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Hybrid simulation for system-level structural response

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ABSTRACT

Hybrid simulations combine physical and analytical components into a single simulation to evaluate the response of a structure, often under seismic ground motion. This allows an experiment to be conducted in which structural components with complex response can be modeled experimentally and more well-known components can be represented within an analytical model. The coordination software UI-SimCor, developed by the MUST-SIM NEES facility at the University of Illinois at Urbana–Champaign, is a hybrid simulation tool which performs the dynamic analysis and other software and hardware coordination tasks for hybrid simulations. In many hybrid simulations, including those that have used UI-SimCor, analytical models with few effective degrees of freedom are typically used. In simulations where system-level behaviors and the response of the analytical components are of importance, a more detailed analytical system is needed. This changeover to a more complex analytical system and increase in general complexity of the hybrid simulation can cause various issues within the UI-SimCor framework. This study discusses the difficulties and issues that arise from having large and complex analytical substructures in hybrid simulation, and the effective mitigation or solutions to those problems.

1. Introduction

Hybrid simulations (HS) combine physical and analytical components (substructures) into a single simulation to obtain a system-level structural response under dynamic ground motion (GM). HS allows for evaluation of entire building systems, with the potential for experimental testing of specific structural components at large scale so that both experimental and analytical behaviors and the interaction between them can be observed. One common practice of HS is that complex mechanisms or components are modeled experimentally (and often at large-scale) while more well-known components are represented within an analytical model.

This study focuses on the development of a HS approach to help achieve the final goal of a Network for Earthquake Engineering Simulation Research (NEESR) project, which is to evaluate system level response of existing reinforced concrete (RC) structures following shear-axial column failure. Although the findings and observations presented herein are applicable in many HS procedures, this study and the presented advancements are related to the use of the UI-SimCor coordination software at the University of Illinois [13,12]. Other similar architectures for HS would similarly benefit from the advancements presented in this study.

Shear-axial column failure, and the system-level collapse resistance of a building after such a failure, is an important topic in RC retrofitting and seismic analysis, as many buildings built prior to the mid-1970s have column detailing which make them susceptible to shear-axial failure. Shear-axial column failure is a difficult mechanism to predict, and current failure models and capacity equations include a high degree of uncertainty and variability [17,7,26,9]. However, the continuous development of HS makes it feasible to analyze a building's response to such a column failure and to understand the collapse-resisting mechanisms of the structure under such extreme conditions.

Modern HS originated from the pseudodynamic testing method firstly reported by Takanashi et al. [35]. Further research on the use of the pseudodynamic method for seismic testing, such as quantifying experimental errors, limitations, and stability issues, was conducted by Mahin and Shing [19]. HS methods have since underwent an accelerated development phase reflected by increasingly complex analytical and physical substructures, employment of high-performance hydraulic loading equipment and development of various HS coordination software [6,33]. HS have also been conducted with geographic distribution of test hardware and software. Yang et al. [37] performed a geographically distributed HS, testing zipper frames with components of the test located at both the

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University of California at Berkeley and at University of Colorado at Boulder. The displacement-based pseudodynamic HS method prevails in recent implementations [32] due to its similar testing setup to a quasi-static test and the many available supporting open-source programs, such as OpenFresco [30] and UI-SimCor [13,12].

Del Carpio et al. [5] discuss the challenges regarding convergence and spurious oscillation that can occur when conducting HS with large numerical substructures. One way to address the challenge of complex numerical modeling in HS is to develop HS coordinating systems that utilize the dynamic solution algorithms within existing FEM software. For example Wang et al. [36] developed a P2P HS system that combines physical testing with numerical substructures modeled in OpenSees and ABAQUS. The architecture of the P2P system allows the equations of motion to be formulated and solved within each substructure's domain using their respective software and only maintaining the displacement and force balances at the boundaries using an initiative algorithm. Another example is OpenFresco [29] which serves as a middleware between physical testing and a numerical simulation conducted in OpenSees. Thus OpenSees is utilized not only for numerical modeling, but also for the dynamic solution of the entire structure model being investigated. Further advancement in OpenFresco were made recently by Del Carpio et al. [5] who proposed an innovative overlapping substructuring technique for collapse HS of steel frame when large deformations were anticipated.

On the other hand, UI-SimCor adopted a different HS coordinator architecture, and is the primary coordinator used at the MUST-SIM lab at the University of Illinois at Urbana–Champaign (UIUC). So far UI-SimCor has been successfully implemented in large scale HS of RC bridges of various configurations [34,11,1] and semi-rigid steel frames [20]. It has also been used for small scale HS of 6-story steel frames [15] and RC bridges [16]. While some of these experiments have complex numerical substructures, they had a limited number of *effective DOFs* (discussed in the following section).

