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Estimation and impacts of model parameter correlation for seismic performance assessment of reinforced concrete structures

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A B S T R A C T

Consideration of uncertainties, including stochastic dependence among uncertain parameters, is known to be important for estimating seismic risk of structures. In this study, we characterize the dependence of modeling parameters that define a structure's nonlinear response at a component level, and the interactions of multiple components associated with a structure's response. We use random effects regression models to estimate correlations among parameters. The models are applied to a component test database with multiple tests conducted by differing research groups. Multiple tests that are conducted by a research group are subject to similar conditions and are conducted to investigate the impacts of particular properties of components. The set of tests can effectively represent components at different locations in a structure, and so are suitable for estimating stochastic dependence in model parameters. Regression models can be applied to the database to compute correlation coefficients that reflect statistical dependency among properties of components tested by individual research groups. It is assumed here that these correlation coefficients also reflect correlations associated with multiple components in a structure. To illustrate, correlations for reinforced concrete element parameters are estimated from a database of reinforced concrete beam-column tests, and then used to assess the effects of correlations on dynamic response of a frame structure. Increased correlations are seen to increase dispersion in dynamic response and produce higher estimated probabilities of collapse. This work provides guidance for characterization of parameter correlations when propagating uncertainty in seismic response assessment of structures.

1. Introduction

Performance-based earthquake engineering enables quantification and propagation of uncertainties in a probabilistic framework to make robust estimations of seismic risk and loss of structures. Quantification and propagation of ground motion uncertainties have received significant attention in the research community, but an important and somewhat less-explored topic is uncertainty in structural modeling (e.g., [12]). The uncertainties related to use of idealized models and analysis methods, as well as uncertainties in a model's parameters, influence assessments of the seismic reliability of a structure. Explicit quantification of uncertainties and characterization of dependence among the random model parameters are essential for propagating these uncertainties when assessing seismic performance.

While quantification of model parameter uncertainties is relatively well studied, stochastic dependence among model parameters has received very little attention, in large part due to scarcity of appropriate calibration data. When it has been assessed or considered in assessments, it is typically in the form of correlation coefficients. Where the random variables have a multivariate normal distribution, correlations provide a complete description of their dependence. They are also useful in first-order and other approximate reliability assessments.

The current state-of-the-art in seismic reliability analysis is to use judgment in quantifying the correlation structure of analysis model parameters. Haselton [25] used judgment-based correlation coefficients when considering model parameter uncertainty in assessing collapse risk of reinforced concrete structures, and showed that variability in collapse capacity was strongly influenced by the correlation assumptions. Liel et al. [38], Celarec and Dolsek [13], Celik and Ellingwood [14] and Pinto and Franchin [54]all used assumed correlations among modeling parameters when propagating modeling uncertainty for seismic performance assessment of reinforced concrete structures.

Although the effects of correlations among random variables on general system reliability problems are well known, few researchers have used observational data to quantify dependence. Idota

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et al. [31] assessed the correlation of strength parameters for steel moment resisting frames using steel coupon tests from production lots. Vamvatsikos [69] used those results to study the effects of correlation of components at different locations in a building on its dynamic response. We are aware of no other studies that directly estimate correlations in component-level or phenomenological modeling parameters in order to study seismic collapse risk.

In this study, we estimate the correlation structure of modeling parameters that define a component's nonlinear cyclic response, and study the interaction of different components on system-level dynamic response. Random effects regression is used with a database of reinforced concrete column tests to infer correlation structure of parameters defining a concentrated plasticity model. The database is composed of reinforced concrete column tests performed by multiple research groups. Correlation coefficients are obtained that represent statistical dependency among parameters within a set of tests conducted by a research group. Multiple tests conducted by a research group are subject to similar conditions and are conducted to investigate the impacts of particular properties of components. Therefore, the set of tests can effectively represent conditions different locations in a structure. And the correlation coefficients can be assumed to reflect dependency among parameters corresponding to components throughout a structural system. The assessment of correlation coefficients is discussed in the subsequent sections. We then use the estimated correlations to assess the effects of correlations on dynamic response of a four-story reinforced concrete frame building, and to explore potential simplified approaches for representing parameter correlations. Although the reported correlation results are for reinforced concrete model parameters, the presented framework can be applied for other types of materials or models.

2. Probabilistic seismic performance assessment

We use the probabilistic performance-based earthquake engineering methodology to assess structural performance (e.g., [35,15]). Nonlinear structural analyses are run using a suite of ground motions to propagate uncertainties related to ground motion variability and seismic hazard. The results from structural analyses are then related to the risk of collapse and other damage states of interest.

