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Review article

Epistemic uncertainty in the seismic response of RC free-plan buildings

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ABSTRACT

Complex building models consider multiple degrees of freedom and modeling assumptions that influence the accuracy of the predicted seismic response. This study evaluates the epistemic uncertainty inherent to modeling assumptions by evaluating the seismic response behavior of six instrumented reinforced concrete free-plan structures in Santiago, Chile. The free-plan structural concept is frequently used in office buildings and consists of a core of shear walls, a perimeter frame, and a flat slab connecting both lateral force resisting systems. Epistemic uncertainties studied in this paper are inherent to the following modeling assumptions: (**1**) the type of finite elements used in the building models; (**2**) the in-plane and out-of-plane stiffness of the diaphragms; (**3**) the interaction between the basement and the surrounding soil; and (**4**) the decision where to apply base fixity. The response uncertainty was first evaluated by comparing predicted and measured vibration periods using ambient vibrations and aftershock records of the 2010 Maule, Chile earthquake. Additionally predicted global and local seismic response parameters such as story shears, torques, and drifts were compared between a predefined *reference* model typically used in design and a set of *variant* models. A statistical evaluation of the modeling uncertainty showed a strong dependency on the response parameter considered. Larger uncertainties were observed for shear force related response parameters, including the influence of soil-structure interaction on base and story shears, while uncertainties for predicting fundamental periods or the depth at which building fixity was assumed had moderate impact on the overall building response. In general, uncertainties identified in core forces were larger than uncertainties in story forces and also larger at the underground stories than in comparison to upper levels.

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1. Introduction

During past decades reinforced concrete (RC) free-plan buildings have become a common structural layout in seismically prone countries such as Chile. Typical lateral force resisting systems in these buildings consist of a combination of core shear walls, a RC moment-resisting perimeter frame, and a post tensioned floor slab that couples the core and perimeter frame and essentially works as an in-plane diaphragm (Encina [1]). Typical story heights (N) range from 18 to 25 stories above ground, and 4 to 8 stories below ground. Fundamental periods for free-plan buildings usually exceed the rule of thumb for frame structures $N/10$. Prior to the Maule, Chile earthquake, in 2010 (M_w = 8.8), little or no information about the seismic performance of these structures was available in the literature. Despite the large magnitude of this earthquake and the severe shaking records in Santiago, these buildings showed good performance, and essentially remained in the linear range without major structural or non-structural damage [2,3]. This performance can be attributed to good structural design, a detailed structural review process, and favorable local soil conditions.

A variety of building models have been proposed to evaluate building response parameters of structures under dynamic loading. One example is a simplified model that represents the building as a single beam with shear deformations, warping, and a diaphragm with bending stiffness, the latter being essential to adequately represent the seismic behavior of these structures [1,4]. On the other extreme, complex Finite Elements Models (FEM) have been used to assess medium-rise buildings [5,6] and super-tall buildings [7,8]. Current standards and technical documents provide guidelines on how to create structural models for tall buildings, e.g., PEER/ATC-72 [9] and LATBSDC [10] with a focus on Performance-Based Seismic Design (PBSD), which principally establishes different categories of behavior for different earthquake intensity levels.

Current literature however, is scarce on the quality of the prediction capabilities of these models, their inherent epistemic uncertainty and their effect on building design and loading responses. Free-plan buildings are particularly sensitive to this epistemic uncertainty given their simplicity and low redundancy. In order to quantify epistemic uncertainty we identified at least three methodologies: (i) stochastic FEM, where variables distribute according to a Probability Density Function (PDF) [11]; (ii) sensitivity analyses, where some assumed variables lie on a range of possible discrete values [12]; and (iii) empirical data and reduction of uncertainty though model calibrations using real data [13,14]. The primary objective of this paper is the assessment of epistemic uncertainty inherent to modeling assumptions rather than parametric variations. Modeling assumptions intrinsically yield larger response variations and typically generate most of the discussion in the review process of building projects since there is little information and guidelines in practice on how to consider them in building design. Uncertainty resulting from small variations within a parameter (e.g. Young's modulus, damping, element dimensions, live loads, mass, and soil stiffness) have been studied by other researchers [10,15,16] and should be routinely evaluated during parametric sensitivity studies within the design process.

