A BUILDING DAMAGE ESTIMATION METHOD FOR BUSINESS RECOVERY

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SUMMARY

Assembly-based vulnerability (ABV) represents a new method to estimate earthquake damage repair cost, loss of use duration, and loss of use cost. ABV treats a building as a unique collection of familiar assemblies (e.g., gypsum board partitions, suspended ceilings, etc.) that may be damaged in an earthquake, rather than treating the building as a monolithic unit that experiences some undifferentiated damage fraction between zero and 100% of replacement cost. Building assemblies are modelled as having probabilistic capacity to resist imposed seismic demand (measured in terms of force, acceleration, drift, etc.). Demand is estimated using familiar structural analytical techniques. Capacity is determined using laboratory test data, earthquake experience data, and in the case of suspended ceilings, reliability techniques. With ABV, building-specific structural analysis is brought to bear on the issue of seismic vulnerability. Furthermore, repair cost and repair duration are modelled using familiar cost estimation techniques and Gantt scheduling. By treating parts of buildings rather than the building as a whole, ABV provides the means to detail impairment of the business revenue stream, for the present example on a suite-by-suite basis in a rental property. It also provides a more defensible, engineering basis for economic decisions regarding seismic retrofit, earthquake insurance, and mortgage lender's risk.

INTRODUCTION

Owners of buildings located in seismically active regions make high-value decisions regarding earthquake preparedness, risk management, and planning for business recovery. The quality of the decision depends on the quality of the risk information available, most notably annual likelihood of various levels of earthquake damage costs and post-earthquake operability. These decisions may involve the need for and amount of earthquake insurance and the efficiency of seismic retrofit. Other parties with financial or regulatory interest in a building have similar information needs. Building operators, tenants, lenders, insurers, and government officials frequently base important decisions on estimates of damage frequency and severity. The better the risk information, the better their decisions are likely to be.

The quality of this information depends on a good seismological model of earthquake occurrence and attenuation, and a vulnerability model that closely reflects the performance of the unique building in question – its susceptibility to damage and the consequent loss of use. The seismological parts of seismic risk analysis are fairly well developed compared with models of building vulnerability to ground shaking. Existing approaches to seismic vulnerability suffer significant shortcomings, as will be discussed below. In this paper a new approach for developing building vulnerability and loss functions is presented. Vulnerability and loss functions obtained using this approach are more consistent with the damage of the components and the structural system, and as such they represent a considerable improvement over existing damage functions.

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CURRENT APPROACHES TO SEISMIC VULNERABILITY

Available damage functions. Two types of models currently exist to estimate earthquake damage and repair time: empirical (based on statistical data) and heuristic (based on judgment or belief). Both approaches attempt to estimate repair costs (and consequently repair duration) for broad classes of buildings as a function of seismic shaking intensity, e.g., modified Mercalli intensity (MMI) or spectral intensity (S_a, S_v, etc.).

Empirical models have been developed by aggregating insurance losses as a fraction of total limits of insurance liability, grouping together all buildings of a common structural classification experiencing approximately the same shaking intensity. All major commercial seismic risk models in the United States rely to varying degrees on such insurance loss data. In these models, insurance limits are equated with replacement costs, for example via an assumed or estimated ratio of insurance limit to value (ITV or LTV). With these data in hand, then, a relationship may be created between repair cost (as a fraction of replacement cost) and shaking intensity. A plot of this relationship is referred to as a *vulnerability function*. An empirical model typically comprises a dozen or dozens of such vulnerability functions, one for each of several structural types.

Because an empirical model is based on actual historic data, its primary advantage is in offering decision-makers confidence in its accuracy, at least in its ability to estimate past earthquake damage. All such empirical models suffer from several important handicaps, however. Insurers dislike sharing sensitive loss data, thus empirical models are typically inaccessible and unverifiable. The aggregate nature of the data causes empirical models to be insensitive to design details. Consequently, empirical vulnerability functions have limited usefulness in evaluating retrofit options or in accounting for construction changes that take place after the earthquakes on which they are based. Empirical loss data frequently fail to remove post-earthquake building improvements from pure damage-repair costs. Furthermore, insurance data tend to become sparse at high ground shaking intensities, limiting their statistical validity. Another important statistical shortcoming of empirical insurance data is the frequent lack of information about damage below the deductible, a figure in some cases equal to 15% of the building value. Finally, insurers often lack adequate normalizing data such building replacement cost, especially for commercial policies where a single "blanket" coverage limit is provided for a large number of insured buildings.

