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FM-2D - open-source platform for the 2-dimensional numerical modeling and seismic analysis of buildings

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ABSTRACT

Computer tools have been recently become available to simplify the implementation of the challenging probabilistic performance-based earthquake engineering (PBEE) framework. Although, these tools assist the user with most of the PBEE definitions (e.g., damage fragility and seismic hazard), they still require the user to provide structural response data. This can be a tedious and demanding task particularly when aiming to obtain robust data by means of nonlinear response-history analysis of detailed numerical models. To that end, an open-source MATLAB-based platform is developed herein to streamline this process. The platform implements state-of-the-art nonlinear numerical modeling recommendations for members and connections and pertinent dynamic analysis methodologies while supporting modeling uncertainty consideration. This is all packaged within intuitive graphical user-interface modules and supported with comprehensive options for visualizing the global and local structural response data.

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Code metadata

Current code version	*v1.0*
Permanent link to code/repository	https://github.com/ElsevierSoftwareX/SOFTX-D-20-00081
Legal Code License	*GNU GPLv3*
Code versioning system used	*none*
Software code language	*Matlab*
Compilation requirements, operating environments & dependencies	*Microsoft Windows + MATLAB runtime + Matlab App Designer*
Link to developer documentation/manual	https://github.com/amaelkady/FM-2D/tree/master/docs
Support email for questions	a.elkady@soton.ac.uk

Software metadata

Current software version	*v1.2112*
Permanent link to code/repository	https://github.com/amaelkady/FM-2D
Legal Software License	*GNU GPLv3*
Computing platform/Operating System	*Microsoft Windows*
Installation requirements & dependencies	*Microsoft Windows + MATLAB runtime + Tcl/Tkl binary + OpenSEES (See manual for details)*
Link to user manual	https://github.com/amaelkady/FM-2D/tree/master/docs
Support email for questions	a.elkady@soton.ac.uk

1. Motivation and significance

The performance-based earthquake engineering (PBEE) framework [1–6] has been increasingly used in designing and retrofitting buildings, particularly within the past decade. At its core, this framework relies on the availability of robust response data for buildings under different earthquake scenarios in order to be able to reliably assess/quantify their structural performance, in terms of damage and economic losses. Structural response data includes global engineering demand parameters (EDP) such as the story-drifts and floor accelerations. Local EDP includes for instance the rotational demands in connections and members' ends. Obtaining

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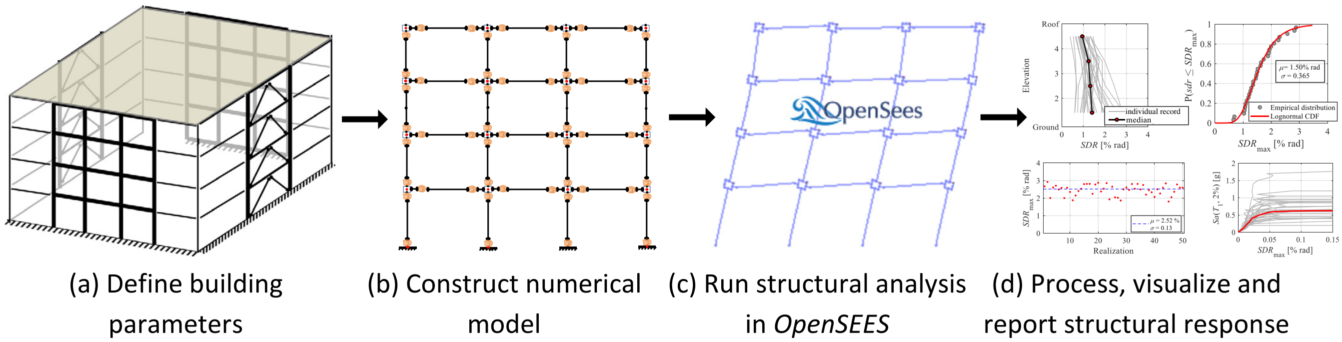

Fig. 1. FM-2D framework and scope.

