SUGGESTED IMPROVEMENTS TO PERFORMANCE-BASED SEISMIC GUIDELINES

Joe MAFFEI[1]

SUMMARY

Recent performance-based seismic guidelines have improved structural engineering practice in the United States, and a number of further improvements can be made. Based on the author's experience over the last four years on several seismic evaluation and retrofit projects, this paper gives recommendations for simplifying and clarifying performance-based guidelines. The paper advocates more explicit instruction on the capacity-design approach, which is a prerequisite to considering nonlinear structural behavior. This involves clarifying key definitions and simplifying the basic seismic evaluation procedure. The recommended procedure emphasizes the capacity side of seismic evaluation rather than the demand side. The procedure highlights six essential steps that should be common to any analysis procedure from linear-static to nonlinear dynamic time-history. The procedure applies to either force-based or displacement-based methods of determining acceptability. An example is given on how, beyond the framework of general performance-based guidelines, specific structural criteria can be defined. The example provides detailed recommendations for the evaluation of concrete wall buildings for immediate occupancy performance.

INTRODUCTION

In the United States, recent performance-based seismic guidelines such as *FEMA 273* [ATC 1997] and *ATC 40* [ATC 1996] have greatly improved the awareness of practicing engineers on important issues in structural engineering for earthquakes. The codification of nonlinear static procedure of analysis contributes to an improved appreciation of mechanisms of nonlinear response. The tabulation of acceptability limits can lead to a better understanding of the behavior modes of structural components.

The new guidelines represent a landmark improvement over previous practice, and may provide the best available engineering framework to date for seismic retrofitting. The documents are relatively new, however, and there is significant opportunity for improving the guidelines.

Case studies of the *FEMA 273* guidelines were recently carried out on some 40 buildings of various structural characteristics spread throughout the United States. Engineering consultants conducted seismic evaluations and retrofit designs for each building. A number of recommendations were made towards improving the guidelines. [Merovich 1999, Maffei 1999].

The findings of these case studies, plus my experience over the last four years with performance-based seismic evaluation and retrofit design of buildings in California, lead me to suggest improvements to our practice. Some of the most important recommendations and areas of study are outlined in this paper. They include suggestions to:

- Clarify and simplify key definitions and procedures of performance-based design, according to the principles of capacity design.
- Correlate, compare, and simplify force-based and displacement-based methods of determining the acceptability of a structure to seismic criteria.
- Consider the appropriateness of using nonlinear analysis methods.
- Develop detailed criteria for the performance-based design of specific structure types and performance levels.

[1] *Consulting Structural Engineer, San Francisco, jmaffei@ruthchek.com*

CAPACITY DESIGN BASIS

For new structures, *capacity design* is a seismic design approach in which distinct structural components, such as member plastic hinges, are chosen and detailed for energy dissipation according to a desired mechanism of nonlinear lateral deformation. All other structural components and actions are provided with sufficient strength to prevent failure under the chosen mechanism. When capacity design is applied to the evaluation of existing structures, the expected strength of structural components is determined and then the mechanism of nonlinear lateral deformation is identified.

The evaluation and retrofit guidelines *FEMA 273* [ATC 1997] and *ATC 40* [ATC 1996] establish, in part, this approach. As pointed out by Powell [1994], a capacity-design approach is in fact a prerequisite to using a nonlinear static procedure. However, the Case Studies project [Merovich 1999] has shown that the *FEMA 273* document does not clearly explain to users that a capacity-design approach must be followed. The *FEMA 273* and *ATC 40* guidelines should provide more explicit instruction in this regard.

Central to the use of *FEMA 273* and *ATC 40*, and to the issue of clearly explaining the capacity-design basis, are the definitions of the terms "force-controlled" and "deformation-controlled." Even the authors of the documents and the expert reviewers on the Case Studies project were not clear or in agreement as to the meanings of these terms. Users of the documents are invariably confused by the lack of clarity in the definitions.

I recommend that the terms force-controlled and deformation-controlled be defined along the lines of capacity-design principles as shown below:

> **Deformation-controlled action:** A component action that reaches its capacity under the governing mechanism. Deformation-controlled actions are the weak links or fuses of the structural response. The demand on deformation-controlled component actions derives from the deformation caused by the earthquake motion. Deformation-controlled actions must be ductile for the response of the structure to be ductile.
>
> **Force-controlled action:** A component action that does not reach its capacity under the governing mechanism. Force-controlled actions are not the weak links of the structural response. The demand on force-controlled component actions derives from the forces delivered by deformation-controlled actions. Force-controlled actions need not be ductile for the response of the structure to be ductile.
>
> **Governing mechanism:** The mechanism of inelastic lateral deformation — determined from a plastic analysis, a nonlinear analysis, or a comparison of relative strengths — that establishes which component actions reach their capacity under the expected pattern of seismic lateral forces.