Heuristic models avoid some of these shortcomings. The two most important examples are ATC-13 (Applied Technology Council, 1985) and HAZUS (NIBS/FEMA, 1995). ATC-13 was developed using a Delphi process, in which several experts were polled on their belief of damage (as a fraction of replacement cost) to a given structure type for a given MMI intensity. HAZUS' vulnerability functions were developed using estimates of drift ratios and floor acceleration given S_a, but the approach nonetheless relies heavily on undocumented engineering judgment, particularly with respect to the relative value and vulnerability of nonstructural components. Heuristic models offer the advantages of general availability and a comparatively open technical approach, but they cannot avoid the problems of verification, insensitivity to design detail or to technological innovation. Since they are based on opinion rather than empirical data, they are often seen as being less accurate.

A NEW APPROACH: ASSEMBLY-BASED VULNERABILITY

Approach summary. The proposed approach attempts to remediate these shortcomings by breaking the vulnerability problem into smaller, more tractable pieces. Instead of treating a building as a monolithic entity identified solely by its location, structure type, and total replacement cost, the building is treated as a collection of parts or *assemblies*, each of which is subjected to a known or modelled demand, and each of which has a probabilistic capacity to resist damage. Examples of assemblies include welded steel moment frame connections, gypsum board partitions; windows; etc. The whole building is treated as a collection of parts, in the same way an automobile is treated as a collection of parts. When an automobile is taken to a body shop after a collision, repair cost is estimated considering the individual tasks required to repair or replace damaged members. In the same way, assembly-based vulnerability (ABV) treats the post-earthquake repair of an earthquake-damaged building as a series of assembly repairs.

Probability of damage to each assembly is also individually calculated based on structural response. The probability distribution of seismic *demand* on each assembly – structural and otherwise – is calculated by conducting a series of structural analyses at various probable input motions. The *capacity* of assemblies is widely tested in engineering laboratories world-wide, for example, in load tests of connections, racking tests of glazing or drywall partitions; dyamic tests of suspended ceiling systems, etc. The ready availability of both demand and capacity for common assemblies is in marked contrast to the paucity of publicly available, verifiable whole-building loss data. These assembly-based data are used to estimate uncertainty in structural capacity and to develop a probability distribution of structural capacity.

Repair costs and repair durations for each assembly type are likewise far more readily available than whole-building loss-of-use data. Standard Gantt scheduling allows the engineer to estimate loss of use by office suite or for the whole building, given the knowledge of which assemblies are damaged. Fragility and loss functions for different ground motions are generated by considering the probability of damage and repair cost combinations. Probability distributions of repair times are developed using different repair scheduling schemes.

The approach is summarized in Figure 1. The chart in Figure 1 is known as an influence diagram (or alternatively as a relevance or decision diagram) and describes the relationship of the various components [e.g., Howard and Matheson, 1981]. The generic models that are required for the overall approach are listed in the vertical block at the left of the diagram. The block horizontal on the top right describes the relationship between these components. The overall model pertains to a single building at a specified site *O*. The five models listed on the left side of the diagram are: seismicity, ground motion, structural response, assembly fragility (actually a collection of many fragility models, one for each assembly type), and repair (again, one for each assembly type). These models are represented by conditional probability distributions. The horizontal block at the upper right represent the parameters of true interest: ground shaking at the site; structural response of the building in question; damage conditions of individual assemblies within the building, repair cost, loss-of-use duration, and finally, total economic value.

The challenge of the approach is to create the required generic computational models listed in the vertical block of Figure 1. For purposes of seismic risk analysis of a single building, a probabilistic model of damage, repair, and loss of use is desirable. Each generic computational model must therefore capture as much of the inherent uncertainty as possible. The outcomes of this model are probability distributions of damage, cost and repair time for the building. Given the number of random variables involved, Monte-Carlo simulation appears to offer the most efficient solution. A Monte Carlo approach is therefore summarized below.

