Assembly-Based Vulnerability of Buildings and Its Use in Performance Evaluation

Keith A. Porter, M.EERI**, Anne S. Kiremidjian,** M.EERI**, and Jeremiah S. LeGrue**

Assembly-based vulnerability (ABV) is a framework for evaluating the seismic vulnerability and performance of buildings on a building-specific basis. It utilizes the damage to individual building components and accounts for the building's seismic setting, structural and nonstructural design and use. A simulation approach to implementing ABV first applies a ground motion time history to a structural model to determine structural response. The response is applied to assembly fragility functions to simulate damage to each structural and nonstructural element in the building, and to its contents. Probabilistic construction cost estimation and scheduling are used to estimate repair cost and loss-of-use duration as random variables. It also provides a framework for accumulating post-earthquake damage observations in a statistically systematic and consistent manner. The framework and simulation approach are novel in that they are fully probabilistic, address damage at a highly detailed and building-specific level, and do not rely extensively on expert opinion. ABV is illustrated using an example pre-Northridge welded-steel-moment-frame office building.

INTRODUCTION

Seismic vulnerability functions, also called motion-damage relationships, are used to estimate earthquake losses and to aid in making seismic risk-management decisions. Figure 1 schematically illustrates a probabilistic vulnerability function for a single building. The horizontal axis shows the spectral acceleration to which the building is exposed, while the vertical axis shows cost as a fraction of building value (often called the damage factor, denoted by Y). The figure shows that at any level of spectral acceleration, denoted by S_a, the damage factor Y is uncertain, with an associated probability distribution that depends on S_a.

One can categorize current methodologies to create motion-damage relationships in two groups: techniques based on structure type—a broad category into which a particular building falls—and techniques based on a detailed structure analysis of the particular building. Among the most familiar and popularly used category-based methodologies are ATC 13 (Applied Technology Council, 1985), and HAZUS (National Institute of Building Sciences, 1997). These approaches characterize a building by its lateral force resisting system and height, and apply generic pre-established vulnerability functions to determine repair cost and loss of use duration. These methods offer simplicity and general applicability, and allow for probabilistic estimation of earthquake-related losses on a regional level. But because they rely on a limited number of structure types, loss estimation for a particular building is problematic: one cannot account for the building's unique structural and nonstructural design.

(KAP) G.W. Housner Postdoctoral Research Fellow, California Institute of Technology, Pasadena, CA 91106
(ASK) Professor, Civil and Environmental Engineering, Stanford University, Stanford, CA 94305
(JSL) Doctoral student, Civil and Environmental Engineering, Stanford University, Stanford, CA 94305

Earthquake Spectra, 17 (2), May 2001, Oakland, CA: Earthquake Engineering Research Institute, 291-312

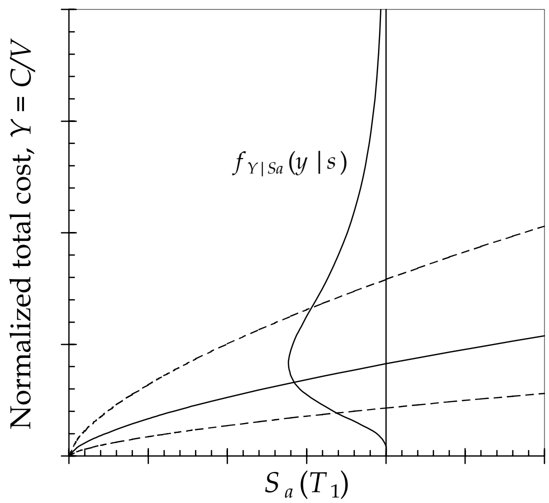

Figure 1. A seismic vulnerability function, in schematic form. Three curves are shown: the mean total earthquake loss as a fraction of replacement cost, and two dashed lines representing ± 1 standard deviation. The figure shows that loss at any particular level of spectral acceleration, loss is uncertain, and has an associated probability distribution, $f_{Y|Sa}(y|s)$.

Several studies have proposed to estimate damage and repair cost based on the structural and nonstructural design of an individual building. Scholl (1980) proposed a methodology to create building-specific seismic vulnerability functions. His approach was further developed by Kustu et al. (1982) and Kustu (1986). In it, structural analysis using response spectra is used to calculate peak structural response in terms of floor drift ratios and peak floor accelerations. The structural response is input to component damage functions, that is, relationships between structure response and damage state of typical building components. Thus one determines the damage state of building components on a floor-by-floor basis.

Using statistics of mean repair cost for each damage state, the analyst can estimate mean total repair cost by component category, summing to determine total cost. The approach is largely deterministic, and a variety of building components are lumped together in the component damage functions. For example, all mechanical, electrical, and plumbing components are reflected in just one or two curves. Because of this, it is impossible to account for differences in performance between alternative component types or installation conditions. Because one cannot distinguish between performance before and after a seismic rehabilitation measure such as anchoring equipment, the benefits of the rehabilitation cannot be evaluated, making cost-benefit analysis impossible. On the more fundamental level of scientific verification, since components are highly aggregated, it can be highly problematic to create or perform laboratory tests to check the aggregate component damage functions.

ASSEMBLY-BASED VULNERABILITY

This paper summarizes a study (Porter, 2000) that developed a new method of calculating seismic vulnerability for individual buildings. The new method, called assembly-based vulnerability (ABV), extends the Scholl (1980), Kustu et al. (1982) and Kustu (1986) technique. The new approach allows for probabilistic performance evaluation and considers building assemblies at a greater level of detail than do these earlier approaches. The technique employs methods used since the early 1980s on probabilistic risk assessments of nuclear power plants.

A simulation approach to implementing ABV is illustrated in Figure 2. Its steps are summarized here and detailed below. Each simulation proceeds as follows: first, one determines the building location, site conditions, and design details, including structural and nonstructural components. Then one selects or generates an acceleration time history appropriate to the building site. Next, a structural analysis is performed to determine the building's peak structural response to that input ground motion. Various parameters of the structural response are then recorded: peak floor accelerations, peak transient drifts, peak member forces, and so on.

Fourth, for each assembly in the building, the appropriate structural response parameter is input to one or more assembly fragility functions to determine the probability that the assembly will be damaged and require repair or replacement. By a method that will be described below, this probability is used to simulate the damage state of each assembly in the building. Fifth, using a probability distribution on the unit cost to repair each assembly, and another on the time required to repair each assembly, one simulates the cost and time to repair all the damaged assemblies. The costs are added up to produce a simulation of the total repair cost. The durations are used in a construction-scheduling procedure to produce a simulation of the loss-of-use duration, which is then used to estimate the loss-of-use cost.

Thus is completed one simulation of shaking, response, damage, repair, and loss. To create a complete seismic vulnerability function, the procedure is repeated many times for each of many levels of ground shaking intensity that the building might experience. Details of these steps are now presented.

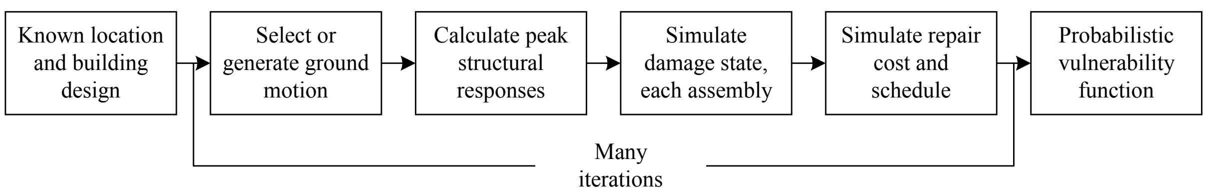

Figure 2. Steps of the ABV methodology.

BUILDING DESIGN

First, the building's location, site conditions, and detailed design are determined. For existing buildings, this includes an examination of actual installation conditions, particular with regard to seismic anchorage or bracing of nonstructural components. A structural model is then created, using techniques familiar to structural engineers. In addition, all damageable structural and nonstructural components in a building must be inventoried using a formal categorization system (or taxonomy) of assembly types, including all damageable structural, architectural, mechanical, electrical, and plumbing assemblies. This step need not be excessively burdensome if assemblies are defined at a moderately aggregated level. There are several advantages of using a standard taxonomy for building assemblies, and of using only moderately aggregated assemblies:

1. A standard taxonomy establishes a common language that researchers and designers can use to compile, exchange, understand, and use damage and loss data.
2. If the taxonomy aligns well with the category systems used in construction-cost estimation, then repair-cost estimation can take advantage of published cost

manuals. These manuals reflect the results of extensive, ongoing surveys of the construction industry by professional cost estimators.