RECOMMENDED EVALUATION PROCEDURE

Another improvement that can be made to seismic evaluation and retrofit guidelines is a simplification and clarification of the evaluation procedure. I recommend the seven-step procedure shown in Table 1.

The procedure can be used with either a computer analysis or hand/spreadsheet calculations. In my experience, the procedure tends to lead engineers to using more simplified analysis procedures than they had at first contemplated. This is because the procedure emphasizes the "capacity side" of the evaluation rather than the "demand side."

Table 1 Recommended Procedure for Seismic Evaluation

Procedure	Remarks
1. Establish expected material strengths.	See Table 3 for an example.
2. Calculate the strength of critical sections (i.e., of deformation controlled actions).	See proposed definition of "deformation-controlled actions."
3. Identify the governing post-elastic mechanism and the associated base shear, *V*.	See proposed definition of "governing mechanism."
4. Calculate *V/W*, equal to base shear divided by seismic weight.	

5. Determine the fundamental period, *T*, and the effective initial stiffness.	Given *T* and *V/W*, a simplified envelope of the nonlinear force deformation response can be constructed.
6. Determine the governing behavior modes of the components (e.g., flexure, shear, sliding shear, boundary compression, foundation rocking) to verify the mechanism.	This step requires checking that capacity exceeds demand for all force-controlled actions, and thus that the assumed mechanism indeed governs. *FEMA 306* (ATC 1999) provides guidance on Behavior modes for concrete and masonry walls.
7. Given the mechanism, behavior mode, *V/W*, *T*, and response spectra, determine acceptability.	Acceptability can be checked using either force-based or displacement-based procedures. Recommend studies to simplify the currently used procedures.

The engineer begins with calculations of the strengths of the structural components, for example in shear and in flexure, and from that information identifies the governing mechanism (Step 3). This can usually be done by a hand plastic analysis, meaning that computer analysis, if used, is not applied until the last step. By doing most of the hand calculations first, the engineer gains a better understanding of the structure, and a greater ability to judge what the analysis model really needs to include. It becomes easier for him or her to come to grips with modelling issues such as the following:

- What are the critical elements and locations for which forces and displacements must be checked?
- Can two-dimensional modelling be used instead of 3-D?
- Given the location of the center of strength [Paulay 1996], does plan torsion need to be specially addressed?

The earthquake demand, represented by the response spectra of the defined earthquake hazard level, is not checked until the last step.

Comparison to Other Procedures

The procedure is somewhat opposite of a traditional structural engineering calculation, which stems from the procedures used for an elastic gravity-load evaluation. In such an evaluation, the loads are known quantities, which are input into an analysis and then checked against capacities. For nonlinear response to earthquake forces, by contrast, the demands are more variable than the capacities, and the forces in fact depend on the capacities. The procedure of Table 1 starts with what (a) is known best and (b) provides the most information to the engineer: the capacities. As a practical matter, the procedure tends to discourage engineers from getting bogged down in a falsely precise analysis of demands.

The basic procedure is applicable to either force-based or displacement-based methods of determining acceptability, which are discussed later in this paper. The procedure is also applicable to either static or dynamic analysis methods. The first six steps of the procedure are in fact identical whether force- or displacement-based methods are used, and whether static or dynamic analyses are carried out. Thus the procedure emphasizes six essential steps that should be common to any analysis procedure: linear-static, linear dynamic, nonlinear static, or nonlinear dynamic time-history.

For most structures the procedure of Table 1 would require a similar level of effort to a conventional linear analysis. However, the procedure also provides the essential insights that would be gained with a nonlinear procedure — namely, that of identifying the governing mechanism and behavior modes. Other aspects of nonlinear procedures can be incorporated if displacement-based acceptance procedures are used.

As in any engineering procedure, some iteration between steps may be required. The procedure here is written for seismic evaluation, but it is also applicable to the subsequent phase of seismic retrofit design by applying the same steps to a proposed design.

