Research paper

Build-X: Expert system for seismic analysis and assessment of 3D buildings using OpenSees

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1. Introduction

The unprecedented evolution in the field of computer science and information technology over the last decades has led to the development of numerous Finite Element software applications focusing on the numerical solution of structural and geotechnical problems. Such tools are able to offer a wide range of modeling options by boasting extensive material and element libraries, ensure algorithmic stability and solution accuracy, and are capable of implementing code-prescribed design procedures. By and large, nonetheless, they are characterized as general-purpose software. This implies that an average user may require considerable amounts of time to just learn their basic features and lots of frustration to master them. Modeling (or epistemic) uncertainty associated with the decisions made during pre-processing is likely to emerge as an issue of concern when the engineer seeks the response of structures under complex loading, as is earthquake ground motion. This uncertainty is further amplified by the implicit assumptions adopted by each software, often deeply hidden in long documentation files, and the case-specific FE model requirements. This denotes that analysis results are plausibly dependent on the user decisions concerning such critical modeling aspects as material constitutive laws, complex structural components, soil-structure interaction, and the selection of analysis parameters involved that may dramatically affect the response.

The need for rigorous engineering judgment becomes even more apparent in the case of seismically excited buildings, a class of problems that involve parameters of increased uncertainty. Given the multi-parametric nature of the nonlinear response of structures and the probabilistic assessment of seismic loading, even the most pertinent FE software might fail to guarantee their users will be able to represent inelastic structural response with a controlled and adequate degree of reliability. On the contrary, even the most rigorous algorithms for nonlinear structural analysis to stochastic excitation rely on the engineer to provide a reliable estimate of the several mechanical parameters, make decisions as per the boundary conditions and the effect of soil compliance and damping at the soil-foundation interface. The engineer is expected to assume own responsibility on how the software operates and interprets the assumptions made. Further, even though very advanced earthquake engineering-oriented software platforms have been developed recently (e.g. [1]), their potential effectiveness is hindered by the lack of a user-friendly interactive environment.

In the early 1990's and by virtue of the rising spread of the microcomputer, research interest moved towards the development of...
knowledge-based 'expert' systems that could provide supportive aid in solving specialized civil engineering problems. These novel codes, based on the principles of artificial intelligence, were built to encompass domain-specific expertise, convey it to unspecialized engineers-users in an interactive manner and apply it to actual problem solving schemes. The area of structural design has traditionally benefited the most from this type of software, because it involves ill-structured problems by definition, where heuristic knowledge is more applicable. We cite here the following notable prototype shells: HI-RISE [2], SPECON (reviewed in Ref. [3]), ERDES [4]. In the subdomain of analysis, the range of relevant work reported is far narrower; we identify SACON [5], an early rule-based system that used backward-chaining to infer suitable analysis strategies and controlling problem parameters for structural analysis problems, SesCon [6], a dedicated consultant for the use of Seams69 structural analysis program, and FEMOD [7], an assistant in FEM-specific topics. Critical evaluations of expert systems applied in structural design, analysis and damage and safety assessment are given in Refs. [3,8]. A comprehensive review of expert systems developed to assist in the field of earthquake engineering is present in Berrais and Watson [9]. Dussom et al. [10] presented QUAKE, an expert tool for selecting site- and structure-specific earthquake time histories. Kounousis et al. [11] proposed a novel PROLOG-based expert tool for using and better comprehending Eurocode 8 provisions. More recently, Berrais [12] presented a prototype knowledge-based tool for the earthquake resistant design of reinforced concrete (RC) buildings with the use of nonlinear dynamic analysis. Further, another study [13] discusses the application of another three expert systems in civil engineering.

To the authors' knowledge, there has been little advancement in this research field since, and no later work related to the seismic analysis of building structures. Moreover, the then developed expert solutions have now become outdated considering the rapid progress in information technology and in the state-of-the-art in earthquake engineering, and most probably unusable by modern computers due to incompatibility issues. In light of the current state-of-practice, which requires more than ever rehabilitation of aging buildings and cost-effective design against seismic forces of new ones, modern expert systems appear essential to aid in conducting demanding seismic analysis of buildings in a reliable manner.