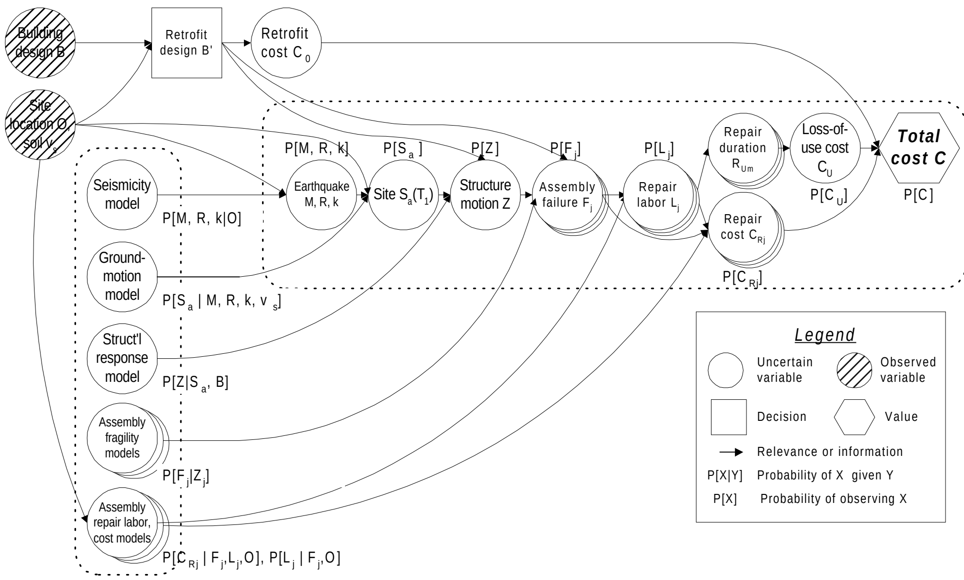

Figure 1 – ABV influence diagram for retrofit design decision situation

The total cost is the cost of repair, cost of labour and cost or down time (or loss of revenue due to closure of the facility). The general formulation for any of these loss computations is given in Equation 1:

$$P[C \mid O] = \sum_{\substack{All \\ assemblies}} \iiiint\!\!\int P[C \mid X]P[X \mid Z]P[Z \mid S] \quad \text{Equation 1}$$
$$P[S \mid M, R, k, O]P[M, R, k \mid O]\text{dx dz ds dm dr}$$

P[*] represents the probability of the argument *. *C* is the cost of repair, or labor, or revenue loss. Physical damage is generically given as *X*. The parameters *Z, S, M, R* and *k* are respectively the structure response, ground shaking, event magnitude, distance from the rupture zone to site *O*, and type of seismic source where the event originates. The conditional probability distributions in Equation 1 correspond to the models listed in Figure 1. These are described in greater detail as follows.

Event and Seismicity. The seismicity model is represented by $P\ [M, R, k|O]$ which describes the probability of that an event will occur of magnitude M at a distance R from the site O and will on a seismic source of type k (e.g. strike-lip, normal, etc.). Fault parameters for much of the United States are presented in database management (DBMS) and geographic information systems (GIS) maintained, for example, by the US Geological Survey [USGS, 1999] or by state and local agencies. These databases provide seismic source names, type of source (e.g. strike-slip fault, subduction zone, etc.), fault geometry, magnitude-recurrence relationships, and geographic parameters required to determine fault distance for any particular site. Thus, it is relatively easy to estimate the probability distribution of earthquake events and their frequency.

Ground motion. The ground-motion model is intended to predict the vibration of the ground at the site of the structure. In the current approach, the propagation of seismic waves from the rupture zone to the site is captured through a simple ground motion attenuation function [e.g., Boore et al., 1997]. This function predicts the median ground motion at a site. The ground motion is assumed most frequently to be lognormally distributed with a specified logarithmic variance. Equations 2 and 3 prove the basic formulation for the Boore at al. [1997] median attenuation function ($\mu_{\ln(Sa(T1))}$) and the corresponding standard deviation (s). From these functions the estimation of $P[S_a|M, R, v_s]$ is a trivial matter, where S_a refers to spectral acceleration at the building's first period; M and R are as before; and v_s is site soil shear-wave velocity. $\sigma_{\ln(Sa(T1))}$ is the logarithmic standard deviation of the spectral acceleration at the period T, and $\Phi^{-1}(U^{(1)})$ is the inverse of the standard cumulative normal distribution evaluated at $U^{(1)}$.