The procedure proposed in Table 1 was written based on the seismic evaluation work done by Rutherford & Chekene Engineers on a number of buildings in the San Francisco Bay area [R&C 1999]. In practice the procedure as proven to be expedient and effective. The procedure is similar to, but broader than, a force-based procedure proposed by Park [1997] for the seismic evaluation of concrete moment frame buildings.

FORCE-BASED OR DISPLACEMENT-BASED ACCEPTABILITY

Various procedures proposed for seismic evaluation are referred to as either force-based or displacement-based. For example, the linear static and linear dynamic procedures of *FEMA 273* [ATC 1997] are force-based, while the nonlinear static procedure is displacement-based. Priestley [1995], among others, has recently proposed a displacement-based procedure. As indicated in the previous section, most of the essential steps of seismic evaluation are identical for both types of procedures — the method of determining acceptability is the central difference.

Inelastic Demand based on Elastic Demand

Both force-based and displacement-based methods require an estimate of inelastic demand based on elastic demand. In force-based methods, a global reduction factor, *R*, has been used for new buildings [ICC 1998, UBC 1997]. The linear procedures of *FEMA 273* use component modification factors, *m*, in combination with a number of global response factors. Essentially these approaches are ductility-based — the *R* or *m* factors depend principally on assumed ductility capacity. The New Zealand structural code [SANZ 1992] makes direct use of displacement ductility, μ, and provides corresponding inelastic design spectra.

In displacement-based methods, two options are referred to in *FEMA 273* [ATC 1997] and *ATC 40* [ATC 1996], the Displacement Coefficient Method, and the Capacity Spectrum Method. As shown in Figure 1, these two procedures can give divergent estimates of displacement demand for the same building and earthquake input, sometimes by a factor of 2 or 3 [Aschheim et al 1998]. The basic technical assumptions behind the two methods also differ markedly. To reduce displacement demands, the Coefficient Method leads the engineer to add stiffness to a building with little concern for strength, while the Capacity Spectrum Method leads to the opposite conclusion.

Under the category of performance-based design, there has been considerable attention paid to various displacement-based and force-based methods, with different procedures each having proponents. The different acceptability procedures have not been correlated with each other, and often the algorithm for applying a procedure is more complicated than it needs to be. Given the disparity of results, the recently proposed procedures may offer little advantage over simpler methods such as the equal displacement and equal energy assumptions that were developed nearly 40 years ago [Blume et al 1961].

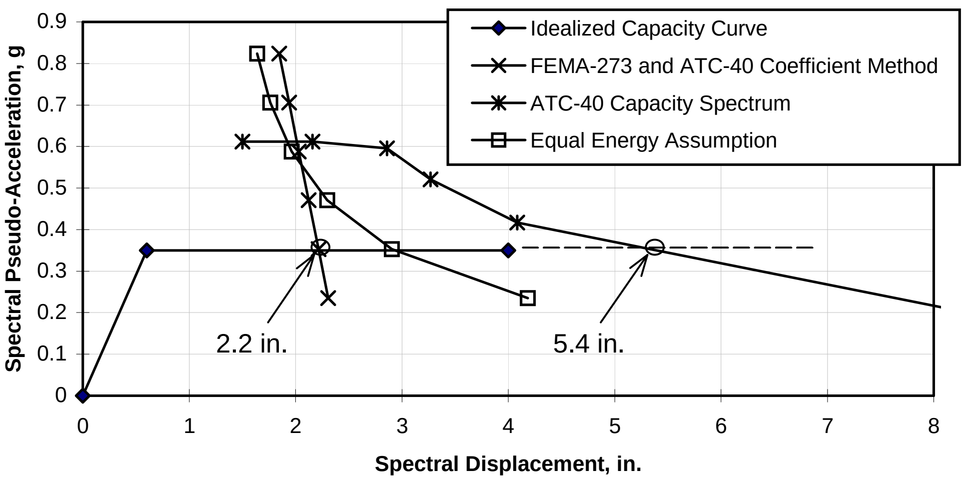

Figure 1 Comparison of Displacement Demands predicted by Displacement Coefficient and Capacity Spectrum Method [Aschheim et al 1988]

Recommended Study

To resolve issues of what methods of determining acceptability are most appropriate, a more direct comparison of different proposed methods is needed. Reformatting different procedures towards a more common basis would facilitate this comparison. It appears, for example, that any displacement-based procedure could be reformulated as a force-based procedure, and vice-versa. The technical issue of how to relate inelastic demands to elastic demands should be investigated in separation from how different procedures are formatted or presented. The input variables to this problem (as indicated in Table 1, Step 7) are the five characteristics listed below:

- Mechanism of response, which can affect the relationship between global and local ductility.
- Behavior mode of the critical (deformation-controlled) actions, which indicates strength degradation and stiffness degradation.
- *V/W*, the lateral strength of the structure divided by its weight.
- *T*, the structure period, which indicates effective initial stiffness.
- The response spectra of the design earthquake input.

