Verifying performance-based design objectives using assembly-based vulnerability

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ABSTRACT: Performance-based design (PBD) approaches are currently in development in the United States. Several key features must still be developed: numerical objectives, a theoretical framework for verifying that a building meets the specified objectives, detailed procedures to implement the framework, and language for performance specifications. This paper addresses the verification framework and detailed procedures using a simulation approach. The framework is entitled assembly-based vulnerability (ABV), which deals with damage at the level of individual building assemblies. The procedure involves six steps: determine the site conditions and building design; select ground-motion time histories; perform structural analysis to determine the structural response; apply response to fragility functions to simulate assembly damage; iterate to compile probabilistic assembly damage ratios; and compare these with numerical objectives from the code. The probability of meeting damage objectives, which are expressed as maximum allowable damage ratios, can be checked against minimum required passing probabilities, thus completing the verification procedure. This process meets the basic requirements of a PBD verification procedure, and allows for maximum design flexibility. The cost is computational effort, but that can be automated and perhaps simplified.

1 INTRODUCTION

A new design philosophy to replace the load and resistance factor design (LRFD) approach in the United States has been under development in recent years. Performance-based design (PBD) sets out performance objectives for all major structural, architectural, and other nonstructural building elements and systems. These objectives describe the degree of observable damage that is allowed to each component or building system in various size earthquakes. Using a PBD approach, a building designer would analyze a building to check whether the objectives are met, and would iterate the design until they were. The designer would not be constrained by prescriptive limits on structural response, but rather would design the building so that it meets the parameters of direct interest, namely limiting the damage to the various building elements.

Two notable documents propose an underlying philosophy for a PBD approach for the United States. Vision 2000 (Structural Engineers Association of California 1995) and FEMA 273 (Applied Technology Council 1997) both provide examples of the type of performance objectives being considered for the United States. These initial PBD documents do not represent complete building codes, but do satisfy some of the basic requirements. One can identify five items needed for a practical PBD approach:

1. Detailed objectives for building components that constitute overall building performance levels.

2. Numerical values for those objectives, plus minimum allowable probabilities for meeting them;
3. A theoretical framework for determining whether a design meets its objectives;
4. Detailed procedures to implement the theory; and
5. Language to formalize or simplify the implementation procedures.

Vision 2000 and FEMA 273 provide detailed objectives for building components, and provide qualitative (but not numerical) objectives. Table 1 shows sample performance descriptions from FEMA 273 for various components, and suggests numerical equivalents for the qualitative terms. Thus items 1 and 2 are nearly done, but the remaining elements are so far lacking. Initial attempts at item 3 have suggested setting drift limits that would indirectly ensure the objectives are met, but theoretical proofs are lacking. In any event, setting drift limits would defeat the purpose of allowing any design that meets the true underlying performance objectives. This paper summarizes a new framework, entitled assembly-based vulnerability (ABV), which can satisfy items 3 and 4.

Table 1. Typical performance descriptions from FEMA 273 (Applied Technology Council 1997).

Example	Qualitative term(s)	Translation
Generally negligible ceiling damage	Negligible, few, little	0 - 1%
Some cracked glazing panes; none broken	Some, minor	1 – 10%
Distributed partition damage	Distributed	10 – 30%
Many fractures at steel moment frame connections	Many	30 – 60%
Most HVAC equipment units do not operate	Most	60 – 100%

2 ASSEMBLY-BASED VULNERABILITY

Assembly-based vulnerability (ABV) was developed for evaluating building performance on a building-specific basis. Its objective was to estimate probabilistically the cost to repair future earthquake damage to particular buildings (Porter 2000), but it can also be used to verify PBD requirements. The key novelty of that framework is that it addresses building performance at the level of individual building assemblies. The ABV approach contrasts with category-based approaches that estimate building damage based solely on shaking intensity, structure type, and in some cases by considering highly aggregated collections of nonstructural components. The ABV methodology has six elements, as shown in Figure 1.

