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Seismic performance of a steel moment-resisting frame subject to strength and ductility uncertainty ☆

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ABSTRACT

The reliable estimation of the seismic performance of structures requires quantifying the aleatory and epistemic uncertainties of the system parameters. This is efficiently achieved for a case study of a four-story steel moment-resisting frame through several important advances. First, a state-of-the-art numerical model is formed with full spatial parameterization of its strength and plastic deformation properties. Empirical relationships derived from experimental data are used to model the cyclic behavior of steel sections using probabilistically distributed parameters that include intra- and inter-component correlation. Finally, incremental dynamic analysis and Monte Carlo simulation are employed to accurately assess the seismic performance of the model under the influence of uncertainties. Of interest is the extent to which model parameter uncertainties may trigger negative demand-capacity correlation in structural fragility evaluation, where, for example, a lower ductility capacity for a component may decrease the threshold for local failure while at the same time raising the local demand estimate from an uncertainty-aware model. With respect to the examined steel moment-resisting frame and considering three construction quality levels (i.e. very good, average, low) as per FEMA P-58, it is shown that, despite the good agreement of the evaluated structural demands obtained with and without consideration of the model parameter uncertainties for well-designed modern buildings, the potential demand-capacity correlation is likely to give rise to unconservative estimates of fragility for local damage-states, especially in cases where substandard quality control is exercised during construction.

1. Introduction

Several uncertainty sources come into play whenever an engineer attempts to assess the seismic performance of a structural system. They may be broadly organized into two main categories, these being the aleatory and the epistemic [1]. Aleatory uncertainties are associated with inherently random factors, such as the earthquake loading, and hence cannot be controlled. By contrast, epistemic uncertainty sources are related to our incomplete knowledge and can be potentially reduced, e.g., by employing testing to determine material properties or using more sophisticated numerical models and methods of analysis.

Up until now, several recent studies (e.g. [2,3]) have concluded that the earthquake "signature" is the dominant uncertainty source. However, current research has, so far, only partially addressed the issue of the uncertainties related to the parameters of the structural model in seismic performance assessment (e.g. [4–11]). For instance, Ibarra and Krawinkler [10] have shown that the model parameter uncertainties can have a significant impact on the predicted collapse performance when considering deteriorating hysteretic models. Nevertheless, the study is limited to single-degree-of-freedom (SDOF) systems and hence the validity of the outcomes to multi-degree-of-freedom (MDOF) systems is questionable. By contrast, Liel et al. [6] investigated the model uncertainty significance for a set of reinforced concrete structures that were efficiently modeled to account for cyclic deterioration in flexural strength. This study concluded that neglecting the modeling uncertainties reduces the dispersion in the response fragility and also shifts the median predictions. Despite the revealing findings of this study, these are bounded to errors associated with the approximate nature of the response surface methodology. The latter was adopted for predicting the median collapse capacity as a function of the model random variables. On a different track,

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Vamvatsikos and Fragiadakis [9] investigated the model uncertainty effects on a steel moment-resisting frame (SMRF) by means of Monte Carlo simulation paired with Latin Hypercube Sampling. The study concluded that the model parameter uncertainties can have an important contribution to the overall response dispersion. Yet, generalization of the findings is limited due to the fact that the probabilistic modeling of the uncertain parameters was not founded on experimental data.

In fact, with respect to the deterioration modeling of steel frames, only limited research (e.g. [9,12–14]) has been focused explicitly on the model parameter uncertainty in the structural component capacity. However, even in these studies, deterioration modeling was based either on expert opinion or on empirical expressions derived from small experimental databases, using simplified assumptions to employ the best possible capacity estimates given the limited available data. To this end, the dependence of the models proposed by e.g. FEMA 355D [15], Mele [16] and Kazantzi et al. [14] for estimating the steel component capacities on a single structural property (i.e. the beam depth), may be considered a step forward. Nevertheless, they have left ample space for more elaborate research toward enhanced steel structural modeling and capacity uncertainty consideration. On account of the above, relatively recently, Lignos and Krawinkler [17] provided detailed relationships for modeling the cyclic deterioration in flexural strength and stiffness of structural steel components [18]. The proposed multi-variable empirical equations allow the prediction of several modeling parameters on the basis of more than 300 steel wide flange beam experiments.

Furthermore, all pertinent studies have been confined so far to a full spatial correlation assumption, meaning that parameter changes are effected uniformly throughout a building, vastly reducing the dimensionality of the problem but at the same time exaggerating its sensitivity to model parameters. Thus, it can be inferred that the holistic quantification of the model parameter uncertainties and how these propagate into the analysis and performance predictions remains an open issue.

