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# FM-2D/3D: GUI FOR THE 2D AND 3D SIMULATION OF STEEL FRAME BUILDINGS

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## Abstract

*Performance-based seismic analysis and assessment of steel frame buildings has become a standard practice. This requires creating nonlinear numerical models which requires knowledge, experience, and time to develop, analyze, and process the results in a meaningful way. To streamline these processes, a computer tool named Frame Modeler (FM-2D/3D) is developed. The MATLAB-based tool stands out with an intuitive graphical user-interface, generalized modelling options, open-source code on GitHub, and, most importantly, employment of state-of-the-art modelling recommendations for steel members and beam-to-column connections. The tool allows for the 2- and 3-dimensional modelling of steel buildings with moment or braced frames within the OpenSees platform using either the lumped or distributed plasticity approach. Multiple analysis procedures can be conducted including Eigenvalue, pushover, response-history, and increment dynamic analysis. Analysis data are internally processed and can be reported or visualized in several ways. This includes the history and profiles of engineering demand parameters, global building response, fragility curves, and the interactive visualization of the local member/component behaviors. FM-2D/3D is a benchmarked tool that is currently being used by researchers worldwide.*

**Keywords:** OpenSees, Numerical modeling, Structural simulation, Steel frames, Software.

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## 1 INTRODUCTION

Developing nonlinear structural models for buildings is a standard task in research and design practice. This has become more common with the emergence of the performance-based framework for structural assessment and design. Creating such models, analyzing them under different hazard loads, and post-processing the results is a lengthy process that requires knowledge of a given analysis software as well as skills related to numerical structural idealization and state-of-the-art approaches in the characterization of the monotonic and cyclic response of the different structural members and joints.

The open-source structural analysis platform *OpenSees* [1] is widely used by researchers and engineers to analyze steel buildings. This platform includes a multitude of element and material formulations that suits the wide range of engineering applications. However, building models in *OpenSees* is challenging. This is exacerbated by the absence of an open source graphical-user interface (GUI). As a result, structural geometry, material, and member definitions must be written directly in *Tcl* code. Recognizing these issues, an open-source software, named *Frame Modeler 2D/3D* [2], is developed to fully automate these procedures for steel frame buildings. This paper describes the architectural layout of this software and its features.

## 2 SCOPE AND FRAMEWORK

*Frame Modeler 2D/3D* can automate the entire simulation process for steel frame buildings as demonstrated in Figure 1. The current version of the software is limited to buildings with both regular elevations and rectangular plan layouts where either perimeter or space lateral force-resisting frames are employed. The 2-dimensional version (*FM-2D v2.2502*) covers moment-resisting frames (MRFs), concentrically braced frames (CBFs), and eccentrically-brace frames (EBFs). The 3-dimensional version (*FM-3D v1.2408*) only covers buildings with MRFs.

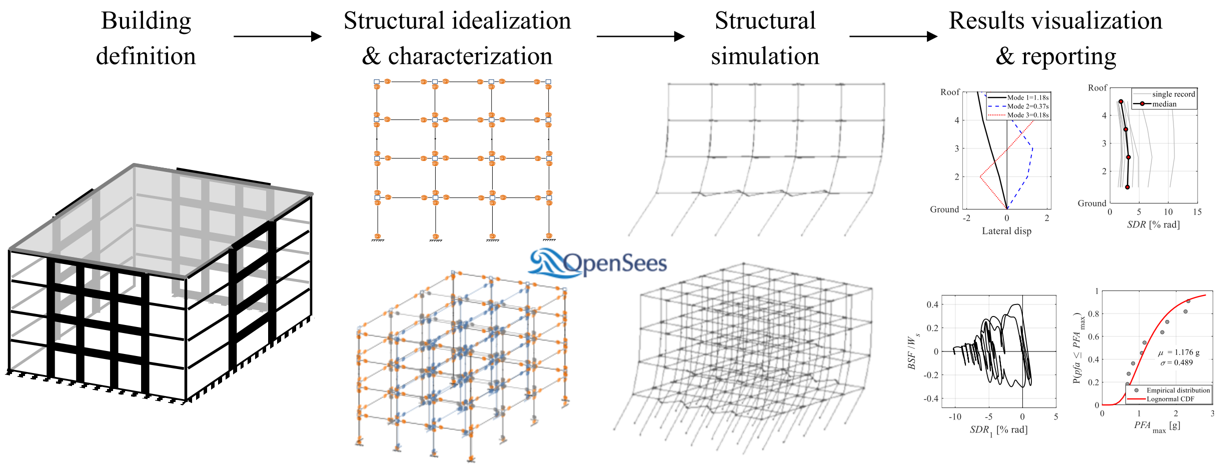


Figure 1: *FM-2D/3D* framework.

