Paper No. 2008. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC EVALUATION OF EXISTING BUILDINGS STATE OF THE PRACTICE

WILLIAM T. HOLMES

Vice President, Rutherford & Chekene Consulting Engineers
San Francisco, California, USA

ABSTRACT

Seismic evaluation of buildings takes many forms and is used to project probable damage levels, develop economic losses, set priorities for mitigation, and to determine specific deficiencies in individual buildings. Because the costs of risk reduction are often high, the results of evaluation have become increasingly important. The social, economic and political issues often associated with seismic evaluation are briefly discussed, but this paper is focused on methods to provide reliable projections of future damage to existing buildings--the essence of evaluation. Evaluation methods ranging from statistical analysis of inventories to nonlinear analysis of individual buildings are discussed. The various evaluation methods have many commonalities and needed improvements are identified.

KEYWORDS

Building; evaluation, inventory; damage states; performance based design; displacement; risk; fragility; probability; rehabilitation; retrofit.

INTRODUCTION

In most seismic regions of the world, older buildings, originally built with inadequate seismic resistance, constitute by far the largest risk of economic and life safety losses. However, the cost of complete remedies, either by replacement or rehabilitation, is so high that prioritization by evaluation of probable performance has become extremely important. Although seismic evaluation is often thought of as simply comparison of certain parameters with predetermined acceptance criteria, any estimate of future seismic performance is based on the same principles and should be considered evaluation in the broad sense. Evaluation, therefore, can occur on many levels and for many different purposes, ranging from estimates of probable loss to inventories by insurance companies, to classification of risk by building classes, to detailed analysis of single buildings. The interest in evaluation can be generated by concern over the direct cost of damage, the loss of business as a result of lost facilities, the loss of facilities critical to post earthquake response and recovery, historical preservation, or importantly, the threat of significant life loss. Although evaluation for the purpose of determining life safety risk is normally performed on older buildings, many of these interests may require evaluation of relatively new buildings as well.

Structural intervention to improve seismic performance--herein called *rehabilitation* [1] --is inextricably entwined with evaluation, but consideration of the intervention process involves issues of strategies, physical techniques, and design methods. All evaluation methods discussed herein could be equally applied to archaic, rehabilitated, or new structural systems, either damaged or undamaged. In fact, analytical techniques used to verify the adequacy of proposed seismic improvements are often identical to those used for detailed evaluation, particularly when performance based design is incorporated into the methodology. However, to create a relatively specific focus for this paper, issues peculiar to seismic rehabilitation or new design processes will not be covered.

The socio-economic issues associated with evaluation will first be summarized and separated from the technical issues. An overview is then given of the various types of evaluations commonly employed. An example of a comprehensive evaluation methodology for individual buildings that in many ways is more advanced than design requirements typically used for new buildings is described in detail. Finally, aspects of current evaluation techniques that need improvement are discussed.

It should be noted that there are hundreds of reports and papers published within the general subject area of seismic evaluation of existing buildings, including a 1995 european state of the art report (Anicic, 1995). In addition, organized efforts are constantly underway world wide to improve and standardize seismic evaluation, making it difficult to paint a definitive picture of the state of the practice. For example, ongoing work in New Zealand, within Eurocode (Part 1.4 of Eurocode 8), and Japanese efforts following the Hyogoken-Nanbu earthquake were not reviewed for this paper. Therefore, it is not proposed that every concept proposed or under development is covered, but rather examples are given of practical methods currently used or proposed for use to evaluate the expected seismic performance of buildings.

SOCIAL ECONOMIC AND POLITICAL ISSUES

Public policy issues such as *when* to evaluate and *when* to retrofit often get mixed with technical issues surrounding *how* to evaluate. If the technical community can reliably estimate probable performance, it should be the responsibility of policy makers to determine acceptable risk for the community, just as the business person decides what life safety and economic seismic risk is acceptable for private facilities. Such decisions can be influenced by availability of funding, considerations of overall benefit-costs, historic preservation, and the potential effect of evaluation and rehabilitation on the availability of low cost buildings, for housing or commercial use.

Aspects of risk reduction programs that require public policy (or building owner) input include selection of which buildings should be included in the program, and under what conditions, and definition of safety or other performance criteria.

Often, the incentive to develop standardized evaluation methods has come as the result of damaging earthquakes. Buildings in the affected area are generally put in one of three categories: 1) the damage is insignificant and no action is needed, 2) the damage is minor and can be repaired , or 3) the damage indicates that the building should be rehabilitated. Criteria to categorize damaged buildings is often built into the evaluation method such that the issue of acceptable risk cannot be clearly identified and considered separately. The disposition of damaged buildings is a complex issue that heavily depends on public policy concerning both risk reduction and regional recovery (Holmes, 1994). Ideally, these policies should be set

---

[1] Terminology is inconsistent and conflicting worldwide. Although there are efforts within the U.S. to use the term *rehabilitation* for any intervention to improve performance, it is understood that this term is used in some countries in other ways. Other terms often associated with improving seismic resistance of existing buildings, but used inconsistently, include, *retrofit, strengthening, upgrading, restoration, reconstruction*, and *repair*. In this document, *rehabilitation* will be used for the general term for improvement of seismic performance and *repair* will be used to denote restoration to original structural characteristics.

prior to damaging earthquakes and would depend, technically, only on reliable estimates of expected performance of the damaged buildings. The issue of damaged building and their disposition is not directly covered in this review. although any general evaluation method should be able to be applied to damaged buildings with appropriate reduction in strength or stiffness of damaged elements.

Historic buildings and monuments create a major issue in seismic regions due to the conflict between preservation of fabric and structural intervention to maintain stability and safety. Special considerations should always be included in any such intervention. However, evaluation methods for such historic buildings should strive for the same goal as methods for normal buildings--reliable estimation of seismic performance. To facilitate appropriate decision making, the evaluation itself should be comparable to the results for other buildings. Considerations of the historic importance of the structure should be incorporated into such decisions as whether rehabilitation is justified at all, to what level should the building be rehabilitated, and which method of intervention is to be used.