3. By referring to a complete taxonomy, researchers can be sure that they are not ignoring important damageable components when they estimate losses to a particular building.
4. Assemblies defined at a moderately aggregated level such as gypsum wallboard partitions can be readily tested in a laboratory for seismic resistance. At a greater aggregation, such as "nonstructural partitions," laboratory testing becomes difficult.

The categorization systems most familiar to construction cost estimators in the United States are those of the RS Means Co. (1997a and 1997b). The assembly category system of the RS Means Co. (1997b), which itself is an extension of the standard UniFormat system (Construction Specifications Institute, 1998), is used here because it represents a reasonable balance between the effort required to create an inventory, and the need to distinguish between the performance of assemblies with similar function but markedly different seismic vulnerability. Assemblies at about this level of aggregation are commonly tested in laboratories to determine their seismic performance.

The assembly taxonomy system of RS Means Co. (1997b) uses three levels of detail to categorize assemblies: division and subdivision, major classification, and line. This system is extended here to account for details of design and installation that are relevant to earthquake damage. First, an additional taxonomic division, entitled *condition*, is added to characterize adequacy of installation for seismic resistance, for example, to indicate seismic anchorage or bracing conditions. Also, new lines are defined to account for problems idiosyncratic of earthquake damage and repair. For example, pre-Northridge welded-steel moment frame (WSMF) connections are separated from beams and columns to reflect their unusual seismic fragility and repair requirements.

GROUND-MOTION SELECTION

In the next stage, ground acceleration time histories are selected for the site. To create a complete vulnerability function, time histories are selected and scaled to cover a range of values of spectral acceleration at the building's fundamental period, denoted by $S_a(T_1)$. The S_a levels range from a small value s_{min} such as 0.05g, through a large value s_{max} that building might experience. Several such recordings must be used for each $S_a(T_1)$ value, in order to capture the variability of detailed time histories with the same spectral acceleration. Ground motions can be scaled within reasonable bounds to produce the required incremental steps in spectral acceleration, but should reflect approximately the proper magnitude, faulting mechanism, distance, and site soil conditions.

Ground motion records can be historic or simulated. They can be created for example from real records using an autoregressive moving average (ARMA) model. Such a simulation approach may be necessary because of the large number of iterations required to create a robust probability distribution on loss. For a discussion of ARMA techniques, see Box et al. (1994), Polhemus et al. (1981), and Conte et al. (1992).

A nonstationary ARMA model was used in the illustration of the present study because it has been successfully used in the past and because it generates ground motion time histories that have amplitude and frequency content that vary over the duration of the record to match the changing characteristics of the real record (Singhal et al. 1997).

STRUCTURAL ANALYSIS

Using the ground motion record prepared in the previous step, the time-history response of the structure is calculated using a nonlinear dynamic structural analysis. Key structural responses are recorded. The response variables of interest depend on the assemblies present in the building. They can include peak values such as peak transient drifts or peak accelerations, or they can reflect an accumulated values such as hysteretic energy dissipated by a particular component. To account for the uncertainty of peak structural response given a particular ground motion, building dimensions, member stiffness, and masses can be treated as random variables and samples generated for each iteration.

BUILDING ASSEMBLY DAMAGE

The objective of the next step is to generate the damage state of every assembly in the building. The building and all of its assemblies are assumed to be undamaged before the earthquake. The peak structural responses collected from the previous step are then input to assembly damageability relationships to simulate the damage state of each assembly. In the present treatment, damage to each assembly is considered to be dependent on only one structural response parameter. It may be that damage to some assemblies can be better predicted by considering two or more response parameters. For simplicity, however, this possibility is not examined here.

More than one possible damage state can be defined for each assembly type. Let N denote the number of possible damage states for a particular assembly type. The N possible damage states must be defined to be mutually exclusive and, with the addition of the undamaged state, collectively exhaustive. Let D represent a discrete random variable to indicate damage state, that is, $D \in \{0, 1, \ldots N\}$, and let d denote a particular value that the random variable takes on for a particular assembly.

The damage state of a particular assembly will depend on the structural response to which it is subjected. Let Z denote the (uncertain) structural response to which a particular assembly is subjected, and let z denote a particular value of Z. As a discrete random variable that depends on Z, D has a conditional probability mass function, denoted by $p_{D|Z}(d|z)$, and a conditional cumulative distribution function, denoted by $F_{D|Z}(d|z)$ (A glossary is provided at the end of this paper that summarizes these and other terms.)

Let the capacity of an assembly type to resist a particular damage state d be represented by an uncertain variable X_d. If the assembly is subjected to structural response $z < X_d$, it does not enter that damage state. If on the other hand $z > X_d$, then the assembly reaches or exceeds damage state d. Because it is a random variable, the capacity X_d has an associated cumulative probability distribution, denoted by $F_{Xd}(x)$. Observe then that the cumulative distribution evaluated at the level of structural response z gives the probability that a particular assembly will reach or exceed damage state d, as shown in Equation 1.

$$\mathrm{P}[D \geq d | Z = z] = \mathrm{P}[X_d < z] = F_{Xd}(z) \tag{1}$$

where

P[A] = the probability that A is true

P[A | B] = the probability that A is true, given condition B

$D \in \{0, 1, \ldots N\}$, represents damage state, where $D = 0$ refers to the undamaged state;

N = number of damage states defined for the assembly. $N = 0$ implies that the assembly is assumed to be rugged, not damageable in an earthquake;

X_d represents the assembly's capacity to resist damage state d; and

$F_{Xd}(z)$ represents the cumulative probability distribution function of X_d evaluated at z.

After an earthquake, a particular assembly is either undamaged ($D = 0$) or in one of several damage states 1, 2, … N. As a simplifying assumption, damage states are assumed to be *progressive*, that is, an assembly passes through damage state d to reach damage state d+1. This appears to be reasonable for the structural and architectural assemblies studied here. If a particular assembly has two or more possible damage states, and each damage state has an associated random capacity X_1, X_2, … X_N, then the probability that the assembly is in or exceeds a particular damage state decreases with each higher damage state, as shown in Equation 2.

$$F_{Xj}(x) \leq F_{Xi}(x) \qquad \text{for } x > 0,\ 1 \leq i < j \leq N \qquad (2)$$

Equations 1 and 2 imply equation 3, which provides the probability mass function for the damage state of an assembly, given the structural response to which the assembly is subjected. This equation says that the probability that an assembly is in damage state d equals the probability that it is damage state d or higher, minus the probability that it is in damage state d+1 or higher.

$$\begin{aligned} p_{D|Z}(d \mid z) &= P[D = d \mid Z = z] = P[D \geq d \mid Z = z] - P[D \geq d+1 \mid Z = z] \\ &= F_{Xd}(x) - F_{Xd+1}(x) \end{aligned} \qquad (3)$$

By considering each damage state in turn, a conditional probability mass function and conditional cumulative probability distribution on damage state D can be created (Equations 4 and 5).

$$p_{D|Z}(d \mid z) = \begin{cases} 1 - F_{X1}(z) & d = 0 \\ F_{Xd}(z) - F_{Xd+1}(z) & 0 < d < N \\ F_{Xd}(z) & d = N \end{cases} \qquad (4)$$

$$F_{D|Z}(d \mid z) = \sum_{\delta=0}^{d} p_{D|Z}(\delta \mid z) \qquad 0 \leq \mathrm{d} \leq \mathrm{N} \qquad (5)$$

Thus, one compiles the capacity distributions for each damageable assembly in the building, and uses these with the results of the structural analysis to create the conditional cumulative probability distribution for the damage state of each assembly. In order to simulate the damage state for an assembly, a sample value u is generated from the uniform (0,1) distribution. (That is, a sample value of the random variable U is drawn, where $0 < U \leq 1$, and every possible value of U has equal probability). The damage state d for each assembly is then evaluated from the inverse cumulative distribution of damage, given by Equation 6. The number of assemblies of each type in each damage state can then be added up. Let $N_{j,d}$ represent the number of assemblies of type j that are in damage state d in a particular simulation.

$$d = F_{D|Z}^{-1}(u) \qquad (6)$$

Note that damage states must be defined in terms of particular repair tasks required to restore the assembly to an undamaged state. As used here, each damage state refers to an observable and unambiguously defined condition of the individual assemblies in the building, not using building-wide macroscopic damage states such as minor, moderate, etc., which are commonly used by category-based approaches such as ATC 13 (Applied Technology Council, 1985) and HAZUS (National Institute of Building Sciences, 1997). No building-wide damage state or damage index is defined in the ABV framework.

