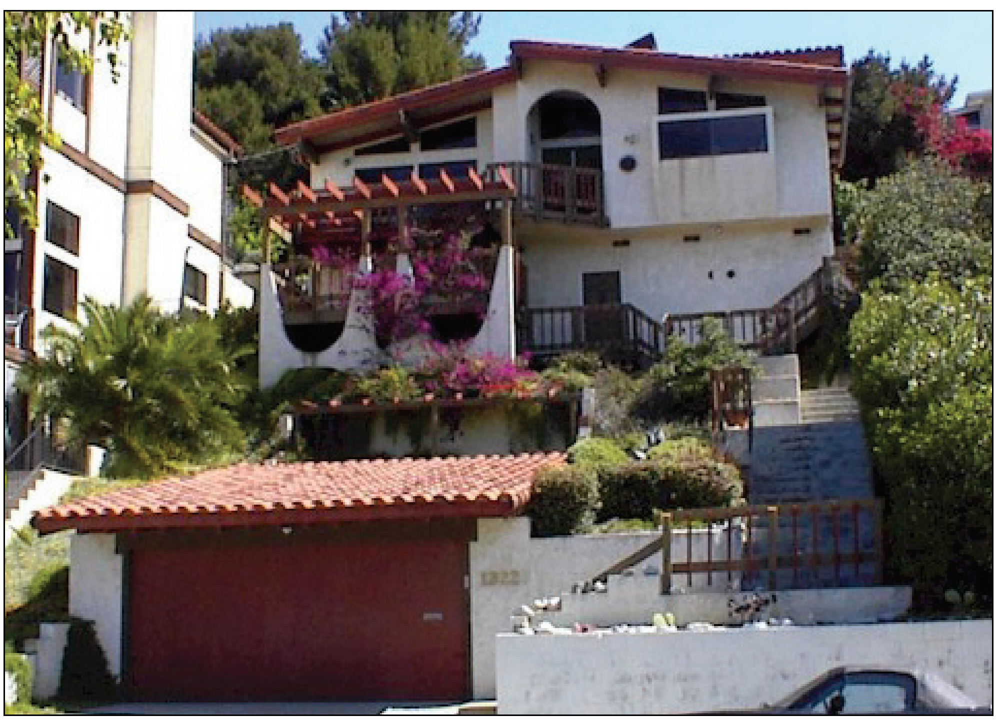

Figure 1. Example of a dwelling that might be evaluated using the FEMA P-50 evaluation form

The FEMA P-50 assessment form includes two primary considerations: development of a Structural Score, considering structural characteristics of the dwelling, and development of a Regional Seismic Hazard Score, considering ground shaking potential and other site-specific geotechnical hazards. Figure 1 illustrates a dwelling to which the assessment method might be applied. The Structural Score starts at 100 and is reduced based on responses to a series of questions regarding structural characteristics; depending on the answers provided, penalty points may be applied, reducing the dwelling Structural Score. The higher the score, the better the anticipated dwelling performance. The Regional Seismic Hazard Score varies from zero to twelve, with zero indicating a very low seismic hazard, and twelve high ground shaking hazard in combination with other site hazards.

Development of the Structural Score requires assessment of five categories including: foundation, superstructure framing and configuration, general condition assessment, nonstructural elements, and local site conditions. Figure 2 shows the first section of the assessment form, assessing of the foundation. Question A-1 asks whether or not the exterior foundation is continuous concrete or reinforced masonry. Figure 3 illustrates the types of behavior that can occur when continuous footings are not present. For the dwelling shown in Figure 3, it is intended that 4.2 penalty points be deducted from the structural score to recognize the potential damage.

A. Foundation: (If the dwelling has a crawl space, the inspector should view all the areas that are accessible.)

*A-1 The exterior footing is:
- a. continuous concrete or reinforced masonry [0]
- b. other footing conditions [4.2]

A-2 The lowest floor of the dwelling is:
- a. slab-on-grade [0]
- b. wood framed over crawl space or basement [2.9]
- c. combination of slab-on-grade and wood framed floor over crawl space or basement [2.9]

*A-3 At the dwelling crawlspace or basement interior, the lowest floor framing is supported on:
- a. continuous stem walls or a combination of continuous stem walls and beams on posts bearing on concrete footings/piers [0]
- b. beams on posts bearing on piers/pad footings [0.8]
- c. beams on posts supported directly on soil [2.2]
- d. not applicable: slab-on-grade [0]