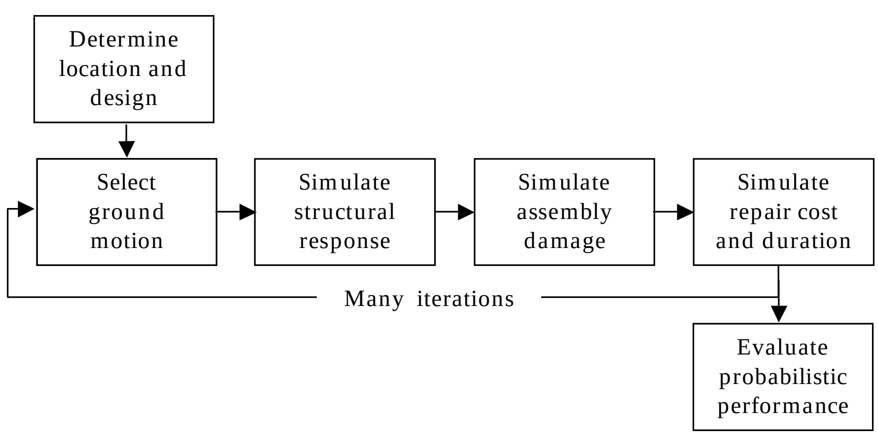

Figure 1. Steps of the ABV methodology.

Briefly, an ABV analysis begins by examining the building location and design to determine the seismic setting and to create a structural and nonstructural model of the building for analysis. The next step is to select or create ground-motion recordings that reflect the seismic hazard levels of interest. Third, one performs a dynamic (time-history) structural analysis of the building to capture structural response under each ground-motion time history. The structural response is used as an input to assembly fragility functions, to determine the damage state of every assembly in the building.

The cost and time to repair the damage is then determined using standard construction cost-estimation and scheduling procedures. Finally, the procedure is iterated many times to reflect the many uncertainties inherent in earthquake damage: ground motions, building characteristics, structural response, assembly fragility, and construction costs and durations. By performing many iterations, one creates a probabilistic model of building damage at a very detailed level, which can then be compared with PBD requirements. Details of these procedures are now presented.

2.1 *Determine building design*

The first step in an ABV analysis is to examine the building location, design and construction and to create an analytical model of its structural elements. Also, the analyst must create an inventory of all elements—structural and nonstructural alike—according to a standard categorization system of assemblies, referred to here as an assembly taxonomy.

The taxonomy attaches to every assembly a unique alphanumeric identifier, a brief description, and a unit for quantifying the assemblies. The use of a standard taxonomy offers several benefits, such as a common language for discussing assembly construction costs and repair costs, a basic unit for laboratory experimentation, and a convenient shorthand for gathering post-earthquake damage data. Several taxonomic systems exist to categorize building components. Notable among these are MasterFormat and UniFormat (Construction Specifications Institute 1995, 1998) and two related systems used by the R.S. Means Co. (2000a, b). These latter two systems include a unique identifier, description, unit of measure, and annually updated construction costs based on surveys of the US construction industry.

Finally, one determines the seismic hazard conditions of interest. For example, if one is concerned with the building's performance under an earthquake that has 10% probability of exceedance in the next 50 years, then the corresponding seismic shaking parameter is determined using standard means, for example, by reference to USGS hazard maps such as Frankel et al. (1996).

2.2 *Determine performance-level ground motions*

Next, a set of appropriate ground-motion time-history recordings are generated that match the site hazard levels determined in the previous step. If the hazard is measured in terms of spectral acceleration, then ground-motion time history recordings are selected that have approximately that level of spectral acceleration (measured at the fundamental period of the building), and that approximately match the site hazard and soil conditions. The recordings can be scaled within reasonable bounds to match the precise level of shaking desired. Somerville et al. (1997) discuss reasonable scaling factors.

Because of the large uncertainty inherent in loss estimation, many iterations are needed to produce a robust estimate of the performance of a building and its constituent assemblies. Consequently, a large number of ground-motion time histories are also required, potentially more than are readily available from historic earthquake recordings. It may therefore be necessary to simulate ground-motion time histories to supplement the recorded ground motions.

New simulated ground-motion time histories can be generated from real, historic ones using a variety of methods. To implement the ABV framework, we used a nonstationary autoregressive moving average model with two autoregressive parameters and one moving-average parameter—that is, an ARMA (2,1) model. This approach generates ground-motion time histories that have similar amplitude and frequency content as the original (real) recording, and vary during the simulated recording similarly to the real recording. Other ground-motion simulation methods exist. We used this one primarily because it has been successfully used in the past, e.g. by Singhal et al.