Several routines to calculate benefit-cost ratios and life-cycle costs for rehabilitation have been developed in the last decade.(e.g. Dong et al, 1988; FEMA, 1992b; Todorovska, 1995). These calculations combine probable damage under various levels of shaking with the probability of occurrence of the shaking and convert these probable future damages to either an annual loss or to a total present worth. The value of losses can then be compared to the cost of rehabilitation or insurance as an aid to decision-making. Losses can include direct structural and nonstructural damage, lost use of the facility, and even the value of lives lost. A recent FEMA (U. S. Federal Emergency Management Agency) document (FEMA, 1992b) includes a particularly complete discussion of potential losses and methods to estimate the value of such losses. These methods depend on the reliability of both the estimates of damage and the probability of future shaking levels, both of which normally carry such variation that results should only be considered advisory. Improved evaluation methods or more complete damage data from actual events could improve confidence in these calculations. Benefit cost ratios of proposed rehabilitation should not be used as an acceptability criteria when evaluating existing conditions without a thorough understanding of the public policy implications.

Another socio-economic issue associated with reducing the seismic risk from existing buildings is the development of rules governing which buildings must be rehabilitated and within what time frame. Similar to the issues discussed above, these rules will primarily be determined by the risk the community finds acceptable and should not be integrated into evaluation methods.

Social, economic, and political issues should be prime considerations in any program to reduce the seismic risk from existing buildings. However, methods of evaluating existing conditions should be constructed to enable consideration of these issues separately from the technical evaluation of future performance. This separation will enable immediate incorporation of technical improvements into these methodologies as well as facilitate development of rational mitigation plans based on accurate relative risks. The technical community should concentrate both on improving evaluation reliability and developing more thorough dialogue with policy makers.

TYPES OF EVALUATION

Seismic evaluations of existing buildings can be performed at many different levels for many different reasons, particularly when the term evaluation is generalized to mean any attempt to predict earthquake damage to buildings. The following levels of evaluation are briefly discussed in this paper, although the definition of categories is somewhat arbitrary and each tends to overlap with one or more of the other:

- Estimates of economic risk for financial institutions
- Estimates of performance for regional loss studies
- Generic screening
- Field screening
- Preliminary evaluation of individual buildings
- Detailed evaluation of individual buildings

Interestingly, a significant portion of the progress towards more reliable evaluation is due to advances in computer technology rather than development of new theories or improved understanding of the nature of structural response to seismic motion. Larger and faster computers have improved our capability to analyze the characteristics of recorded ground motions, estimate future ground motions at any site, document and analyze damage data, perform repetitive calculations required by evaluation of large inventories, record and analyze the results of laboratory tests of structural elements, and model and analyze complex structures, linearly or nonlinearly. The majority of the methods discussed below require use of computers in one way or another, but this is now a commonly accepted requirement.

Estimate of Economic Risk for Financial Institutions

Techniques to obtain rapid and inexpensive estimates of probable or maximum future losses are needed by the insurance industry and other financial institutions to measure the risk represented by inventories of thousands of owned or insured buildings. This is done today by computer programs that require input of only the building's location and a few basic structural characteristics. The programs calculate expected shaking at the site based on distance from known sources, or from previously input regional shaking intensity maps. The first generation programs now in use generally pre-date practical Geographic Information System (GIS) technology and are based on coordinate geometry calculations. Direct economic losses based on Damage Probability Matrices (DPM) are then derived. Table 1 illustrates a DPM from the ATC 13 document (ATC, 1985).

Table 1. A typical Damage Probability Matrix. The central damage factor measures the damage as a percentage of building replacement cost. The entries in the table are the percentage of buildings in each damage state for the given MMI shaking intensity. (ATC, 1985, p 205)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=36						
	VI	VII	VIII	IX	X	XI	XII
0.00	50.9	***	***	***	***	***	***
0.50	49.1	86.6	20.0	1.1	***	***	***
5.00	***	13.4	80.0	88.9	62.5	7.8	***
20.00	***	***	***	10.0	37.5	71.1	21.4
45.00	***	***	***	***	***	21.1	74.1
80.00	***	***	***	***	***	***	4.5
100.00	***	***	***	***	***	***	***

There are many such examples of systematic development of seismic vulnerability (e.g. Gulkan et al, 1992; Jara et al, 1992). Losses can be adjusted up or down considering certain seismic attributes of the building and site soil conditions. Losses from business interruption can also be estimated with relationships between directly losses and probable downtime.

By combining probabilistic characteristics of shaking intensity with DPMs or fragility curves, losses can be estimated probabilistically and put in the format of probable annual loss, facilitating determination of appropriate insurance premiums. Similarly, if a single event is modeled and loss parameters set at the pessimistic end of the distributions, a worse case scenario can be estimated for a given inventory for the purpose of setting aside proper reserves. Although the individual calculation methodologies involved for these estimates are well documented in the literature, the base data of seismic source geometry and DPMs , as well as program's user interface, is typically proprietary.

Although a specific probabilistic loss calculated from a DPM may be inaccurate for any individual building, the aggregate losses averaged over many buildings of a similar type are limited only by the accuracy of the DPMs themselves. DPMs are usually generated using a combination of actual loss data and expert opinion, and due to the difficulty of collecting statistically relevant loss data for many different building types, the accuracy of currently used DPMs is largely unknown.

Estimate of Performance for Regional Loss Studies

Considering that it is not feasible to adequately mitigate seismic risk in most areas, post earthquake planning and response is extremely important. An important component of planning is development of realistic regional damage scenarios. Scenarios normally include estimates of building damage and closures, casualties, condition of essential response facilities, condition of transportation systems, and availability of utilities such as power, gas, and water. Results of these studies can be used to maximize efficiency of community wide rehabilitation and replacement programs, develop effective emergency response plans, and prepare for efficient economic recovery.

In the U. S., FEMA, through the National Institute of Building Sciences (NIBS) is developing a computer-based standardized methodology to prepare regional loss studies. As part of the project, a summary state of the art document (RMS/CUREe, 1995) was prepared that provides an excellent background as well as an annotated bibliography covering the subject. The computer program, called *HAZUS*, is written in a GIS environment, allowing maximum flexibility for inputting geographic data such as inventory location, soils maps, and layout of lifelines. It will incorporate estimates of all significant type of regional losses and include analysis of effects on local economies. The program is currently undergoing beta testing and is expected to be released by FEMA in late 1996. Although intended for use in the U. S., seismic characteristics and inventory data appropriate for other areas could be input into the calculation shell.

