EaRL

Software for Earthquake Risk, Loss, and Lifecycle Analysis

Version 2.2507
Manual

Prepared by

Prof. Ahmed Elkady
Associate Professor
National Infrastructure Laboratory (N|I|L), University of Southampton,
United Kingdom

Prof. Dimitrios G. Lignos
Full Professor
Resilient Steel Structures Laboratory (RESSLAB), École Polytechnique
Fédérale de Lausanne (EPFL), Switzerland

July, 2025

Table of Contents

Disclaimer

USERS ARE ADVISED TO REFERENCE THIS SOFTWARE AS FOLLOWS:

Elkady, A. and Lignos, D. G. (2020). "EaRL - Software for earthquake risk, loss and lifecycle analysis." *SoftwareX*: 12. DOI: 10.1016/j.softx.2020.100607.

Download and Support Links

GitHub repository: https://github.com/amaelkady/EaRL

Registration for software updates: https://forms.gle/CkfSBmjhqATJZQJj6

Video tutorials on YouTube: https://www.youtube.com/playlist?list=PLz_XdUL-6Y_nbmyXU7Pcdg_XDwvwgGXjF

1. Installation

The step-by-step installation procedure of the software, in Windows, is discussed in this section. Note that EaRL v2.0 executable is only made available for Windows machines, however, the software can run directly on a Mac machine using the Matlab source code. Figure 1.1 shows all the files/folder that are downloaded by the user through the EaRL's GitHub repository. These are as follows:

1. *EaRL_Installer.exe* this is the main installation file.
2. *EaRL Manual.pdf* this is EaRL's manual and installation guide.
3. *Supporting Documents* this folder includes all the pre-formatted and template files that can be modified by the user and imported into the different modules in EaRL.
4. *USGS Hazard MAT Data* this folder contains the source seismic hazard data for western united states regions based on the USGS maps. This folder can be imported by the user into EaRL as part of the Hazard Data module.

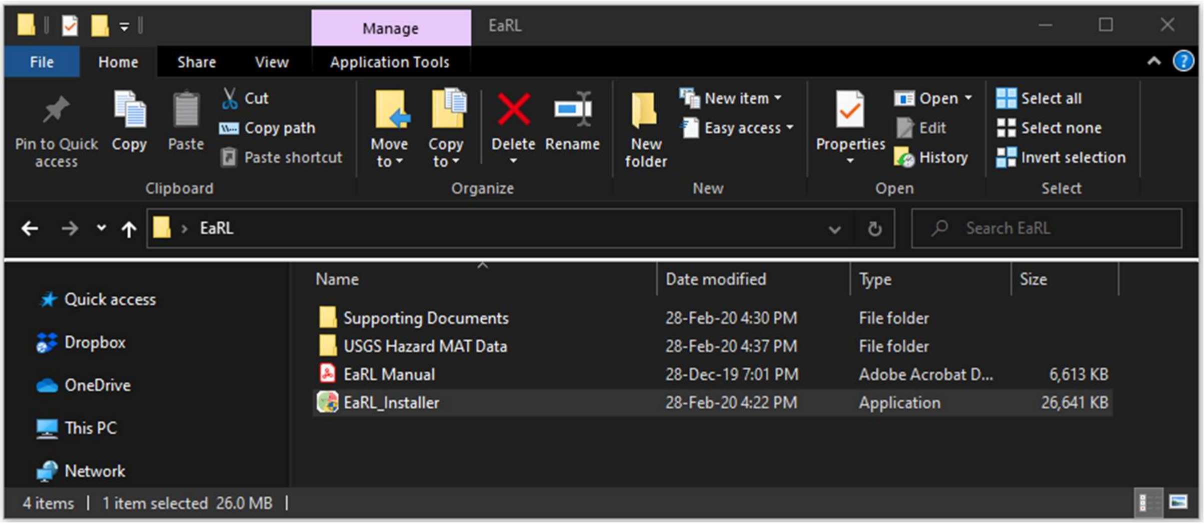


Figure 1.1. Downloaded software files and folders

The software can be installed by running the *EaRL_Installer.exe* executable file. As demonstrated in Figure 1.2, the installation process is similar to any software. The user is prompted to different windows to approve the installation process and set the installation directory. By default, the installation directory is "*C:\Program Files\University of Southampton\EaRL*". Note that if MATLAB runtime was not already installed on the local PC, the user will be prompted to download the latest runtime environment (about 700Mb). An internet connection is required in this case.

Once installed, the executable file EaRL.exe, as well as other files, can be found in the default installation directory under ".....*\University of Southampton\EaRL\application\EaRL.exe*" as shown in Figure 1.3. To benefit from the OpenSEES-based features in EaRL, the user will need to independently install Tcl/Tk and OpenSEES on the PC. OpenSEES installation is described https://opensees.berkeley.edu/OpenSees/user/download.php. After installation, the user must make sure the executable *OpenSEES.exe*, which was already generated during the installation procedure, is working properly from the installation directory. Finally, it is important to note that EaRL should be opened by running the *EaRL.exe* file from the installation directory using administrator privileges. Otherwise, features that utilizes OpenSEES would not work properly.

The users are highly recommended to register their information online using the following form link: https://forms.gle/CkfSBmjhqATJZQJj6; so that they are able to receive notification e-mails will be sent regarding future releases and/or bug-fixes.