The assembly capacity distributions of Equation 1 can be created by a variety of means. Empirically based capacity distributions can be created from laboratory experiments or from earthquake experience. For example, Swan et al. (1998) describe a method to derive a capacity distribution from earthquake experience data. That study focuses on component functionality, that is, whether a particular piece of equipment is functional or not. However, the same approach can be used to derive capacity distributions that refer to other types of physical damage such as whether a window is cracked or fallen out. Where inadequate laboratory or earthquake experience data exist, under certain conditions one can create theoretical capacity distributions using reliability methods.

If data are inadequate to create an empirical or theoretical capacity distribution for an assembly, a judgment-based distribution can be used. The HAZUS methodology, for example, relies extensively on judgment to create aggregate component fragility functions from the empirical detailed fragility data that were available to the investigators (National Institute of Building Sciences, 1997). It was desired to avoid reliance on expert opinion for the present study, because expert opinion is often perceived by decision-makers to weaken the credibility of the overall analysis.

However, where judgment-based capacity distributions are necessary, the quality of expert opinion can be maximized through careful means of eliciting judgment. Tversky et al. (1974) discuss some of the potential problems—biases of judgment—that arise when eliciting judgments of probability. Spetzler et al. (1972) detail a methodology to interview experts to encode probability beliefs, with due attention to minimizing the effect of such biases.

REPAIR COST

The purpose of the next step is to generate the total repair cost for each simulation, based on the damage states of all the damageable assemblies in the building. Let $C_{j,d}$ denote the uncertain cost to restore one unit of assembly type j from damage state d to an undamaged condition. It reflects the direct cost to the owner including all materials, equipment, labor. Unit repair costs are assumed to be random variables with characteristic cumulative probability distribution $F_{Cj,d}(c)$, where c is a given value of unit cost. One must compile the cost distribution for each damage state of each damageable assembly in the building.

The repair cost $C_{j,d,}$ is simulated by generating a sample u from the uniform (0,1) distribution and applying the inverse method. That is, in the simulation, the unit cost is taken as the inverse cumulative distribution of $C_{j,d}$ evaluated at u. The total repair cost for the building is the sum of unit repair costs times the number of damaged assemblies (Equation 7).

$$C_R = \sum_j \sum_d F_{Cj,d}^{-1}(u) N_{j,d} \tag{7}$$

where

$C_{j,d}$ = the uncertain cost to repair an assembly of type j from damage state d

$F^{-1}_{Cj,d}(u)$ = the value of the unit repair cost $C_{j,d}$ with non-exceedance probability u.

C_R = total repair cost

$N_{j,d}$ = number of assemblies of type j in damage state d

A refinement of this approach is to separate the costs not directly attributable to the repair of particular assemblies, such as contractor overhead and profit, mobilization and demobilization, etc., and to calculate these separately, rather than including them in $C_{j,d}$.

LOSS OF USE

Earthquake losses accrue from loss of use as well as from direct damage, so it is necessary to estimate the time to repair the building. If income derives from the operation of parts of the building, such as from rent from apartments, office suites, or floors, then it is necessary to estimate the repair duration from each part. These parts are referred to here as the operational units of the building.

If each operational unit in the building can be described as requiring a set of critical structural, architectural, mechanical, electrical and plumbing features to be functional, then the time to restore the damaged critical components can be used to estimate loss of use cost.

One can estimate the time to restore critical components using standard scheduling procedures. A schedule can be visualized with a Gantt chart, which depicts tasks as horizontal bars whose length indicates the duration of each task. Vertical and horizontal lines connect the bars; these lines indicate the order in which tasks must be completed. To estimate loss of use duration then, one must determine which tasks must be performed, the order in which they can be performed, and the duration of each task.

Duration of one repair task

Each task in the schedule consists of repairing all similar assemblies in one operational unit of the building. For example, one task might be to repair all broken windows in a particular office suite. The time required for a standard construction crew to restore one unit of assembly type j from damage state d to the undamaged state is denoted $U_{j,d}$. Unit repair durations are assumed to be random variables with characteristic cumulative probability distribution $F_{Uj,d}(\nu)$, where ν is a particular value of $U_{j,d}$.

During a simulation, the time to repair assemblies of type j from damage state d can be generated by generating a sample u from the uniform (0,1) distribution and applying the inverse method, as shown in Equation 8. The duration of repairs to all assemblies of type j in damage state d located in operational unit m is given by Equation 9.

$$U_{j,d} = F^{-1}_{Uj,d}(u) \tag{8}$$

$$R_{j,d,m} = \frac{N_{j,d,m} U_{j,d}}{wE_j} \tag{9}$$

where

$R_{j,d,m}$ = workdays to restore all instances of assembly type j located in operational unit m from damage state d.

$N_{j,d,m}$ = number of instances of assembly type j located in operational unit m that are in damage state d. This is counted up from the damage simulation data, just as $N_{j,d}$ was. In fact, $\sum_m N_{j,d,m} = N_{j,d}$.

$U_{j,d}$ = time for one crew to restore one instance of assembly type j from damage state d to an undamaged state, measured in hours. Mean values are published in cost manuals, and variances can be estimated.

w = number of working hours per workday.

E_j = number of crews available for restoring assembly type j. The type of work and construction practice typically determines the crew size.

Duration of repairs to an operational unit and loss of use cost

Components are restored in a logical order that is dictated by construction practice, facility layout, tenant needs, and the construction contractor's labor and subcontractor availability. Scheduling is therefore idiosyncratic to a repair contract, and modeling for the generic case is problematic. However, several simplifying assumptions can be made to approximate the actual schedule:

- Within an operational unit, crews working on the same repair task work in parallel. Different repair tasks are performed in series.

- Repairs are performed in an order that follows the numbering of MasterFormat divisions, following standard procedures for new construction. For example, structural components are repaired before nonstructural finishes.

- Constraints due to tenant requirements are neglected while critical components remain unrepaired, on the assumption that tenants cannot occupy the facility until critical repairs are completed.

- In an operational area, one trade operates at a time. When that trade completes its work, the next trade is free to begin, once it completes its work elsewhere on site. If the next trade is not currently on site, a change-of-trade delay occurs.

- The duration of a change-of-trade delay varies depending on the size and complexity of the work and on labor and subcontractor availability, which may in turn depend on local economic factors. Bounding cases can be assumed. The slow-repair case has long change-of-trade delays of days or weeks; the fast-repair case can have short change-of-trade delays of one or two days.

- Repairs to different operational units can begin simultaneously if sufficient contractor labor is available. Alternatively, a contractor can concentrate on one operational unit until work for its trade is completed, then move on to the next operational unit where repairs appropriate for the contractor's trade await. These situations can be included in the bounding cases: the first, fast repair; the second, slow.

With these assumptions in mind, it is possible to estimate the time required to repair a single operational unit. Let

R_m^* = time to repair operational unit m, measured in workdays from the date on which repair work is begun in the facility.

$R_{j,d,m}$ = time to restore all instance of assembly type j located in operational unit m from damage state d to an undamaged state, measured in days, from Equation 10.

R_T = change-of-trade delay. Can be assumed based on bounding cases.

$R_{T0,m}$ = initial delay before first task in operational unit m. Can be assumed based on bounding cases.

n_m = number of trade changes involved in the repair of operational unit m. Determined from the damage simulation.