Estimates of damage to buildings form a significant portion of regional loss studies. Historically, methods used were similar to those used by the insurance industry, applying relationships between shaking intensity and damage levels to different building types. In the development of HAZUS, it was concluded that the traditional DPM parameters of percentage of replacement cost and shaking intensity (See Table 1) were not sufficiently flexible to allow separation of structural and nonstructural damage, to be adequate measures of number of casualties, loss of building function, or to describe to planners the likely condition of the community. It was decided that, if the building inventory was placed into descriptive damage states, a more realistic picture of post earthquake conditions could be created, and improved algorithms for casualties and business interruption could be derived. In addition, spectral ordinates were considered the most flexible and technically accurate measure of shaking characteristics at any site. A damage estimating methodology was devised using a structural response analogy developed over the last 15 years by Freeman (Freeman, 1994), the Capacity Spectrum Method. Building types are represented by characteristic nonlinear force deflection curves ("pushover curves"). Response spectra, created by conventional attenuation equations (or otherwise input into the program), are converted to plots of spectral acceleration versus spectral displacement and superimposed on a pushover curve representing a given building type. The intersection of the two curves is taken to represent the displacement demand of that class of structure. Fragility curves for the same class of structure are then used to translate the displacement demand into the various damage states. The method is generally described in Figure 1, taken from documentation in progress (RMS, 1995) The damage states can then be used directly to estimate direct losses, building disruption and casualties. The method offers great flexibility to represent all types of structural behavior; site specific response and initial pushover curves and fragilities are being calibrated to match currently available damage data and expert opinion. New building types can be added or adjustments made to representative pushover curves as new data becomes available.

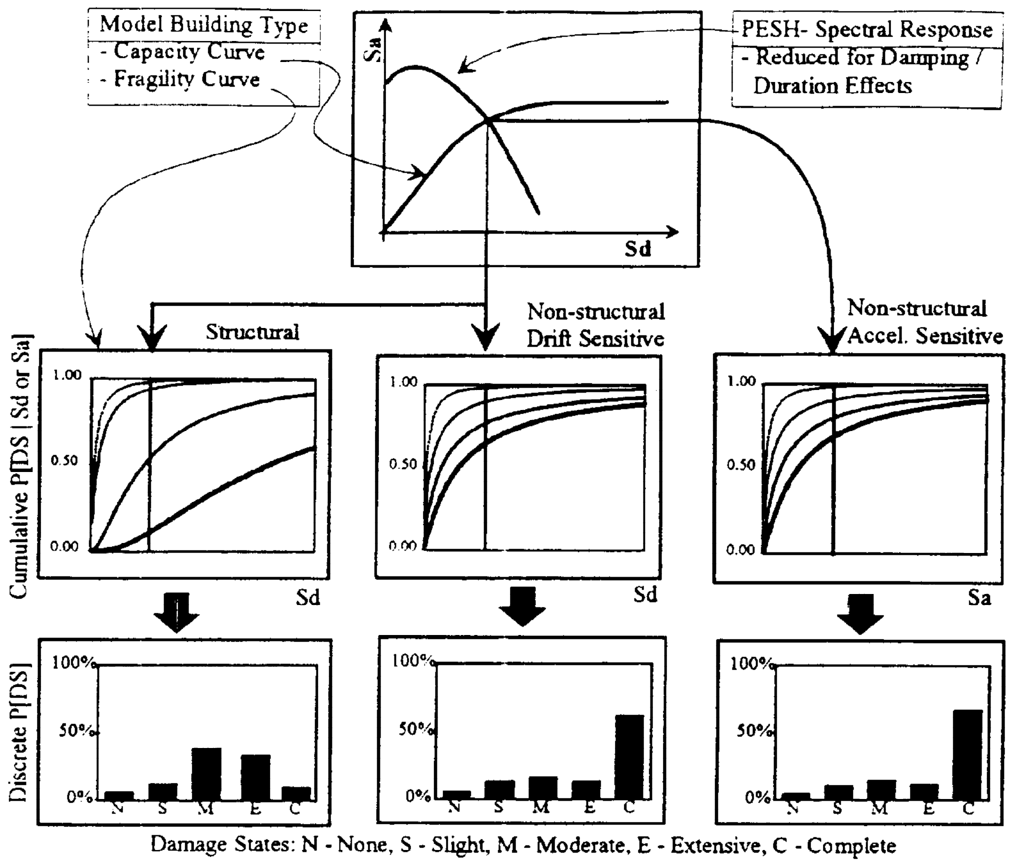

Figure 1. The building damage algorthm incorporated into the NIBS standardized earthquake loss program, HAZUS (RMS, 1995, p. 5-60)

Generic Screening

The first step in most risk reduction programs is an initial screening of the complete building inventory. The purpose of such screenings is to reduce the overall evaluation problem as much as possible with generic data such as age, building size, and structural type. Occupancy and site condition are also often used. At this level of evaluation, only three categories of buildings can be created: 1)Seismically adequate, 2) Unknown, but potentially inadequate, and 3) Known to be inadequate. Buildings placed into the "Adequate" category may include very small or unoccupied buildings, buildings with adequate seismic designs by reason of their construction date, and certain building classes that may have long histories of adequate performance in the area under consideration. The "Inadequate" group could include classes of buildings known to consistently perform poorly such as certain types of unreinforced masonry or concrete frames without ductile detailing. Other buildings, that unfortunately often form a large majority, must be categorized "Unknown." These categories can be created within known databases, considering the actual building types represented, or within community wide inventories in which the exact content of building types and ages can only be estimated by local expert opinion. This process, assuming that numbers of each building type is known or can be estimated, can be used to obtain a rough approximation of the seriousness of the seismic risk represented by the inventory without the more costly process of a specific loss study as described above.