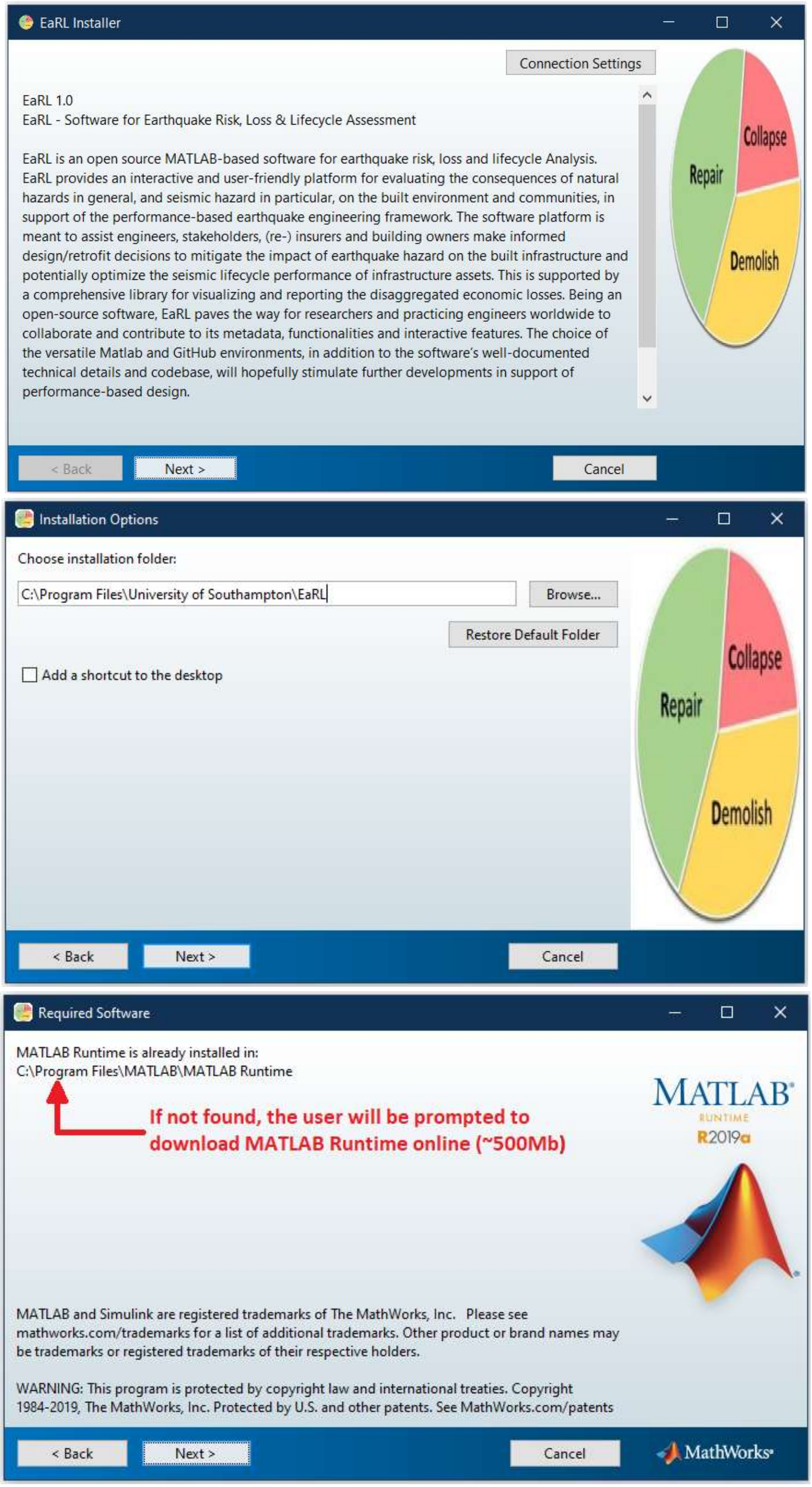


Figure 1.2. Installation steps

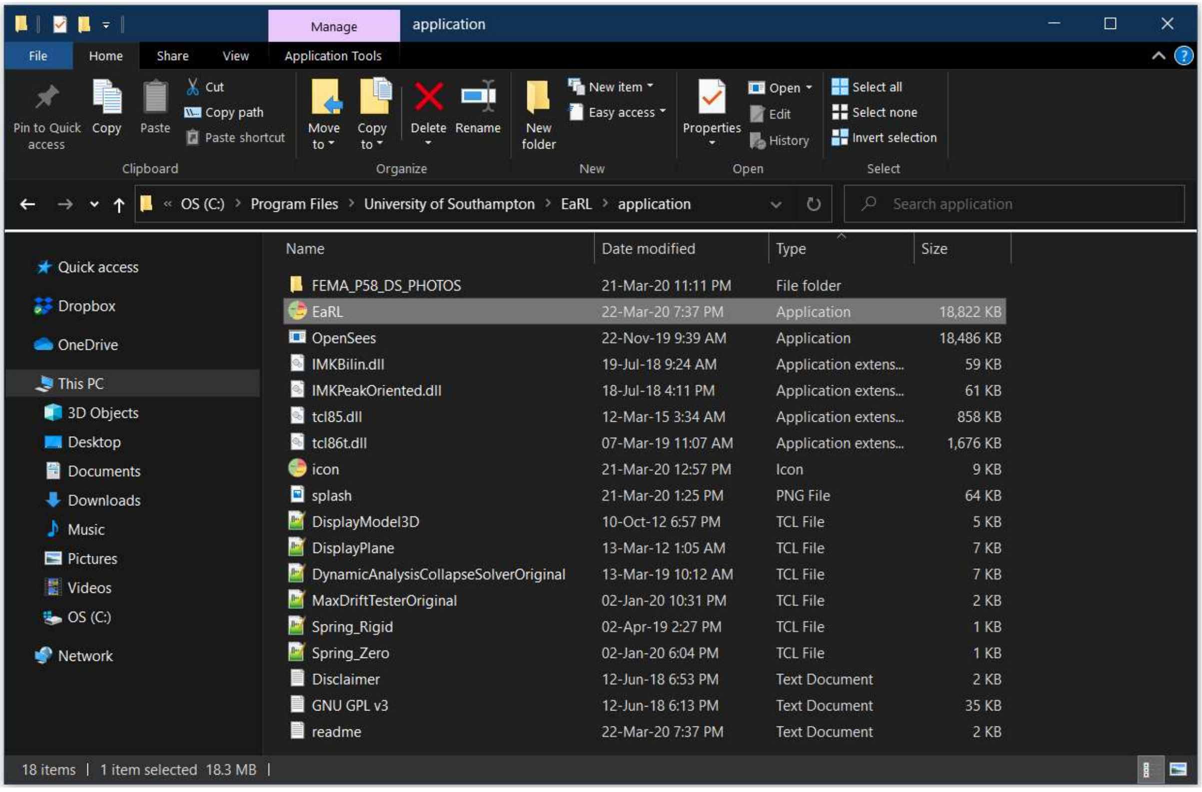


Figure 1.3. Installed files and folders in the default installation directory

2. 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 repairs in damaged buildings, and the associated downtime until the building regains its functionality. These losses can cause dire long-lasting impact on national economies. This has been demonstrated by major earthquakes worldwide (Goltz 1994; Ghosh 1995; Comerio and Blecher 2010; Clifton et al. 2011; Saatcioglu et al. 2013). Consequently, governments and building owners are interested in predicting and minimizing potential earthquake-induced economic losses as a measure of structural seismic resilience.

Modern building codes aim to limit structural damage under a design-basis earthquake and structural collapse under a low probability of occurrence seismic event. These objectives are achieved by design and detailing rules and seismic design provisions at the component level and the system level. Nonetheless, structural and non-structural damage is still observed because the status-quo in seismic resistant design mobilizes the concept of ductility to dissipate the energy during an earthquake.

Targeting specific performance objectives, beyond the scope of design standards, has been the basis of the performance-based earthquake engineering (PBEE) framework since the early 2000s (SEAOC 1995; Cornell and Krawinkler 2000; FEMA 2000). Target performance objectives are not only concerned on how to reduce casualties and injuries, which is a fundamental objective. The physical damage to ensure continuous functionality particularly in community-critical structures is a major performance objective. The PBEE framework, as formulated by the Pacific Earthquake Research (PEER) center (Porter 2003; Moehle and Deierlein 2004), is demonstrated in Figure 2.1. This framework aims at explicitly quantifying performance decision variables (DVs) such as expected annual losses or downtime associated with earthquake repairs. These DVs aid the effective communication of the design or retrofit process to building owners, shareholders and engineers. In particular, for a given intensity measure (IM), which is typically obtained based on seismic hazard analysis at the building location, 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 structural and non-structural content as well as the availability of damage fragility functions for each one of the components. The last step is the loss analysis where DVs are computed.

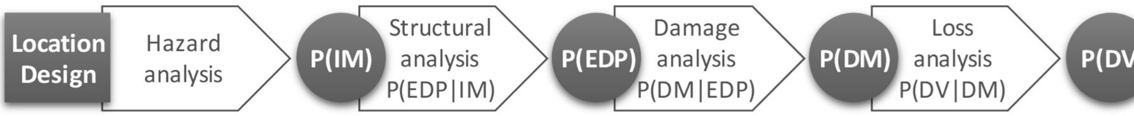


Figure 2.1. Overview of the PBEE framework [based on Porter (2003)]

A new publically-available MATLAB-based (MATLAB 2019) computational platform/standalone software is developed and presented herein. 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.

3. Methodology and Computation Algorithms

Referring to Figure 3.1, under a given earthquake scenario (or equivalent intensity measure, IM), a building can experience one of three basic events: i) Collapse (C) due to large lateral deformations coupled with deteriorating structural component strength/stiffness and increasing P-Delta forces; ii) Demolition (D), in the case of no-collapse (NC), may be triggered due to irreparable large residual deformations; iii) Repair (R) of damaged structural (SC) and non-structural (NSC) components in the case of no-demolition (ND). EaRL incorporates the two main building-specific story-based loss-estimation methodologies available in literature to compute the expected losses arising from each event. The first methodology is the one originally developed by Deierlein (2004); Krawinkler and Miranda (2004); 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; Hamburger et al. 2012). A brief summary of the computation procedures in each methodology is provided in the following sections with emphasis on direct monetary losses as the main decision variable. In these summaries, the letter symbols P and *f* are used to refer to the cumulative probability function (CDF) and the probability density function (PDF), respectively. Any seismic intensity measure (IM), that is acceleration-based, may be considered in EaRL including the spectral ordinate at the first-mode period of a building (i.e., $Sa(T_1)$), and the state-of-the-art geometric mean of the spectral ordinates within a given range of periods (i.e., Sa_{avg}). This entails the consistent definition of the IM across all modules in EaRL. Future EaRL releases will support other IMs.

