A Performance-Based Earthquake Engineering Method to Estimate Downtime in Critical Facilities

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SUMMARY:
A method is offered to estimate downtime (the time to restore a facility to operability, not total repair time) for second-generation performance-based earthquake engineering. It applies in cases where downtime is primarily controlled by nonstructural systems (although red-tagging and lifeline failure are addressed); restoration begins immediately after the earthquake; and components are repaired in parallel. It uses fault trees to relate component damage to a building's post-earthquake operability; component fragility functions to estimate the occurrence probability of basic events; and uncertain component repair times conditioned on various possible damage states. The method meets four criteria for second-generation performance-based earthquake engineering: (1) it estimates a system-level performance metric of interest to the facility stakeholder, i.e., time required to restore some critical function that defines the top event; (2) it acknowledges and propagates all important sources of uncertainty; (3) it (can) employ nonlinear dynamic structural analysis; and (4) it considers the detailed components that comprise the system. The methodology is illustrated using a real facility, in particular a computer data center. Results compare reasonably with HAZUS-MH, ATC-13, the actual downtime history of the facility, and the judgment of an operator of the facility who participated in the development and review of the fault tree.

Keywords: downtime, performance-based earthquake engineering, fault trees

1. DOWNTIME VERSUS REPAIR TIME IN PBEE-2

The objective of 2nd-generation performance-based earthquake engineering (PBEE-2) is to estimate the future seismic performance of buildings, bridges, and other aspects of the built environment in system-level terms of interest to stakeholders, while treating individual building components, accounting for all important sources of uncertainty, and using the state-of-the-art in nonlinear dynamic structural analysis. The performance measures have often been described as including repair costs, life-safety impacts, and loss of functionality, or "dollars, deaths, and downtime." This was the vision of researchers affiliated with the Pacific Earthquake Engineering Research (PEER) Center who initially developed PBEE-2, and of the developers of the ATC-58 document that offers guidelines for implementing PBEE-2. This manuscript focuses on the last-named performance measure: downtime.

The ATC-58 guidelines, and before them the research of one of us (Porter 2000; Mitrani-Resier 2007), specify a method to estimate the time required to effect all repairs, from the time when the first repair workers arrive at the building to the time when the last worker leaves. As useful as this downtime measure is, some facilities serve an essential function that can resume before the last wall is repainted and the last cracked window is replaced. The manuscript offers a method to estimate the uncertain amount of time that passes between the earthquake and when the facility resumes its essential function.

2. PRIOR APPROACHES TO ESTMATING DOWNTIME

Downtime of individual facilities has been estimated using empirical, analytical, and expert-opinion approaches. By “empirical” is meant using regression analysis to relate observed repair times to degree of damage or shaking intensity. By “analytical” is meant using engineering and construction-contracting principles in the sequential modelling of seismic hazard, structural response, physical damage, and repair time. By “expert opinion” is meant drawing on engineering judgment to relate a whole-building damage state to restoration time.

Of these, empirical and expert-opinion approaches generally treat buildings as indistinguishable instances of a category of structure type, occupancy type, or both. In the United States, ATC-13 (1985) and HAZUS-MH (NIBS and FEMA 2009) are important examples of methods that treat building downtime using such categories, largely relying on expert opinion to relate damage to restoration time. ATC-13 explicitly treats downtime as a measure of functionality; HAZUS-MH considers downtime in terms of repair time. Comerio and a colleague (2006, 2010) offer rare empirical evidence of downtime from 4,900 woodframe residential buildings affected by the 1989 Loma Prieta and 1994 Northridge earthquakes, quantifying downtime in terms of time to start and complete repairs.

Analytical approaches offer the ability to treat buildings as unique entities. Such approaches can be traced at least to Czarnecki (1973) who proposed an analytical approach to estimating repair cost using a structural model to estimate the demands imposed on individual building components, which are then related to physical damage and repair cost. Kustu et al. (1982) added the use of empirical relationships between structural response and building-component damage, which is then related to repair cost, explicitly separating the analysis of damage from that of repair cost. In a series of related works, Beck et al. (1999), Porter (2000), and Mitrani-Reiser (2007) treat building damage in somewhat finer detail, and approached repair-time as a problem in construction scheduling. The uncertain damage state of each building component is simulated, the repairs ordered in a logical sequence, the uncertain time required to effect each repair simulated and combined using Gantt scheduling. Figure 1 illustrates one simulation of the repair schedule for the hypothetical building described in Porter (2000). ATC-58 adopts a scheduling approach, adding treatment of economies of scale and explicit assumptions about how many workers can fit into a given space to effect repairs. Notably, ATC-58 also offers a large, vetted library of component fragility functions and consequence functions that relate structural response to uncertain damage, and damage to uncertain repair time.

