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EaRL: An Open-Source Software for Earthquake Risk, Loss and Lifecycle Assessment

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ABSTRACT: Evaluating earthquake-induced losses, such as structural repair costs, downtime and casualties, is becoming a standard practice within the performance-based earthquake engineering framework. Nonetheless, this evaluation is a demanding task that requires defining several components such as seismic hazard, structural response, building contents, damage fragilities and their consequences. This paper introduces EaRL; a recently developed software for evaluating building-specific earthquake risk, loss and life cycle costs. The software employs state-of-the-art damage fragilities and loss assessment methodologies including that of FEMA P-58. The software also incorporates an intuitive graphical user-interface, a wide range of data visualization options and collective features that adapt to different users' preferences when defining the different loss project components. Most importantly, unlike existing software and toolboxes, EaRL provides a well-documented open-source code that is developed entirely in MATLAB and shared through GitHub. This offers practicing engineers and researchers alike with a familiar platform for modifying and further-developing the software's codebase and functionalities.

KEYWORDS: software; performance-based earthquake engineering; loss assessment; FEMA P-58.

1 INTRODUCTION

Earthquakes can have severe implications on the population and the economy. Direct implications on the population include casualties and injuries as a result of collapsed structures and/or falling debris. Direct implications on the economy include monetary losses, due to repair works in damaged buildings, and the associated downtime until the building regains its functionality. Consequently, governments and building owners are interested in predicting and minimizing potential earthquake-induced economic losses as a measure of structural seismic resilience. This is particularly the case for key buildings that are critical for emergency-relief or economic activities.

Quantifying these different loss metrics and targeting a specific loss threshold as a performance objective has been the basis of the performance-based earthquake engineering (PBEE) framework since the early 2000s (Cornell and Krawinkler, 2000, FEMA, 2000, SEAOC, 1995). The current PBEE framework (Moehle and Deierlein, 2004, Porter, 2003) aims to explicitly quantify performance decision variables (DVs) such as expected scenario-based losses, risk-based annual losses and downtime associated with earthquake repairs. These DVs aid the effective communication of the design or retrofit option to building owners, stakeholders and engineers.

The PBEE process is illustrated in Figure 1. For a given building asset subjected to a given earthquake (i.e., intensity measure, IM), the DV computation process starts with the quantification of the structural response; that is the engineering demand parameters (EDP) of interest at each story/floor. Damage analysis is then conducted to compute the decision measures (DM). This analysis requires the knowledge of the building's structural components and non-structural contents as well as the damage fragility functions for each one of those components/contents. The last step is the loss analysis where DVs are computed; those are typically monetary and time loss values.

The aforementioned PBEE computations are obviously elaborate and require the user

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knowledge of many aspects related to seismic hazard, structural analysis, damage/loss fragility and probabilistic methods. For that reason, high resolution building-level applications are relatively limited in literature and practice. Even then, researchers tend to utilize archetype building topologies and associated generic contents to minimize the associated PBEE work load. This issue was somewhat alleviated within the past decade with the development of a number of computer-aided tools to facilitate the PBEE process [8–12]. Most of these tools either offer limited interactive user-interface or have an intricate one with limited visualization capabilities. Most importantly, most of these tools are not open-source and those that are open-source cannot be simply modified by the "common" user given the use of advanced programing languages and presence of limited documentation. The ability to modify and/or contribute to the source code is a critical feature, given the ever-evolving developments in the PBEE framework. For these reasons, a user-friendly open-source MATLAB-based (2019) computational platform/standalone software was developed. The software, named *EaRL*, incorporates state-of-the-art loss analysis methodologies and a wide range of options to quantify, visualize and report the total and disaggregated losses. The following sections describe the software architecture and main features.