The above recommendations characterize the problem of determining acceptability according to a global basis, but the results of the proposed study could also be applied to component-by-component acceptability procedures.

APPROPRIATENESS OF ANALYSIS METHODS

Many engineers assume that, compared to conventional design, performance-based design always requires a more complicated structural analysis, such as a nonlinear static procedure. This should not be the case.

In many instances, performance-based design is used when a building owner desires better than life-safety performance: either immediate occupancy, or some measure of damage control. Nonlinear procedures are actually less important to use for immediate-occupancy or damage-control performance levels than they are for life-safety or collapse-prevention performance levels. The reason is that for the stricter performance levels such as immediate occupancy, nonlinear response is limited, and thus an elastic model can acceptably capture the behavior. An example of specific structural criteria for immediate occupancy performance, based on a linear analysis, is discussed subsequently in this paper.

Currently in California, nonlinear procedures are used more frequently for existing buildings than for new buildings. This is somewhat illogical because many of the existing buildings being evaluated have little ability to achieve nonlinear deformations, whereas new buildings in high seismic zones are intended to have high ductility capacities. Except for seismic-isolated structures, nonlinear analysis procedures are not required for new buildings [ICBO 1997]. If the capacity-design procedure proposed in this paper is used, few buildings, new or existing, should require nonlinear analyses. When a nonlinear analysis procedure is used for an existing structure with non-ductile components, the ability of the procedure to properly account for strength degradation in the components should be carefully examined.

DEVELOPMENT OF DETAILED GUIDELINES

An example of specific performance-based structural criteria is given in Table 2. The criteria were initially developed for a hospital building in California, for immediate occupancy performance for the given design response spectra. The criteria are rewritten here to apply to any typical concrete wall building with concrete beam and column gravity framing. The criteria are force-based, use a linear analysis, and include requirements for component actions for the reinforced concrete walls, columns, and beams. The analysis is made without reducing the input or results, for example by an *R* factor. The full elastic response is used.

In a conventional evaluation, the walls of the building would be designated as the seismic-force-resisting system and the columns and beams would not be designated as part of the seismic force-resisting system. For the criteria given here, this distinction is unnecessary. The columns and beams do not need to be included in the computer model because they will have only a small, and beneficial, effect on the force and displacement results. The actions on the columns and beams can be approximated by a hand analysis that applies the displacement results of the computer analysis.

Behavior Modes and Detailing

The proposed criteria explicitly consider a number of possible behavior modes that can occur in concrete wall structures [ATC 1999, Paulay and Priestley 1992]. For brittle behavior modes such as wall shear in diagonal tension, the criteria require the structure to remain elastic, or for the behavior mode not to govern over ductile behavior modes. For ductile behavior modes such as wall moment or foundation rocking, a limited amount of nonlinear response is permitted.

Generally, a displacement ductility of up to 2.5 is considered acceptable for ductile behavior modes. At such a ductility level, flexural cracks that open upon yielding are likely to close again and residual crack width will be small. If compression strains are kept below 0.003, spalling is not expected. Strains can be estimated using the procedure of the SEAOC Blue Book [SEAOC 1999].

Detailing for confinement is required for collapse prevention in the maximum credible ground motion, but it is not necessary for immediate occupancy performance. Because compression strains are limited to 0.003 for immediate occupancy performance, the cover concrete is not expected to spall, and thus there is no demand for confinement of the concrete core. The seismic evaluation handbook, *FEMA 310* [ASCE 1998] implies an opposite conclusion; the document incorrectly requires confined wall boundaries for immediate occupancy performance but not for life-safety performance.

Expected Strength

The criteria proposed here are based on expected material strengths, rather than lower-bound strengths, and strength-reduction factors, ϕ, are not used. Typically, expected strength of reinforcing steel is about 1.15 times the specified yield strength [ATC 1999, Park 1997]. Table 3 gives expected material strength values used for a 1960s-designed concrete building in California. The values were based on test data that were available from other buildings of the same era.