Existing conventional FEA software lack a strict internal construct to responsibly drive the user throughout the process of building the structural model and specifying the seismic loading. Thus, novice computer users or inexperienced structural engineers are likely to experience severe difficulties and delays, particularly in cases where nonlinear behavior is examined, or, even worse, end up with underestimation or overestimation of seismic response. This very gap in engineering practice is attempted to be bridged by Build-X, the expert system presented herein. Although the concept of expert systems is admittedly more applicable to ill-defined problems, as design is, efforts were made to gather reliable knowledge on numerical modeling and seismic analysis methods from the state-of-the-art and state-of-practice, transform it into a rule base and apply it appropriately.

Build-X is a front-end knowledge-based tool developed with the aim of assisting practicing engineers in predicting the seismic response of 3D modeled buildings. It takes advantage of the sophisticated Open System for Earthquake Engineering Simulation (OpenSees) platform to provide through its graphical user interface:

- Stepwise guidance during the pre- and post-processing stages,
- Automations that accelerate the finite element model development,
- Expert advice for addressing various building-specific issues that are key factors to the reliable prediction of its seismic response, as will be presented in the following.

Build-X proceeds beyond the state-of-the-art by improving the credibility of the finite element model at hand, as well as the efficiency of the analysis procedure as a whole, since it minimizes the probability of modeling mistakes and cuts down on the time and effort required by the user, notably in the case of multi-story buildings featuring shear wall members and compliant foundation systems. Furthermore, seen as having a dual role, it can be an intelligent pre- and post-processor for OpenSees, dedicated to the analysis and assessment of building structures subject to earthquake effects.

It should emphasized that the focus here is not on OpenSees per se. OpenSees is just the FE code selected for the core problem solution; it could very well be any other script-based FE solver instead. For instance, one could follow the same rationale and develop a pre/post processing expert system using *.inp or Python scripting for Abaqus or APDL language for ANSYS.

This text is organized as follows: first, the main features of the software are presented along with the system architecture. Second, the sequence of operations is briefly described the seismic analysis methods supported by the system and a verification case study, followed by conclusions.

2. Software overview

2.1. Basic concept behind the system

Build-X was developed exclusively for Microsoft Windows operating systems. Its source code is written in VB.NET and was developed in the Microsoft Visual Studio environment. A procedural programming language was preferred over a logic paradigm-oriented one (e.g. PROLOG) because it fits better the needs of the software, where many mathematical evaluations are to be processed and a neat GUI is to be designed. In cooperation with OpenSees, it facilitates static analysis for gravity loads, Eigenvalue analysis, Modal Response Spectrum analysis and Nonlinear Static (Pushover) analysis of 3D building structures. In fact, Build-X operates as a real-time converter of the user's choices into a Tool Command Language (Tcl) script to be used as input to the OpenSees platform. After OpenSees generates the analysis output, Build-X is called back to process and present it in a visually comprehensive way. Overall, the software displays the following key characteristics:

- A wizard-resembling sequential flow of actions that prohibits navigational disorientation of the user during the modeling process. The user is encouraged to determine the configuration of the structural model of the building through a series of logical and strictly defined modeling steps that prevent them from skipping or missing significant aspects.
- Expert knowledge provided a priori for simulating critical components of the building in a reliable manner and for selecting the most appropriate case-specific analysis parameters, eliminating the probability of modeling errors.
- Background code automations implemented at every pre-processing step that drastically reduce the time required for the Finite Element model of the building to be completely defined.
- A user-friendly visualization engine that allows the user to inspect the Finite Element model throughout its generation and review the structural response obtained by the solver.

2.2. System architecture

The internal software architecture differs from that of a conventional event-driven GUI program. Build-X is structured according to the principles of a knowledge-based system [9], consisting of seven distinct, yet interacting components, as demonstrated in Fig. 1:
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