In this study, a 10-story RC building is analyzed under a severe earthquake GM, and is substructured for HS to allow physical experimentation of three lower-floor columns in the MUST-SIM NEES facility at UIUC, with the remainder of the building system modeled in the computer program OpenSees [22]. A large three-dimensional analytical substructure (thousands of DOFs) is used with nonlinear modeling of all elements, as collapse-resistance mechanisms in building structures often involve large amounts of inelastic deformation. The challenges that arise from using such a complex numerical model and potential adjustments to the HS coordinator/architecture in order to mitigate these challenges is presented in the following sections.

2. Prototype building and analytical model

In this section, the analytical model that is used in the HS is presented. Note again that in this paper the main objective is to develop a HS method that is applicable for evaluating the response of such a model and to demonstrate the issues and the proposed solutions. To conduct a successful HS, which will allow for evaluation of system-level behaviors of older RC buildings subjected to seismic GM, a representative pre-1970s 10-story RC building structure is designed according to ACI 318-63 [2], and a detailed analytical model of the structure is developed. The building is designed based on a review of the design and layout of several actual RC structures constructed during that time period [10]. Typical building characteristics included tall 1st stories (for lobbies, etc.), as well as deep spandrel beams with shallower interior beams, allowing for more interior space and higher ceilings, while putting more of the seismic demand on the exterior of the structure. More discussion of the review of pre-1970s construction can be found in Murray and Sasani [23]. For the representative structure, the building plan consists of two 6.10 m (20′) spans in the north–south (transverse) direction and six 6.10 m (20′) spans in the east–west (longitudinal) direction. The structure has 400 mm × 710 mm (16″ × 28″) spandrel beams on the first floor with 400 mm × 560 mm (16″ × 22″) spandrel beams on other floors. Interior beams are 400 mm × 460 mm (16″ × 18″) on all floors. The first story height is 4.27 m (14′-0″), while other stories have a height of 3.20 m (10′-6″). Floors consist of one-way 115 mm (4.5″) slab, supported by intermediate beams at the midpoint of longitudinal beams. Concrete is designed with an $f'_c = 27.6$ MPa (4 ksi) and all steel is Grade 60. A typical floor plan is shown in Fig. 1. Note that the second floor is identified as the top of the first story.

The representative building is modeled in OpenSees [22], an open source modeling software capable of nonlinear modeling of building structures. Two-node beam–column elements are used to model all beams, columns, and slabs within the structure. Elements are nonlinear using a concrete constitutive relationship with no tensile strength, and a bilinear steel model with 2% strain hardening. A force-based formulation is used for the beam elements, which compared to a displacement formulation, allows for a reduced number of nodes and elements in the model. Columns of the structure have 4 integration points while beams and slabs have 3 integration points (but are represented with more elements). The slabs of the floor system are not modeled as shells, but rather as a grid of nonlinear beam elements (sized based on their tributary areas), using half of their linear torsional stiffness [18]. Nonlinear shell elements are not used because they have not been extensively verified in OpenSees, and the use of a grid of beam elements representing slabs has been successfully used in the past with good agreement with physical data (e.g. [27]). Beam sections are modeled as T and L sections to account for the contribution of the adjacent slab. The layout of nodes and connecting elements in the structural model in OpenSees are shown for a typical floor plan in Fig. 2. Note that the node clusters around columns are used for modeling the rigid joints of the system and the bar-slip deformations at the faces of the joints. Joint damage is outside the scope of this study so the joints are modeled using stiff linear elements. Bar-slip deformations were accounted for through modification of the Gauss–Lobatto integration point weights to amplify deformations at the element ends. The amount of amplification was calibrated against column tests by Sezen [31] and Lynn et al. [17].

The gravity loads of the structure are distributed among all of the nodes in the floor based on their tributary area. The live load is assumed to be 3.11 kN/m^2 (65 psf) for design, which is used as an average value representing the live load applied to different parts of the floors. The floors are also subjected to 1.92 kN/m^2 (40 psf) of dead load in addition to the weight of the structural components, accounting for partitions, floor finishing, drop ceilings, as well as mechanical, piping and fixtures. Masses used in the seismic analysis are distributed among all of the nodes, similar to the distribution of the gravity forces, and include the dead load and 25% of the live load [8]. Bar-slip behavior is explicitly accounted for in the OpenSees model. Bar-slip is a flexural response that occurs in RC elements which results in concentrated rotations at the end of beams and columns due to strain penetration of the rebar into joints and foundations. The model used in this study was calibrated against several large-scale tests which measured the effect of these rotations on the response [17,31]. As the purpose of this paper is to discuss the HS process as it relates to a large analytical model and not the specifics of modeling techniques in OpenSees, further discussion of the details of the analytical model are not presented here. For more info regarding