Figure 2 shows a flowchart of *FM-2D/3D*'s front-end and back-end operations. The front-end operations take place through a GUI starting with the selection of the frame type (MRF, CBF, or EBF) and the model units. This is followed by the parameter definitions for the numerical model (linear vs nonlinear, bare steel vs composite slab, transformations, etc.), the building (geometry, loads, materials, etc.), and the analysis (analysis procedure type, ground motions, damping, etc.). Once a building project is fully defined, background operations commence. This involves the construction of the building *Tcl* file, running the specified analysis procedure, and post-processing the results (i.e., processing recorders' output). Once the analysis is finished, the user will have access to the back-end operations through a GUI. This includes the ability to visualize the simulation results or report them in plain text format. The procedure allows users to manually modify the *Tcl* file prior to running the analysis. This can be beneficial for adding new elements/material or model definitions, without the need to modify the source code itself.

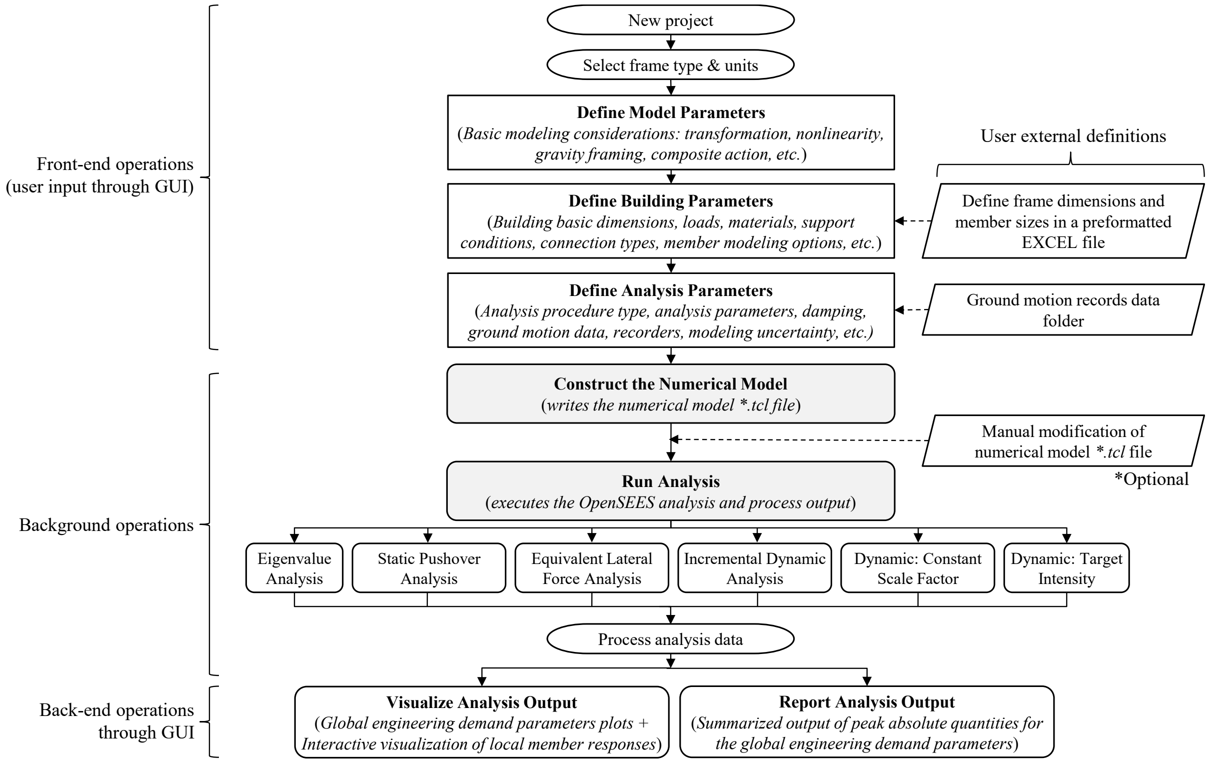


Figure 2: Flowchart demonstrating the front-end and back-end operations of *FM-2D/3D*.

## 3 USER INTERFACE AND PROJECT DEFINITIONS

One of *FM-2D/3D*'s key advantages is its intuitive GUIs. The main console, shown in Figure 3(a), has a simple layout following the flowchart shown earlier in Figure 2. This comprises the project file management buttons at the top followed by the three main project definition buttons and then the execution and visualization buttons. Each of three project definitions are defined through different GUIs of similar layout. Figure 3(b) shows the GUI for the building parameter module. The data fields in all modules are supported with tip messages describing the field's meaning. Data checks combined with warning messages are used to point out any mistakes in data entry. While all project definitions take place through GUIs, the lateral-force resisting system's geometry (e.g., bay widths and story heights) and member sizes (e.g., column and beam sections, double plate sizes, gravity system members, etc.) are specified through a pre-formatted EXCEL worksheet. Figure 4 shows the individual sheets used to define the beam and column sections. These sheets are supported with dropdown menus for selecting the members sections from an embedded database that includes both American and European databases for hot-rolled sections.