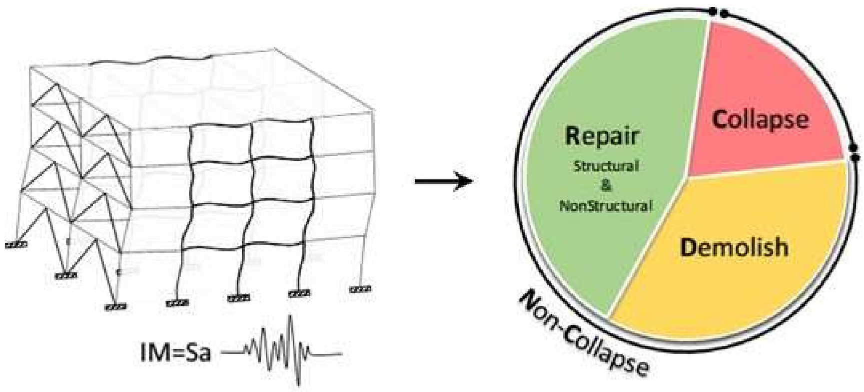


Figure 3.1. Potential events in the aftermath of an earthquake

3.1 PEER Methodology

Referring to Figure 3.2, for a given intensity measure level *im*, the PEER methodology commences by computing the expect loss due to the collapse event E[C] as the product of the probability of collapse at *im* and the cost of replacing the building, C_{replace}. The probability of collapse CDF can be deduced from the structural response data (assuming collapse is simulated in the numerical model) or by directly specifying the parameters of the collapse CDF, as discussed in detail in Section 6.2. Following, the demolition CDF at *im*, P(D|*im*), is computed by integrating the demolition CDF conditioned on the residual deformation magnitude over the residual deformation PDF conditioned on *im*. The expected demolition loss E[D] is then computed as the product of P(D|*im*), probability of no-collapse, P(NC|*im*) and C_{replace}. Finally, in order to compute the expected repair loss E[R], the procedure loops over each damage state $_j$ for each structural/non-structural component *c* at each story/floor level *n*. The probability of being in DS_{cj} at *im* is computed by integrating the fragility function representing the probability of being in DS_{cj} given the controlling EDP over the PDF of the controlling EDP_{cn} conditioned on *im*. The repair cost associated with DS_{cj} is then computed as the product of $P(DS_{cj}|im)$, the number of component units (*nUnits*), the repair cost associated with DS_{cj} ($C_{\text{repair},\, cj}$), the probability of no-collapse ($P(NC|im)$) and the probability of no-demolition ($P(ND|im)$). Summing all repair costs of each damage state for each component at each story, $E[R]$ is obtained.

3.2 FEMA P-58 Methodology

The FEMA P-58 methodology (FEMA 2012; Hamburger et al. 2012) relies on a modified Monte-Carlo method (Metropolis and Ulam 1949) 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. The employed 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 3.3 briefly shows the procedure outline in FEMA P-58 as implemented in EaRL. In summary, for a given realization *i* at intensity *im*, the procedure starts by querying the collapse fragility CDF by using a uniformly distributed random variable. The CDF represents the probability of collapse at *im*. In case of collapse, the associated loss is computed as the building replacement cost C_{replace}. In case of no collapse, the procedure continues in a similar manner to query the demolition fragility CDF using a random variable representing the probability of demolition at edp_{i}, which is the generated uniformly-distributed random EDP, of relevance to the demolition fragility (see Section 13), within realization *i* at *im*. If the demolition event is not triggered, the procedure checks the associated repairable damage. Essentially, for a component *c* at a given story/floor level *n*, the component's damage fragility curves are queried at edp_{i} using a random variable. If there is damage, this query returns the number of a single damage state that was triggered. The main difference with the PEER methodology is that, in the latter, all damage states are considered through integration by using the total probability theorem. If the damage state is identified, the repair cost (and other consequences) may be computed by multiplying the repair cost associated with this damage state and the number of component units per story/floor. Note that since the repair cost and other damage consequences have an associated uncertainty, another random variable is used to determine the consequence value for each realization. The procedure then continues throughout all the component and stories/floor while summing up the damage consequence, before moving to the next realization.