(1997). For a discussion of ARMA (2,1) simulation methods, see for example Box et al. (1994), Polhemus et al. (1981), and Conte et al. (1992).

2.3 *Perform structural analysis*

The analyst next performs a time-history structural analysis to determine the response of the structure to an input ground motion. The particular parameters of the structural response that are of interest depend on the particular assemblies present in the building. For example, some assemblies are primarily sensitive to acceleration, e.g. rigid electrical equipment fixed to the floor. Others are sensitive to transient or residual drifts, such as full-height architectural partitions or exit doors. Structural components can be primarily sensitive to peak applied load, ductility demand, or hysteretic energy. Each relevant response parameter must be identified and recorded for each structural analysis.

2.4 *Determine assembly damage states*

Each damageable assembly in the building must be associated with a set of relevant damage states that it can enter in an earthquake, and one or more structural response parameters to which the assembly is primarily sensitive. In addition, a probabilistic relationship between structural response and assembly damage is required. These relationships are typically referred to as fragility functions. They give the probability of reaching or exceeding a particular damage state as a function of the structural response to which the assembly is exposed.

Let each assembly's possible damage states be defined by a mutually exclusive and collectively exhaustive set that is indexed by the variable $D = 0, 1, \ldots N$, where $D = 0$ represents the undamaged state, N represents the number of possible damage states, and $N \geq 1$ for a damageable assembly. (A damage state can also be associated with an additional continuous variable that describes the severity of damage within that damage state, but this complication is ignored here for simplicity.) Let Z represent the random structural response to which the assembly is exposed, and let z represent a particular value of that response. Z and z can be multidimensional; for simplicity they are assumed here to be scalar. Let d represent a particular value that D takes on. Then an assembly fragility for a particular damage state d is represented by the function $g_d(z)$, as shown in Equation 1, in which the notation $P[A|B]$ refers to the probability that A is true, given that B is true.

$$g_d(z) = P[D \geq d \mid Z = z] \tag{1}$$

Such a fragility function is identical to a cumulative probability distribution on the (random) structural response at which the assembly enters or exceeds damage state d. The level of structural response that causes the assembly to reach or exceed damage state d is referred to here as the assembly capacity relative to d, and the probability distribution on that capacity is referred to here as the capacity distribution for damage state d. Let X_d represent the (random) capacity for damage state d, and let x represent a particular value of X_d. Let $F_{Xd}(x)$ represent the cumulative probability distribution function of X_d. Thus,

$$F_{Xd}(z) = g_d(z) = \mathrm{P}[D \geq d \mid Z = z] \tag{2}$$

If damage states are defined so that an assembly with $N \geq 2$ must enter damage state i before it can enter damage state $j > i$, then the probability that an assembly is in damage state d after being subjected to structural response z is given by Equation 3. The probability that it is in any damage state less than or equal to d is given by Equation 4, which is referred to as the conditional cumulate distribution on damage state. The notation $p_{A|B}(a|b)$ refers to a conditional probability mass function, i.e., the probability that the random variable A takes on the particular value a given that the random variable B takes on the particular value b. The notation $F_{A|B}(a|b)$ refers to a conditional cumulative probability distribution, i.e., the probability that the random variable A takes on the particular value less than or equal to a, given that the random variable B takes on the particular value b.

$$p_{D|Z}(d \mid z) = \begin{cases} 1 - F_{X1}(z) & d = 0 \\ F_{Xd}(z) - F_{Xd+1}(z) & 0 < d < N \\ F_{Xd}(z) & d = N \end{cases} \tag{3}$$

$$F_{D|Z}(d \mid z) = \sum_{\delta=0}^{d} p_{D|Z}(\delta \mid z) \qquad 0 \le d \le N \tag{4}$$

Given the conditional cumulative distribution on damage state for every damageable assembly in a building, plus the structural responses z produced by the structural analysis, one can simulate the damage state of every assembly in the building using the inverse method: for each assembly, draw a random number u from a uniformly distributed random variate that can take on any value between 0 and 1. Equation 5 then gives the simulated assembly damage state.