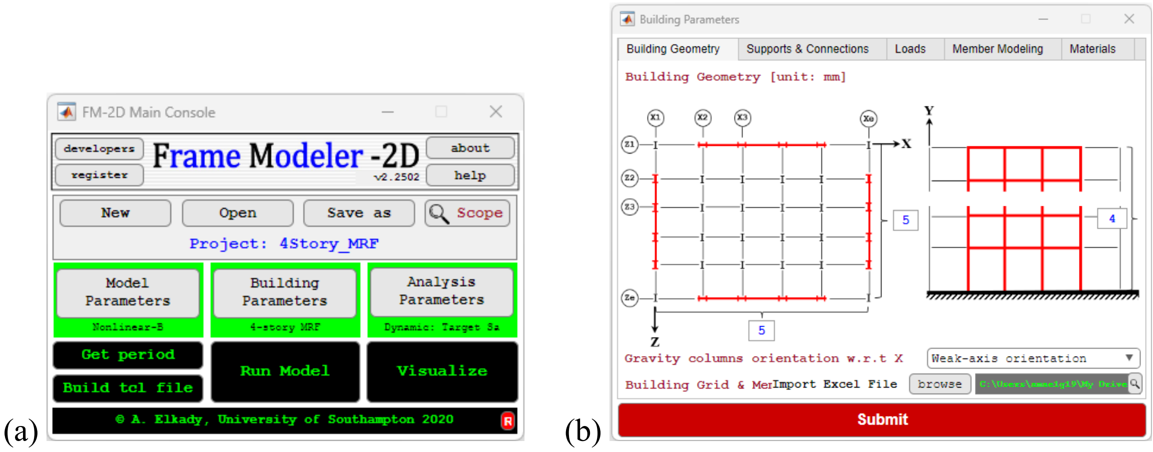


Figure 3: (a) The main console and (b) the building parameters modules.

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | | Axis 1 | Axis 2 | Axis 3 | Axis 4 | Axis |
| 2 | Story 1 | W24X103 | W24X103 | W24X103 | W24X103 | |
| 3 | Story 2 | W24X103 | W24X103 | W24X103 | W24X103 | |
| 4 | Story 3 | W24X103 | W24X103 | W24X103 | W24X103 | |
| 5 | Story 4 | W24X62 | W24X62 | W24X62 | W24X62 | |
| 6 | Story 5 | | | | | |

MF Columns | MF Beams | Column Splice | GFS Columns

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | | Bay 1 | Bay 2 | Bay 3 | Bay 4 |
| 2 | Floor 2 | W21X73 | W21X73 | W21X73 | |
| 3 | Floor 3 | W21X73 | W21X73 | W21X73 | |
| 4 | Floor 4 | W21X57 | W21X57 | W21X57 | |
| 5 | Floor 5 | W21X57 | W21X57 | W21X57 | |
| 6 | Floor 6 | | | | |

MF Columns | MF Beams | Column Splice | GFS Columns

Figure 4: Member size definition through a pre-formatted EXCEL worksheet.

# 4 MAIN FEATURES

## 4.1 Availability and open-source code

The software is publicly available through a GitHub repository [3]. This includes the source code as well as a compiled installation executable (compatible with MS Windows machine), either of which can be used to run the software. The latter can be used by general users while the former can be used by users aiming to modify/update the code. The software is supported with a detailed technical manual as well as supporting tutorial videos [4]. To support the software development by other users, the MATLAB source code is well organized and commented. This includes descriptions of the node and element numbering system. The hierarchy/inter-dependency of the different code files can be consulted as well from the "developers" button in the main console.

## 4.2 Project file management

Any project developed within *FM-2D/3D* is stored in a single MATLAB [5] database file **.mat*. This file is transferable across different machines, simplifying collaboration between different users.

## 4.3 Numerical modeling

As per the user preference, *FM-2D/3D* can idealize the building using either the fiber-based or the lumped-plasticity approaches as demonstrated in Figure 6. In doing so, the software allows for the consideration of several structural details and state-of-the-art modeling guidelines. Key numerical modeling features include:

- Modeling of the MRF's fully rigid beam-to-column joints with either reduced beam sections, welded, or bolted extended endplate connections [6].