In the simplest case of screening, a single building type is identified as the worst risk and scheduled for mitigation with the balance of the inventory left uncategorized. Evaluation, in these cases, is incidental to the rehabilitation process, as buildings are checked against mandated rehabilitation requirements. A clear example of this process is the program to reduce the risk from unreinforced masonry buildings in California using procedures originally developed in Los Angeles and eventually codified in the Uniform Code for Building Conservation (ICBO, 1994). New Zealand has adopted similar regulations governing these buildings (NZNSEE, 1985). Other examples of generic screening include decisions to identify and rehabilitate certain residential building types in selected areas of China in the early eighties (Niu, 1981), and the requirement to evaluate essential facilities in Mexico City following the 1985 earthquake.

When more complete screening or categorization is accomplished, buildings or building types within the Unknown and Inadequate categories are often prioritized for further evaluation or rehabilitation. This is commonly done using scoring methods that combine several parameters such as building type, importance, number of occupants, or site soils

Field Screening

The evaluation methods discusses above are generally done with little or no knowledge of the characteristics of individual buildings--other than generic categories-- and the results are only valid as averages over large numbers of similar buildings. The variation in vulnerability between buildings of the same class can only be done if additional characteristics are gathered on a building-by-building basis. This is often done in rapid field surveys, allotting as little as one-half hour per building. The effectiveness of such surveys vary greatly depending on the inventory. If information is being gathered on selected building types that feature few finishes and important seismic features can easily be seen, masonry churches in Italy, for example (Doglioni, 1992), effective grading can be accomplished. Much less can be deduced in field reviews of highly varied inventories in metropolitan areas. In such cases, base data, such as age and construction type, is often needed to supplement information available from rapid field observations. The goal of evaluation of buildings at this level is normally the assignment of a seismic performance or risk index, that can be used for prioritization. In some cases, categories of Adequate, Unknown, and Inadequate, as discussed above, can be created but absolute cutoffs between categories must be set very conservatively unless only well studied building classes are included.

Evaluations of single building are also often performed at this level, without calculations and relying of past performance of similar buildings and engineering judgment. Unless the building falls into a clear Adequate or Inadequate category, the results must be given qualitatively, equivalent to indexing within the entire building population. A rapid screening methodology of this type was developed in the U. S. (FEMA, 1988). Similar to other screening methods, its reliability has not been systematically measured.

Perhaps the best screening method is a judgmental placement of individual buildings into preset categories. These methods require no analysis, but are limited to use by experts and require drawing-level knowledge of the structures. The University of California successfully used a system in the seventies with simple descriptors of *good, fair, poor, and very poor* (McClure, 1988). Although these categories were defined, primarily with reference to life safety, the classifications were sometimes difficult to interpret in various zones of seismicity, or between different experts. An improvement in the method may be to define the categories by describing probable damage states for a given level of shaking, that may enable more flexible use and consistent classification.

In a review of many of the many rapid assessment methods proposed or in use, A. Corsanego suggests that assignment of indices based only on physical characteristics, without calculated estimates of actual capacity, may be most useful on older buildings of a single class, whereas more modern building types using a variety of construction materials and methods may require at least preliminary estimates of capacity (Corsanego 1995). Corsanego also expressed concern about the difficulty of collecting sufficient damage data to confirm or calibrate indexing methods, which has been a continuing problem with damage probability data as well as indexing systems.

Methods for Evaluation of Individual Buildings

For the purposes of this paper, any method that requires knowledge of the structure in enough detail to perform even simplified analysis is classified evaluation of individual buildings, rather than screening. This covers a wide variety of methods and may involve spending anywhere from a day to several weeks performing an evaluation on an individual building. Most systems of evaluation developed to date have incorporated various levels or phases of review. In the manner, simple or clear cut cases can be classified efficiently without extensive analysis.

The most obvious way to evaluate an existing building is to analyze its compliance with the provisions for new buildings. This method has two major shortcomings: 1) there is no explicit method to consider older materials and methods no longer covered by code, or structural elements that may not meet current detailing requirements (e.g. ductile reinforcing patterns in concrete), 2) the performance standard--that standard "built-in" to codes for new buildings and often ill defined-- is preset and difficult to adjust. In the majority of regions where significant evaluation or rehabilitation has been done, special guidelines or standards have been developed in response to these problems as well as to obtain consistency of results within the engineering community.

In some cases, such as Mexico City after the 1985 earthquake, significant changes in criteria would indicate use of the new code unless extensive site and building analysis is done. In that circumstance, significantly damaged buildings and all critical facilities used the post earthquake code developed for new buildings as evaluation and design criteria.

Special considerations for seismic evaluation of existing buildings in the U. S. has been under development for some time (e.g. Culver et al, 1975), but no particular method developed into a standard, commonly used procedure. In 1985, FEMA undertook an ambitious program to provide tools to reduce the risk from existing buildings (Morelli, et al, 1993). Part of that program included development of a nationally applicable and practical evaluation guideline. In 1991, rather than developing a new methodology, FEMA, through subcontractors BSSC and ATC, developed FEMA 178, *A Handbook for the Seismic Evaluation of Existing Buildings* (FEMA, 1992a), that was based on the document previously developed by ATC, *Evaluating the Seismic Resistance of Existing Buildings* (ATC, 1987). The entire methodology is intended to prevent life threatening damage for the ground motion intensity used as a basis for the design of new buildings. Higher performance levels that might be appropriate for essential or critical facilities are not covered.

The FEMA 178 handbook is somewhat unique among evaluation documents in that the performance history of different building types is directly incorporated into the methodology rather than used simply as background in the development of the procedure. List of possible deficiencies, based on observation of past performance, form the initial review. If no conditions exist that would indicate the possible presence of a deficiency, the building is considered to be in compliance with the guidelines, and no further analysis is required. In many cases, however, observed potential deficiencies require analysis. The analysis is an equivalent lateral force procedure, parallel to the code methods for new buildings. Acceptability criteria is included for most elements and systems expected to be found in the building stock of the United States, based upon the probable difference in performance with equivilent new elements. The force levels used for the analysis procedures is approximately 75% of those used for the design of new buildings.

The FEMA 178 document filled an important need at a time when the interest in seismic evaluation and rehabilitation was high and has become widely used in the United States. Canada has also adopted a similar document .

Japanese engineers were confronted with their first significant demand to evaluate and strengthen existing buildings, primarily damaged structures, following the 1968 Tokachi-oki earthquake. This interest led to the development of several standards for evaluation and rehabilitation covering reinforced concrete, steel, and wood construction. The standard for reinforced concrete buildings is particularly complete and detailed and is intended to evaluate the seismic performance of existing and damaged reinforced concrete buildings, except high-rises (Hirosawa, 1994).