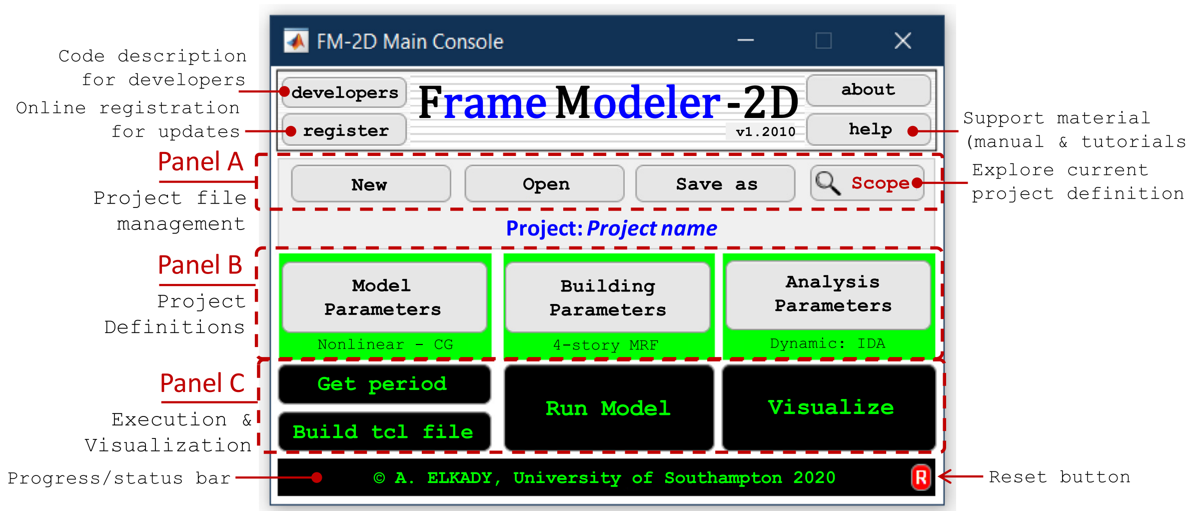

Fig. 2. FM-2D's main console.

structural response data based on dynamic nonlinear analysis is arguably the most demanding and time consuming step of the PBEE framework. This step requires: (1) characterizing the nonlinear hysteretic response parameters of the different connections and members, (2) incorporating these responses in an idealized numerical model representation of the building, (3) computing and allocating loads and masses in the numerical model, (4) conducting static and/or dynamic analysis procedures using a given structural analysis software, and finally, (5) reading and processing response data to be used in subsequent PBEE stages. This is a laborious step that can take weeks and sometime months to complete, particularly when dealing with large building portfolios that may include different geometries and configurations. Most importantly, this step requires a skilled engineer who is familiar with the specifics of numerical modeling guidelines and simulation techniques, that are being continuously updated in literature. This becomes even more cumbersome when attempting to explicitly incorporate numerical modeling uncertainties in the structural analysis using methods such as Monte Carlo simulation [7].

While existing PBEE software packages; e.g. [8–10], provide assistance with most of the PBEE framework steps (such as the definition of seismic hazard and damage fragility data of structural component), the burden of obtaining structural response data lies entirely on the user. Some software provide tools to generate structural response data based on simplified analysis methods or non-model-based empirical approaches that only require a limited number of building and seismic demand parameters to be defined by the user (e.g., Ruiz-García and Chora [11], Hwang and Lignos [12]). However, this simplicity is coupled with reduced accuracy in the generated structural response data and consequently an increase in the uncertainty associated with the computed economic losses. To that end, there is a need for a computational tool that simplifies and expedites the creation, analysis and processing of detailed system-level numerical models.

Acknowledging this issue, an open-source MATLAB® -based [13] computational platform is developed. This platform aims to automate, streamline and speed the numerical modeling and analysis of framed buildings (and potentially, buildings in general). The platform is packaged as an interactive software named Frame Modeler-2D (FM-2D). As illustrated in Fig. 1, FM-2D automates the construction of robust 2-dimensional (2D) numerical models of frame buildings within the Open System for Earthquake Engineering Simulation (*OpenSEES*) platform [14,15] using state-of-the-art numerical modeling guidelines, conducts different types of nonlinear analysis procedures while incorporating numerical modeling uncertainties, processes the structural response data and provides interactive means for reporting and visualizing this data in a comprehensive manner.

2. Software description

2.1. Software interface and operational outline

FM-2D's functionalities and operations are accessed and initiated, respectively, through the graphical user interface (GUI) (i.e., the main console) shown in Fig. 2. The console is divided into three main panels. Panel A is the project file management panel.

