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ISSUES WITH APPLYING PERFORMANCE-BASED ENGINEERING TO DISTRIBUTED INFRASTRUCTURE SYSTEMS

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ABSTRACT

The performance-based earthquake engineering (PBEE) paradigm has been revolutionary for many aspects of earthquake engineering, due to its ability to incorporate ground motion hazard, structural response, component damage and system-level decision variables. It also rigorously accounts for uncertainties and produces metrics useful for a number of decision-making contexts. The performance-based engineering approach has been most widely used for assessing single facilities such as buildings. In principle, the approach applies to distributed infrastructure systems as well, though there are a number of complications; specifically, quantifying seismic hazard to wide regions, evaluating system-level decision variables as a function of component damage, and managing computational expense are significant challenges. This talk will discuss the parallels between single-building and infrastructure-system PBEE, and discuss approaches for overcoming the challenges with infrastructure assessment. The increasing availability of algorithmic solutions and software tools for addressing those challenges means that many opportunities exist in the near future to apply and extend this area of research.

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The performance-based earthquake engineering (PBEE) paradigm has been revolutionary for many aspect of earthquake engineering, due to its ability to incorporate ground motion hazard, structural response, component damage and system-level decision variables. It also rigorously accounts for uncertainties and produces metrics useful for a number of decision-making contexts. The performance-based engineering approach has been most widely used for assessing single facilities such as buildings. In principle, the approach applies to distributed infrastructure systems as well, though there are a number of complications; specifically, quantifying seismic hazard to wide regions, evaluating system-level decision variables as a function of component damage, and managing computational expense are significant challenges. This talk will discuss the parallels between single-building and infrastructure-system PBEE, and discuss approaches for overcoming the challenges with infrastructure assessment. The increasing availability of algorithmic solutions and software tools for addressing those challenges means that many opportunities exist in the near future to apply and extend this area of research.

Introduction

The PEER performance-based engineering framework has been a transformative paradigm for earthquake engineering, in its ability to frame structural performance assessment in terms of metrics compatible with a broader variety of decision-making than only verifying code compliance [1,2]. For example, the ability to predict annual exceedance rates of dollar losses or facility downtime provides direct support to evaluate the costs and benefits of high-performance design schemes or retrofit options.

PBEE for buildings

Mathematically, the analysis can be framed using the well-known "PEER integral"—a key

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concept that has facilitated this approach [1].

$$\lambda(DV) = \int_{\mathbf{DM}} \int_{\mathbf{EDP}} \int_{IM} G(DV|\mathbf{DM}) dG(\mathbf{DM}|\mathbf{EDP})\, dG(\mathbf{EDP}|IM)\, |d\lambda\,(IM)\,| \tag{1}$$

where $\lambda(DV)$ is the annual rate of decision variable (DV) such as repair cost exceeding some threshold, **DM** is a vector damage measure indicating the discrete damage states of each component in the building, **EDP** is a vector of engineering demand parameters such as story drift ratios and peak floor accelerations, *IM* is a scalar ground motion intensity measure such as spectral acceleration at a specified period, and $\lambda(IM)$ is the annual rate of ground motions with shaking that exceed the given *IM* level. With the above notation, bold denotes a vector, $G(\ |\ )$ denotes a complementary cumulative distribution function (and $dG(\ )$indicates its derivative), and the specific values of *DV*, **DM**, **EDP** and *IM* have been omitted from the notation for brevity.

This integral formulation highlights two notable features of this assessment approach. First, the $\lambda(IM)$ term covers exceedance rates of a range of *IM* levels, rather than considering only a single shaking intensity (as is often done in code assessments). This allows the analyst to understand the role of small but frequent earthquakes, and large “beyond code” shaking. Second, the calculation goes beyond assessing Engineering Demand Parameters (the final metric for many other engineering assessments), to assessing damage to components and the Decision Variables (i.e., repair costs, recovery time, and injuries and fatalities).

FEMA P-58 [3] has been instrumental in standardizing the above concepts. It evaluates equation (1) by using Monte Carlo simulation for the **DM** and **EDP** integrals, and numerical integration for the *IM* integral. This is a practical choice, as the *IM* integral is with respect to a scalar parameter, while the **DM** and **EDP** integrals would be over vector parameters and so much more difficult if not impossible to evaluate easily and accurately.

PBEE for distributed infrastructure

Distributed infrastructure systems have received relatively less attention with regard to this PBEE approach, although certainly there are many important efforts in this area [4–7]. For distributed infrastructure, concepts similar to equation 1 can be applied, but there are some challenges.

A notable one is that the distributed nature of the systems means that there is no scalar *IM* that can be used. In comparison to equation (1), the integral then becomes:

$$\lambda(DV) = \int_{\mathbf{DM}} \int_{\mathbf{EDP}} \int_{\mathbf{IM}} G(DV|\mathbf{DM}) dG(\mathbf{DM}|\mathbf{EDP})\, dG(\mathbf{EDP}|IM)\, |d\lambda\,(\mathbf{IM})\,| \tag{2}$$

The presence of this vector creates a new challenge for quantifying and evaluating this integral. Hazard maps are inappropriate for specifying regional **IM** values, as they represent ground motion amplitudes that are unlikely to all come from a single earthquake rupture. Ground motion maps for a given earthquake scenario are sometimes used, but this has the shortcoming that it does not capture impacts of alternate rupture scenarios. Further, direct calculation of ground motion hazard for a vector **IM** is not practical for any reasonably sized network. For these reasons, full PBEE assessment of distributed infrastructure systems requires switching to a Monte Carlo solution of the **IM** integral instead. This can be done either in a pure Monte Carlo approach, or with some form of optimization or clustering that will reduce the number of realizations and thus the number of network analyses [8–11].

A related challenge is that the vectors of **IM**s and **DM**s have correlation (i.e., ground motions have special correlation spatially, and damage to bridges or other network components of similar types will not be independent. The former can be quantified from past ground motion recordings [e.g., 12], and the latter typically requires judgement at present if it is even considered [7]. Improved characterization of these correlations is an important topic for future work.

A final note when comparing equations (1) and (2) is that infrastructure risk is often characterized using fragility functions relating *IM* as the site directly to the Damage Measure for a given component (e.g., a bridge or a pipe segment). Those fragility functions may be pre-calibrated using dynamic structural analysis, empirical data, or judgement. This is done to utilize a wider range of fragility modeling approaches, and to manage computational complexity. This means that in practice the **EDP** terms in the assessment are omitted and the calculation is better described by the following equation

$$\lambda(DV) = \int_{\mathbf{DM}} \int_{\mathbf{IM}} G(DV|\mathbf{DM}) dG(\mathbf{DM}|\mathbf{IM}) |d\lambda\left(\mathbf{IM}\right)| \tag{3}$$

where all terms are as defined above.

Conclusions

There are parallels between performance-based earthquake engineering assessments of individual structures and distributed infrastructure, but also significant differences. Of particular focus in this abstract is that distributed infrastructure requires a vector of ground motion intensity measure values at the locations of all damage-susceptible components in the region. This creates complexity in the analysis procedure and typically means that intensity measures are characterized using Monte Carlo simulation rather than numerical integration in the “PEER integral.” There remain opportunities in performing this characterization, but given the proven utility of the performance-based earthquake engineering paradigm, continued efforts to enable practical PBEE assessment for infrastructure systems are likely to pay dividends for the profession.

Acknowledgments

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