2 SOFTWARE ARCHITECTURE

2.1 *User interface*

EaRL's main console is shown in Figure 2. The console is divided into four intuitively laid-out panels. From top to bottom, the panels are: 1) File management panel; i.e., to create, open, or save a project; 2) main project definitions panel; i.e., definitions of building, structural response, damage fragility and hazard data; 3) supplementary project definitions and features panel; i.e., supporting modules and embedded databases; 4) computation, visualization and reporting panel.

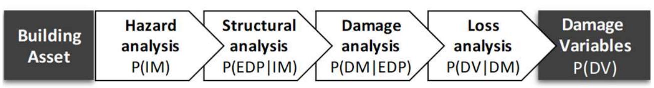

Figure 1. The PBEE framework.

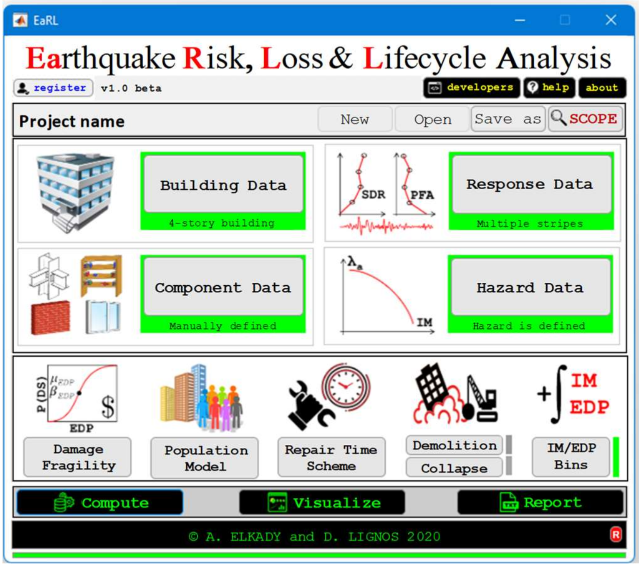

Figure 2. EaRL's main console.

2.2 *Operational layout*

EaRL's operational outline, shown in Figure 3, follows the same sequential order of the PBEE framework, in which the four main project parameters are defined. A loss project is first defined based on the *Building data*. These involve data such as *building's* number of stories, floor area, replacement cost, demolition cost, and population model. This is followed by the definition of the *Component data*; that is the building' structural members, non-structural elements and contents, along with their damage fragilities and associated consequences. This is then followed by defining the "*Response data*"; that is the EDP values along the building height resulting from a given earthquake/seismic intensity. Finally, if time-dependent DVs need to be computed, the "*Hazard data*" should be defined; this is essentially the seismic hazard curve for the building site. The following sub-sections describe the key features and functionalities with each of the aforementioned definitions.

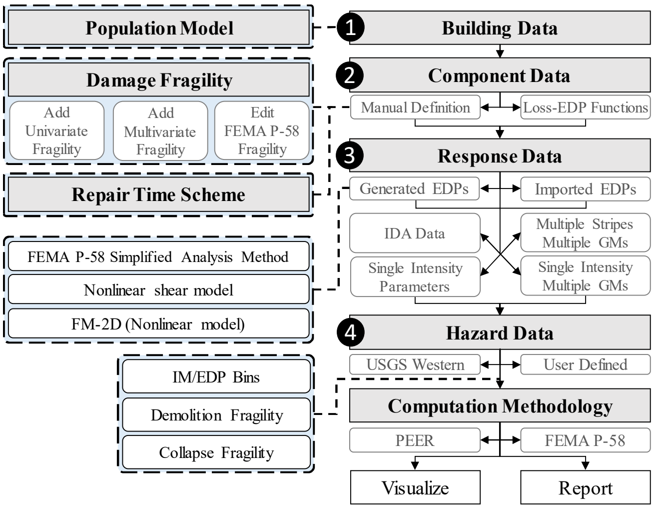

Figure 3. *EaRL*'s operational procedures layout.

2.3 *Project file*

EaRL projects *are* saved as a single "*.*mat*" MATLAB data file. This file is editable which allows users to modify it outside of the user interface. The file is also transferable which makes project-sharing between collaborators feasible.