$$\mu_{\ln(Sa(T1))} = b_1 + b_2(M_w - 6) + b_3(M_w - 6)^2 + b_5\ln(r) + b_V\ln(V_s/V_a) \qquad \text{Equation 2}$$

$$s = \exp(\sigma_{\ln(Sa(T1))}\Phi^{-1}(U^{(1)}) + \mu_{\ln(Sa(T1))}) \qquad \text{Equation 3}$$

The ground motion parameter S_a describes only the peak response of the structure (or its equivalent one degree of freedom system). The response of the various assemblies, however, depends on characteristics of the entire earthquake time history and the resulting structural vibration. Thus it is necessary to have ground motion time history information at the site to capture better the response of the structural system and the individual assemblies. Under the current model, a suite of earthquake ground motions are simulated using a nonstationary autoregressive moving-average (ARMA 2,1) model such as described by Polhemus & Cakmak [1981]. These are used in the evaluation of the response of the structure.

Structural response. Structural response is represented by $P[Z|S_a, B]$, where Z refers to a vector of peak structural response parameters, such as peak acceleration of the 3rd-floor diaphragm, S_a is as before, and B is building design. Conventional software packages such as DRAIN-2D provide a deterministic structural response quantities. More advanced dynamic structural analysis programs are currently available; however, for the purposes of this demonstration, the structural model shown in Figure 2 is analyzed using DRAIN-2DX. The model is subjected to the ground motion record simulated in the previous step. The resulting peak responses Z (drift, floor acceleration, etc.) are recorded for later use. Figure 3 shows the 3rd story drift for the demonstration building subjected to 2400 simulated ground motions (80 simulated records scaled to 30 $S_a(T_1)$ values). The figure also shows imputed lognormal distributions of Z conditioned on each of the $S_a(T_1)$ values.

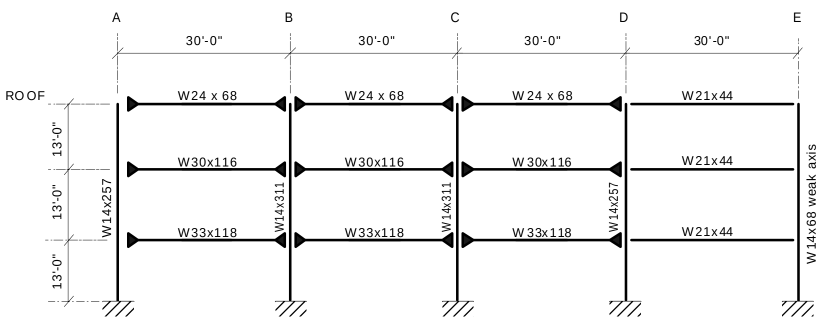

Figure 2 – Structural model used in demonstration building

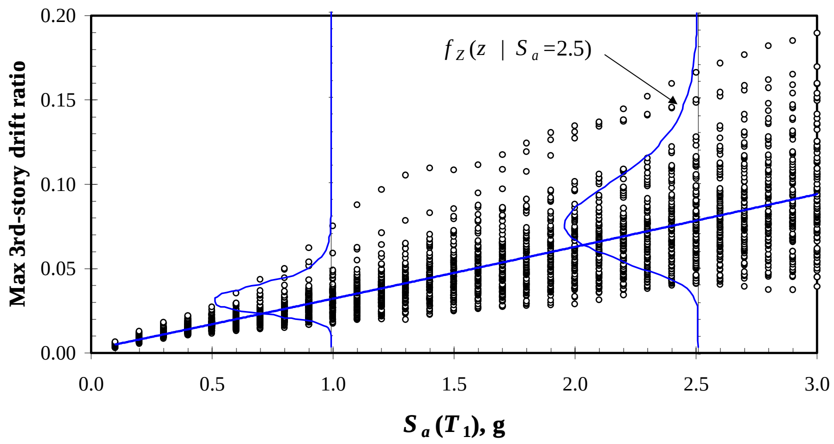

Figure 3 – Sample peak structural response using DRAIN-2DX

Assembly fragility. $P[F_j|Z_j]$ represents an assembly fragility model, where F_j refers to the failure of a particular type of assembly j such as visible cracking of 5/8-in. gypsum-board partition on metal stud, and Z_j refers to the peak structural response to which the partition is exposed, e.g., peak interstory drift angle of the 3rd floor. Such an assembly fragility model must be established for every assembly in the building of interest. Creating a complete set of these models has been a central focus of the research. Figure 4 shows a sample fragility model for drywall partitions. The fragility model is based on data from laboratory tests by Rihal [1982].