A-4 For a foundation on a slope of 3 horizontal to1 vertical or steeper, the top of the footing or foundation stem wall on which wall studs or posts are supported is:
- a. sloped parallel to the ground slope [3.7]
- b. stepped [1.8]
- c. at a constant elevation with no steps [0.6]
- d. not applicable [0]

*A-5 At the dwelling perimeter walls, where the foundation system supports a wood framed floor:
- a. the foundation sill plate (mudsill) is bolted to the foundation with average anchor bolt spacing of 72 in. or less [0]
- b. the foundation sill plate is fastened to the foundation with retrofit anchors equivalent to 72 in. or less anchor bolt spacing [0]
- c. the anchor bolts have average spacing that is > 72 in. but <= 108 in. [1.7]
- d. the anchor bolts have > 108 in. average spacing [4.6]
- e. the foundation sill plates have extensive decay, splitting, or inadequate edge distance at one third or more of the anchor bolt locations such that significant slip of the sill plate could occur [10.0]
- f. the anchor bolts have significant corrosion at one third or more of the anchor bolts locations such that significant slip of the sill plate could occur [10.0]
- g. there are no foundation anchor bolts [15.0]
- h. there are no foundation sill plates to connect to the foundation [15.0]
- i. not applicable [0]

Total ____

Figure 2. Section A of the FEMA P-50 form, assessing structural aspects of the foundation

The assessment of the Structural Score includes two broad types of assessment items. The first category includes items associated with significant damage and possible risk to occupants, for example lack of dwelling anchorage to the foundation (Figure 4), and lack of bracing at the front of garages (Figure 5). The second category includes assessment items related more to damage and repair cost than safety, for example heavy roofing, brittle or heavy finishes on exterior walls, number of stories, and general condition of the dwelling, etc.

Development of the Regional Seismic Hazard Score requires consideration of ground shaking potential and potential for liquefaction, earthquake-induced landslide, and surface fault rupture. As shown in Figure 6, points are assigned for ground shaking, and then additional points may apply if site hazards apply. In the United States, the ground shaking potential can be easily determined by accessing the United States Geological Survey (USGS) web site, making this information easily determined for all dwelling locations.

Figure 7 provides an illustration of the seismic hazard mapping information that can be accessed in interactive form on the USGS web site. Access to other site hazard information varies by state and within states. For dwellings located in California, much of the information can be easily obtained from a California Emergency Management Agency (CalEMA) web site. Web links are provided in the assessment form for all identified seismic hazard information from all states.

Figure 3. Seismic performance at discontinuous footings. This foundation type would result in 4.2 penalty points being assigned, reducing the Structural Score