2.4 *Response data definition*

Defining the structural response data (i.e., EDP values) is arguably the most challenging step when conducting loss analysis. In practice, structural response data can be obtained through different means. For example, the data can be obtained by running nonlinear numerical models or using empirical equations. Furthermore, numerical models may be analyzed for a single or multiple ground motion (GM) records; each of which may be scaled at a single or multiple intensities. As such, a total of six options are provided within *EaRL*, to define the EDP data, as shown in Figure 4. The first four options are used to import EDP data that are readily available by the user:

- Import EDP data from multiple GM records scaled up to collapse. This type of data is typically obtained through incremental dynamic analysis procedures.
- Import EDP data from multiple stripe analysis (i.e., multiple GM records scaled at multiple seismic intensities).
- Import EDP data from multiple GM records, scaled at a single seismic intensity.
- Import the distribution parameters (i.e., median and standard deviation data) of the different EDPs at a single seismic intensity.

Each of the aforementioned options has its dedicated user-interface. Pre-formatted EXCEL sheets are also provided to simplify the data entry process prior to importation. Plotting options are also provided to visualize and check the imported data. The last two options can be used to auto-generate EDP data without the need to create and run intensive numerical models:

- Generate EDP data by constructing a nonlinear multi degree-of-freedom (MDoF) shear model and running dynamic response-history analyses using the OpenSees platform (Mckenna 1997). This all done within the module.
- Generate EDP data based on the Simplified Analysis Method as discussed in detail in FEMA P-58.

Furthermore, *EaRL* supports a total of 11 reference EDPs that are commonly used in literature. This includes basic global EDPs such as the story-drift and residual-drift ratios and the peak absolute floor acceleration as well as local EDPs such as member rotation and damageable wall drift. Additional generic EDPs can also be defined by the user.

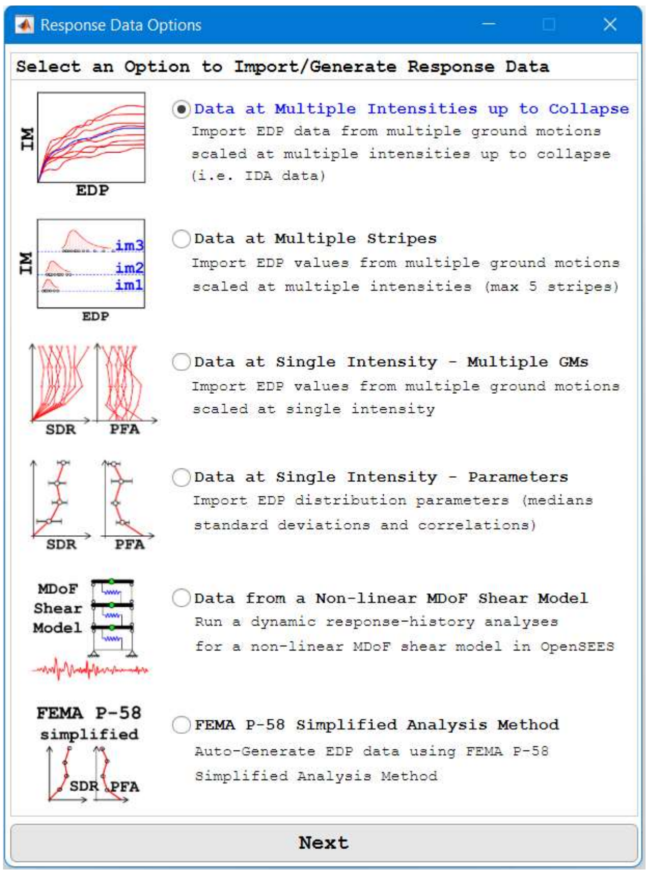

Figure 4. Structural response data definition options.