Equation 10 estimates the time required to repair damage in operational unit m.

$$R_m^* = \sum_j R_{j,d,m} + n_m R_T + R_{T0,m} \tag{10}$$

Loss-of-use cost is often a direct function of loss-of-use duration, the simplest example being lost income on a rental property (Equation 11).

$$C_U = \sum_m R_m U_m \tag{11}$$

where

C_U = total loss-of-use cost

R_m = time to repair operational unit m, measured in calendar days from the earthquake, accounting for R^*_m plus weekends and time between the earthquake and the date on which work is begun. R_m is bounded below by repair duration for building-service equipment and repair duration for common access areas.

U_m = daily rental income from operational unit m

Peculiarities of individual lease arrangements are not reflected in this simple relationship, e.g., voiding of a lease if the building is unavailable for an extended period of time, relocation costs, or costs reflecting higher lease at the temporary location of the tenant. For a specific building these costs are understood relatively well and can be easily included in the model.

TOTAL COST

Total cost, denoted by C, consists of direct repair cost (C_R, from Equation 7) and loss-of-use cost, denoted by C_U, from Equation 11. Other indirect costs and benefits are not captured in this equation, for example, changes in building value associated with perceptions of the safety or the building, code-compliance requirements triggered by repairs, or market effects such as demand surge. (Demand surge refers to the increase in repair costs sometimes associated with catastrophic earthquakes and hurricanes.)

$$C = C_R + C_U \tag{12}$$

COMPILING A VULNERABILITY FUNCTION

As noted above, each simulation produces a single value of C. Numerous simulations for each value of S_a will produce a range of samples of C. From these samples, one can calculate the mean value of cost, its standard deviation, and shape of its distribution. By repeating the process over a wide range of spectral accelerations, and performing regression analysis on the resulting data, one produces a probabilistic seismic vulnerability function for a particular building.

This vulnerability function is similar to those produced by category-based methodologies such as ATC 13 (Applied Technology Council, 1985) and HAZUS (National Institute of Building Sciences, 1997), with some important differences. First, the ABV vulnerability function accounts for the building's unique details of structural design because it uses structural analysis of that particular building. Second, it accounts for the building's unique architectural, mechanical, electrical, and plumbing features and details of their installation, rather than relying on the broad assumptions and judgments that are necessary when applying category-based approaches to particular buildings. Third, details of the causes of cost are available to identify which assemblies or portions of the building are contributing most strongly to overall cost. This allows a designer or analyst to quantify the costs and benefits of changing the components or their installation conditions, that is, to assess the value of seismic rehabilitation measures.

These benefits come at a significant expense of labor: an ABV analysis requires the compilation of numerous ground motion recordings, the creation of an analytical model of the structure, and an inventory of the building's assemblies. For assemblies whose capacity and repair cost distributions are not already known, these must also be created, which is potentially the most time-consuming aspect of the methodology. Once these items are available, however, the actual computation is fairly straightforward and can be readily automated, and the assembly fragilities can be re-used in later studies.

RANDOMNESS AND UNCERTAINTY

The ABV approach results in an explicit, defensible estimate of the uncertainty in the seismic vulnerability of a building. This is important, because uncertainty is a key feature of seismic risk management decisions. If one had perfect knowledge of when earthquakes occur and exactly how much damage they do, earthquake loss management would be as simple as cost-benefit analysis: choose the seismic design, strengthening scheme, or other measure that results in the greatest present value of the building. But imperfect knowledge is the rule in each aspect of earthquake loss estimation: when and how strong an earthquake will occur; the response of the structure to the earthquake; the consequent damage; and the costs to repair the damage.

Because imperfect information causes such great uncertainty in the timing and amount of future losses, and because those losses can represent a large fraction of a building owner's total wealth, cost-benefit analysis (which assumes risk neutrality on the decision-maker's part) is an inappropriate decision-making approach. To understand the amount of resulting uncertainty and its sources is to begin to manage it. If one can quantify uncertainty on loss as well as its mean value, one can use sophisticated decision-making methodologies such as decision analysis, which explicitly consider uncertainty and the decision-maker's risk attitude. A decision-analysis approach to making building-specific seismic risk management decisions is described in Porter (2000).

USING ABV TO CHECK PERFORMANCE-BASED DESIGN OBJECTIVES

The damage-estimation technique of ABV also provides the data needed to verify numerical performance-based design objectives. Current code design methods safeguard life-safety and serviceability by prescribing strength and stiffness requirements for the structural system, with limited focus on nonstructural building aspects. By contrast, Vision 2000 (Structural Engineers Association of California, 1995) and FEMA 273 (Applied Technology Council, 1997) attempt to establish a performance-based design (PBD) philosophy whose goal is to satisfying broader, predictable seismic performance objectives.

FEMA 273 associates four performance levels—operational, immediately occupiable, life safe, and collapse prevention—with varying earthquake hazard levels: 50% exceedance probability in 50 years, 20% in 50 years, 10% in 50 years, and 2% in 50 years. For each performance level, performance objectives are defined in detail by structural element and other building components. Component performance is expressed generally in qualitative terms such as "isolated dislocations," "minor cracking," or "generally operational." These terms, while not directly useful in an engineering calculation, can be associated with numerical values. Table 1 shows a sample translation of qualitative terms to numbers. Quotations in the table are drawn from FEMA 273 (Applied Technology Council, 1997).

Once performance objectives are quantified, they can be checked by engineering calculation. Holmes (2000) proposes six general requirements for a procedure to verify that a design (new or retrofit) meets PBD objectives. It must (1) accommodate any ground motion as input, (2) consider structural degradation and duration of ground motion, (3) model ductile and brittle elements, (4) model casualties, repair costs, and downtime, (5) the reliability of its outputs must be explicitly stated, and (6) it must have industry consensus. Because ABV produces detailed assembly damage statistics, it can meet many of these requirements, and at present only lacks a methodology to estimate casualty risk, and industry consensus.

Table 1. Illustrative translations of qualitative performance terminology. The qualitative term used in a PBD code is shown in the left column. A reasonable numerical translation and an example are shown in the second and third columns.

Qualitative term	Translation	Example
Negligible, few, little	0 - 1%	"Generally negligible [ceiling] damage:" less than 1% of ceiling area is damaged.
Some, minor	1 – 10%	"Some cracked [glazing] panes; none broken:" Between 1% and 10% of lites visibly cracked; no glass fallout.
Distributed	10 – 30%	"Distributed [partition] damage:" between 10% and 30% of partitions need patching, painting or repair, measured by lineal feet.
Many	30 – 60%	"Many fractures at [steel moment frame] connections:" between 30% and 60% of connections suffer rejectable damage.
Most	60 – 100%	"Most [HVAC equipment] units do not operate:" at least 60% of HVAC components inoperative.

FRAMEWORK FOR GATHERING EARTHQUAKE DAMAGE STATISTICS

The ABV approach also suggests a framework for systematically gathering damage data during earthquake field surveys. Much of the literature on earthquake experience focuses on identifying what can happen, that is, it identifies damage modes and explains causes of component failure. Quantitative statistics in field surveys are often limited to macroscopic effects: number of housing units lost or bridges damaged.

While this information is valuable, it would also be valuable to gather fragility data, that is, to quantify the relationship between the seismic demand and the probability that components will fail when subjected to that level of demand. A useful procedure to gather fragility data must include four crucial features:

1. Standard component names. Components should be categorized using a generally accepted taxonomic system, so that data from different locations and earthquakes are readily comparable with each other.
2. Standard failure modes. Failure modes should be described relative to important and widely understood performance goals. For example, failure could be described using the performance goals described in FEMA 273 (Applied Technology Council, 1997).
3. Standard quantification of the structural response. Each component must be associated with a level of seismic demand to which it was subjected. The demand to which components were subjected is often evident from nearby damage or can be estimated with later structural analysis.
4. Damage ratio. For each assembly type and damage mode, one must know both how many failed and how many did not fail, at a given level of seismic demand. Often the total number (failed plus not failed) is missing from survey data.

The ABV framework includes all four features, and can provide a pattern for gathering earthquake data that can be readily understood by researchers and directly used in loss estimation and risk management. ABV's taxonomic system is extended from a widely used assembly category system. It uses failure modes that are directly relevant to performance goals and repair costs. Each assembly is associated with well-understood structural response parameters that can be directly calculated from a structural analysis. Finally, assemblies are quantified in well-defined units that make calculation of damage ratio straightforward.