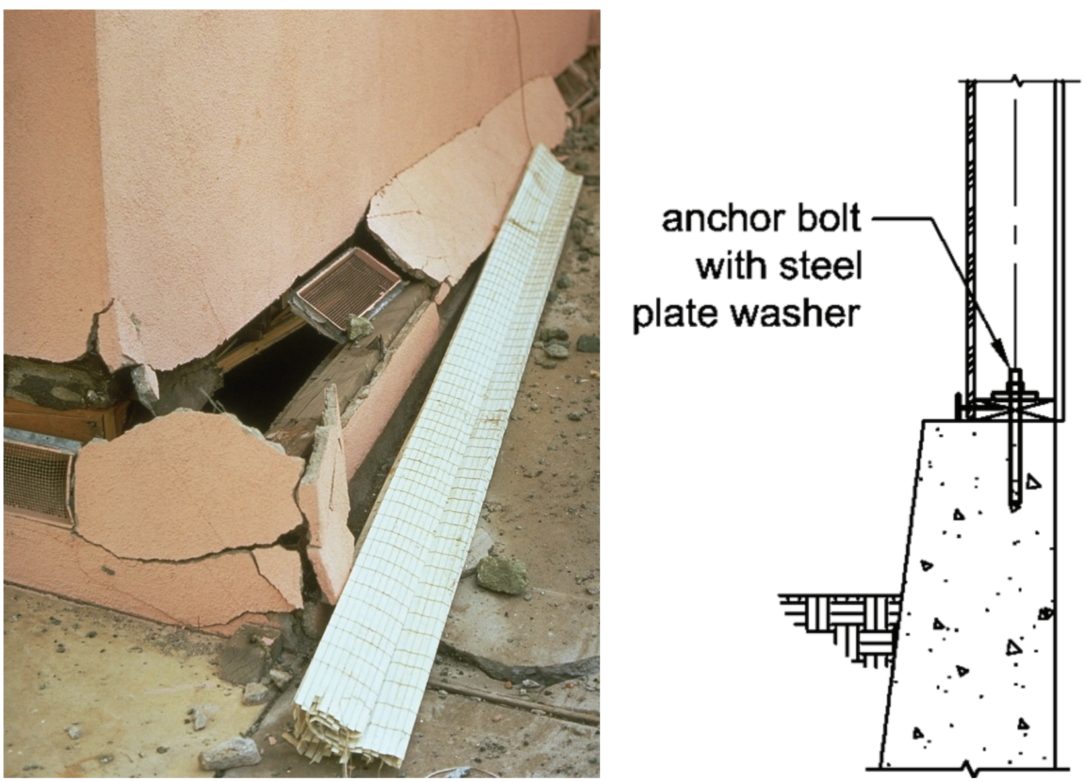

Figure 4. Dwellings are vulnerable when anchor bolts are not provided to anchor the wood framing and foundation. The figure on the right shows typical anchor bolts. The figure on the left shows a dwelling that was damaged because it did not have anchor bolts

Figure 5. Dwellings are vulnerable where little bracing wall is provided at garage doors

F. Regional Seismic Hazard Score

F-1 Enter points for shaking hazard potential for location of dwelling (from Table 1). [_____]

F-2 Are ground failure hazards to be looked up using Tables 2, 3, and 4? yes, go to F-3.
no, proceed to F-6 and enter 4.0 points for ground failure hazards

F-3 Is this dwelling located in a liquefaction zone (from Table 2) or landslide zone (from Table 3)? yes, go to F-4.
no, go to F-5.

F-4 Proceed to F-6 and enter ground failure hazard points in accordance with the following table:

Ground Shaking Points	Ground Failure Points
0	2
2, 4	3
6, 8	4

F-5 Is the dwelling located in a fault rupture zone (from Table 4)? yes [2]
no [0]

F-6 Total ground failure points from F-2, F-4, or F-5 (no summation). [_____]

Total Seismic Hazard Score (Sum of F-1 and F-6) [ ]

Figure 6. Section F of the assessment form, addressing Regional Seismic Hazard Score

Once the Structural Score and Regional Seismic Hazard Score have been determined, a Seismic Performance Grade can be assigned (Figure 8). In addition, items that can be retrofit and the possible improved score are identified (Figure 9). Using the assigned Seismic Performance Grade and the potential improved grade with retrofit, the homeowner can use the grade descriptions provided to better understand expected seismic performance of their dwelling.

Quantified Grades and Descriptions

Written descriptions of anticipated performance are provided for grouped grades (A, B, C and D). These descriptions are a key part of communicating with the homeowner, community, or other stakeholders regarding earthquake consequences. Abbreviated descriptions of grades are provided on the assessment form (Figure 10), and more detailed descriptions are provided in Section 2.4 of the FEMA P-50 document. The grades give an indication of the generally anticipated seismic performance of the assessed dwelling, given its structural characteristics and location.

Items qualitatively addressed by the descriptions include:

- Overall seismic performance, described as excellent, good, fair or poor.

- Anticipated level of structural damage, described as minor, moderate, moderate to major, and severe. The likelihood of finish damage is noted at all grades.
- Likelihood of continued occupancy, described as likely but not certain, following post-earthquake inspection and minor repairs, following structural repairs, and following significant structural repairs.
- For Grades A and B, consideration of seismic retrofit is encouraged, for Grades C and D, seismic retrofit is strongly encouraged.