Comparison to New Building Requirements

The criteria allow flexural demands up to 2.5 times greater than capacities, which is roughly consistent, in the case of concrete wall buildings, with requirements for new buildings that are essential facilities. By the Uniform Building Code [ICBO 1997] the building would be designed with an R factor of 5.5 and importance factor, I of 1.5. With a ϕ factor of 0.85 and a ratio of expected strength to nominal strength of 1.15, the proposed value of 2.5 compares to a value of 2.7 from by the UBC. The calculation is (5.5 x 0.85)/(1.5 x 1.15) = 2.7.

Table 2 Example of Specific Performance-Based Structural Criteria

Performance Objective:	Immediate Occupancy for the 10% in 50 year ground motion
Building Type:	Concrete wall building with concrete beam and column “gravity” framing.
Analysis Method:	Linear response spectrum or static analysis using unreduced demand. Beams and columns can either be explicitly included in the model, or beam and column actions can be calculated subsequently from the induced displacement, where the unreduced elastic displacement is used.
Mechanism Check:	Hand calculations or demand capacity ratios verify that a story mechanism (for example a weak-pier, strong spandrel mechanism) does not occur for actions up to
Acceptability Method:	Force based, using actions (such as M and V) from analysis, compared to component nominal strengths (such as M_n and V_n) using ϕ = 1.0 and expected material strengths.

Action	Performance Requirement	Acceptability Criteria
Wall Moment:	Flexural cracks to remain small (e.g., 1/8 inch) and no significant spalling should occur.	$M \leq 2.5\ M_n$, and $\varepsilon_c \leq 0.003$ (strain calculation per 1997 UBC). Boundary confinement is not required for immediate occupancy. Flexural yielding to low ductility is acceptable.
Wall Shear in Diagonal Tension	Shear failure does not occur. Any shear cracks are minor.	$V \leq V_n = V_c + V_s + V_p$, per *FEMA 306* [ATC 1999]. V_c is based on $0.25\sqrt{f'c}$ MPa ($3\sqrt{f'c}$ psi) times factors α and β.

Wall Sliding Shear	Sliding shear does not occur	$V \le V_{nf}$ (ACI 318 shear friction) and $V \le 0.67\sqrt{f'c}$ MPa ($8\sqrt{f'c}$ psi)
Wall Overturning	Foundation overturning permitted to limited displacement.	$M \le 2.5\ M_R$, use 1.0*D* for resisting moment. Check for induced displacement on beams and columns per criteria given below.
Wall Diagonal Compression	Diagonal compression (web crushing) failure does not occur.	$V \le 0.67\sqrt{f'c}$ MPa ($8\sqrt{f'c}$ psi), based on *FEMA 306* information
Lap Spice Length	Allow only limited lap-splice slip.	Check for class A lap length per ACI 318-99 Section 12.2.3. If necessary consider references given in *FEMA 306*.
Beam moment:	Flexural cracks to remain small (e.g., 1/8 inch) and no significant spalling should occur.	$M \le 2.5\ M_n$
Beam Shear	Shear failure does not occur. Any shear cracks are minor.	$V \le V_n = 3\beta\sqrt{f'c} + V_s$, similar to *FEMA 306*
Column Moment	Flexural cracks to remain small (e.g., 1/8 inch) and no significant spalling should occur.	$M \le 2.5\ M_n$, and $\varepsilon_c \le 0.003$
Column Shear	Shear failure does not occur. Any shear cracks are minor.	$V \le V_n = V_c + V_s + V_p$, per Priestley and Kowalsky

Table 3 Example of Expected Material Strengths

Material	Specifications given in the structural drawings	Expected Strength
Reinforcing Steel, 25mm (#8) and larger	ASTM A432	f_y = 450 MPa (65 ksi)
Reinforcing Steel, 22mm (#7) and smaller	none	f_y = 340 MPa (49 ksi)
Concrete	25.8 MPa (3750 psi) regular weight	f'_c = 31 MPa (4500 psi)

The value of 2.5 for flexural demands should possibly be reduced, to 2.0 say, in cases where buildings have a shorter period than the site period. This is similar to the C_1 variable of *FEMA 273* [ATC 1997]. The proposed criteria for shear behavior modes is generally more restrictive than what is used for new buildings that are essential facilities. These two points indicate that codes for new essential facilities may not be sufficient to provide immediate occupancy performance. The situation can be worse for structural systems such as moment frames that use higher *R* values.