ILLUSTRATION OF ABV WITH AN EXAMPLE BUILDING

EXAMPLE BUILDING DESCRIPTION

The ABV method is generally applicable to any building whose assembly fragilities can be characterized as a function of structural or ground motion parameters. The approach is illustrated here using the example of a hypothetical Los Angeles office building. As shown in Figure 3, the building is a three-story pre-Northridge welded steel moment frame (WSMF) structure, with the WSMFs located at the perimeter. The perimeter frame shown in the elevation was designed for the SAC project to meet pre-Northridge standards in Los Angeles. The plan and nonstructural design aspects were developed for the present study.

The building has three 30-ft. bays in each direction plus 10-ft chamfers at each end. Beams are A36 steel. Columns are A572 Grade 50. Diaphragms are concrete topping on metal deck. Interior partitions are constructed of gypsum board over 3-5/8 in. metal studs with wallboard screws. The exterior is clad with lightweight glazed aluminum panels with gypsum board on the interior side. Ceilings are constructed of a suspended aluminum T-bar system with lay-in tiles and fluorescent lighting fixtures and perimeter attachment. Two gearless traction elevators provide vertical transport. Firm soil is assumed. Mean values are used for yield strength instead of nominal values. No splice or doubler plates are used.

Columns are fixed at the base. Dimensions are centerline. Beams are modeled as elastic elements with nonlinear springs at each end. The contribution of interior gravity frames to structural the response is accounted for by an additional column (column line E in Figure 3) tied to the frame by a rigid link. The building houses commercial office space. Monthly rental income is $2.50/sf net, i.e., calculated based on tenant square footage exclusive of common spaces. The ground floor is shared by office space, a lobby, and building service equipment. Upper stories are wholly devoted to office space. The total building replacement cost is estimated to be $4.9 million.

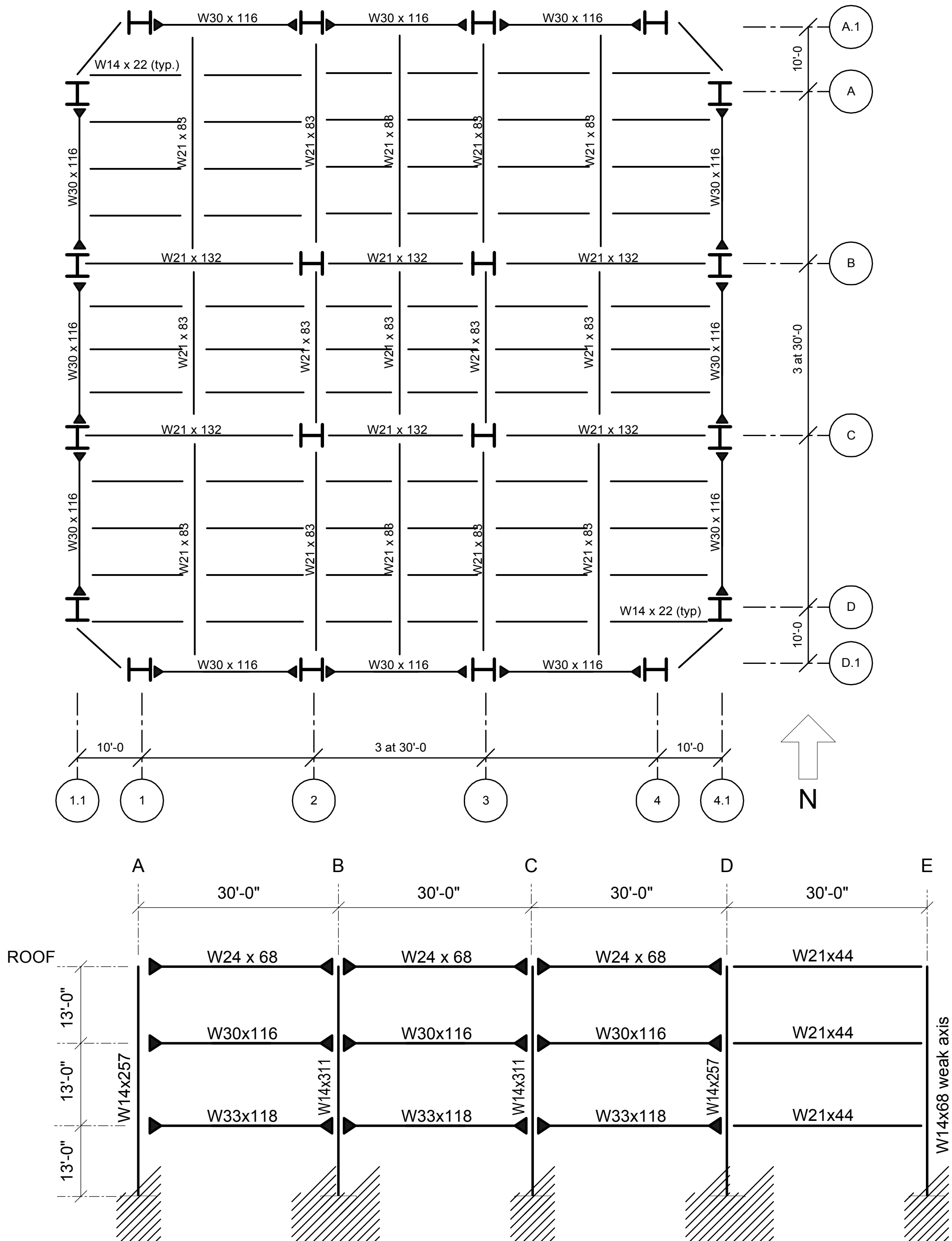

Figure 3. Structural model of the example three-story office building: plan and west frame.

CHARACTERIZATION OF GROUND MOTION

A set of earthquake ground motions were created by Somerville et al. (1997) for the project on steel structures supported by the Federal Emergency Management Agency (FEMA), referred to as the SAC-steel project. Some of the ground motions are scaled versions of real earthquakes; others were created using broadband simulation methods. All of the ground motions were scaled to approximate spectral ordinates from the 1996 United States Geological Survey probabilistic ground motion maps in the period range of 0.3 to 4 seconds (Frankel et al., 1996). For this study, we used 40 of the ground-motion records created for the Los Angeles area. For computational convenience, only ground motions with a 0.02-second sampling rate were used.

ASSEMBLY FRAGILITY AND COST FUNCTIONS

Table 2 and Table 3 list the assemblies considered in the sample application, their capacity data and repair-cost data. Table 2 lists the damageable assemblies used in the building, how they are quantified in the inventory, their damage states, the relevant response parameter, and the median and logarithmic standard deviation of the capacity to resist that damage state. The median capacity is denoted by x_m, the logarithmic standard deviation by β. A lognormal distribution is used for each capacity X_d, as shown in Equation 13, in which X_d represents the capacity to resist damage state d, and $\Phi(s)$ represents the cumulative standard normal distribution evaluated at s. The unit repair costs and repair durations shown in Table 3 are quantified the same way, and the random variables are likewise assumed to be lognormally distributed with the parameters shown.

$$F_{Xd}(x) = \Phi\left(\frac{\ln(x/x_m)}{\beta}\right) \tag{13}$$

The WSMF connection capacity is derived from data published in SAC (1995a). Rihal's (1982) data were analyzed to develop capacities for metal-stud drywall partitions. Laboratory tests performed by Behr et al. (1998) were used to describe glazing capacity. Capacities for electrical components come from Swan at al. (1998). Sprinkler capacities were derived from Porter et al. (1998). Suspended ceiling capacity was derived using reliability methods, based on the geometry and material properties of the components that constitute a suspended ceiling. The interested reader is referred to Porter (2000) for the derivation of these capacity distributions. No judgment-based fragility functions were used in the analysis of the example building.

Median repair costs and durations for architectural elements and for sprinklers were calculated based on RS Means (1997b). Repair costs and durations for WSMF connections based on replacing damaged moment connection with SAC (1995b) haunched WT fixtures. The distribution of repair cost for this fixture is calculated from an unpublished construction cost estimate created for the owner of a large steel-frame building damaged in the Northridge earthquake. All other cost and time parameters were estimated by judgment. While published data on these items were not available to the present author, they should be readily available to engineering firms familiar with post-earthquake repairs. For the present illustration, they were estimated conservatively and are shown in italics to indicate lower confidence in their accuracy.