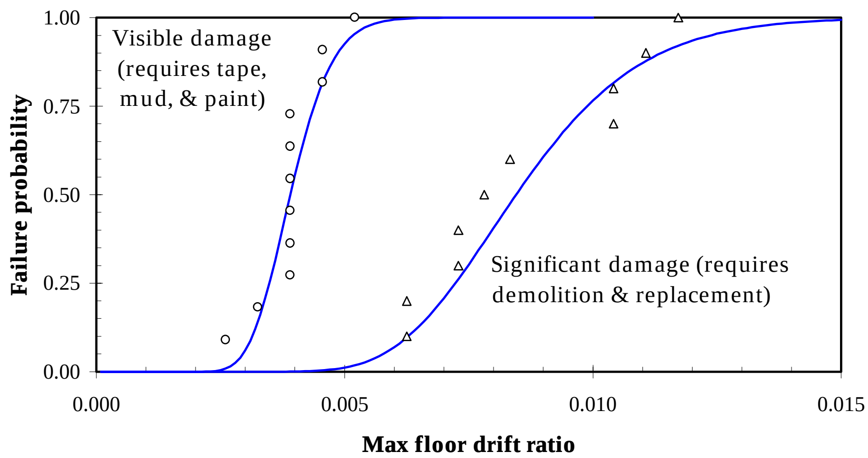

Figure 4 – Sample assembly fragility model: 8'x8' drywall partition on 3-5/8" metal stud

Where laboratory or earthquake experience data are unavailable or inadequate to develop assembly fragilities, theoretical models may be created using reliability analysis methods. Such a method was used to generate the fragility functions for suspended ceilings. In this approach the critical failure modes for suspended ceilings are identified and the probability of each mode estimated using fundamentals of structural reliability theory. The probability that an assembly fails under an imposed peak structural response Z (which may be seen as demand) is defined as the probability that the assembly capacity is less than demand. If E_f represents the event that an assembly fails, z is the imposed structural response, X is the (random) assembly capacity, x_m is the median capacity, and β is the logarithmic standard deviation X, then the failure probability $P[E_f|z]$ is given by Equation 3. Damage to an assembly can be simulated using Equation 5, where $I[c]$ is the indicator function: true if condition c is true; false otherwise; and $U^{(2)}$ is a sample realisation of a uniform variate. A simple modification of Equation 4 is used for assemblies that have two or more identified failure modes, such as gypsum-board partitions.

$$P[E_f \mid z] = F_X(z) = \Phi((\ln(z) - \ln(x_m))/\beta) \qquad \text{Equation 4}$$

$E_f = I[U^{(2)} < F_X(z)]$ Equation 5

Unit cost. Assembly labor and repair-cost models are represented by $P[L_j|F_j, O]$ and $P[C_{Rj}|F_j, L_j, O]$, respectively, where L_j refers to the labor (in laborer-hours) required to repair a single instance of assembly type *j*, F_j and *O* are as before, and $C_R j$ refers to the cost in dollars to repair an instance of assembly type *j*. $C_{R,j}$ is based in part on mean repair-cost data published in RS Means [1996]. Statistical distributions and variances are assumed for the relevant parameters: material unit cost to building owner $C_{m,j}$, productivity $C_{p,j}$ (units of type *j* repaired per labor hour), labor unit cost $C_{l,j}$ (dollar cost to owner per labor hour used to repair assembles of type *j*). Total cost $C_{R,j}$ per damaged assembly instance is then represented by Equation 6.

$C_{R,j} = C_{m,j} + C_{l,j}/C_{p,j}$ Equation 6

Total repair cost per damaged assembly $C_{R,j}$ is obtained using Monte Carlo simulation, and an appropriate probability distribution is fitted through the result. For instance, Figure 5 shows a sample repair-cost model for drywall partitions in Los Angeles. The repair cost is calculated by multiplying the number of damaged units by the unit repair costs, and summing over all assembly types. Figure 6 shows the preliminary results for 600 simulations of repair costs.