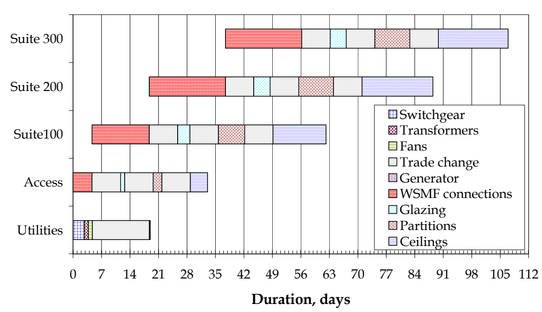

Figure 1. Gantt scheduling approach to estimating downtime

Post-earthquake operability of a facility is a distinct but related question. Operability—whether a facility works or not immediately after an earthquake—has long been addressed using fault-tree analysis, especially in the study of the seismic reliability of nuclear power plants (US Nuclear Regulatory Commission 1975; Levine and Vesely 1976). Fault-tree analysis (FTA) involves constructing a logic diagram that relates the occurrence of an undesirable event (called a top event, where “facility rendered inoperative” is an example of such an event) through Boolean operators (and, or, etc.) to basic events (such as “switchgear overturns”) whose probability can be estimated as a function of ground motion. FTA allows one to estimate the probability of the top event occurring, either as a function of ground motion, or during a specified period of time. FTA has been applied to manage the seismic reliability of critical facilities other than nuclear power plants; see e.g., Porter et al. (1993, 1998) or Johnson et al. (1999).

3. COMBINING FAULT-TREE ANALYSIS AND PBEE-2

Fault-tree analysis can be used to estimate in closed form the probabilistic time required after an earthquake to restore a facility to functionality, considering its unique features, lifelines and other necessary systems, their seismic fragility, and their probabilistic repair time. The method begins by constructing a fault tree with post-earthquake inoperability as the top event; structural failure, non-structural failure, and off-site perils as lower events; and these are further developed until one reaches basic events in terms of the failure of particular structural, nonstructural, and lifeline failures. For example, Figure 2 depicts the top of a fault tree for a particular computer data center that we examined. Not shown in the fault tree, but commonly needed, is the number n of identical components reflected in a basic event, and the number of failures m that would cause the basic event to occur. For example, there might be two redundant halon tanks indicated by the basic event, "halon tanks fail," both of which must fail for the basic event to occur, in which example $n = m = 2$.