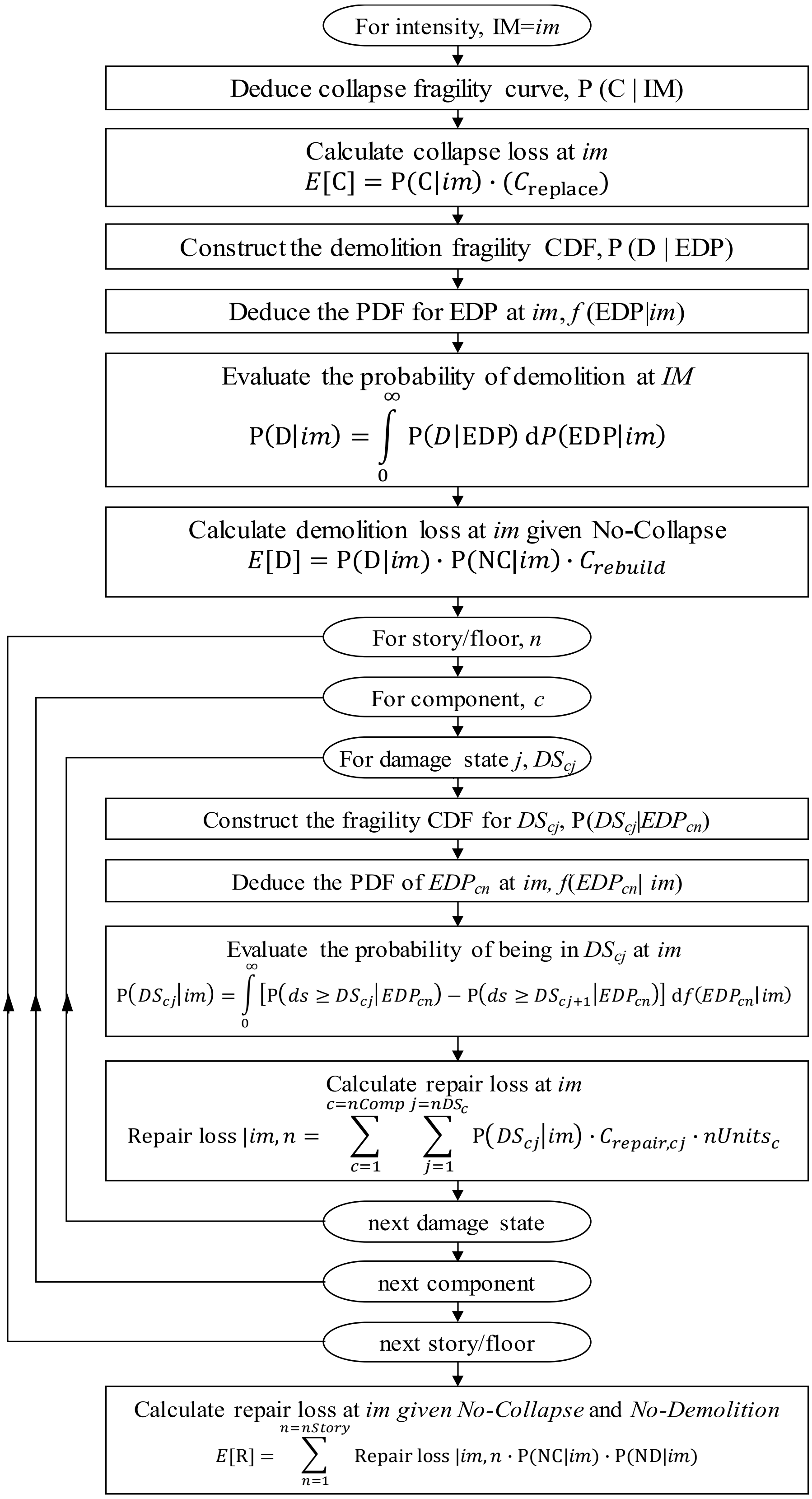


Figure 3.2. Flowchart of the PEER loss estimation methodology

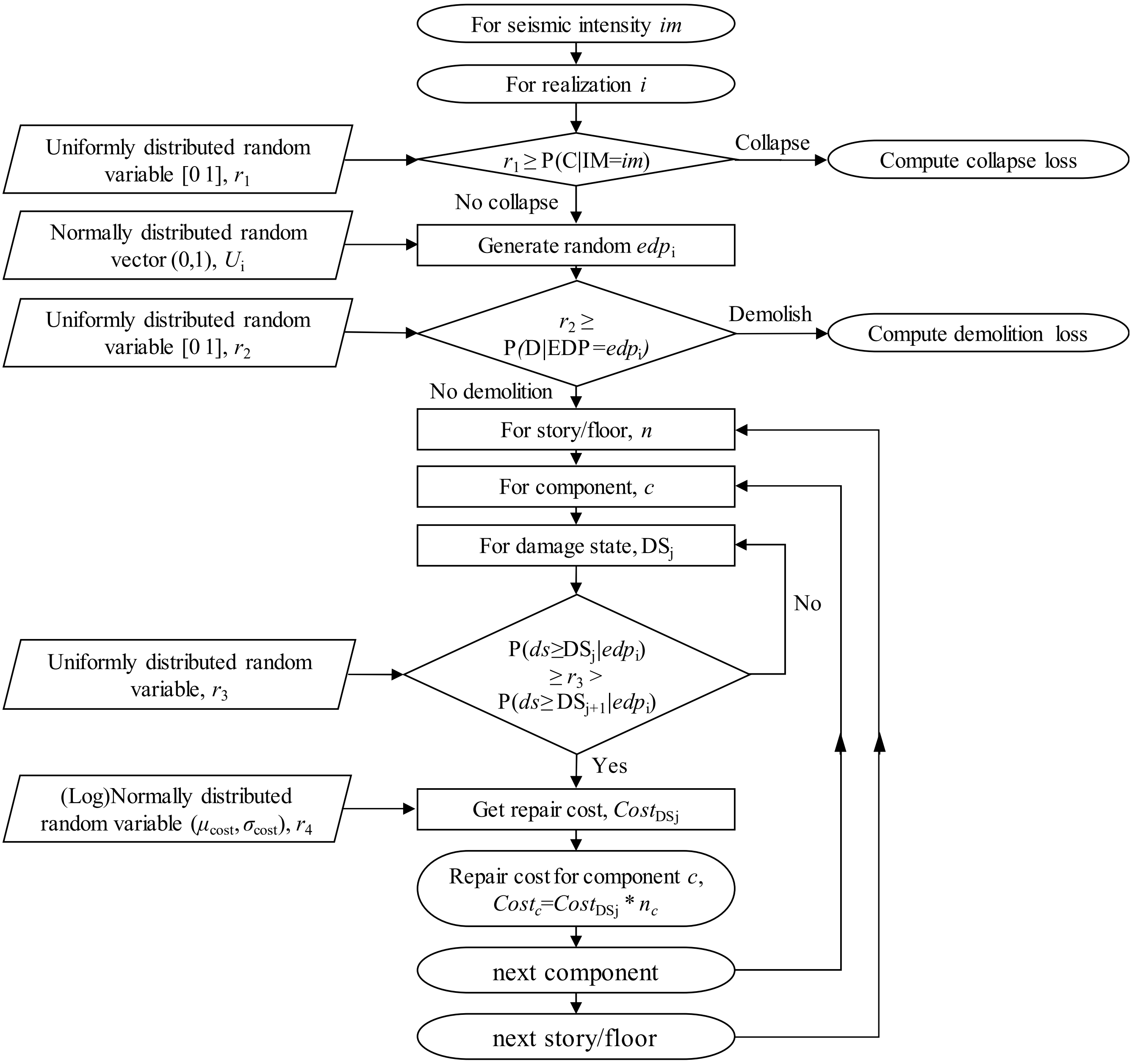


Figure 3.3. Flowchart of the FEMA P-58 loss estimation methodology

4. EaRL's Operational Outline

EaRL's operational outline is illustrated in Figure 4.1. It follows the same sequential order of the PBEE framework as shown in Figure 2.1. A loss project is first defined based on the Building data. These involve the number of stories, floor area, replacement cost and the population model as discussed in Section 6. This is followed by the definition of the Component data; that is the building content and their damage fragilities and associated consequences. This data can be explicitly defined by manually specifying all component details in the building or by using implicit story-based Loss-EDP functions. These assume a generic distribution of component types/performance groups. The "Component data" is supported by a comprehensive "optional" module for modifying or providing additional fragility functions. The next step is to define the Response data; that is the EDP values along the building height. This data can either be imported from previously conducted nonlinear response-history analysis (NRHA) or automatically generated from simplified nonlinear analysis procedures. In either case, data can be imported/generated for different dynamic analysis procedures, including incremental dynamic analysis (IDA) and basic NRHA at single or multiple seismic intensities. For the computation of time-dependent decision variables, the Hazard data should be defined. The seismic hazard curve, for the building location, can be either imported or extracted from hazard maps that are integrated within EaRL (see Section 9). The fragility functions for demolition and collapse can be explicitly defined as part of the project. Otherwise, these events are ignored by default and only consequences of the repair event are considered in the loss estimation. Once the project is fully defined, either the PEER or the FEMA P-58 methodology, is chosen for the loss estimation. Losses can then be either visualized, or reported in formatted text files, or exported in a raw MATLAB file format.

The current version of EaRL evaluates direct monetary losses (i.e, cost associated with collapse, demolition and repairs), repair time, injuries, casualties and potential issuance of unsafe placards. Nonetheless, the user is able to obtain the full disaggregated loss analysis data such that it can be further processed to compute other DVs. EaRL v2.0 conducts loss analysis in a single orthogonal building direction at a time.