The *Standard for Evaluation of Seismic Capacity of Existing Reinforced Concrete Buildings,* by the Japan Building Disaster Prevention Association, features three levels of evaluation, each one being more complex and time consuming, but more reliable, than the previous. An index measuring capacity is compared with a preset "judgment" index based on a combination of seismic demand, the level of analysis, and the importance of the use of the building. For the first level, the capacity is measured using the horizontal strength of the building based on the sum of horizontal cross sectional area of the structure, a factor for configuration. and a factor measuring damage or deterioration. For the second level, the capacity index considers the capacity, failure mode, and ductility of each element and incorporates more complicated indices measuring configuration and damage or deterioration. The capacity in level three considers a limit analysis of the entire structure and incorporates appropriate ductility for combination with the configuration and damage indices (Hirosawa, 1994).

Current Developments

Many sophisticated techniques are currently being used on individual projects, including in-place measurement of dynamic properties, in-place load tests, laboratory testing of duplicated structural elements, detailed finite element analysis of isolated elements of systems, and nonlinear time history analysis of entire structures. However, perhaps the broadest and most complete methodology intended for general use by practitioners currently in development is the *Guidelines and Commentary for Seismic Rehabilitation of Existing Buildings*, by the Building Seismic Safety Council, under funding by FEMA in the United States. The Guidelines are the culmination of the previously mentioned FEMA program directed at existing buildings. The Applied Technology Council is BSSC's subcontractor to develop the Guidelines and the American Society of Civil Engineers is also involved in the 5 year, $8 million effort. A 75% completion draft was published for internal use in December of 1995 (ATC, 1995)., and the 100% draft in due to BSSC in September of 1996. An additional year has been scheduled for review and concensus approval. Many presentations have been given and overview papers completed on this project (e.g. Hamburger, 1995), including several to be given at this 11th World Conference, so only a broad summary will be given here.

Framework. The Guidelines were originally intended for the purposes of design of rehabilitations, but it was quickly recognized that, if an unaltered existing building was put through the analysis and acceptability procedures, the results would represent an evaluation of as-is conditions. Because the methodology is thought to be more reliable and less conservative than other existing methods, it is expected to be widely used for both evaluation and rehabilitation.

The project was ambitious from the start, seeking to incorporate all of the following characteristics:

- Consider both structural and nonstructural components
- Explicitly cover most, if not all, structural elements found in existing buildings in the United States, including those of wood, masonry, concrete, steel, and common combination of these materials
- Apply in all seismic zones
- Allow for simple designs where appropriate
- Provide sufficient guidance to yield consistent results and to be enforceable by building officials.
- Incorporate designs intended for several different levels of seismic performance (performance based design)
- Adaptable for use either by owners of individual buildings who voluntarily desire to reduce their seismic risk, or by local jurisdictions as a required standard in programs that target certain buildings or groups of buildings.
- Cover new technology such as base isolation and the addition of damping devices.
- Allow for easy addition of new test data covering the behavior of existing components, strengthened components, or new innovative technology.
- Based on scientific principles such that the basic dynamic structural response to the shaking and material behavior would not be obscured.

Because of the high economic impact of seismic rehabilitation, the document was not intended to serve as a national minimum standard or adopted in toto into codes, but would be most useful if applicable to the wide variety of current rehabilitation demands in the country. In fact, the need to be performance based stemmed from the wide range of probable applications including, for example, owners who desire certain seismic building performance to protect their business, owners who simply want to reduce their seismic risk within a certain budget, and jurisdictions who want to locally adopt standards to protect the public safety.

Design flexibility to achieve a wide variety of performance is achieved by specifying the intended performance through a Rehabilitation Objective that consists of 1) a desired damage state (performance level) for 2) a given level of shaking defined probabilistically or deterministically (hazard level). Four Performance Levels are defined and termed, *Operational, Immediate Occupancy, Life Safety, and Collapse Prevention,* as shown in Figure 2. Any hazard level can be used, but national maps are available for spectral ordinates with 2%, 5%, and 10% chance of exceedance in 50 years, and these levels are expected to be commonly used. A smaller serviceability event may also sometimes be considered with a 50% chance of exceedance in 50 years.

As explained above, the document is intended primarily for local voluntary use. But in order to set a common national index, a Rehabilitation Objective called the *Basic Safety Objective* is specifically defined as performance that meets the Life Safety Performance Level for a ground motion with a 10% chance of exceedance and, in addition, meets the Collapse Prevention Level for a rare, large event (2% chance of exceedance in 50 years).

Analysis Methods. In order to provide tools for the wide range of probable users of the guidelines, several methods are provided for designing rehabilitation measures. For certain smaller and simpler building types, a *Simplified Method* is defined. Four *Systematic Methods* are provided for more general use.

The Simplified Method is based on the same equivalent static force procedures used in U.S. codes for new buildings and is an extension of the FEMA 178 evaluation procedure previously discussed. In essence, the procedure consists of checking the rehabilitated structure with the FEMA 178 evaluation criteria. When all new, existing, or altered elements meet the criteria, the rehabilitation is considered to meet the Life Safety performance level for the event with a 10% chance of exceedance in 50 years, for which is was originally developed. The entire suite of Rehabilitation Objectives featured in the balance of the document in not