$$d = F_{D|Z}^{-1}(u) \tag{5}$$

Let $N_{j,d}$ represent the number of assemblies of assembly type j that are in damage state d, determined by counting the damages in a particular simulation. Let M_j represent the total number of assemblies of that type in the building, damaged or otherwise, determined from the building inventory. The damage ratio for that assembly type, denoted by $R_{j,d}$, is then given by Equation 6. Let $Q_{j,d}$ represent the maximum allowable damage ratio for the given hazard level, given by the code performance objectives. The building can be said to pass the objective if $Q_{j,d} \ge R_{j,d}$. Let $S_{j,d}$ be a passing variable, i.e., a binary number indicating whether the building passes the performance objective for assembly type j and damage state d in one particular trial, as shown in Equation 7a. Alternatively, a maximum allowable damage ratio $Q_{j,d}$ could be defined in terms of any damage state of d or greater, in which case Equation 7b would indicate whether the building passes the objective in a particular trial. (In Equation 7b, N refers to the number of possible damage states, as before.)

$$R_{j,d} = \frac{N_{j,d}}{M_j} \tag{6}$$

$$S_{j,d} = \begin{cases} 1 & if \quad Q_{j,d} \ge R_{j,d} \\ 0 & if \quad Q_{j,d} < R_{j,d} \end{cases} \tag{7a}$$

$$S_{j,d} = \begin{cases} 1 & if \quad Q_{j,d} \ge \sum_{\delta=d}^{N} R_{j,\delta} \\ 0 & if \quad Q_{j,d} < \sum_{\delta=d}^{N} R_{j,\delta} \end{cases} \tag{7b}$$

2.5 *Iterate to quantify probability of meeting objectives*

A single simulation of ground motion, structural response, and assembly damage gives only one possible outcome of the earthquake. The building could pass a particular performance objective in one simulation and fail it in another. It is most reasonable to develop a PBD code philosophy based on the notion that the building should pass its performance objectives with at least a given probability. These passing probabilities could be defined for each performance objective, or for simplicity, the code-writing authority could define a single passing probability that applies to every performance objective.

By iterating the process many times, one can determine the probability that a particular performance objective will be met. Let T represent the number of times the simulation is performed, and let $V_{j,d}$ represent the minimum required passing probability for the performance objective for assembly type j and damage state d. The building passes the performance objective for assembly type j and damage state d if Equation 8 is true. In the equation, the superscript t is applied to the passing variable S to indicate a particular trial t.

$$V_{j,d} \leq \frac{1}{T}\sum_{t=1}^{T} S_{j,d}^{t} \tag{8}$$

Thus, PBD verification would amount to checking that Equation 8 is true for each performance objective. If the building fails to meet any objective, the design can be iterated until every objective is met, either by changing the building stiffness or by changing the design of the particular components that fail the verification tests.

3 CONCLUSIONS

Assembly-based vulnerability (ABV) represents one possible framework for verifying that a building meets a set of detailed performance-based design (PBD) objectives. It offers several desirable features of a PBD-verification procedure: (1) it accommodates any ground motion as input, (2) it can consider structural degradation and duration of ground motion, (3) it can model ductile and brittle elements, (4) it can model repair costs and downtime (not discussed here; see Porter 2000), (5) the passing probability is explicitly stated and can be explicitly tested, (6) it is comprised of standard engineering techniques and therefore promises industry consensus, and (7) it allows for maximum design flexibility: the engineering is not constrained by arbitrary drift limits or other structural response parameters, as long as the performance goals are met. (Items 1 through 6 were proposed by Holmes 2000).

Several elements remain to be developed before a PBD approach can be established in the United States, and before ABV can be used to verify PBD objectives. First, numerical damage ratios must be equated with the qualitative damage descriptions that currently appear in discussions of PBD codes. Second, minimum allowable passing probabilities must be defined, in acknowledgment that it is not generally possible to assure 100% confidence of meeting any particular objective. Third, fragility functions must be developed for a variety of common building assemblies. (It is difficult to see how this can be avoided, given that PBD as currently conceived addresses building performance at the level of detailed assemblies.) Fourth, procedures must be developed to simplify the implementation of the verification procedures. Perhaps factors similar to those in load and resistance factor design (LRFD) can be developed that can be applied to nominal structural response and assembly capacities. Finally, appropriate language must be created to implement the verification procedure.

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