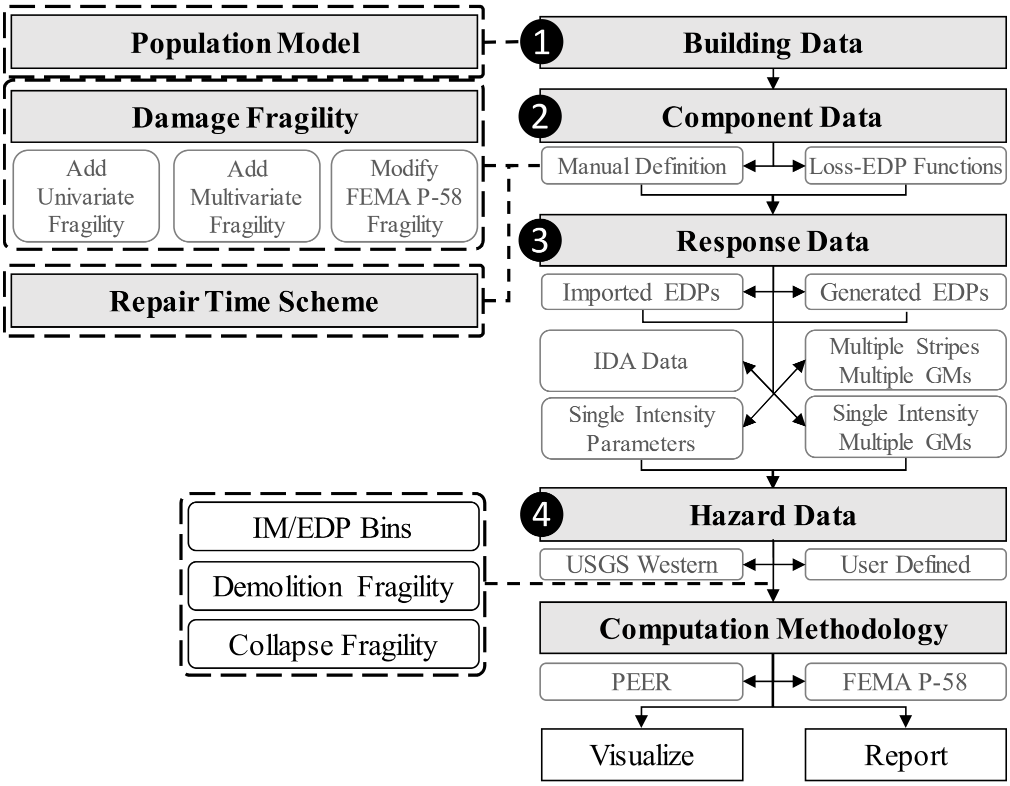


Figure 4.1. Flowchart of project definition in EaRL

5. EaRL Main Console and Components

Figure 5.1 illustrates the main console of EaRL, which is divided into four main panels:

5. Panel A is the project file management panel, which includes the following buttons:

- "New" create a new project file
- "Open" open an existing project file
- "Save As" save an open project under a different name
- "Scope" shows a summary of the current project definitions

The EaRL project is saved as a transferable MATLAB **.mat* file and can be loaded through the toolbox at any time. Moreover, after starting a new project, the user is prompted to select the project units ("Imperial" or "SI").

6. Panel B includes four buttons that define the four main components of any project:

- "Building Data" defines basic data for the analyzed building
- "Response Data" defines the structural response data
- "Component Data" defines structural and non-structural content of the building
- "Hazard Data" defines the seismic hazard for the building location

For a new project, the first three components should be defined. The "Hazard Data" should only be defined if the user would like to compute the EAL of a building.

7. Panel C includes optional modules:

- "Damage Fragility" for defining new fragilities or editing existing component fragility data
- "Population Model" for defining the building peak occupancy and its variations over time
- "Repair Time Scheme" for defining the scheme/strategy and sequence that will be followed when repairing damaged different components at different story/floor levels
- "IM/EDP Bins" define the range and accuracy of the IM and EDP bins used in loss computations and integration, respectively
- "Demolition" defines the demolition fragility function
- "Collapse" defines the collapse fragility function

8. Panel D includes three buttons:

- "Compute" to run the loss analysis
- "Visualize" to visualize the results
- "Report" to save the results

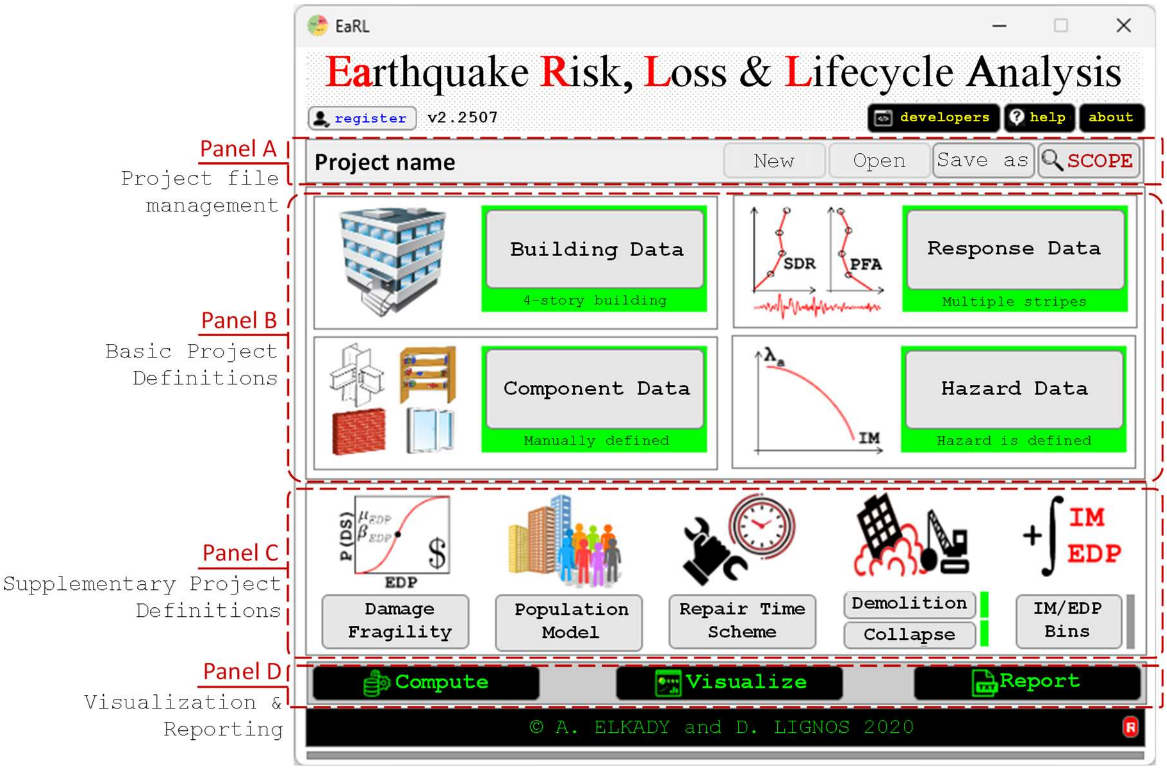


Figure 5.1. EaRL v2.0 main console

6. Building Data Module

A new project is defined by specifying main characteristics and attributes of the building under consideration. This data is entered through the Building Data module shown in Figure 6.1. The user should define the building construction material(s) and the lateral load-resisting structural system(s). This information is used to filter the component fragility database that is integrated into the toolbox; hence, simplifying the subsequent steps of selecting the building's components. Other Building Data include the number of stories, the footprint and total floor areas, as well as the demolition and total replacement cost of the building. Note that the demolition cost is the cost of demolishing a standing but heavily damaged structure, whereas the replacement cost is that of rebuilding a new structure. This data can also be used to auto-generate structural response EDPs or to directly estimate story-based losses, as discussed later on.

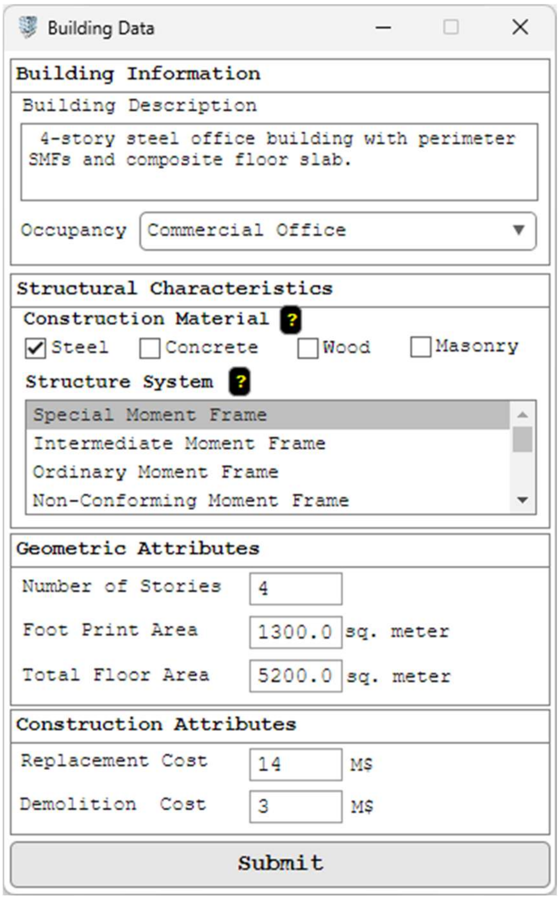


Figure 6.1. The building data module

7. Component Data

The Component Data module is shown in Figure 7.1. This defines the building content (i.e., components). Currently, there are three available options. These may be expanded in future versions of software.