Recommendations

The proposed criteria tend to give much more specific requirements to the engineers than *FEMA 273*. I recommend that specific requirements such as in Table 2, focused on a particular building types and performance levels, should be developed as part of a revision, expansion, and calibration of *FEMA 273*. This would greatly improve the usability and reliability of the document.

To my knowledge, no one has examined from a performance-based perspective whether the codes for new essential facilities would provide immediate occupancy performance. This would be a useful study.

CONCLUSION

Recent performance-based seismic guidelines such as *FEMA 273* [ATC 1997] have greatly improved the awareness of practicing engineers in considering nonlinear response and the behavior modes of structural components. The recommendations given throughout this paper are some of the essential changes and expansions that should be made to performance-based guidelines to improve their usability and effectiveness.

REFERENCES

ASCE, 1998, *Handbook for the Seismic Evaluation of Existing Buildings — A Pre-standard*, prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Report No. *FEMA 310*, Washington D.C.

ATC, 1996, *Seismic Evaluation and Retrofit of Concrete Buildings*, prepared by the Applied Technology Council (ATC-33 project) for the California Seismic Safety Commission, Report No. *ATC-40*, Redwood City California

ATC, 1997, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, prepared by the Applied Technology Council (ATC-33 project) for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Report No. *FEMA 273*, Washington D.C.

ATC, 1997, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, prepared by the Applied Technology Council (ATC-33 project) for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Report No. *FEMA 273*, Washington D.C.

ATC, 1999, *Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings*, prepared by the Applied Technology Council (ATC-43 project) for the Partnership for Response and Recovery, published by the Federal Emergency Management Agency, Report No. *FEMA 306*, Washington D.C.

Aschheim, Mark, Joe Maffei, and Edgar Black, 1998, "Nonlinear Static Procedures and Earthquake Displacement Demands," *Proceedings, Sixth U S National Conference on Earthquake Engineering*, Seattle, Washington, Earthquake Engineering Research Institute, June

Blume, John A., Nathan A. Newmark, and Leo H. Corning, 1961, *Design of Multistory Reinforced Concrete Buildings for Earthquake Motions*, Portland Cement Association, Skokie, Illinois.

BSSC, 1992, NEHRP Handbook for the Seismic Evaluation of Existing Buildings, prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Report No. FEMA 178, Washington D.C.

ICBO, 1997, *Uniform Building Code*, Volume 2, Structural Engineering Design Provisions, International Conference of Building Officials, Whittier California.

ICC, 1998, *International Building Code 2000*, Final Draft, International Code Council, Falls Church Virginia, July

Maffei, Joe, 1999, *Case Studies of FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Final DAP Report*, J. Maffei, member of the Design Assessment Panel, Oakland CA, June

Merovich, A. T., 1999, *Case Studies of the NEHRP Guidelines for the Seismic Rehabilitation of Buildings, Final Project Report*, prepared for the Building Seismic Safety Council, Washington D.C.

Park, R., 1997, "A Static Force-Based Procedure for the Seismic Assessment of Existing Reinforced Concrete Moment Resisting Frames," *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol. 30, No.3, September

Paulay, T., 1996, Seismic Design for Torsional Response of Ductile Buildings, *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol. 29, No.3, September

Paulay, T. and M. J. N. Priestley, 1992, *Seismic Design of Reinforced Concrete and Masonry Buildings*, John Wiley and Sons, New York

Powell, Graham., 1994, "Nonlinear Analysis," *The Developing Art of Seismic Engineering, SEAONC Fall Seminar Papers*, Structural Engineers Association of Northern California, San Francisco, CA, November

Priestley, M. J. N., 1995, "Displacement Based Seismic Assessment of Existing Reinforced Concrete Buildings," *Proceedings of Pacific Conference on Earthquake Engineering*, Vol. 2, Melbourne, pp 225-244.

R&C, 1999, *Seismic Evaluation Reports for Edwards Building, Quillen and Blackwelder Buildings, Mudd Chemistry Building, Herrin Hall and Labs, Wurster Hall, Briggs Hall.* (Individual project reports from 1997 to 1999) Rutherford & Chekene Consulting Engineers, San Francisco CA

SANZ, 1992, *Code of Practice for General Structural Design and Design Loads for Buildings* NZS4203, Standards Association of New Zealand

SEAOC, 1999, *Recommended Lateral Force Requirements and Commentary*, Seismology Committee, Structural Engineers Association of California, Sacramento California.