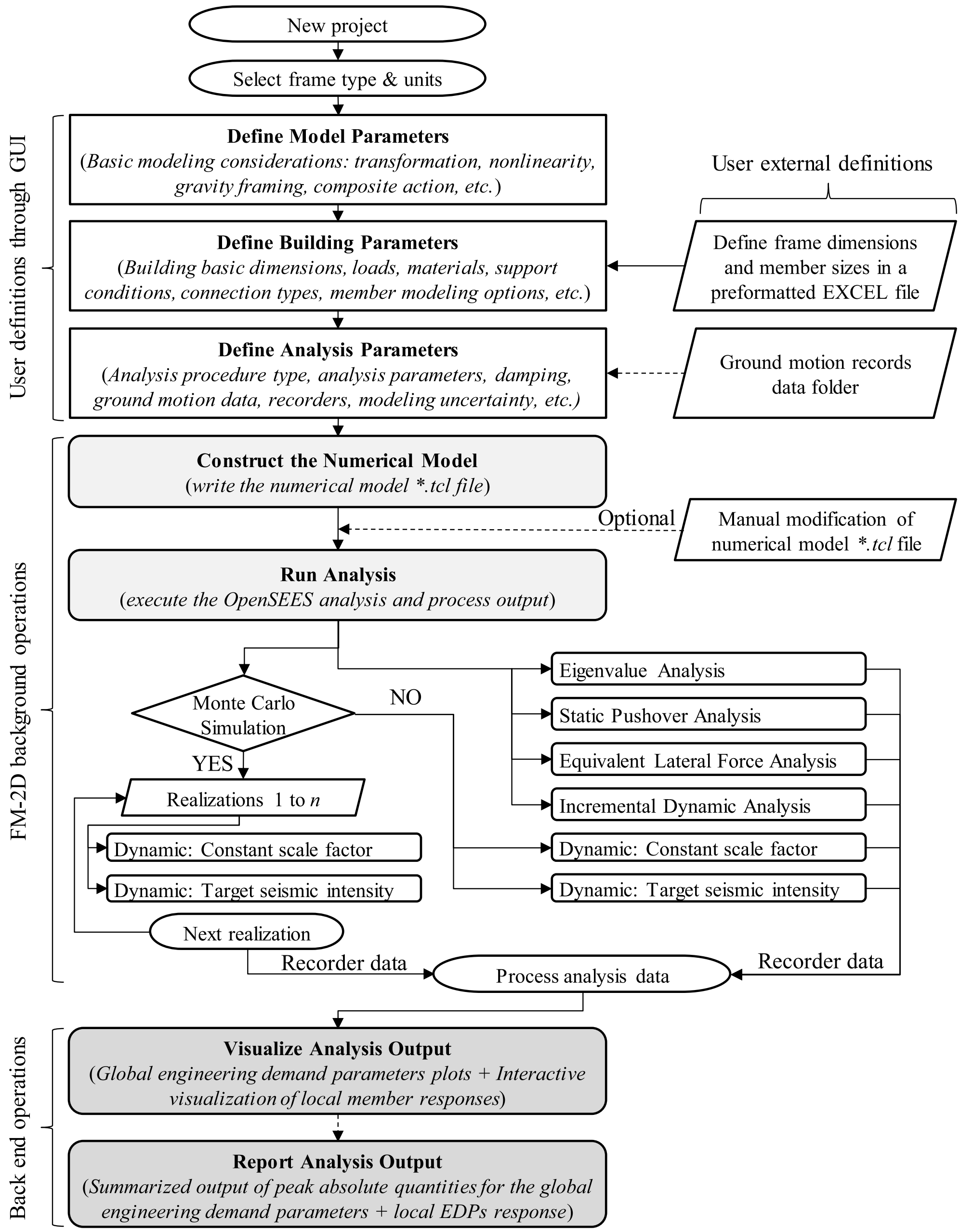

Fig. 3. Outline of operational procedures in FM-2D.

Panel B is the project definition panel where the user define the project input data. Panel C is used for executing FM-2D's back-end operations and visualizing/reporting the output.

The outline of FM-2D's operational procedures is illustrated in Fig. 3. Briefly, the outline can be divided into three main procedures: (1) User definitions; that is the input data provided by the user through the different GUI modules, (2) Background operations; which are the processes and functions executed by FM-2D to construct the numerical model, run the analysis and process the output, and (3) End operations; that is the visualization and reporting of the output structural response data.