The numbers in Tables 2 and 3 should be viewed in the light of their intended purpose: to illustrate the general ABV framework, rather than to present definitive fragility and cost distributions. The research emphasis at this stage is development of the methodology, rather than an attempt to populate a large library of fragility and cost functions.

Table 2. Assembly capacity. The table shows median and logarithmic standard deviation of capacity for the damageable assemblies in the example building, (x_m and β, respectively) in terms of the relevant structural response: peak ratio of beam-end elastic moment to yield capacity (demand-capacity ratio, or DCR), peak transient drift ratio (TD), and peak diaphragm acceleration (PDA).

Assembly	**Unit**	**Damage state**	**Response parameter**	x_m	β
WSMF connections	Bm-col. Conn.	SAC damage [(1)]	DCR	1.6	1.7
WSMF connections	Bm-col. Conn.	Same, > W1, C1[(2)]	DCR	3.3	1.8
Glazing	30 sf pane	Cracking	TD	0.040	0.36
Glazing	30 sf pane	Fallout	TD	0.046	0.33
Drywall partition	8'x8'	Visible damage	TD	0.0039	0.17
Drywall partition	8'x8'	Signif. damage	TD	0.0085	0.23
Acoustical ceiling	One room	Collapse	PDA	$46/x_s$[(3)]	0.80
Unbraced sprinklers	12 lf pipe	Fracture	PDA	4.2g	0.87
Braced sprinklers	12 lf pipe	Fracture	PDA	8.4g	0.87
Low volt. switchgear	Set	Inoperative	PDA	1.1g	0.64
Med. volt. switchgear	Set	Inoperative	PDA	1.6g	0.80
Motor installation	Set	Inoperative	PDA	0.79g	0.52
Generator	Set	Inoperative	PDA	0.87g	0.51

(1) SAC (1995a), pg. 7-33, including G, C, W, S, and C, excluding P (panel-zone damage)
(2) i.e., the same SAC damage states, except that the incipient damage states W1 and C1 are not included
(3) x_s = (ceiling length + width)/2, ft. The result is in terms of gravity, g.

Table 3. Assembly repair cost and repair duration. The table shows median and logarithmic standard deviation (x_m and β, respectively) of repair cost per damaged assembly, and of total hours to repair a damaged assembly. Costs are for a building in the city of Los Angeles, in 1997 dollars.

Assembly	**Repair**	**Unit**	**Cost/unit ($)** x_m	**Cost/unit ($)** β	**Time/unit (hr)** x_m	**Time/unit (hr)** β
WSMF connections	WT[(1)]	Conn.	23,900	0.58	8	0.58
Glazing	Replace	30-sf pane	439	0.26	0.4	*0.5*
Drywall partition	Patch	8'x8'	50	*0.5*	0.4	*0.5*
Drywall partition	Replace	8'x8'	192	*0.5*	1.5	*0.5*
Acoustical ceiling	Replace	sf	2.21	*0.5*	0.016	*0.5*
Unbraced sprinklers	Replace	12 lf	156	*0.5*	1	*0.5*
Braced sprinklers	Replace	12 lf	156	*0.5*	1	*0.5*
Low volt. switchgear	Anchor[(2)]	Set	*1000*	*1.0*	*8*	*1*
Med volt. switchgear	Anchor[(2)]	Set	*1000*	*1.0*	*8*	*1*
Motor installation	Anchor[(2)]	Set	*1000*	*1.0*	*8*	*1*
Generator	Anchor[(2)]	Set	*5000*	*1.0*	*16*	*1*

(1) Replace moment connection with SAC (1995b) haunched WT
(2) Service existing equipment, restore to its original position, and install seismic anchorage

EXAMPLE BUILDING VULNERABILITY FUNCTION

For each S_a value in {0.1, 0.2, … 1.5g}, twenty simulations of ground motion, structural response, damage state, repair cost, and loss-of-use duration and cost were performed. Since a nondegrading structural model was used, the analysis was limited to values of $S_a \leq 1.5$g, an approximate upper bound of validity. At higher values, local and global collapses are increasingly likely and would not be reflected by the structural analysis. The emphasis of the present analysis is therefore on lower levels of damage. Figure 4 shows the resulting loss amounts as a fraction of building replacement cost. The solid line fit to the data represents mean vulnerability. The mean residual coefficient of variation, denoted by $\delta_{y|x}$, was calculated for the example building to be 0.60.

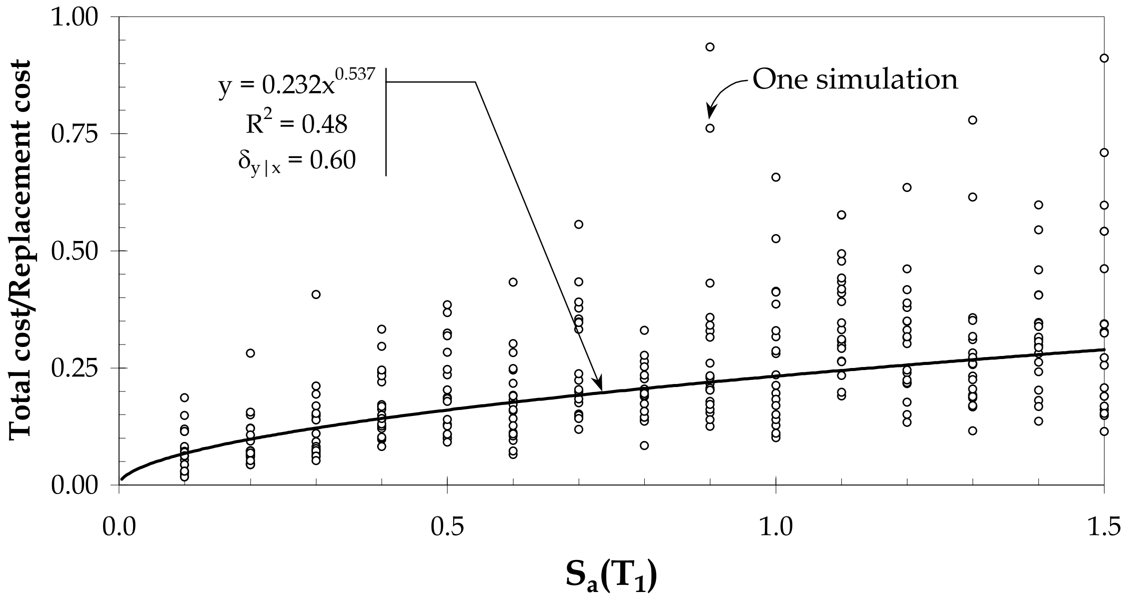

Figure 4. Seismic vulnerability function for the example building. Each dot represents one simulation of ground shaking, structural response, damage, and repair. $S_a(T_1)$ measures spectral acceleration at the building's fundamental period. Total cost refers to repair plus loss of use. Twenty simulations are shown per increment of S_a. The solid line represents a best fit on the mean.

The results shown in Figure 4 represent slow-repair assumptions: change-of-trade delays are taken as R_T = 14 days, and only one crew is available for each repair task. That is, a single crew repairs a particular assembly type in operational unit m = 1, then immediately moves to operational unit m = 2, etc. Two weeks pass before the next trade arrives to commence work on operational unit m = 1.

Losses for a fast-repair assumption have also been calculated, where R_T is assumed to be 2 days, and all operational areas are assumed to undergo repairs in parallel. That is, enough crews are available so that all operational units may undergo repairs on the same assembly type simultaneously. This assumption leads to a vulnerability function that is somewhat lower than the slow-repair function because of smaller loss-of-use costs. Thus, the total vulnerability for the sample building appears to be modestly sensitive to the speed at which repairs are performed.

Figure 4 shows that there is substantial uncertainty in the damage factor: on average, the residual coefficient of variation on loss is 0.60. This is the accumulated uncertainty resulting from four explicitly considered sources of variability:

- Uncertain ground motion time history for a given spectral acceleration;
- Uncertain assembly damage given the structural response to the ground motion;
- Uncertain repair costs for given damages; and
- Uncertain productivity of repair crews.