Recent studies [1] as well as empirical evidence after the Maule earthquake in 2010 have validated the significance of floor diaphragms in the behavior of free-plan buildings. In common practice the diaphragm is modeled with infinite in-plane rigidity and a reduced out-of-plane flexibility. This assumption allows an important reduction in the number of Degrees Of Freedom (DOF) of the model as well as in computational time. Several studies [17,18] have examined the implications of this modeling assumption and demonstrated that this assumption mainly affects low-rise buildings with short periods and small out-of-plane diaphragm stiffness relative to the stiffness of the lateral-load resisting system. By considering the in-plane deformation of the floor slab, the periods and displacements increase, and the seismic stresses decrease [19]. Conversely, when the rigid diaphragm assumption is applied to levels with abrupt changes in lateral stiffness, such as the transition zone between the first level and the basements, a significant shear stress is generated in the core walls; also known as *back-stay* effect [20]. For high-rise buildings, out-of-plane (bending) diaphragm stiffness becomes significant [19,21].

Another important parameter when assessing the dynamic response of free-plan buildings is the constraint of the surrounding soil and the interaction thereof with the basement floors of the structure. Generally, Soil-Structure Interaction (SSI) increases internal damping, lengthens the vibration periods, increases the lateral displacements of the structure, and changes the stresses at the base depending on the frequency content of the seismic motion as well as the dynamic characteristics of the soil and structure [22–24]. Several approximations have been made for SSI models in high-rise buildings [25,26]; most of which use simplified models, i.e. the soil is represented by a discrete arrangement of springs and dampers to provide computational efficiency with reasonable accuracy.

Current seismic codes do not provide explicit recommendations on how to model basements, the number of levels to include in the structural model or how to connect the model to the ground. This leads to discretional interpretations on "how and where" to apply the minimum shear requirements for building design. Incorporating basements in the model usually generates an increase in building periods and displacements, as well as a reduction in seismic stresses for elements above ground level [27].

The objective of this study is to quantify the epistemic uncertainty in modeling assumptions of FEM models in the linear range. Hereby, the following modeling aspects are evaluated: (**1**) the type of finite elements used; (**2**) the in-plane (axial) and out-of-plane (bending) stiffness of the diaphragm; (**3**) the simplified SSI model; and (**4**) the building connection at the basement level. The rationale behind the selection of these four modeling aspects is predominantly based on true assumptions made in engineering practice, which are known to generate controversies during the review process of building projects.

Six existing free-plan buildings, located in Santiago, Chile are considered. For each building, a detailed FEM was built using the software packages ETABS and ANSYS. Additionally, a Response Spectrum Analysis (RSA) was carried to estimate the following response parameters: vibration periods, shear stresses, overturning moment to shear stress ratio, dynamic eccentricity, lateral displacements, and lateral and torsional inter-story drifts. The model uncertainty is estimated from a relative comparison using the mean and standard deviations of the ratio of predicted results from *variant* models and *reference* models. This investigation also includes a comparison between measured and estimated building periods for the first four vibration modes. The recommendation of a "most accurate" model is beyond the scope of this paper, as the selection of modeling techniques influences the building response and the selection of a "most suitable approach" depends on the specific needs and allowances of the respective project. Hence, quantitative comparisons will enable the reader in making proper case-based decisions.

2. Selected buildings

Figs. 1 and 2 depict photographs, elevations and floor plans of all six buildings selected for this study and referred to hereafter as Buildings A through F. All buildings have RC cores of shear walls, a RC perimeter frame, post tensioned RC slabs and are founded on