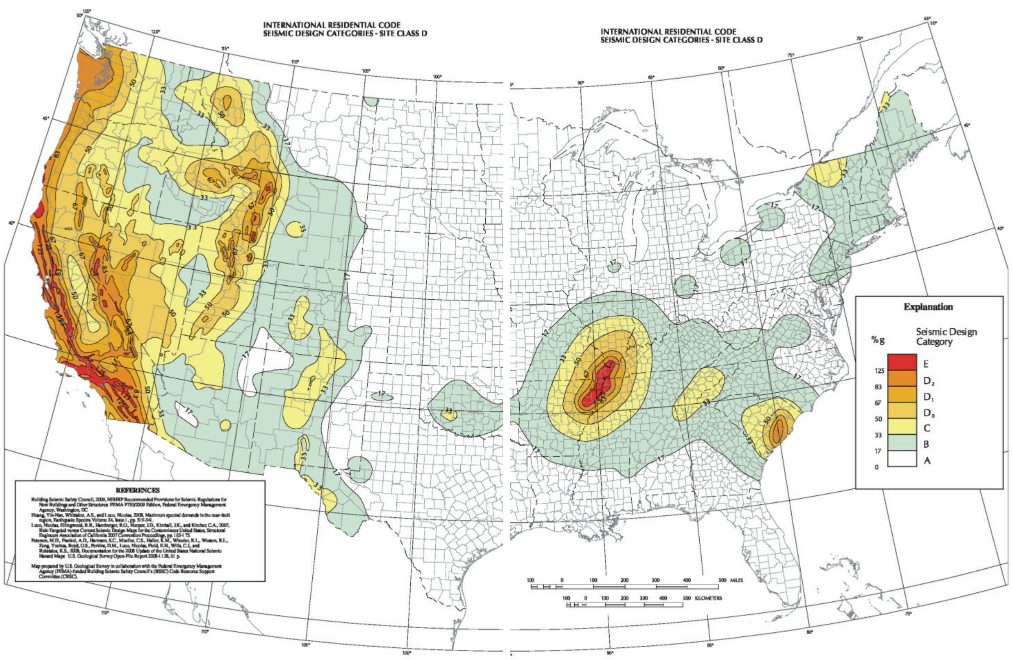

Figure 7. Seismic hazard mapping, illustrating information available in interactive format from the USGS web site

Table 5. Seismic Performance Grade Based on Structural Score and Regional Seismic Hazard Score

Seismic Hazard Score		0 - 1	2 - 3	4 - 5	6 - 7	8 - 10	11 - 12
Structural Score	1.0 - 45.9	B-	C+	C	D	D-	D-
	46.0 - 64.9	B+	B	C+	D+	D	D-
	65.0 - 74.9	A-	B+	B	C	C-	D+
	75.0 - 84.9	A-	A-	B+	B-	C	C
	85.0 - 100	A	A	A-	B+	B	B-

Figure 8. Assessment form assignment of Seismic Performance Grade based on Structural Score and Seismic Hazard Score

Item	Retrofit Description	Points (circle applicable number)	Priority Retrofit
A-1	Provide continuous reinforced concrete foundation	4.2	
A-3	Provide foundation pads under interior posts	1.4	Yes
A-5	Add anchor bolts or retrofit anchors	1.7 4.6 10.0 15.0	Yes
B-2	Add bracing walls at dwelling exterior	3.2	
B-3	Install lighter roofing	1.6 3.5	
B-4	Install plywood/OSB or steel frame at garage front	3.0	Yes
B-5	Change exterior wall finish	1.0 2.5 3.5	
B-8	Improve bracing at perimeter walls below lowest floor	4.0 7.0 14.0	Yes
C-2	Repair cut structural framing	1.5	
C-3	Repair deteriorated stucco	1.0 2.0	
C-4	Repair deteriorated foundation	0.6 1.3	
D-1	Strap exterior chimney to roof and floors	1.0	
D-2	Provide bracing and flexible water and gas connections for water heater	1.0	Yes
D-3	Provide earthquake-activated gas shut-off valves	1.0	Yes
D-4	Anchor exterior stairs, deck and porch roof	1.0	Yes
E-3	Repair footing cracks	1.0 2.7	
E-6	Improve rain water routing away from foundations	1.3 2.6	Yes

Figure 9. Section H of the assessment form, identifying Structural Score penalty points that can be regained with retrofit

4. Anticipated Seismic Performance[1]

Following anticipated seismic events:[2]

Grade A, A-: Excellent Performer
(Potential minor structural and finish damage, earthquake damage ratio[3] of 0%-10%, continued occupancy is likely)

Grade B, B+, B-: Good Performer
(Potential moderate structural and finish damage, continued occupancy likely following minor structural repairs, earthquake damage ratio[3] of 0%-50%, seismic retrofit measures are encouraged)

Grade C, C+, C-: Fair Performer
(Potential moderate to major structural and finish damage, structural repairs may be required prior to continued occupancy, earthquake damage ratio[3] of 10%-60%, seismic retrofit measures are strongly encouraged)

Grade D, D+, D-: Poor Performer
(Potential severe structure and finish damage requiring significant repairs prior to re-occupancy, earthquake damage ratio[3] of 20% – 100%, significant seismic retrofit measures are strongly encouraged)