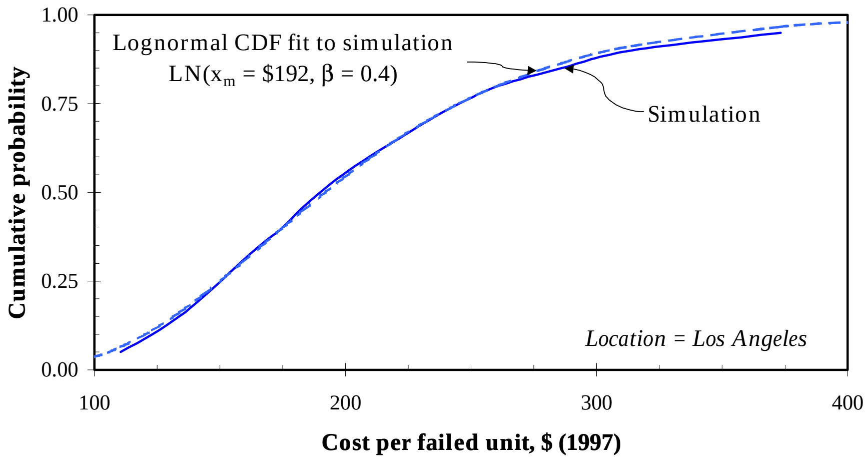

Figure 5 – Sample repair-cost model: demolish and replace 8'x8' drywall partition

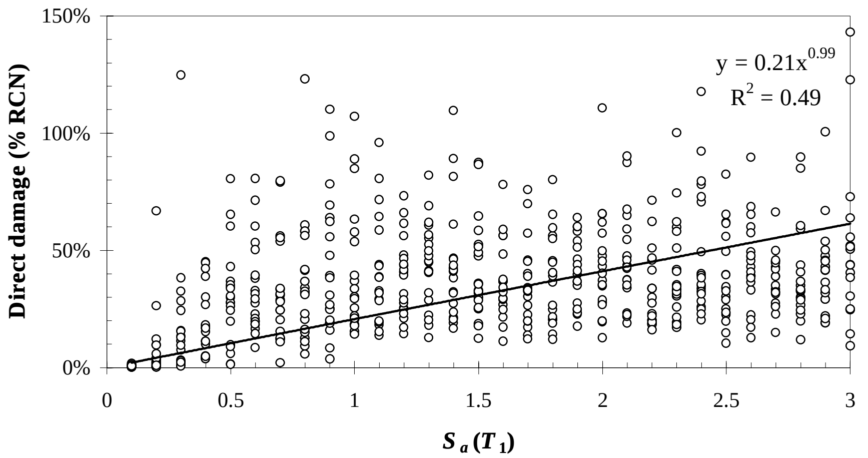

Figure 6 – Preliminary direct-damage simulations for demonstration building

Repair scheduling. Given a damage state determined in the previous step, repairs are scheduled using standard Gantt scheduling techniques. Mean repair productivity statistics are obtained from RS Means [1997]. Figure 7 shows a single simulation of repair duration for a single damage state, and illustrates how ABV provides insight into how a rental revenue stream is affected by damage repairs on the basis of parts of the building, rather than treating loss of use as a homogenous whole. In the figure, a simple scheduling assumption is made: repairs to one assembly type are performed by a single standard construction crew, who complete their work in one suite or operational area, and then move to the next. Alternatively, a fast-track scheduling assumption may be made: enough repair crews are hired so that repairs of all operational areas may are made in parallel, with minimal delays for change of trade. Figure 8 shows preliminary results for 600 simulations using the fast-track repair assumption.