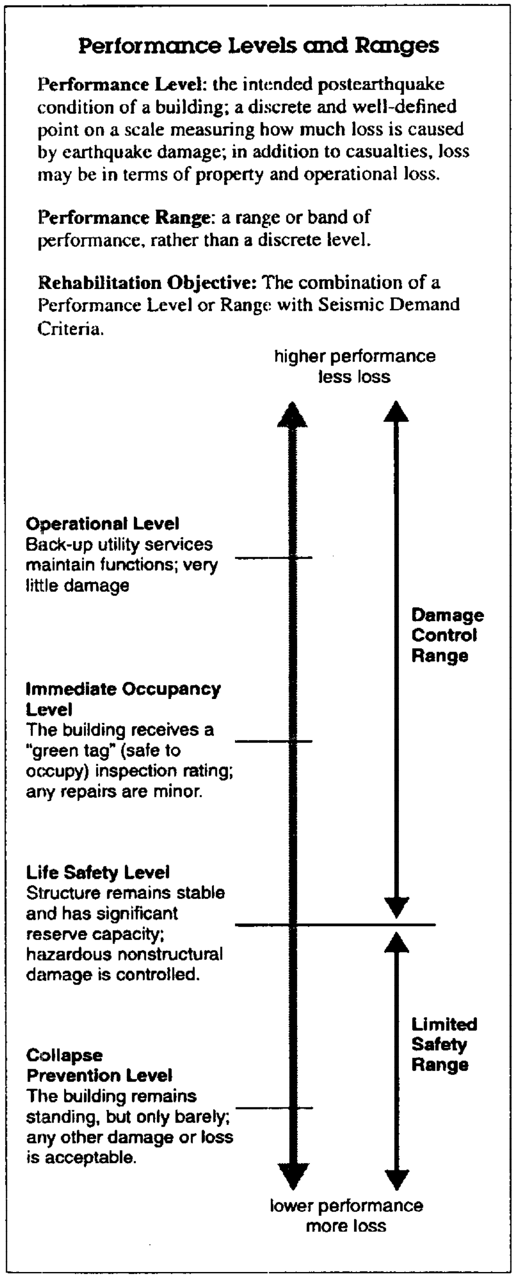

Figure 2. Performance Levels used in the FEMA Guidelines (ATC, 12995, p 1-20)

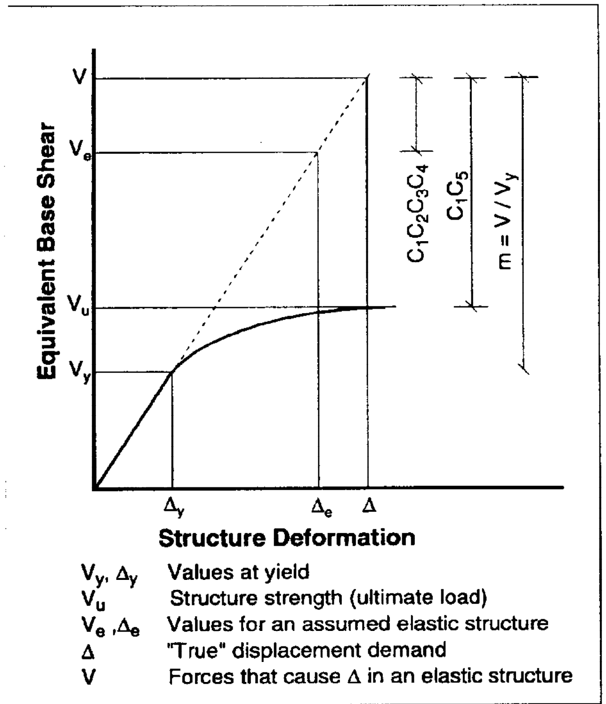

Figure 3. The basis for the Linear Analysis Procedure in the FEMA Guidelines (ATC, 1995, p C3-2)

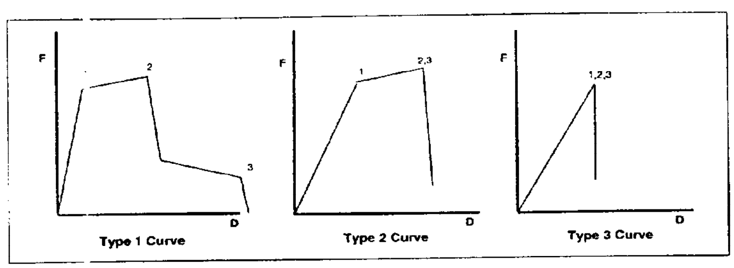

Figure 4. General component behavior curves used in the FEMA Guidelines (ATC, 1995, p 2-35).

available for the Simplified Method. Since this method is based on a previously developed system for evaluation of buildings, it will not significantly enhance our current evaluation capability.

The Systematic Methods are all based on the deformation demands put on the structure from the seismic motion, and therefore represent a significant departure from other U.S. building codes. Use of deformation allows much better evaluation of mixed systems with widely ranging stiffnesses and ductilities, as are commonly found in rehabilitated structures. The methods vary in level of effort and complexity, and are termed the Linear Static Procedure (LSP), the Linear Dynamic Procedure(LDP), the Nonlinear Static Procedure (NSP), and the Nonlinear Dynamic Procedure (NDP). The seismic demand used in the Systematic Methods is represented by a response spectrum created from mapped parameters and considering site specific soil conditions. Since all four methods can be applied to an existing structure with no rehabilitation measures in place, they can be used for evaluation, to take advantage of the better measure of capacities of elements as well as to consider rehabilitation objectives other than Life Safety.

The linear methods are intended to provide an option for practicing engineers to use familiar methods, while actually performed analysis and design on a very different basis.. Although demand and capacity is specified to measure deformations, appropriately proportional force-related actions, such as axial load, moment, and shear, are used in the analysis and acceptability criteria. Fictitious lateral forces that will create a deformed shape appropriate for design purposes are determined by adjusting the calculated elastic deformation response to the probable inelastic deformation response. Coefficients are used for this purpose that consider the period, damping, and hysteretic behavior of the structure, as shown in Figure 3. Individual structural components are checked for adequacy for either deformation capacity or strength as appropriate. Deformation capacity is given in the document as a multiplier of yield capacities. Specific guidance is given to estimate the maximum force expected on a brittle element, which is to be resisted by capacities determined by traditional yield strength methods. Capacity design or limit state design procedures are encouraged to determine maximum force demand on components. Acceptable component capacities, whether based on deformation or strength, are given for the various performance states for all common materials.

The LSP and LDP are similar in concept with the LSP using a first mode approximation of the linear response and the LDP being based a conventional linear spectral analysis

The NDP represents full nonlinear time history analysis that at the present time is considered overly burdened with assumptions and too time consuming to be developed into a realistic code-like methodology. However, since realistic structural deformations are being used as the primary analysis parameter in the Guidelines, this procedure can easily be formally integrated when more consensus is reached on models for material behavior, appropriate representative time histories are developed, and computer programs are developed to make the analysis more practical and consistent.