Evaluation of structural collapse is particularly important since seismic design provisions in building codes aim to provide adequate collapse safety of structures even in extreme events. Collapse response of structures is associated with highly nonlinear component behavior, and modeling collapse requires structural analysis models that can capture large inelastic deformations with significant cyclic strength and stiffness degradation in the elements due to repeated cycles of loading. Here we use concentrated plasticity elements to capture such effects, and perform nonlinear dynamic analysis to assess structural collapse risk.

The concentrated plasticity model proposed by Ibarra et al. [29], which has been frequently used to simulate sidesway collapse in frame structures (e.g., [78,17]), is used in this study to model component response. Specific attention is given to the correlation of model parameters used to define plastic hinges in seismic resisting moment frames. Phenomenological concentrated plasticity models are well-suited for modeling collapse of structures [16]. Model parameters that define concentrated plasticity models are generally related to physical engineering parameters by empirical relationships. These relationships link component design parameters (e.g. axial load ratio, spacing of transverse reinforcement) to model parameters via equations calibrated using regression analysis. Modeling uncertainty is more pronounced for collapse response simulations than for elastic or mildly nonlinear simulations, due to both the relatively limited knowledge of parameter values (due to more limited test data) and the highly nonlinear behavior associated with collapse.

The concentrated plasticity model has a trilinear "backbone curve", shown in Fig. 1, defined by five parameters: capping plastic rotation ($\theta_{cap,pl}$), effective stiffness (secant stiffness up to 40% of the component yield moment, EI_{stf}), yield moment (M_y), capping moment (M_c), and post-capping rotation (θ_{pc}). A sixth parameter, γ, controls the rate of deterioration (under cyclic loading) of basic strength, post-capping strength, unloading stiffness, and accelerated reloading stiffness.

The uncertainty in these modeling parameters is large, as estimated by a predictive model for these parameter values that will be discussed further below. These predictive model is a function of design parameters such as the axial load ratio, shear span ratio, lateral confinement ratio, concrete strength, rebar buckling coefficient, longitudinal reinforcement ratio, ratio of transverse tie spacing to column depth, and ratio of shear at flexural yielding to shear strength [27]. Axial load ratio is a particularly important variable in predicting component model parameters such as capping and post-capping rotation capacity and cyclic energy dissipation capacity.

For a given structural design, the parameters associated with elastic and peak strengths are moderately uncertain: the $EI_{stf}/EI_g, M_y$ and M_c/M_y parameters have logarithmic standard deviations of 0.28, 0.3 and 0.1, respectively. The parameters associated with more nonlinear displacement capacities and cyclic deterioration, however, are highly uncertain: the $\theta_{pc}, \theta_{cap,pl}$ and γ parameters have logarithmic standard deviations of 0.73, 0.59 and 0.51, respectively. We note that the variability on these parameters are significantly larger than the variability associated with other physical model parameters due to the underlying behavioral effects (reinforcing bar buckling, local flange buckling, fracture) that control the degrading response. These large variations in degrading behavior at large inelastic deformations have also been reported by Fell et al. [19] for prediction of buckling and fracture in steel braces, and Kunnath et al. [36] for simulating reinforcing bar buckling and fracture.

In this study, we aim to characterize correlation of these model parameters in a structure. Parameter correlations are grouped into within-component and between-component correlations. The former refers to correlations among modeling parameters that define response of a single component, whereas the latter refers to correlations among parameters from differing components, as illustrated Fig. 2. This distinction is useful because within-component correlations can be estimated from tests of individual components,

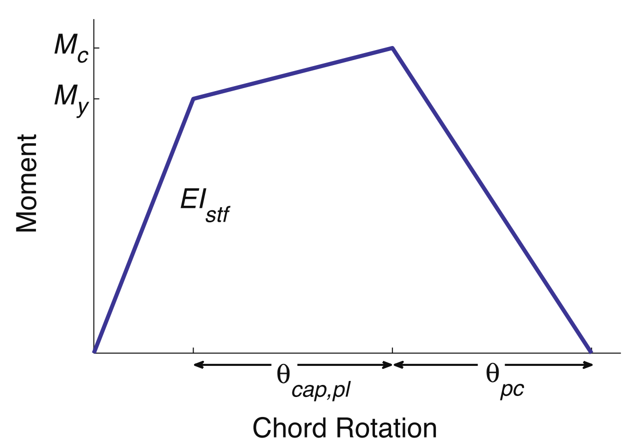

Fig. 1. Ibarra et al. [29] model for moment versus rotation of a plastic hinge in a structure. The model parameters of interest are labeled.