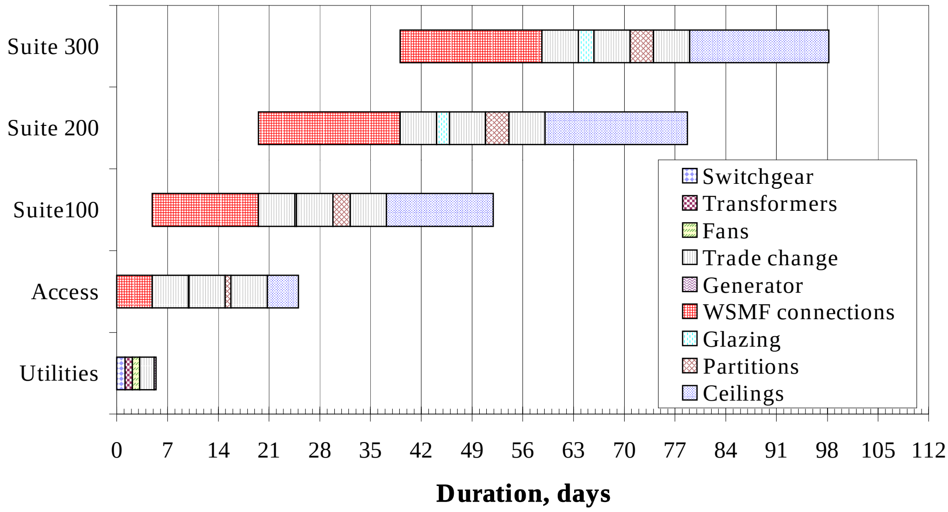

Figure 7 – One simulation of loss of use duration: repair assemblies in series (by rental unit)

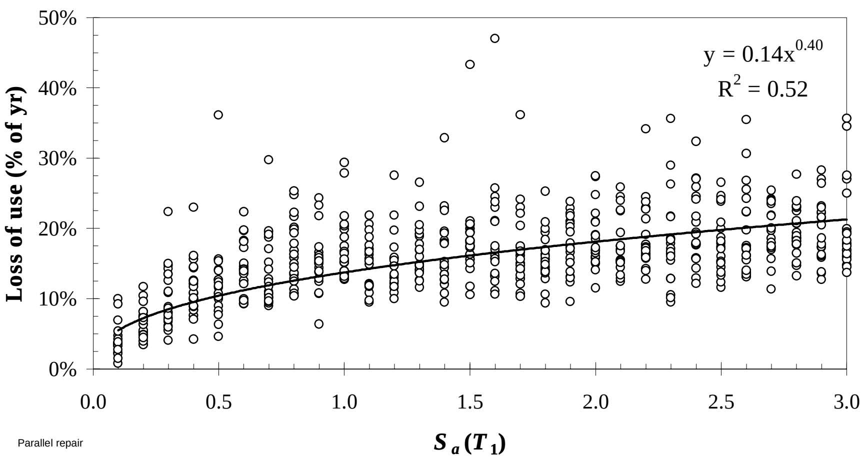

Figure 8 – Preliminary fast-track loss of use simulations for demonstration building

CONCLUSIONS

The advantage of this approach is that it is based on fundamental structural and nonstructural components and system behaviour in an earthquake. It does not rely either on empirical whole-building damage and loss data nor on heuristic information about the damage state of the structure or its components. Instead, using ABV, each building is approached as a structural system that supports a unique configuration of architectural, mechanical, electrical, plumbing, and furnishing assemblies. The vulnerability to direct loss is also treated individually for each building. Retrofit and other decisions can then evaluated in terms of cost and benefit to that particular building, accounting for its unique setting, configuration, and construction characteristics. Furthermore, knowledge of which *particular* building assemblies are damaged allows for a more detailed estimate of indirect losses. Such information is particularly useful for retrofit and reconstruction decisions.

The models formulated in the ABV approach are based on published empirical or theoretical data and are thus easily verifiable. The modular nature of the ABV approach results in ready integration of data that are far more easily acquired than are whole-building loss statistics from earthquakes.

The approach has certain obvious limitations, the most significant of which is the creation of a fragility model for each assembly in the building of interest. A library of these will, in time, be created and maintained; in this paper only a sample of these functions are presented. Another difficulty with the current approach is that it does not lend itself to application to a large number of buildings, since the component fragilities are estimated for each building individually. The main components of the ABV approach, however, have been automated for the present study leading to considerable computational efficiency. Bazzurro and Cornell [1999] have examined means to limit the number of simulations required to determine mean structural response leading to additional savings in computation time. This issue is currently being addressed to obtain an optimal solution.

In summary, the ABV approach allows for more accurate, dependable, and building-specific earthquake risk analyses to be performed than are currently possible using existing class-based empirical and heuristic models.

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