The results shown in Figure 4 omit uncertainty on structural response given the ground motion, which could theoretically be included in the analysis, but in this application was not. Uncertain structural response would increase total uncertainty by some unknown amount, perhaps to 0.70 or 0.75.

This uncertainty does not mean that the ABV approach is no good, that it produces too much uncertainty to be useful in loss estimation and risk management. Rather, it indicates that even with highly detailed information on ground motion, assembly damageability, and so on, there remains substantial uncertainty in total loss. Furthermore, it represents a lower of uncertainty for category-based methods, which use less detailed information in order to model a wider variety of similar buildings.

EXAMPLE BUILDING PERFORMANCE EVALUATION

The example building was analyzed for the component damage objectives shown in Table 4. In the table, "damage ratio" is defined as the fraction of such components damaged; the figures shown in the last two columns represent the maximum allowable damage ratio, as interpreted from FEMA 273 (Applied Technology Council, 1997) according to the translations shown in Table 1.

The life-safety (LS) performance level was tested for a ground shaking level of S_a = 1.5g, equivalent to the level of shaking associated with 10% probability of exceedance in the next 50 years for the selected Los Angeles site. Immediate occupancy (IO) was tested using S_a = 0.8g, which is the level of shaking with 50% exceedance probability in the next 50 years.

Figure 5 shows estimated probabilities of achieving the performance objectives for this building, based on 100 simulations for each earthquake level. That is, the figure shows the fraction of simulations in which the simulated damage ratio was less than the allowable damage ratio of Table 4.

The figure shows that the building almost certainly fails both overall life-safety (LS) and immediate occupancy (IO) requirements, primarily because of the fragility of the WSMF connections and the acoustical ceiling. The fragility of unanchored switchgear also prevents the building from passing immediate occupancy performance requirements.

Table 4. Sample maximum allowable life-safe (LS) and immediate-occupancy (IO) performance levels. The table shows the maximum fraction of assemblies reaching or exceeding the named damage state that would qualify as passing the stated performance levels.

Assembly	Damage state	Unit	Max damage ratio LS	Max damage ratio IO
WSMF connections	Fracture	ea	0.01	0.00
Exterior glazing	Visible cracking	lite	0.30	0.10
Drywall partition	Noticeable damage	8 lf	1.00	0.10
Acoustical ceiling	Collapse	ea	0.30	0.01
Traction gearless elevator	Inoperative	ea	1.00	0.00
Gas water heater	Inoperative	ea	1.00	0.00
Wet-pipe sprinkler system	Leakage	12 lf	0.10	0.01
Building heating terminal unit	Inoperative	ea	1.00	0.00
Chilled water cooling tower	Inoperative	ea	1.00	0.00
Switchgear – low voltage	Inoperative	ea	1.00	0.00
Switchgear -- medium voltage	Inoperative	ea	1.00	0.00
Motor installation	Inoperative	ea	1.00	1.00
Generator	Inoperative	ea	1.00	1.00

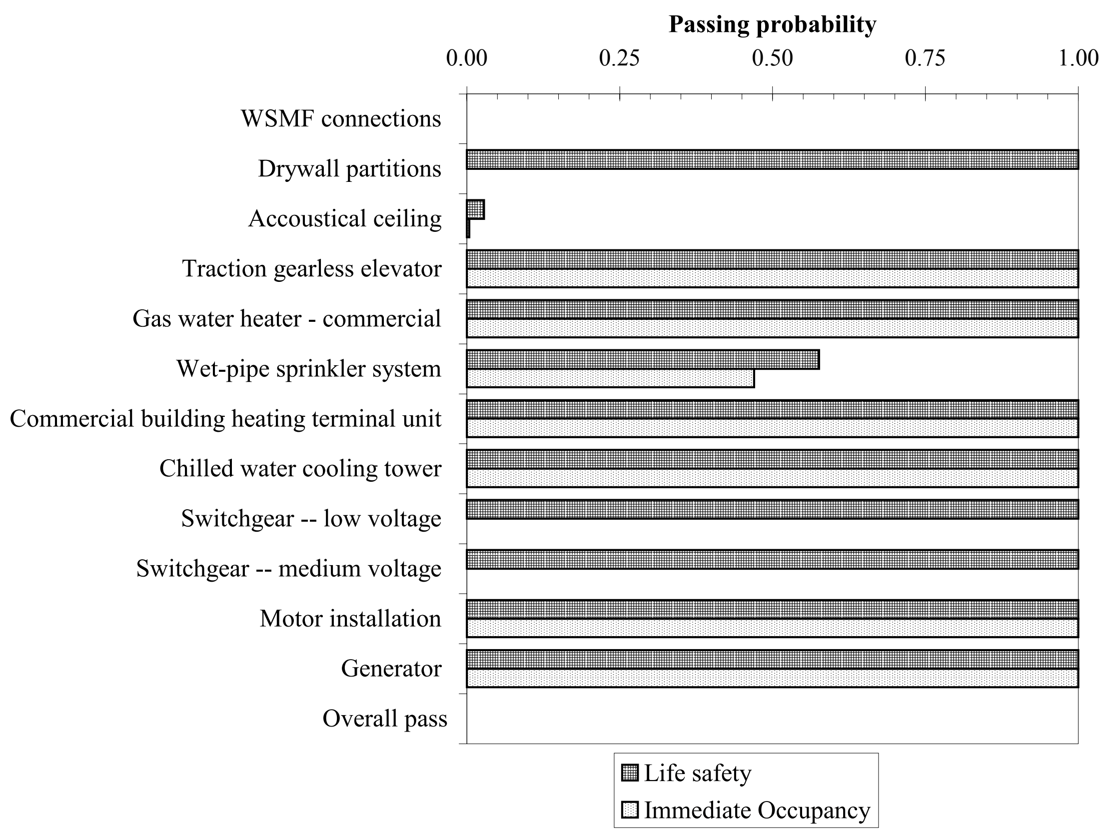

Figure 5. Probability of the example office building meeting sample performance levels. Each pair of bars shows the probability that a particular assembly will pass its performance objectives under the life-safety (LS) and immediate occupancy (IO) performance levels.

CONCLUSIONS

This paper has summarized a rigorous methodology for developing building-specific seismic vulnerability functions. The development of the methodology is detailed in Porter (2000). The approach, entitled assembly-based vulnerability (ABV), accounts for the detailed structural and nonstructural design of a building, rather than relying on category-based vulnerability functions that are more appropriate for use in macroscopic (multi-building) loss estimation.

The vulnerability functions developed with ABV are probabilistic and can account for uncertainty in ground motion, structural response, assembly fragility, repair cost, repair duration, and loss due to downtime. Because the methodology produces detailed damage simulations at the assembly level, the analyst can calculate the probability that a particular building will meet detailed performance-based design objectives. The assembly-level resolution also means that a designer or analyst can examine the benefits of alternative design, rehabilitation, or retrofit details, to which a category-based approach is not sensitive.

Each module of the approach can be implemented though state-of-the-art engineering methods and data. This modularity means that an analysis based on ABV can be improved incrementally as new data or structural analysis tools become available. For example, one can use new fragility information on one particular assembly type to improve the accuracy of an entire building vulnerability function, without changing other aspects of the model.

These benefits come at a cost: an ABV analysis involves all the work of a structural analysis, plus the creation of an inventory of building assemblies and the compilation of assembly capacity and repair-cost distributions. While the capacity and cost distributions can be reused in later analyses, they must first be created from laboratory or earthquake experience data or from theoretical fragility models, and compiled in a central library. The computational aspects of the approach however can be readily automated.

Because of its reliance on structural analysis of single buildings, the method is not intended to model the seismic vulnerability of entire classes of buildings in the manner of ATC 13 (Applied Technology Council, 1985) or HAZUS (National Institute of Building Sciences, 1997). However, if applied to a wide variety of particular buildings selected to represent the diversity of existing construction, ABV could be used to produce vulnerability functions for common generic structural types.