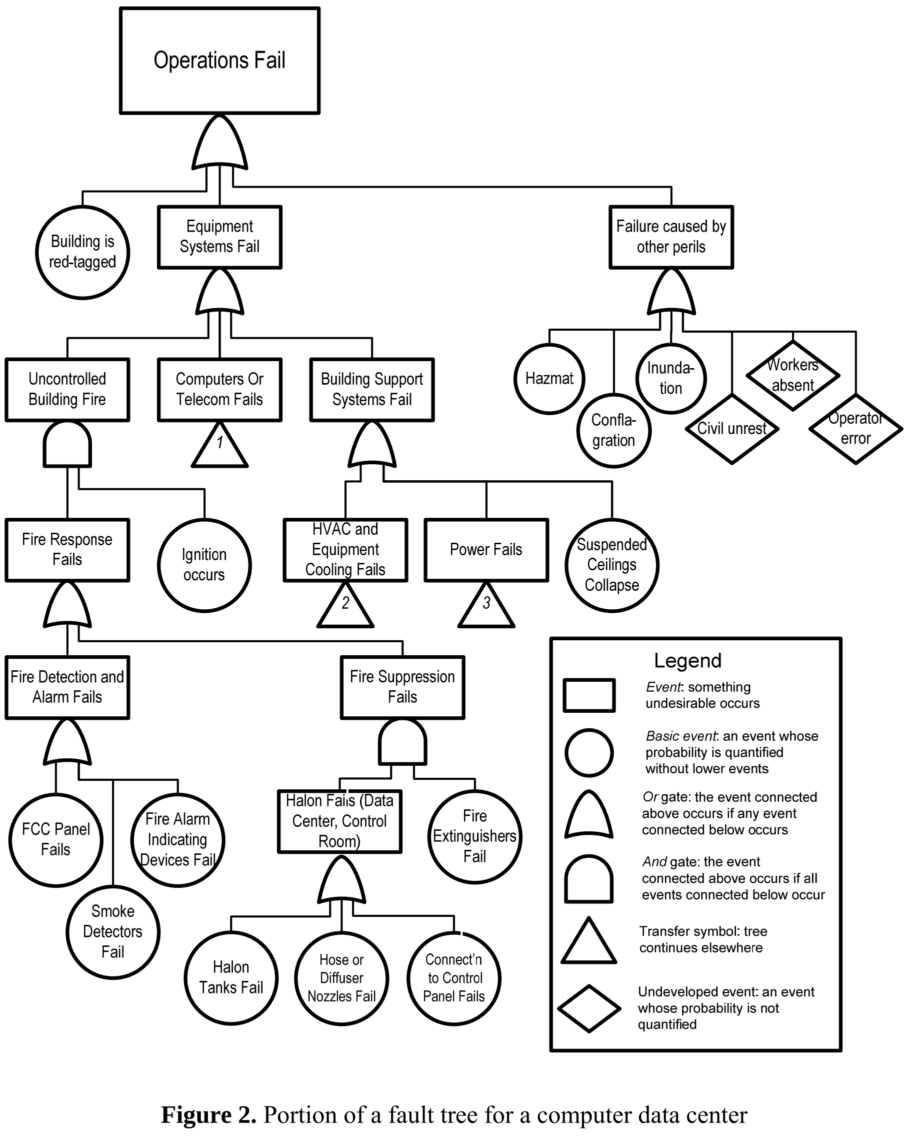

Figure 2. Portion of a fault tree for a computer data center

Basic-event probabilities are taken as the occurrence probability conditioned on shaking for each component (its fragility function evaluated at each of a set of shaking levels), times the probability that the component would not be restored within a specified time t given that it had to be repaired (the complement of the cumulative distribution function of repair time conditioned on damage). In the following discussion, both are idealized using lognormal cumulative distribution functions, but other parametric or nonparametric distributions can be used equally well. Whatever functional form best represents the fragility and repair time should be used.

Let

- i = an index for components reflected by a basic event
- θ_i = median capacity of component i
- β_i = logarithmic standard deviation of capacity of component i
- q_i = median time to repair component i given that it is damaged
- b_i = logarithmic standard deviation of time to repair component i given that it is damaged
- n = number of identical instances of a particular component reflected in a basic event
- m = minimum number of components out of n whose failure would cause the basic event to occur
- t = a given period of downtime
- r = a particular value of ground-motion intensity, such as a particular value of peak ground acceleration at the facility
- h_i = ratio of excitation imposed on component i to ground motion.
- $P_u(r,t)$ = probability that an upper event u is still occurring after time t, given shaking r

Basic-event probabilities are then calculated for specified values of r and t. Where $n = m = 1$,

$$F_i\left(r,t\right)=\Phi\left(\frac{\ln\left(r\cdot h_i/\theta_i\right)}{\beta_i}\right)\cdot\left(1-\Phi\left(\frac{\ln\left(t/q_i\right)}{b_i}\right)\right) \tag{1}$$

Otherwise,

$$F_i\left(r,t\right)=\left(\sum_{k=m}^{n}\binom{n}{k}\left(\Phi\left(\frac{\ln\left(r\cdot h_i/\theta_i\right)}{\beta_i}\right)\right)^k\left(1-\Phi\left(\frac{\ln\left(r\cdot h_i/\theta_i\right)}{\beta_i}\right)\right)^{(n-k)}\right)\cdot\left(1-\Phi\left(\frac{\ln\left(t/q_i\right)}{b_i}\right)\right) \tag{2}$$

where Φ denotes the standard normal (Gaussian) cumulative distribution function. When θ measures the zero-period acceleration of the base of a component and r is peak ground acceleration, it is common (though not necessary) to estimate h_i as follows

h_i = 1 if the component is located in the bottom 1/3rd of the height of the building,
1.5 if in the middle 1/3rd
2.0 if in the top 1/3rd

A better (if more labor intensive) approach would be to perform a number of nonlinear dynamic structural analyses at many levels of ground motion r and derive h_i as a function of r. In any case, given the basic-event probabilities as calculated above, the calculation of upper-events probabilities is no different from standard fault-tree analysis. For the reader who is unfamiliar with the math, an upper event that is connected to basic events $\{i, i+1, \ldots i+j\}$ by an "and" gate, that upper event is still occurring after time t with probability shown in Equation (3). For an "or" gate, the upper event is still occurring after time t with probability shown in Equation (4).

$$P_u\left(r,t\right)=\prod_{k=i}^{i+j}F_k\left(r,t\right) \tag{3}$$

$$P_u\left(r,t\right)=1-\prod_{k=i}^{i+j}\left(1-F_k\left(r,t\right)\right) \tag{4}$$

Equations (3) and (4) are iteratively applied to the events next higher in the fault tree, until one reaches the probability that the top event is still occurring after time t, given ground motion r. Performing the calculation at many levels of ground motion r and t produces a 3-dimensional surface representing the top-event probability as a function of r and t, which we denote here by $P_{top}(r,t)$, i.e., the probability that the downtime is at least t given shaking r.