It is hoped that the NSP will provide a reasonable compromise between the potential inaccuracies of the linear procedures and the impracticality of the NDP. The NSP is based on the development of a "pushover" curve of lateral force versus roof displacement. The pushover curve is developed using a series of static analyses of a structural model that incorporates incremental changes of element stiffness and strength to represent damage. A displacement demand, estimated by first mode response, is used to define the deformed shape to be used for design, similar to the LSP, but nonlinear behavior is used to determine the details of the structural deformed shape. Consideration of nonlinear behavior in development of the pushover curve enables better approximation of local element displacement demands as well as maximum force demands. Although certain limitations of this analytical procedure are recognized, particularly complications from effects of higher mode response, torsion, or the presence of flexible diaphragms, it represents a major improvement over previous methods for most buildings.

Acceptability Criteria. Acceptability criteria for structural components have been developed for various performance levels by studying available dynamic test data. Envelopes of hysteretic curves have been created in accordance with preestablished rules and, in general, behavior categorized as shown in Figure 4. Strength and deformation capacities have then been established for various Performance Levels using consistent rules. Direct incorporation of expected cyclic behavior into the procedure provides a significant advantage over previous evaluation methods in that new test results of existing or altered components can be used immediately. In addition, parameters for untested components can be more easily estimated by comparison with similar assemblies with established values. Similarly, new technologies can be easily integrated into this analysis and acceptability format, reducing the time from development to general use.

NEEDED IMPROVEMENTS

Although the methods and techniques discussed above are either in use or nearly ready for use, none is considered to be without need of improvement. Improvements in the following areas could enable more efficient or more reliable evaluation for any of the purposes discussed.

Collection of Damage Data

The reliability of all evaluation methods is largely unknown. The collection of actual damage data sufficiently detailed to allow calibration of methods to evaluate individual buildings, or statistically complete enough to allow calibration of evaluation of inventories, is extremely time consuming and expensive. Most often, only damaged buildings are studied, perhaps distorting conclusions, and certainly preventing statistical analysis. Although there are examples of extensive collection of data for individual building types such as wood frame house in the U. S. (Steinbrugge, 1990), or Italian masonry buildings (Doglioni, 1992), this information is often adequate only for the narrow purpose for which is was collected, and is seldom transferable to other regions. The Applied Technology Council has collected a limited set of building-by-building data from the 1994 Northridge earthquake (ATC 38, in progress), but information on individual buildings is limited to that available from the street. In the U. S., data collection is often hindered by the privacy rights of individual owners. The Architectural Institute of Japan has collected an enormous and complete data set from the 1995 Hyogoken-Nanbu earthquake (AIJ, 1995), which will certainly be useful to determine fragilities by building type; however, even with this effort, information on the probable cause of damage within a given building type may be difficult to deduce.

Systematic, consistent, and practical data collection plans should be developed that will enable calibration of each type of evaluation effort currently used in seismic risk reduction programs. If data collection methods are consistent, data on many building types would be useful world wide. In addition, plans must be developed to efficiently use the data, because true calibration requires extensive and thorough analysis, consensus of the results, and the existence of procedural methods to efficiently incorporate changes.

Development of Standardized Damage States

The development of a standardized damage state scale would be extremely useful, tying the various evaluation techniques together, and enabling better transfer of data and technology between countries.

There are many similar scales in existence--e.g., damage states as defined in the MSK scale, or as listed in references (AIJ, 1995), (ATC, 1985), (RMS, 1995)--but none sufficiently general to provide consistency among the many possible uses. For example, in addition to describing damage for data collection, damage states are now being used in *performance based design*, to describe a desirable limiting damage to be used in the design of new buildings or rehabilitation of existing ones. A standard scale is needed that covers the entire range of performances and that can be used to measure the losses of primary interest: damage costs, loss of use of the building, and risk to life. Given such a generalized scale, more precise descriptions could be developed for each damage state to cover individual building types, including those that may be locally unique. The Structural Engineers Association of California have the beginnings of such a scale in their Vision 2000 document (SEAOC, 1995), which includes 10 steps ranging from *Fully Operational* to *Collapse*. However, this scale may not have sufficient flexibility to serve all needs. It may be necessary, for example, to describe damage to structural and nonstructural systems of a building separately to be adequate as a universal scale.

Another practical use of a comprehensive damage scale is to serve as an evaluation rating methodology. Given limited but description choices, evaluators of buildings in California seem to be more consistent when asked to place a building in a descriptive damage state than attempting to show compliance with specific technical criteria. In addition, a building categorized in a standardized damage state for a given seismic event is probably more useful to most owners than knowing compliance or non compliance with technical standard. Such a technique, possibly called *performance based evaluation*, is consistent and simply an extension of performance based design.

Practical Determination of Seismic Displacement Demand

Considering the expected nonlinear behavior of certain elements and the mixed systems found in many existing buildings, the most practical and reliable methods for evaluation and rehabilitation of existing buildings at the present time incorporate displacements as the primary response parameter, rather than force. Until full 3-D nonlinear time history analysis is more practical for general use, simplified and reliable methods to determine displacement demands appropriate for evaluation and design are needed. Although the Guideline being developed in the U.S. incorporate a useable method, consensus has not been reached on many of the details and limitations.

Material/Component Acceptability Criteria

Research of structural systems is generally aimed at improvement of the performance of new elements and components. Little information is available on the dynamic behavior of archaic systems found in older existing buildings. Whatever test data that is available is often based on static loading and incomplete in the nonlinear range. In order to more reliably evaluate existing buildings and efficiently rehabilitate them, considerable additional test data is needed concerning the structural systems commonly found in existing buildings.

Development of Practical New Methodologies

Despite the advancements in analysis techniques, practical evaluation methodologies currently in use do not adequately measure effects of duration of ground motion. Development of practical measurement of damage indices and development of design methods considering energy demands of seismic ground motion may therefor provide important improvements in reliability of seismic evaluation.

REFERENCES

Anicic, Drazen (1995). Repair and retrofit of building structures -- state-of-the-art report. In: *Proceedings of the Tenth European Conference on Earthquake Engineering, Vienna, Austria* (Duma, ed.), Vol.3, pp. 2199-2207. A.A. Balkema, Rotterdam.