With respect to the user definitions (i.e., input), three sequential steps are required to define an FM-2D project. In the first step, the user specifies the basic numerical modeling parameters and assumptions. This includes, (a) the type of geometric transformation to be used, (b) whether the numerical model (with respect to the material models) is linear (elastic) or nonlinear (plastic) and (c) whether or not to consider the column panel zone's deformation in shear [16] and the in-plane rigidity of the floor diaphragm. Additionally, key contributions by the floor slab's composite action and the gravity framing system to the building strength and stiffness can be considered in the numerical model using the most recent recommendations [17–19]. The second step involves defining the building parameters. This comprises the building geometry, member sizes, loads, materials, connection types, support and boundary conditions. To expedite this – otherwise lengthy – process, member sizes definition is done through a single pre-formatted EXCEL® file which is then imported into FM-2D through the GUI. This is further supported by the full integration of the European and American steel cross-section catalogs (a total of about 1300 cross-section) and the associated geometric properties databases [20,21]. The last step involves selecting the analysis procedure type and specifying its parameters. The platform employs a total of six analysis procedure types; covering those most utilized in practice. For dynamic

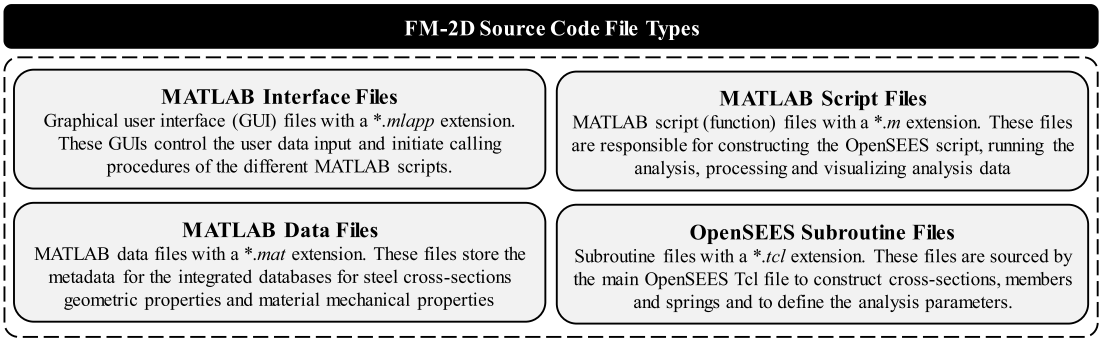

Fig. 4. Source code file types.

analysis procedures, a robust module is provided for importing ground-motion record data files with different formatting. Also, two types of seismic intensity measures can be employed including the spectral acceleration at the first-mode period, $Sa(T_1)$, and the average spectral acceleration for a given period range, Sa_{avg}. It is worthy to note that when defining a project, FM-2D GUIs provide the user with a "high resolution" control over most of the numerical modeling parameters; thus eliminating any room for ambiguous modeling assumptions. Additional control can be achieved through the modification/amendment of the platform's source code.

FM-2D platform is based on a well-structured and documented codebase that is developed entirely in MATLAB [13] programming environment, which is fairly popular within the civil engineering and research communities. This allows users (practicing engineers and researchers) to further develop and contribute to its modeling and simulation capabilities seamlessly through the GitHub platform. As demonstrated in Fig. 4, the platform source code comprises four types of files; MATLAB's **.mlapp* graphical user interface files, **.m* script (function) files and **.mat* data files and *OpenSEES *.tcl* subroutine (procedure) files. A number of considerations were taken into account to help users understand, navigate and modify the source code. First, the source code is broken down into small logical procedures/functions in separate files. Second, the notation of the nodes, sections, elements and materials tags defined in the idealized numerical models is systematically planned and documented in the manual. As such, new component models developed by different users can be simply packaged in an OpenSEES procedure file and added to FM-2D. Lastly, a dedicated GUI is available for the user to be able to inspect the code's organizational chart and the dependency between the different source code files.