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2.5 *Component fragility*

Two options are provided to define the building's structural, non-structural components and contents. In the first option, this data can be explicitly defined by manually specifying all component details in the building (e.g., name/type of the component, number of units and their story/floor location). Given that this step can be tedious and labor intensive, an intuitive and interactive interface is provided to streamline this process as shown in Figure 5. This interface integrates the full component database of FEMA P-58. This comprises more than 750 different components and their associated damage/loss fragilities. The interface employs multiple drop down menus that can be used to filter the database and select a target component based on its category (e.g., superstructure, exteriors, electrical, furniture, etc). Alternatively, the user can define this data in a pre-formatted EXCEL sheet and then import it.

For each of these components, the user is able to modify the damage fragility function parameters of the integrated database, as well as the values of the damage monetary and repair time consequences. The user is also able to define and add new components to the fragility database through the interface shown in Figure 6. Notably, *EaRL* supports the definition of multivariate fragility functions. Multivariate fragility functions are becoming more popular as they provide better estimates of damage compared to the common univariate ones (Lignos and Karamanci, 2013, Yazdi et al., 2016, Elkady et al., 2018). This option is not currently available in other software.

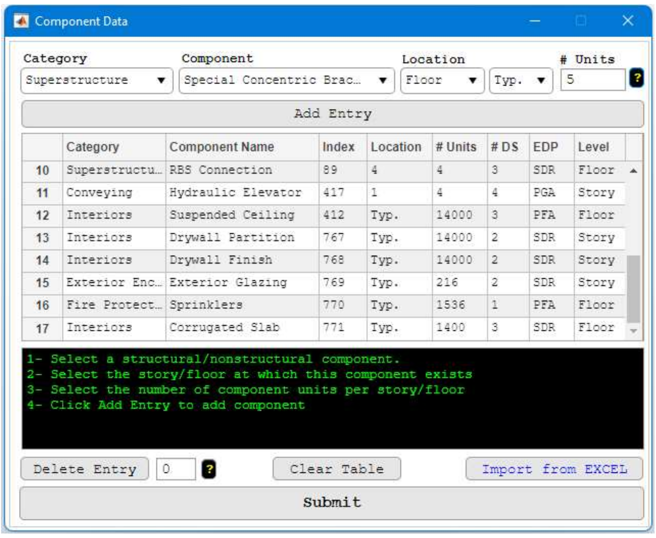

Figure 5. Manual definition of building components.

Alternatively, the second option involves defining building components indirectly by using implicit story-based Loss-EDP functions. These functions directly relate expected DVs (e.g., monetary losses) at a given story/floor to the story/floor EDPs. These DV-EDP functions are commonly known as the "story-loss functions" that are developed based on surveyed/investigated building portfolios with generic distribution of components. Contrary to the explicit manual definition option, this approach requires minimal information to be provided by the user, at the expense of accuracy. The current version of *EaRL* employs the story-loss functions developed by Ramirez and Miranda (2009) and Papadopoulos et al. (2017) for office buildings with conforming/non-conforming reinforced concrete frames and modern capacity-designed steel moment and braced frames, respectively.

2.6 *Seismic hazard*

EaRL's seismic hazard module currently has the United States' 2008 updated seismic hazard maps (Petersen et al., 2008) integrated within. This enables the user to simply define the hazard for buildings located within the US, by only specifying basic information about the building coordinates and soil type. Alternatively, the hazard curve can be defined manually.

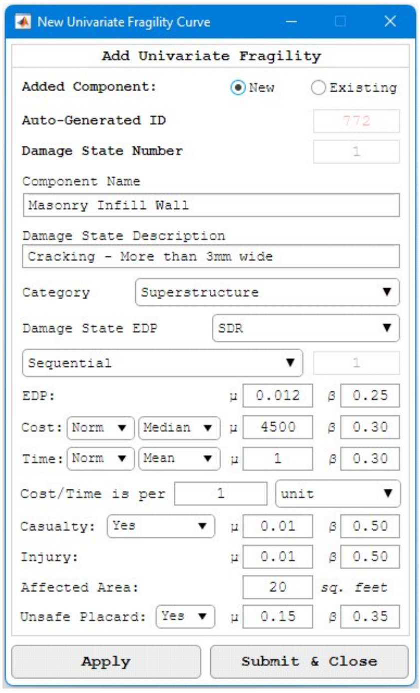

Figure 6. Defining new univariate component fragility.