Architectural Institute of Japan (AIJ)(1995). *Preliminary reconnaissance report of the 1995 Hyogoken-Nanbu earthquake, English edition.* Architectural Institute of Japan, Tokyo.

Applied Technology Council (ATC)(1985). *Earthquake damage evaluation data for California, ATC-13.* Applied Technology Council, Redwood City, Ca.

-- (1987). *Evaluating the seismic resistance of existing buildings, ATC-14.* Applied Technology Council, Redwood City, Ca.

-- (1995). *Guidelines for the seismic rehabilitation of buildings and commentary, 75% complete draft; ATC 33.03.* 3 vols. Prepared for the Building Seismic Safety Council with funding from the Federal Emergency Management Agency. .Applied Technology Council, Redwood City, Calif.

Corsanego, A. (1995). Performance indices and field seismic capacity assessment. In: *Proceedings of the Tenth European Conference on Earthquake Engineering, Vienna, Austria* (Duma, ed.), Vol. 2, pp. 2715-2721. A.A.Balkema, Rotterdam.

Culver, C.G., H.S. Lew, G.C. Hart & C.W. Pinkham (1975). *Natural hazard evaluation of existing buildings.* National Bureau of Standards, Washington, D.C.

Doglioni, F. (1992). Knowledge of the seismic vulnerability of churches through the analysis of damages caused by the seism in Friuli (1976): possible utilizations in planning projects of aseismic improvement. In: *Learning from practice: a review of architectural design and construction experience after recent earthquakes; proceedings of the Joint USA/Italy Workshop, Orvieto, Italy,* pp. 149-176. National Science Foundation, Washington, D.C.

Dong, Wie Min, Haresh Shaw, Felix Wong, and Jong Eup Kim (1988), *Guide to IRAS: An Insurance/Investment Risk Assessment System on Personal Computers*, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.

Federal Emergency Management Agency (FEMA)(1988). *Rapid visual screening of buildings for potential seismic hazards, FEMA 154 and 155.* Federal Emergency Management Agency, Washington, D.C.

-- (1992a). *NEHRP handbook for the seismic evaluation of existing buildings, FEMA-178.* Building Seismic Safety Council, Washington, D.C.

-- (1992b). *A Benefit-Cost Model for the Seismic Rehabilitation of Buildings, FEMA-227 and 228,* Federal Emergency Management Agency, Washington, D.C.

Freeman, Sigmund A. (1994), Capacity Spectrum Method, *SEAONC 1994 Fall Seminar, The Developing Art of Seismic Engineering*, Structural Engineers Association of Northern California, San Francisco, CA.

Gulkan, P, O. Ergunay & H. Sucuoglu (1992). Earthquake vulnerability, loss and risk assessment in Turkey. In: *Proceedings of the Tenth World Conference on Earthquake Engineering, Madrid, Spain*, Vol. 1, pp. 539-543. A.A.Balkema, Rotterdam.

Hamburger, Ronald O. (1996). Performance based guidelines for seismic rehabilitation of buildings. Paper submitted to International Conference on Retrofitting of Structures, Columbia University, New York City, 1996.

Hirosawa, M., S. Sugano, T.Kaminosono (1994). *Seismic evaluation method and restoration techniques for existing and damaged buildings developed in Japan.* Building Research Institute, Ministry of Construction, Tokyo.

Holmes, W. T. (1994). Policies and standards for reoccupancy repair of earthquake-damaged buildings. *Earthquake Spectra*, 10, pp. 197-208.

International Conference of Building Officials (ICBO) (1994), Appendix Chapter A1, Earthquake Hazard Reduction in Existing Unreinforced Masonry Buildings, *Uniform Code for Building Conservation*, ICBO, Whittier, CA.

Jara, M., J.J. Guerrero & J. Aguilar (1992). Seismic vulnerability of Mexico City buildings. In: *Proceedings of the Tenth World Conference on Earthquake Engineering, Madrid, Spain*, Vol. 1, pp. 545-550. A.A.Balkema, Rotterdam.

McClure, F. E. (1984). Development and implementation of the University of California Seismic Safety Policy, *Proceedings of the Eighth World Conference on Earthquake Engineering, San Francisco, USA*, Vol. VII, p 859, Prentice Hall, New Jersey.

Morelli, U. and C. Rojahn (1993). Seismic rehabilitation of buildings: the FEMA program. In: *Earthquake hazard reduction in the central and easter United States: a time for examination and action; proceedings of the 1993 National Earthquake Conference, Memphis, Tenn.*, Vol.2, pp. 5-14. Central United States Earthquake Consortium, Memphis, Tenn.

(The) New Zealand National Society for Earthquake Engineering (NZNSEE)(1985). *Earthquake risk buildings: recommendations and guidelines for classifying, interim securing and strengthening.* NZ National Society of Earthquake engineering, Wellington.

Niu, Z. (1981). Chinese aseismic criterion for evaluation of industrial and civil buildings. Paper from Chinese Academy of Building Research, Beijing, China.

Risk Management Software (RMS)(1995), Draft Technical Manual for *Development of a Standardized Earthquake Loss Estimation Methodology*, National Institute of Building Sciences, Washington D. C.

Risk Management Software(RMS) & California Universities for Research in Earthquake Engineering(CUREe)(1993). *Assessment of the state of the art : earthquake loss estimation methodologies* (in progress); *Task 1 Report for the project to develop a nationally applicable standardized earthquake loss methodology.* National Institute of Building Sciences, Washington D.C.

Steinbrugge, K.V. and S.T. Algermissen (1990). *Earthquake losses to single-family dwellings: California experience - USGS Bulletin 1939-A.* United States Geological Survey, Denver, Co.

Structural Engineers Association of California (SEAOC) (1995), Performance Based Seismic Engineering of Buildings, Vision 2000 Committee, SEAOC, Sacramento.

Todorovska, M. I., and L. R Jordanovski (1995), A Probabilistic Model for Assessment of the Total Losses for a Building, In: *Proceedings of the Tenth World Conference on Earthquake Engineering, Madrid, Spain*, Vol. 1, pp. 1017-1022,. A.A.Balkema, Rotterdam.