Equations (2), (3) and (4) assume independence of lower events conditioned on r. Kennedy and Ravindra (1984) recommend a more-conservative approach be used for nuclear power plants: that perfect correlation be assumed for identical components, identically installed, located at the same level and oriented in the same direction if it is more conservative to do so (i.e., when it results in higher failure probabilities). Without offering the proof, we assert that available evidence of the seismic performance of common mechanical, electrical, and plumbing components suggests that such an assumption is overly conservative for facilities other than nuclear power plants.

With $P_{top}(r,t)$ and the seismic hazard curve for the site, one can calculate a variety of useful measures, especially the expected value of downtime given shaking r, and the probability that a facility will be rendered inoperative for at least a time t at least once during a planning period τ. The math should be familiar to the reader who is familiar with probabilistic seismic risk analysis, and is not repeated here.

4. VALIDATION

To test the methodology, we applied it to a real computer data center in Southern California. We constructed the fault tree in collaboration with the data-center operators after examining every component in the facility that mattered to the post-earthquake operability of the facility. We performed a red-team exercise with different operators and engineers of the data center, in which the team tried to think of ways that the facility could fail that were not reflected in the fault tree. We revised the fault tree appropriately. We generally took the required values of θ, β, q, and b from a new database developed for ATC-58, and from other sources such as Johnson et al. (1999) where ATC-58 was lacking. We then calculated the downtime-hazard curve, by which we mean the probability of exceeding downtime t during a specified planning period (here, $\tau = 50$ yr), as a function of t.

The downtime hazard curve we calculated is readily compared with alternative models, particularly ATC-13 (1985) and HAZUS-MH (2009). For the former, we used the damage probability matrix for a generic industrial high-technology facility housed in a generic reinforced concrete shearwall building. For the latter, we used the downtime model for a generic financial institution housed in a generic low-rise reinforced concrete shearwall with a high-Code seismic design. The comparison is illustrated in Figure 3, which shows general agreement between the facility-specific model developed here and the generic models of ATC-13 and HAZUS-MH. The derived model agrees with the judgment of the facility operators within a factor of 2. It also agrees with the actual earthquake experience of the facility, which in 20 years of operation has not experienced downtime exceeding 2.5 hours. The model estimates the probability of at least 2.5 hours of downtime in 20 years to be 22%. While none of these validation exercises is definitive, each does tend to strengthen the argument that the method is valid.

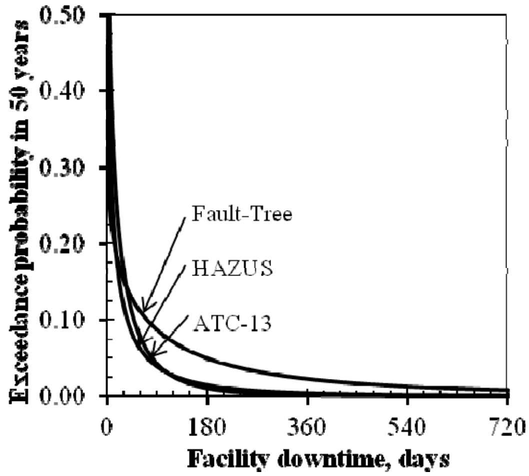

Figure 3. Downtime hazard of fault-tree method compared with HAZUS-MH and ATC-13

5. CONCLUSIONS

We offer an analytical and method to estimate the uncertain time to restore an essential facility to functionality. It considers the facility-specific topology of the facility: its unique combination of structural, nonstructural, and lifeline components. It relies on new component-restoration-time data developed for 2nd-generation performance-based earthquake engineering (PBEE-2), and employs well-established principles of fault tree analysis to relate component failure to facility functionality. The method differs from PBEE-2 as encoded in the ATC-58 guidelines in that it quantifies the duration non-functionality, as opposed to the (generally longer) time required to repair all damaged components in the facility. The methodology assumes that restoration begins immediately after the earthquake, which seems appropriate for essential facilities. The methodology was validated by comparing its estimate of downtime hazard with that estimated using ATC-13, HAZUS-MH, as well as the facility's actual earthquake performance history and the judgment of the facility operators.

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