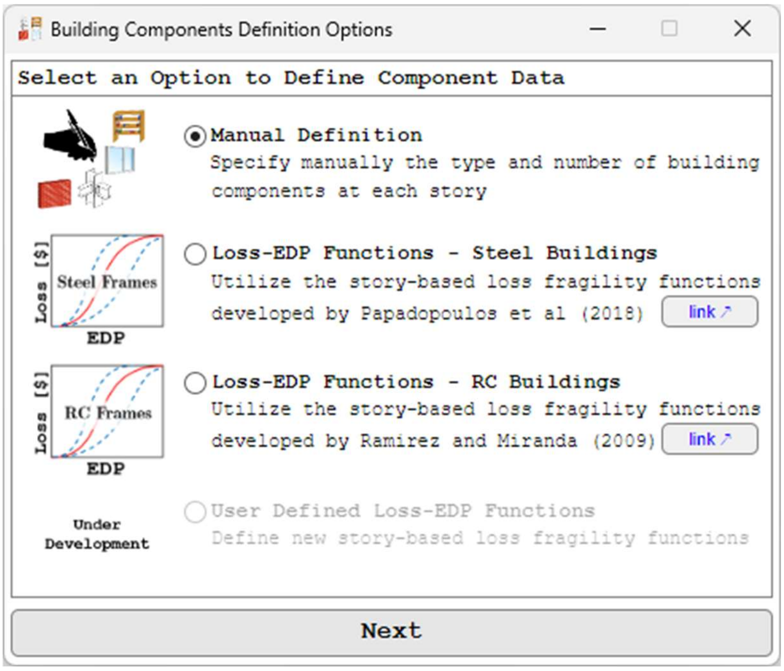


Figure 7.1. The component data module

7.1 Manual Definition of Building Components

According to the FEMA P-58 methodology, any component should fall in one of the four main groups: a) Substructure, b) Shell, c) Interiors, and d) Services. Each group is subdivided into sub-groups, labeled as “Category”. Referring to Figure 7.2, a total of 11 Categories exist in EaRL. The repair cost associated with each component damage state can be per:

- ➢ Number of units/panels/etc.
- ➢ Segment length of the component
- ➢ Square area

The structural and non-structural components of a building can be manually defined through the module shown in Figure 7.3. There are two ways for the data entry. These are outlined herein.

9. Components can be defined using the module’s dropdown menus through the following process:

- o Select the component category. This will filter the component list in the “Component” dropdown menu.
- o Select the component.
- o Select the story/floor location of the component. If this exists at each story/floor, select “Typical”.
- o Based on the component type, specify the number of units or the floor area or the segment length for this component at this specific location. Once a component is selected, a tip text will appear in the tip text box (the black field with yellow text, see Figure 7.3) to inform the user on what type of units should be provided.

- Click “Add Entry” to add the component to the building component table.
- To remove a given component from the table, the user can specify the number of table entry for this specific component and then click on “Delete Entry”.
- After entering all the components, click “Submit” to save data to the project.

10. **Directly importing a component list from an Excel spreadsheet:** Click “Import from EXCEL” to browse for the EXCEL file. This file can have any name with one of the following extensions: xls, xlsx, xlsm, csv. The file should have a sheet named “*Template Component Data.xls*”. The format of this sheet is illustrated in Figure 7.4. In particular, within this sheet, three columns of data are required:

- Column #1 (ID): includes the ID of the component based on its index in the database. For the database, the user can consult the “Supporting Documents” folder that is downloadable together with the installation files of EaRL.
- Column #2 (Level): includes the component level whether its story- or floor-based.
- Column #3 (Location): includes the component story/floor location (e.g. 1, 2, 3, etc.). If the component exists in all stories/floors, “Typical” should be specified. <u>It should be noted that a Typical Floor does not include the ground floor</u>.
- Column #4 (# Units): the value to be inserted in this column depends on the component. In particular, a) for components where cost is defined per unit/panel, the number of component units per story/floor should be inserted; b) for components where cost is defined per segment length, the user should insert the total length of the component per story/floor in the same pre-specified project units; c) for components where cost is defined per floor area, the user is not required to add any specific value since the floor area is already defined in the “Building Data” module (Accordingly, a “0” value may be added). Alternatively, the user can insert a different floor area for this specific component in the same pre-specified project units.

Please consult the sample file named “*Template Component Data.xls*” that is provided with EaRL’s supporting documents for reference. In this file, two additional columns are added (see Figure 7.4). One column (i.e., 5th column) automatically shows the component name based on the component ID, which is specified by the user. The other column can be used by the user to add comments for future reference. It is recommended that a user employs the sample file for future projects to prevent potential data-import problems arising from improper formats.