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2.7 *Demolition fragility*

In literature, lateral residual story drift ratios (*RDR*) are typically used as a trigger for the building demolition decision. Recent research showed that vertical residual deformations (*VRD*), resulting from cumulative damages in columns (e.g., local buckling or crushing), can be equally important (Elkady et al., 2020), particularly in buildings subjected to long-duration earthquakes. To that end, the user is able to define univariate or bivariate demolition fragility functions, as shown in Figure 7. The latter is not currently implemented in other exiting software.

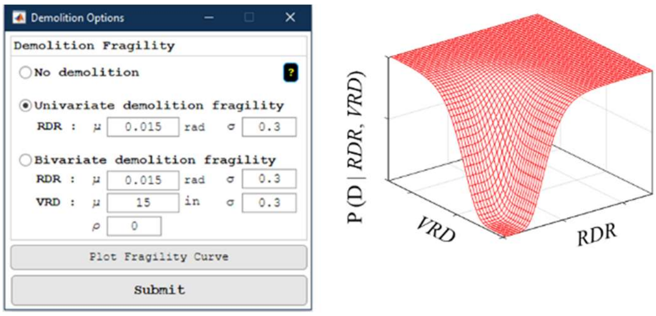

Figure 7. Demolition fragility module.

2.8 *Repair time scheme*

EaRL computes a number of damage consequences including the time required to repair the damaged building components. The total repair time highly depends on the sequence of repair works. *EaRL* gives the user full control over the envisioned repair scheme in the aftermath of an earthquake. In particular, the user is able to specify a) if different building component types should be repaired in a sequential or simultaneous manner, b) which component type groups will be repaired simultaneously, c) if same component type units should be repaired in series or in parallel and d) if repairs should take place at each floor level simultaneously. These controls allow for a more accurate estimate of the repair time.

2.9 *Population model*

Damage consequences related to potential human injuries and casualties as a result of fallen debris from damaged components are computed in *EaRL*. This computation requires the user to define the building population model. The population model describes the peak occupancy, which is the number of people per unit area and the associated variations in this peak value with respect to the month, day and hour. This model can be defined from the interface shown in Figure 8. By default, the population model is extracted from the integrated population model data defined in FEMA P-58 based on the building occupancy type (e.g., commercial or residential). Furthermore, the user may specify the target “Evaluation Time”; that is whether injuries and casualties will be assessed, during the FEMA P58 computation, at a randomly generated time or at a specific user-defined time.

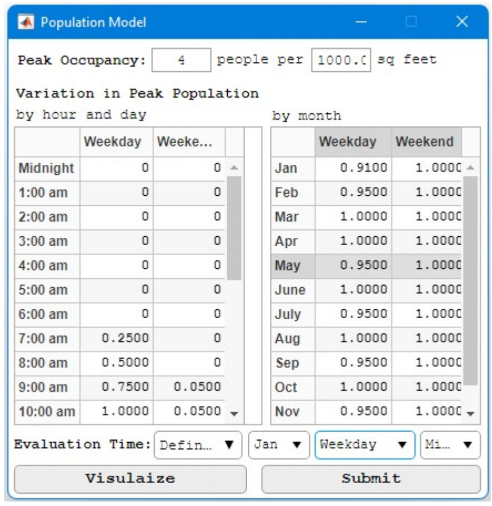

Figure 8. Population model interface.