Figure 10. Section G of the FEMA P-50 assessment form, describing anticipated seismic performance by Seismic Performance Grade

The four descriptors above were developed based primarily on the engineering judgment of the original ATC-50 writers and the FEMA P-50 update project management committee, supplemented by damage data from the 1971 San Fernando and 1995 Northridge Earthquakes and by a pilot study of 400 dwellings, conducted in the Los Angeles area as part of ATC-50 development. These descriptors are described as being relative to the performance of the overall group of detached single-family wood-frame dwellings. While not quantitative, these descriptions identify for the homeowner issues that can result from earthquake events, for which the homeowner may want to prepare.

A final quantitative description of performance was developed for FEMA P-50 by EQECAT using proprietary software to identify possible ranges of damage ratios (repair cost as a portion of dwelling replacement cost). In order to provide these ratios, EQECAT conducted loss analyses based on 76 dwelling models with characteristics incorporating the assessment items identified in the seismic assessment form (for example 16 dwelling models with structural scores between 46 and 64.9). These dwelling models were analyzed at 100 dwelling sites covering the range of seismic hazard (Seismic Design Categories C to E), and a range of seismic events deemed credible by the U.S. Geological Survey. 500 year losses were identified (1 in 500 chance of exceedance in 1 year). This was discussed as being an approximation of an expected major earthquake event, from which the homeowner might need to recover. Using this approach, damage ratio ranges (ranges of cost to repair as a portion of cost to replace the dwelling) were developed as follow:

- Grade A - 0% to 10%
- Grade B - 0% to 50%
- Grade C - 10% to 60%
- Grade D - 20% to 100%

The development of these quantitative damage ratio ranges for FEMA P-50 with a rigorous engineering basis is a significant step forward in providing an understanding of possible earthquake consequences to the homeowner. This was a first study with a limited scope, so it is hoped that additional studies in the future can confirm and extend this information. At this time the damage ratio ranges are very broad due to the wide variation in possible seismic hazard, combined with the wide variability in the dwelling configuration and construction. Ratios this broad may not provide a convincing incentive to homeowners to invest in retrofit in order to move to a higher grade. With additional studies it may be possible to develop damage ratios more specifically tied to building configurations and vulnerabilities and thereby reduce the ratio and better convince the homeowner of the benefit of retrofit.

Performance-Based Engineering Support of Quantification in Retrofit

The intent of the FEMA P-50 document is to encourage retrofit of dwellings in order to increase the Seismic Performance Grade and reduce the damage ratio. Beyond convincing individual homeowners to invest in retrofit, possible incentives include government rebates or lower insurance rates. It is also possible that seismic grade could be taken into consideration by lending institutions. This results in society making an investment in improved seismic performance, which creates the need for reasonable assurance that this investment will generally result in performance improvements identified by the change in grade.

Some retrofit guidance is currently available (codes, standards, guidelines), but this guidance:

- Addresses some but not all of the assessment items identified in the FEMA P-50 form
- Does not have a consistent performance objective

- Is not necessarily written in mandatory code language
- Does not provide rigorous minimum requirements
- Is not rigorously linked to improvements in building performance and reduction in damage ratio

Therefore, thorough and consistent retrofit guidance needs to be developed that can specifically support the qualitative and quantitative descriptions of performance provided in the grade descriptions. This will involve a number of challenges including development of relationships between performance descriptions (e.g. continued occupancy) and quantifiable engineering parameters (e.g. deflection), and coordinated efforts between developers of retrofit provisions and loss modelers that can confirm that objectives are generally met. This process is further made challenging by the wide variation of configurations and construction inherent in the residential building stock, the need for great cost-effectiveness in both retrofit design and construction cost, and the need for code requirements that can be implemented by a contractor without involvement of an engineer.

Conclusions

An initial step has been taken towards use of performance-based engineering principles in the FEMA P-50 simplified seismic assessment method for detached single-family wood-frame dwelling. The use of these principles provides a range of descriptors, both qualitative and quantitative, to communicate possible consequences of earthquake events to the homeowner. It is hoped that this communication provides incentive to the homeowner to retrofit their dwelling, thereby improving performance. Additional work is needed to further develop damage ratio information, and to develop retrofit guidance specifically supporting the performance described in the Seismic Performance Grade descriptions.

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The discussion of future needs is based on the opinions of the author, and not drawn from the FEMA P-50 or P-50-1 documents.

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