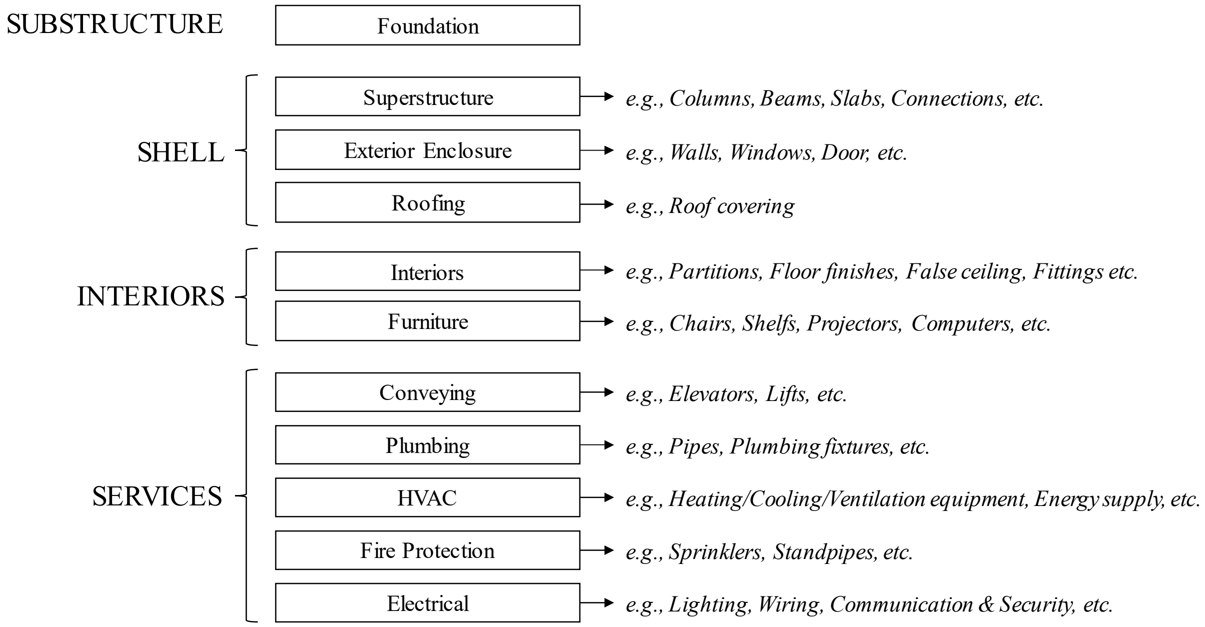


Figure 7.2. Component groups and categories

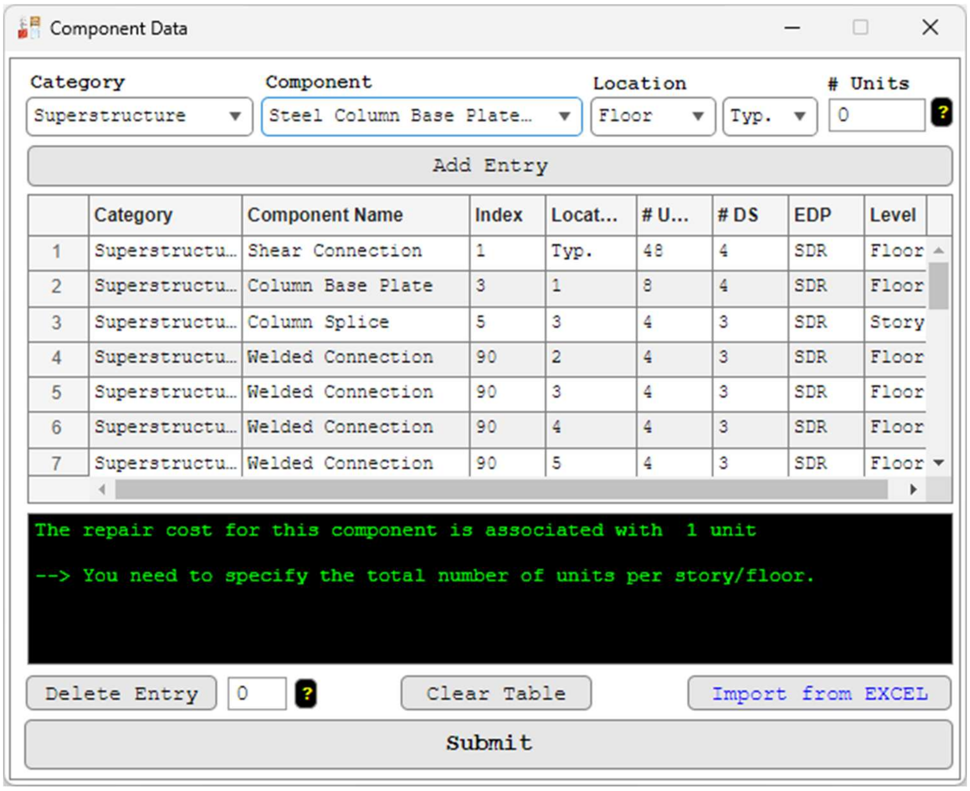
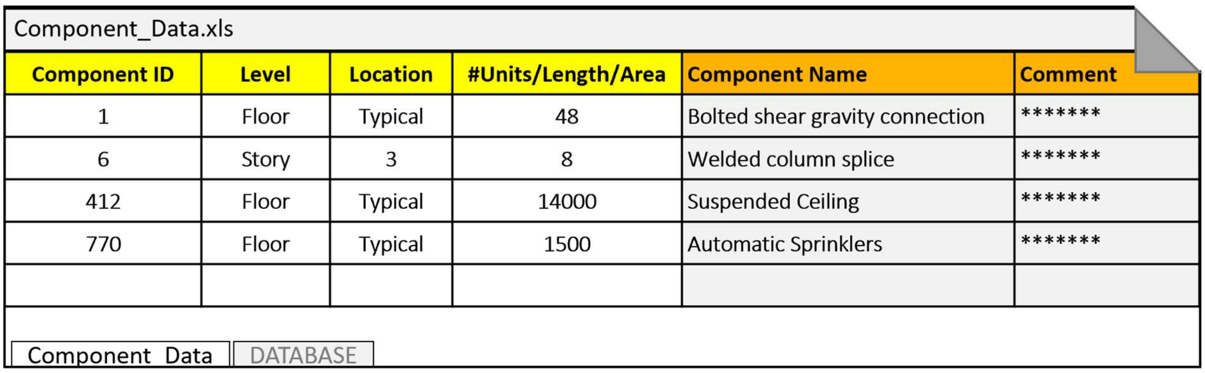


Figure 7.3. Manual component definition module



Component_Data.xls

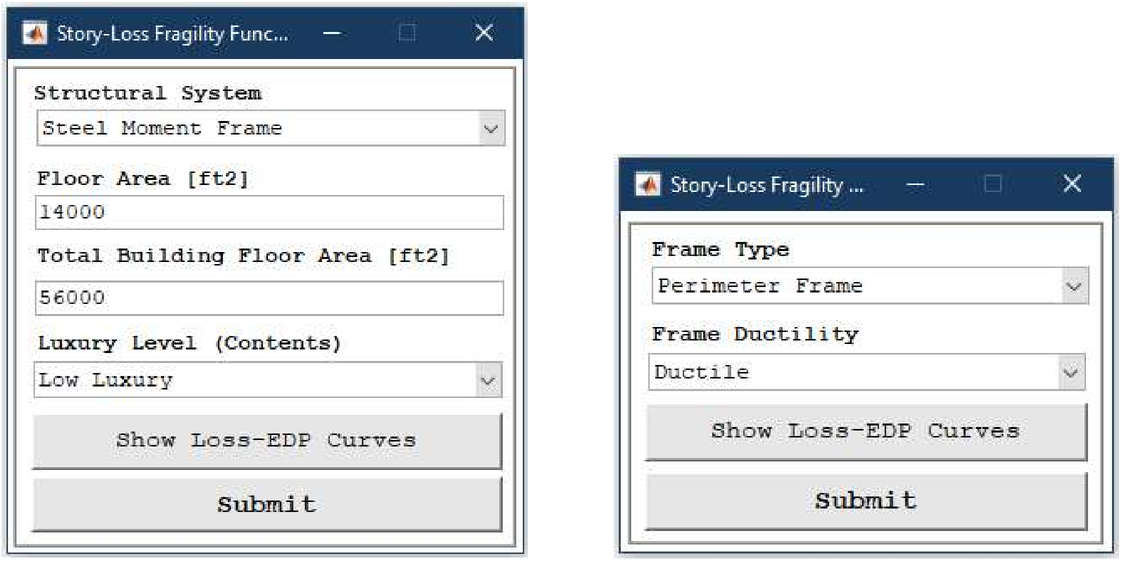
Component ID	Level	Location	#Units/Length/Area	Component Name	Comment
1	Floor	Typical	48	Bolted shear gravity connection	*******
6	Story	3	8	Welded column splice	*******
412	Floor	Typical	14000	Suspended Ceiling	*******
770	Floor	Typical	1500	Automatic Sprinklers	*******

Component_Data | DATABASE

Figure 7.4. EXCEL file format for manual component definition

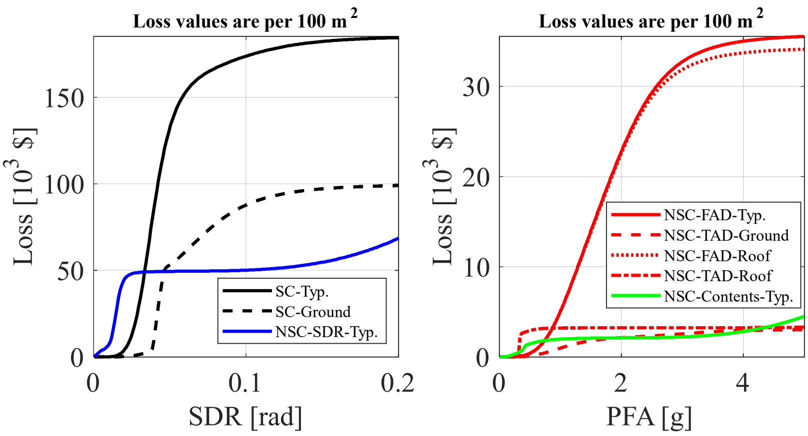
7.2 Story-Based Loss-EDP Fragility Functions

Rather than manually defining the components, a simplified approach can be used to utilize functions that directly relate expected monetary losses (i.e., DV: decision variable) at a given story/floor to the story/floor EDPs. These DV-EDP functions are commonly known as the “story-loss functions”. 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. To utilize these functions, the user should provide additional information regarding the building typology as shown in Figure 7.5. Furthermore, by clicking “Show Loss-EDP Curves”, the Loss-EDP functions that will be implemented will be plotted as shown in Figure 7.6. Further details can be found in the respective developers’ publications, which can be directly accessed using the “link to publication” button in Figure 7.1.