2.10 *Loss methodology*

EaRL incorporates the two main building-specific story-based loss-estimation methodologies available in literature to compute the expected losses arising from each event, as shown in Figure 9. The first methodology is the one originally developed by Moehle and Deierlein (2004), Aslani and Miranda (2005) within the Pacific Earthquake Engineering Research center (PEER) framework. The second methodology, and the most recent, is the one developed by Yang et al. (2009) and implemented in FEMA P-58 (FEMA, 2012). The latter employs Monte Carlo simulation method to query damage in a building, rather than directly integrating across all ranges of EPD, damage and consequence fragilities. This makes it a computationally efficient methodology. Additionally, Monte-Carlo simulation can simply be used to generate large number of artificial structural response data (noted as *realizations*) using seed response data obtained from a limited number of response-history analyses. As part of this process, supplemental uncertainty can be incorporated to the generated structural response data to account for modelling uncertainties.

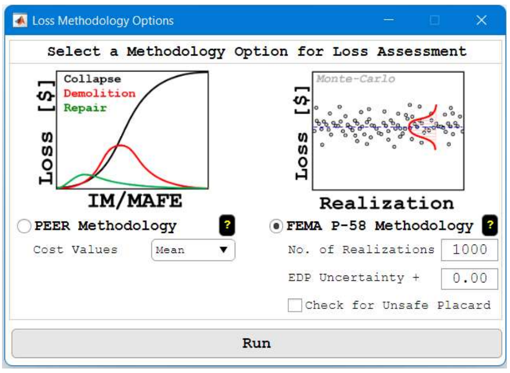

Figure 9. Loss methodology options.

2.11 *Loss visualization*

The current version of *EaRL* evaluates direct monetary losses (i.e., cost associated with collapse, demolition and repairs), repair time, injuries, casualties and the probability of issuing unsafe placards. A comprehensive list of options is available to plot loss distributions and breakdowns or to report them in text files.

Figure 10 shows one of this visualization options; that is the *loss summary* interface for FEMA P-58 methodology computations. This interface includes the following: a) a scatter plot of the repair cost for each realization, (b) the histogram distribution of the repair costs, (c) the total loss breakdown for a given realization at a given intensity stripe, (d) the repair loss profile breakdown with respect to the component type at a given realization and at a given intensity stripe, (e) the annual rate of exceeding a given repair cost along with the mean cumulative annual repair cost, (f) a summary of the expected probability of collapse, probability of demolition, probability of issuing an unsafe placard, the number of injuries and casualties. Using the knob at the bottom left corner of the window, the user can select the intensity stripe of interest (when multiple *IM*s are employed). Similarly, the slider and spinner controllers may be used interchangeably to navigate between the different realizations.

2.12 *Source code and development*

EaRL platform is fully developed in MATLAB. The entire source code is a combination of MATLAB's **.mlapp* graphical user-interface (GUI) files and **.m* function files. The source code is available online through GitHub. To help users comprehend and be able to navigate the source code and modify/add specific functions, the MATLAB script files are thoroughly commented and organized. A "*Developers*" interface, shown in Figure 11, is provided where users can inspect 1) *code hierarchy*; i.e., the dependency and the relation between the different source code GUI and function files as well as the description of each function and its output variable; and 2) *code variables*; i.e., the list of all the variables used within the source code, including their name, type (scalar, vector, matrix, structure, etc.) and their parent module(s) or function(s).

