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Reliability based multi-objective robust design optimization of steel moment resisting frame considering spatial variability of connection parameters

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ABSTRACT

The focus of this paper is on achieving robustness in the seismic design against uncertainties in the design process. In this regard, we present a reliability based robust design optimization approach to achieve designs that are not only safe and cost efficient, but also robust against uncertainties. The aim here is to adjust easy-to-control *design parameters* to reduce the variability of the seismic response to hard-to-control *noise parameters* while also considering design safety and budget. The proposed approach is demonstrated with a steel moment resisting frame design, considering uncertainties and spatial variability in connection parameters. Here, the sizes of the steel sections constitute the design parameters, while the uncertain and spatially variable parameters of the Ibarra–Krawinkler connection model are treated as noise parameters. The design objectives include the collapse prevention reliability conditional on a maximum earthquake intensity level, as well as the initial cost of the structure. To reduce computation demands in calculating the seismic response variation, design parameters that have a negligible effect on seismic response are first eliminated through sensitivity analysis. Furthermore, the seismic response variation is evaluated parametrically to investigate the effect of connection parameter spatial variability. Finally, the authors demonstrate the use of proposed robust design optimization approach to obtain a Pareto Front, a collection of optimal designs that are optimized for both reliability and cost.

1. Introduction

Beam–column connections are generally designed to prevent fracture before beams yield to ensure ductility. However during the 1994 Northridge earthquake, premature fractures were observed in the connections of steel frame buildings which resulted in brittle structural failure [1]. This observation led to extensive research on the seismic behavior of steel frame connections, through which several connection models were developed, including the bilinear model [2–4], the Fouch and Shi model [1,5], the Kishi and Chen model [6,7], and the Ibarra Krawinkler (IK) model [8].

These connection models define force–deformation relationships with multiple imprecisely-known, connection-related parameters, values of which are determined based on experience, engineering judgment, or statistical analysis. Furthermore, hard-to-control variability in fabrication and material properties exacerbate the imprecision of these parameter values. This connection parameter uncertainty naturally leads to variability in seismic response, the level of which depends on the sensitivity of the structural design to connection behavior. Hence, *robustness* (i.e. insensitivity) of seismic behavior to the connection behavior is a desirable property, and must be evaluated as part of the structural design process.

Of course, another important source of uncertainty in seismic design is the ground motion variability, which has been studied extensively by many researchers. For instance, Shome et al. [9] employed a probabilistic approach to study the seismic demand variability under various seismic intensity measures, while Takewaki [10] and Moustafa [11] used the critical excitation method to consider the worst case seismic response due to a class of allowable earthquakes. The robustness of the structural design against ground motion variability has also recently been studied [12]. However, the effect of connection behavior on the seismic response of a steel frame has not yet been studied in published literature, which is precisely the focus of this paper.

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The *Robust Design* approach aims to achieve product (or process) design that is insensitive to uncertainty in *noise parameters* by carefully selecting *design parameters*. In this study, robust design approach is employed to ensure robustness in seismic design. The connection parameter uncertainty is treated as the noise parameter and the steel section sizes as the design parameters. Herein, the robust design problem is solved through multi-objective optimization techniques, which have previously been implemented in several studies on steel moment resisting frame design [13,14]. These previous studies, however, focused primarily on optimizing safety and cost of the design without explicitly considering robustness as a criteria. In our study, multi-objective optimization is formulated considering *robustness* against uncertainty, *safety*, and *cost*, as three distinct design objectives. This multi-objective design approach is then integrated with reliability analysis, in which the collapse prevention reliability index is treated as safety criteria.

In this paper, the application and feasibility of this multi-objective, reliability-based, robust design method is demonstrated on a multi-story, multi-bay steel moment resisting frame design. For this novel method to be successfully implemented, two distinct tasks must first be completed. The first task entails determining the sensitivity of connection parameters on seismic response. This task is necessary to eliminate parameters with a negligible sensitivity on the seismic response, so as to reduce the computational demand for calculating seismic response variation. Until recently, there was a lack of reliable statistical information regarding the connection parameter values [15]. Hence, there is a need to update the earlier research undertaken to determine the seismic sensitivity of connection parameters [1,7,16,17]. Here, we will present a sensitivity analysis for the IK model parameter sensitivities, focusing on both pushover analysis and incremental dynamic analysis, utilizing recently published, reliable statistical information regarding the connection parameters. The second task entails determining the effect of spatial variability of the connection parameters on seismic response. Spatial variability of connection parameters are caused due to connection behavior varying at different locations in a structure due to material, geometric, and fabrication variability. Earlier studies by and large assumed a perfect correlation between the parameters of spatially distributed connections within a structure. Connection parameters, however, are not fully correlated (i.e. exhibit a spatial variability), and thus, connection parameter uncertainties must be evaluated separately for each connection (i.e., each connection parameter for each member should be considered as a random variable). Here, we present a parametric study based upon both the pushover and incremental dynamic analyses completed to evaluate the effect of spatial variability on seismic response variation.