It is not known whether ABV produces loss estimates that are more accurate for a particular building than a category-based approach would produce. If "more accurate" means a smaller uncertainty on loss, then the ABV approach probably meets that criterion, since the uncertainty it produces must be a lower bound for a category-based vulnerability function that refers to a broad category of similar buildings, expert opinion notwithstanding on the uncertainty of the category-based vulnerability function. (As noted above, expert opinion typically underestimates uncertainty unless it is elicited very carefully.)

If "more accurate" means that the mean squared error from ABV is less than the mean squared error from a category-based approach, then the question can be answered, but at great cost. Answering it would require performing a large number of ABV analyses on a variety of buildings, and then waiting for an earthquake, or by performing shake-table tests of a large number of full-scale buildings.

In the end, an ABV model is only as accurate for a particular building as its constituent ground motion recordings, structural model, and assembly capacity and cost distributions. These at least are within the control of the analyzing engineer, who also has access to the building and its details. This is in contrast with an answer provided by experts years ago who were thinking of other buildings under other conditions with other objectives in mind.

GLOSSARY

ABV: Assembly-based vulnerability, a framework for developing building-specific seismic vulnerability functions.

ARMA: autoregressive moving average, a method to generate a random, artificial time series such as an earthquake accelerogram. ARMA models can include time-varying amplitude and variance similar to an original time series.

ATC 13: A document by the Applied Technology Council (1985) that, among other contributions, presents seismic vulnerability functions for a wide variety of structure types.

Conditional cumulative probability distribution: denoted generically by $F_{X|Y}(x|y)$, it gives the probability that X will take on a value less than or equal to x, given that the uncertain variable Y takes on the particular value y.

Conditional probability mass function: denoted generically by $p_{X|Y}(x|y)$, it gives the probability that the uncertain variable X will take on the particular value x, given that the uncertain variable Y takes on the particular value y.

Cumulative probability distribution: denoted generically by $F_X(x)$, it gives the probability that an uncertain variable X will take on a value less or equal to a particular value x.

HAZUS: A standard methodology and its associated software implementation for estimating economic and other loss associated with earthquake shaking. (Other perils such as wind and flood are also addressed by HAZUS.) See National Institute of Building Sciences (1997).

Gantt chart: a chart that depicts tasks to be performed as horizontal bars whose length indicates the duration of each task. Tasks are connected by lines that indicate the order in which the tasks must be accomplished.

PBD: performance-based design, a design philosophy that seeks to ensure that a building will meet certain observable performance goals after being subjected to given levels of ground shaking.

Seismic vulnerability function: a motion-damage relationship between financial or other loss and some measure of shaking intensity.

WSMF: welded-steel moment frame.

ACKNOWLEDGMENTS

Portions of this research were funded by the Kajima Corporation; by the Haresh Shah Family Foundation; and by the Achievement Rewards for College Scientists Foundation. Their support is gratefully acknowledged.

REFERENCES CITED

Applied Technology Council, 1985, *ATC 13: Earthquake Damage Evaluation Data for California*, Redwood City, CA, 492 pp.

Applied Technology Council, 1997, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings,* prepared for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, *FEMA 273*, Washington DC, 429 pp.

Behr, R.A., and Worrell, C. L., 1998, Limit states for architectural glass under simulated seismic loadings, *Proc., Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components, ATC 29-1 January 22-23, 1998, San Francisco,* Applied Technology Council, Redwood City, CA, 229-240.

Box, G.E.P., Jenkins, G. M., and Reinsel, G. C., 1994, *Time Series Analysis; Forecasting and Control, 3rd ed.,* Prentice Hall Inc., Englewood Cliffs, NJ, 598 pp.

Construction Specifications Institute, 1998, *UniFormat 1998*, Alexandria, VA.

Conte, J. P., Pister, K. S., and Mahin, S. A., 1992, Nonstationary ARMA modeling of seismic motions, *Soil Dynamics and Earthquake Engineering 11,* Philadelphia PA: Elsevier Science Publishers, 411-426.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E. V., Dickman, N., Hanson, S., and Hopper, M., 1996, *Seismic Hazard Maps for the Coterminous United States, USGS Open File Report 96-532,* U.S. Geological Survey, Menlo Park, CA, 110 pp.

Holmes, W. T., 2000, A vision for a complete performance-based earthquake engineering system, *Proceedings, 12th World Conference on Earthquake Engineering, January 30 – February 5, Aukland, New Zealand,* International Association for Earthquake Engineering, paper 8368, 7 pp.

Kustu, O., 1986, Earthquake damage prediction for buildings using component test data, *Proceedings, Third U.S. National Conference on Earthquake Engineering, August 34-28, Charleston, South Carolina,* Earthquake Engineering Research Institute, El Cerrito, CA, **2**, 1493-1504.

Kustu, O., Miller, D. D. and Brokken, S. T., 1982, *Development of Damage Functions for Highrise Building Components, JAB-10145-2,* URS/John A. Blume and Associates, San Francisco, CA.

National Institute of Building Sciences, 1997, *HAZUS Earthquake Loss Estimation Methodology: Technical Manual, Volumes I, II, and III, NIBS Document Number 5201,* Federal Emergency Management Agency, Washington, DC.

Polhemus, N. W. and Cakmak, A. S., 1981, Simulation of earthquake ground motions using autoregressive moving average (ARMA) models, *Earthquake Engineering and Structural Dynamics, Vol. 9,* John Wiley & Sons, Ltd., New York, NY, 343-354.

Porter, K. A., 2000, *Assembly-Based Vulnerability of Buildings and Its Uses in Seismic Performance Evaluation and Risk-Management Decision-Making, a Doctoral Dissertation,* Stanford University, Stanford, CA, 148 pp.

Porter, K., Scawthorn, C., Taylor, C., and Blais, N., 1998, *Appropriate Seismic Reliability for Critical Equipment Systems: Recommendations Based on regional Analysis of Financial and Life Loss, MCEER 98-0016,* Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 104 pp.

Rihal, S. S., 1982, Behavior of nonstructural building partitions during earthquakes, *Proceedings of the Seventh Symposium on Earthquake Engineering,* Department of Earthquake Engineering, University of Roorke, India, November 10-12, 1982, 267-277.

RS Means Co., 1997a, *Building Construction Cost Data, 1998, 56th Ann. Ed.,* Kingston, MA, 678 pp.

RS Means Co., 1997b, *Assemblies Cost Data, 23rd Edition (1998),* Kingston, MA.

SAC Connection Venture, 1995a, *Technical Report: Analytical and Field Investigations of Buildings Affected by the Northridge Earthquake of January 17, 1994, Report No. SAC-95-04,* Sacramento, CA.

SAC Joint Venture Guidelines Development Committee, 1995b, *Interim Guidelines: Evaluation, Repair, Modification and Design of Steel Moment Frames, Report No. SAC-95-02,* Sacramento, CA, 6-52.

Scholl, R. E., 1980, *Seismic Damage Assessment for Highrise Buildings, Open File Report 81-031,* U.S. Geological Survey, Menlo Park, CA, 143 pp.

Singhal, A., and Kiremidjian, A.S., 1997, *A Method for Earthquake Motion-Damage Relationships with Application to Reinforced Concrete Frames, Technical Report NCEER 97-0008,* National Center for Earthquake Engineering Research, Buffalo, NY, 218 pp.

Somerville, P., Smith, N., Punyamurthula, S., and Sun, J., 1997, *Development of Ground Motion Time Histories for Phase 2 of the FEMA/SAC Steel Project, Report No. SAC/BD-97/04,* SAC Steel Project, Sacramento, CA, 30 pp.

Spetzler, C. S. and Stael von Holstein, C.S.S., 1972, Probability encoding in decision analysis, *Proc., ORSA-TIMS-AIEE 1972 Joint National Meeting, Atlantic City, NJ, 8-10 November 1972*, 603-625.

Structural Engineers Association of California, 1995, *Vision 2000*, California Governor's Office of Emergency Services, Sacramento, CA.

Swan, S. W. and Kassawara, R., 1998, The use of earthquake experience data for estimates of the seismic fragility of standard industrial equipment, *ATC-29-1, Proc., Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components,* Applied Technology Council, Redwood City, CA, 313-322.

Tversky, A. and Kahneman, D., 1974, Judgment under uncertainty: heuristics and biases, *Science*, September 27, 1974, **185**, 1124-1131.