- Modeling plastic hinges in wide-flange steel columns [7] and the shear deformations in column web panel zones [8] using latest guidelines that consider section geometry and axial load levels.
- Modeling the contributions of the gravity framing system (in the case of buildings with perimeter frames) while considering the gravity connection type [9]. The current version supports flush endplate, header endplate, and fin plate connections [10, 11].
- Considering the column splice location along the story height and its type (pinned or fixed).
- Considering the presence of a composite floor slab and its impact on the stiffness and strength of the beams and beam-to-column connections [12].
- Controlling the element type assigned to the elastic elements, as whether fiber-based or *elasticBeamColumn* elements.
- Controlling the mid-span sagging boundary conditions in CBF beams.

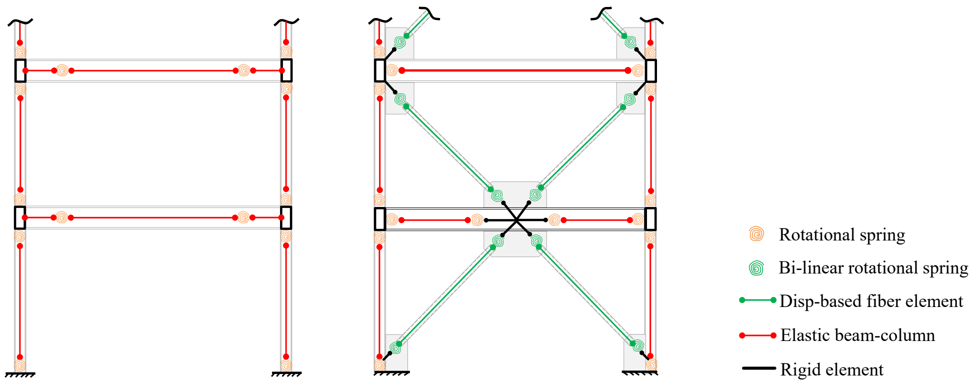


Figure 6: General 2-dimenstional idealization of MRFs and CBFs using the lumped plasticity approach.

## 4.4 Analysis options

Several static and dynamic analysis procedures are made available. Those include 1) Eigenvalue analysis, where vibration periods, modes, and mass participation factors are computed, 2) static pushover analysis with the ability to control the load pattern, 3) static equivalent lateral force (ELF) analysis to support code-based design procedures, 4) dynamic analysis using a suite of ground-motion recorders scaled to a specified intensity (i.e., strip analysis) or by a specified scale factor, and 5) incremental dynamic analysis up to collapse. Ongoing developments, that are currently in beta release, includes tsunami pushover and time-history analysis.

## 4.5 Global and local response reporting and visualization

The user has the option to save data (i.e., recorders) for all standard global engineering demand parameters (EDPs, such as story drifts, residual drifts, and floor accelerations) as well as local members responses (e.g., moment-rotation response of rotational springs). For all analysis types, the recorded data is processed and can be visualized using several ways following common practice. This includes, as can be seen in Figure 1, Eigenmodes, base shear versus story drift, EDP profiles, IDA curves, and collapse fragility. For either 2D or 3D models, the user can explore the local response of members and connections through an interactive GUI, as shown in Figure 5.

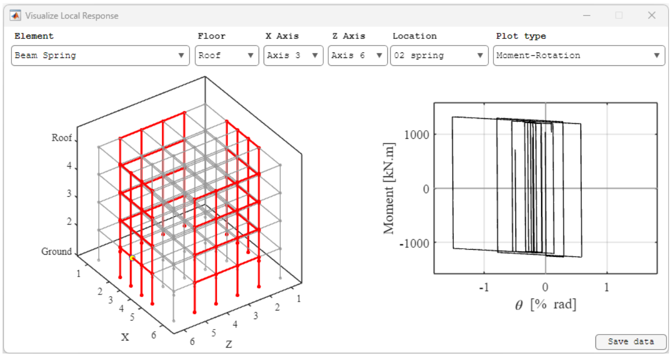


Figure 5: Visualization of local member responses through an interactive GUI.

## 5 SUMMARY

A MATLAB-based software, *FM-2D/3D*, was developed to streamline the process of modeling and analyzing steel frame buildings within the *OpenSees* platform. The software is open source allowing for modifications and further developments. Noth 2-dimensional and 3-dimensional modeling options are available combined with state-of-the-art modeling guide-lines for various steel components and connections. The software stands out with an intuitive graphical-user interface, generalized modeling options, and strong interactive visualization modules.

The software was first developed in 2022. Since then, multiple benchmarks and updates has been added following internation userbase feedback. Additionally, *FM-2D/3D*'s EDP output is compatible with another companion open-source software, *EaRL*, [13] that computes earthquake-induced direct economic losses.

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