The present paper is organized as follows. The IK model and its recently published statistics are overviewed in Section 2 followed by introduction of the case study structure in Section 3. The seismic sensitivity of connection parameters is discussed in Section 4, the role of spatial variability of connection parameters is evaluated in Section 5, and the multi-objective, reliability-based, robust design methodology is illustrated in Section 6 through the design of a multi-story, multi-bay steel moment resisting frame. In Section 7, the research findings are summarized, conclusions are drawn, limitations of the present work are discussed and possible future work is proposed.

2. IK model and its statistics

First proposed by Ibarra et al. [8], the IK model is characterized by three strength parameters [M_y: the effective yield moment; M_c: the capping moment (the post yield strength ratio defined as M_c/M_y); and the residual moment: $M_r = \kappa M_y$, where κ is the residual strength ratio]; four deformation parameters [Θ_y: the yield rotation; Θ_p: the pre-capping plastic rotation; Θ_{pc}: the post-capping plastic rotation; and Θ_u: the ultimate plastic rotation capacity], and one cyclic deterioration parameter: Λ as shown in Fig. 1. In a recent extensive experimental study, Lignos and Krawinkler [15] calibrated the connection parameter values against the experimental measurements under various loading histories for a database of more than 300 steel sections. From this work, they reported statistical information for IK model connection parameters [15], which are implemented in this study (see Table 1).

In this research, all connections are assumed to be *other-than reduced beam sections (RBS)*[1], with A572 grade 50ksi steel as the material for all beams and columns. In the research of Lignos and Krawinkler [15], the mean value of κ is suggested to be 0.4, while standard deviation is not provided for κ due to the insufficient data. Herein, κ is assumed to be subject to a normal distribution, and the coefficient of variation is assumed to be 0.1 since an exact value is unavailable in the literature. The spatial correlation between Θ_p, Θ_{pc} and Λ, determined from multivariate distributions provided by Lignos and Krawinkler [15], is shown in Table 2. Since only the correlations between Θ_p, Θ_{pc} and Λ are provided in Lignos and Krawinkler [15], other IK model parameters for the same connection are deemed mutually independent. The ultimate plastic rotation capacity, Θ_u, was reported to be heavily dependent upon the load history [9]. For a stepwise cyclic load, Θ_u for beams (with other-than RBS beam connection) ranges from 0.05 to 0.06 rad. Herein, a value of 0.06 rad is assumed for Θ_u.

3. Case study structure: initial design

A four-story, four-bay, steel frame structure[2], designed in accordance with ASCE 7 [19] and AISC 341 [20], is employed in this study (Fig. 2). The beam and column sections are grouped into eight categories, denoted from S_1 to S_8. In the sensitivity and spatial variability analysis, section sizes S_1 to S_8 are defined as W24 × 207, W24 × 207, W24 × 162, W24 × 162, W30 × 108, W30 × 108, W24 × 84 and W24 × 84, respectively. This configuration leads to a seismic weight of 940 kips (4181 kN) for the second, third and fourth floors and 1045 kips (4648 kN) for the roof. For the case study structure, the median maximum inter-story drift ratio under the maximum considered earthquake hazard level is 2.48% and the fundamental period is 0.94 s.

4. Evaluating seismic sensitivity of connection parameters

Sensitivity analysis is a commonly used tool in seismic engineering with a number of methods available in the literature to rank the statistical importance of parameters [1,21,22]. Herein, the perturbation method is employed due to its reported simplicity and efficiency [1,23]. In this method, the model with all connection parameters set at their mean (or median) value is referred to as the 'nominal model.' The value of the connection parameter under study is perturbed to its mean ± 2 × standard deviation for a normal random variable and to median × $e^{\pm 2 \times \text{dispersion}}$ for a lognormal random variable, with all other connection parameters set at their mean (or median) value. The models with the connection parameters perturbed to their largest value and their smallest value are henceforth referred to as the 'upper level model' and 'lower level model,' respectively. A pushover analysis and an incremental

[1] In the work of Lignos and Krawinkler [15], connections are categorized as connections with 'reduced beam sections' and connections with 'other-than reduced beam sections', and statistics are provided separately.

[2] The case study example is adapted from FEMA P695 [18].