Aiming to provide such an outlook this research attempts to quantify the model parameter uncertainty for a case study of a well-designed contemporary four-story SMRF, considering three levels of construction quality (i.e. very good, average and low). To efficiently reduce the complexity of the problem, following the findings of Fragiadakis et al. [19], mass and stiffness parameters are considered deterministic (as they contribute the least to structural performance variability) while the strength and ductility properties of the components are fully parameterized. The empirical relationships derived from experimental data and recently proposed by Lignos and Krawinkler [17] are used to model the cyclic behavior of steel components via parameters that determine the pre- and post-capping plastic rotation, the cyclic deterioration in flexural strength and stiffness, the effective yield strength and the post-yield strength ratio of steel components subjected to cyclic loading. Such variables are completely described at the local level by probabilistic distributions that incorporate intra-component and inter-component correlation information throughout the entire structure. The magnitude of component uncertainties, are calibrated to correspond to three construction quality levels considering the dispersion estimates proposed by Lignos and Krawinkler [17] and the recommendations of FEMA P-58-1 [20] to account for differing levels of quality control. Incremental dynamic analysis [21] is employed to accurately assess the seismic performance of the model, for any combination of the parameters in tandem with an efficient Monte Carlo simulation algorithm based on record-wise incremental Latin Hypercube Sampling (LHS) to propagate the uncertainties from the model parameters to the actual system demand and capacity [22].

Our aim is twofold. First, we seek to quantify the effect of realistic parameter uncertainties on structural response and extract default dispersion values to be used for performance assessment of regular low-rise capacity-designed SMRFs at different levels of construction quality control. Second, we shall investigate the effect of the demand-capacity (DC) correlation on the fragility estimation. The DC correlation accounts for the intuitive fact that component properties tie together the model response and the component fragility, in the sense that for instance, lower component capacities in a structural model may result to higher demands and consequently lead to a left-shifted fragility function. While its existence has been suggested by Cornell et al. [23], given that this potential source of bias is typically ignored even in the most advanced seismic performance assessment guidelines (e.g. FEMA P-58-1 [20]) it becomes important to map its effect and potential consequences for loss calculations.

2. Analytical modeling

2.1. Structural model

The effect of the model parameter uncertainties on the seismic performance will be quantified by means of a case study steel moment-resisting frame building. The building consists of four stories, the first being 4.6 m (15ft) high and the ones above 3.7 m (12ft). It was designed as an office building to 2003 IBC [24] and AISC [25] for the Los Angeles area and it has a rectangular floor plan consisting of 3 bays at 9.1 m (30ft) in the North–South direction and 4 bays at 9.1 m (30ft) in the East–West direction. Our focus will be the East–West framing, in which only the two middle bays are moment-resisting. The columns of the moment-resisting bays were assumed to be fixed at their bases, whereas they are also spliced at the mid-height of the third story. The beams were designed as reduced sections (RBS) with their 'dogbone' geometries detailed according to FEMA 350 [26]. The moment-resisting frames (MRFs) are also capacity-designed, implying that the final steel section sizes satisfy the AISC strong column–weak beam requirement.

The building's seismic performance was evaluated using a 2D analytical model with elastic elements in OpenSees [27] were plastic hinge formation (point plasticity) was allowed at column ends as well as at the 'dogbone' location for beams. The stiffness of the rotational springs used to represent the point hinges was set to be 10 times larger than that of the associated element as shown in Ibarra and Krawinkler [10]. P–$\varDelta$ effects were included using a first-order treatment of geometric nonlinearity. In addition, a leaning column was added to account for the destabilizing effect of the gravity frame loads without axially stressing the lateral load resisting columns. Furthermore, the mathematical idealization of the frame includes shear deformation due to panel zones by means of a model proposed by Krawinkler (see [28] for a detailed description), which uses a set of rigid links to form a parallelogram. The shear strength and stiffness of the panel zone is depicted by a trilinear rotational spring, which for the case at hand is located at the upper right corner of the parallelogram (see Fig. 1). In addition, due to limitations related to the adopted analytical model, the interaction between moment and axial force was disregarded at column elements. This however, is anticipated to have only minor effect on the column strengths of the considered capacity-designed steel MRF, given that plastic hinging at low to moderate drift levels in such buildings is concentrated mainly at beam ends. Hence, local damage levels are unlikely to be affected by such simplification. The first three vibration periods of the analyzed frame were found to be 1.33, 0.40 and 0.19 s, whereas 2% Rayleigh damping was assumed at the first and third mode of vibration. Fig. 1 depicts the 2-D model used for the East–West MRF along with the beam and column section sizes. Additional details regarding the frame configuration, design and idealization can be found in Lignos et al. [29].