2.2. Platform functionalities and features

FM-2D quantifies the structural response of buildings under static and dynamic loads. FM-2D's main functionalities and features are highlighted below:

- **Building Systems:** The current platform release (v1.2112) supports steel buildings with moment-resisting frames (MRF), concentrically-braced frames (CBF), eccentrically braced-frames (EBF) as well as reinforced concrete MRFs. The buildings can be numerically idealized in the 2-dimensional (2D) space based on either the lumped or distributed (fiber-based) plasticity modeling approach [22,23].
- **Structural Analysis:** The platform employs a total of six analysis procedure types covering those most utilized in practice (refer to Fig. 3):
  - Eigenvalue (modal) analysis to obtain the fundamental periods of the building, the corresponding mode shapes and model mass participation factors,
  - Static linear/nonlinear pushover analysis using a pre-specified mode pattern,
  - Static linear/nonlinear analysis using a pre-specified equivalent lateral force (ELF) profile which is useful when conducting ELF design procedures as per ASCE [24],
  - Incremental dynamic analysis (IDA) for tracing seismic structural response up to collapse [25],
  - Multi-stripe linear/nonlinear response-history analysis by scaling a set of ground motion records using a constant scale factor or using a target seismic intensity at a pre-specified period [26].
- **Modeling Uncertainty:** In PBEE, as well as parametric sensitivity or reliability studies, it is pertinent to quantify the effect of numerical modeling uncertainties on the structural response. The uncertainties associated with phenomenological component models' parameters (e.g., ASCE [27], NIST/ATC [28], Lignos et al. [29]) or with other building/dynamic parameters (e.g., material properties, damping coefficient and building loads) can be specified in FM-2D. These uncertainties are incorporated in a Monte Carlo simulation scheme [7], as part of a dynamic analysis procedure, where a pre-specified number of numerical model "realizations" are randomly generated and analyzed for each ground motion record.
- **Visualization and reporting:** The platform employs comprehensive options for visualizing and reporting the global and local engineering demand parameters. The user can explore the force–deformation responses of all the frame elastic elements and nonlinear springs through the interactive GUI shown in Fig. 5.

3. Impact and conclusions

This paper introduces FM-2D; an open-source Matlab-based interactive platform for modeling and analyzing numerical models within *OpenSEES*, in support of system-level numerical studies in general and the performance-based earthquake engineering framework in particular. By streamlining all the aspects of the numerical modeling process, the platform will save practicing engineers and researchers lots of time and effort that is typically allocated for developing and running such detailed numerical models. It will also pave the way towards large parametric system-level studies for reliability and modeling sensitivity quantification. As an open-source platform with a modular and well-structured codebase, FM-2D allows users to collaborate and contribute to its functionalities and features in a seamless manner; thereby addressing the continuous developments in the numerical modeling field. MATLAB and GitHub are chosen as development and

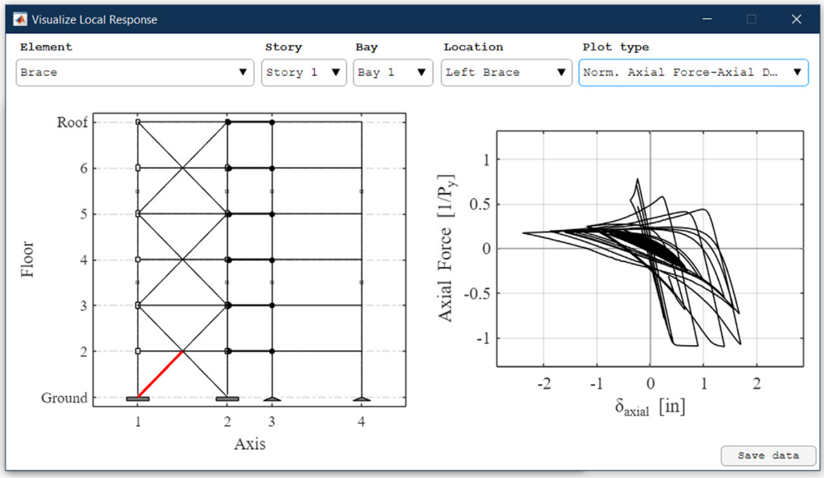

Fig. 5. FM-2D's interactive visualization interface for local member responses.

collaboration environments, respectively, for their simplicity to use and popularity among engineers. The full technical manual is available in the software GitHub repository, including illustrative step-by-step examples. Comprehensive video tutorials are also available at a dedicated YouTube playlist: https://www.youtube.com/playlist?list=PLz_XdUL-6Y_m10fBEMmzPKqI00wdzbDUN.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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