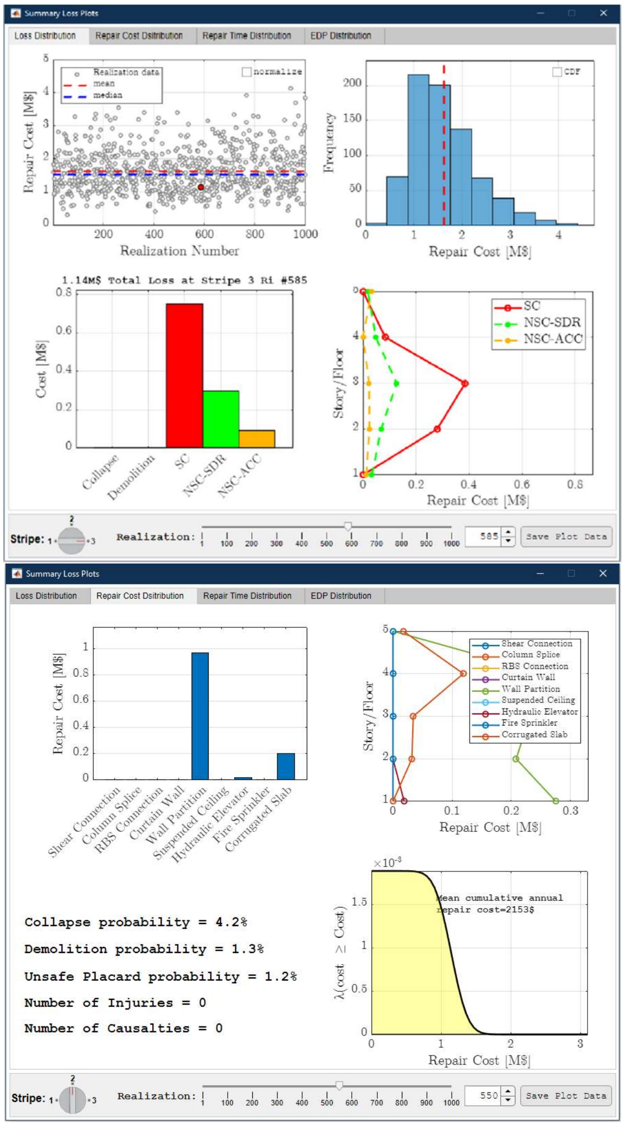

Figure 10. Summary plot interface for the FEMA P-58 option.

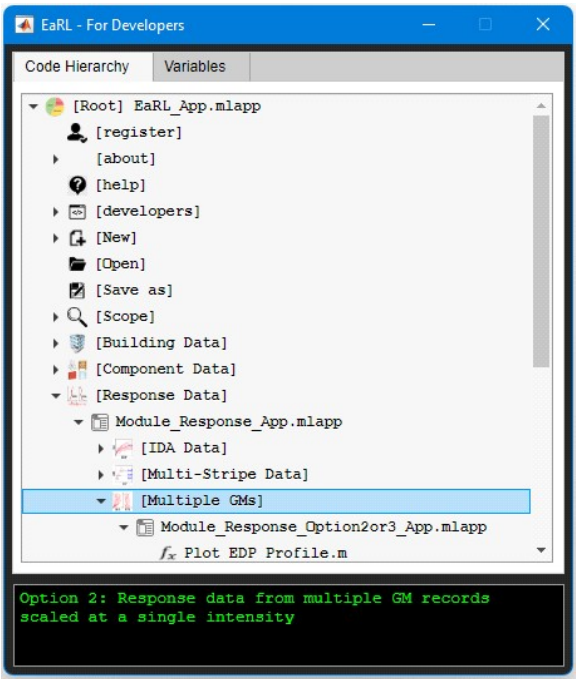

Figure 11. Developers interface.

3 CONCLUSIONS

A new platform/software named EaRL is developed. The software provides an interactive and user-friendly platform for quantifying building-specific economic consequences of earthquakes (direct monetary and repair time losses as well as casualties and injuries), in support of performance-based design and assessment. *EaRL* is an open-source software that is fully developed within the popular MATLAB programing language. The software codebase is carefully documented to encourage first-time users, researchers and practicing engineers worldwide to collaborate and contribute to its metadata, functionalities and interactive features. The source code, installation executable and full technical manual are available at GitHub (https://github.com/amaelkady/EaRL). Video tutorials are also available in a YouTube playlist (https://youtube.com/playlist?list=PLz_XdUL-6Y_nbmyXU7Pcdg_XDwvwgGXjF).

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