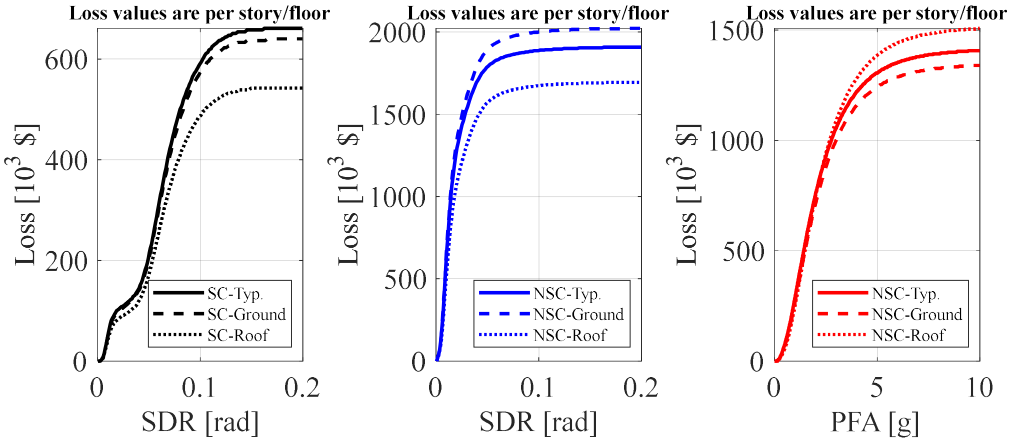


(a) Steel Frames (Papadopoulos et al. 2017) (b) RC MRFs (Ramirez and Miranda 2009)

Figure 7.5. Story-loss fragility module



(a) Steel moment frames (Papadopoulos et al. 2017)



(b) Reinforced concrete moment resisting frames (Ramirez and Miranda 2009)

Figure 7.6. Plots of story-loss fragility functions

8. Response Data Module

The Response Data module is shown in Figure 8.1. In EaRL v2, a total of six options are available to define the EDP data:

11. Option 1: Import EDP data from multiple ground motion records scaled up to collapse. This type of data is typically obtained through incremental dynamic analysis (IDA) (Vamvatsikos and Cornell 2002).
12. Option 2: Import EDP data from multiple stripe analysis (i.e., multiple ground motion records scaled at multiple seismic intensities).
13. Option 3: Import EDP data from multiple ground motion records, scaled at a single seismic intensity.
14. Option 4: Import the median and dispersion data of the different EDPs at a single seismic intensity.
15. Option 5: Generate EDP data by constructing a nonlinear multi-degree-of-freedom (MDoF) numerical model and running dynamic response-history analyses using OpenSEES (Mckenna 1997).
16. Option 6: Generate EDP data based on the Simplified Analysis Method as discussed in detail in FEMA P-58.

EaRL employs a wide range of reference EDPs that can be used by the user. Table 1 provides a summary of those EDPs. The story-drift ratio (SDR) and the peak "absolute" floor acceleration (PFA) are mandatory EDPs that should be provided in each project. Additional/optional EDPs include the horizontal residual-drift ratio (RDR) and vertical residual deformation (VRD) that are used to compute demolition losses (see Section 11), as well as EDPs related to individual building components as those summarized in Table 1. Note that for the RDR and VRD files, values at first-story only (these typically represent the maximum absolute values of all stories) should be provided in radians and mm (or inches), respectively. These units must be consistent with those used to define the demolition fragility function (see Section 11).

Table 1. Summary of EDP abbreviations and definitions

EDP	**Abbreviation**	**Units**	**Notes***
Peak story drift ratio	SDR	rad	defined for 1:*n* story levels
Peak floor acceleration	PFA	g	defined for 1:*n*+1 floor levels
Peal Floor Velocity	PFV	in/sec or m/sec	defined for 1:*n*+1 floor levels
Residual drift ratio	RDR	rad	defined for 1 levels (max)
Vertical residual drift	VRD	in or mm	defined for 1 levels (max)
Shear link rotation	LINK ROT	rad	defined for 2:*n*+1 floor levels
Beam rotation	BEAM ROT	rad	defined for 2:*n*+1 floor levels
Column rotation	COL ROT	rad	defined for 1:*n* story levels
Damageable wall drift	DWD	rad	defined for 1:*n* story levels
Effective drift	ED	rad	defined for 1:*n* story levels
Racking drift	RD	rad	defined for 1:*n* story levels
Generic story-based EDP	GENS1/2/3	By user	defined for 1:*n* story levels
Generic floor-based EDP	GENF1/2/3	By user	defined for 2:*n*+1 floor levels

*n: number of building stories

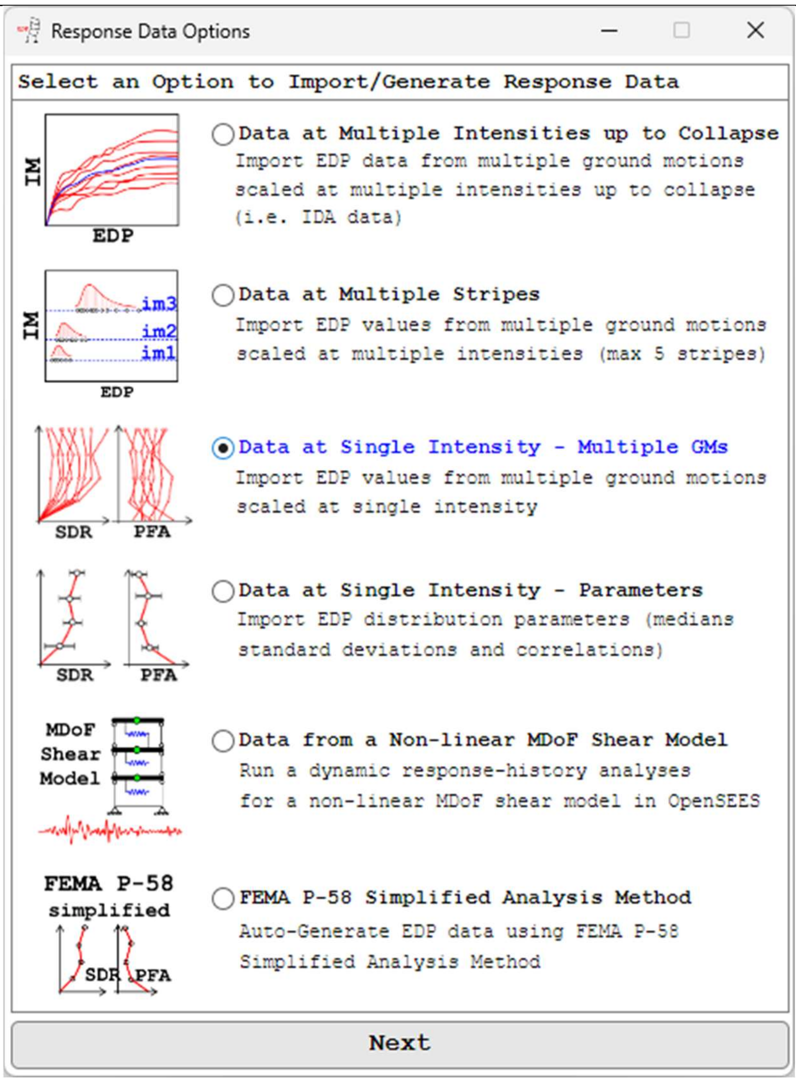
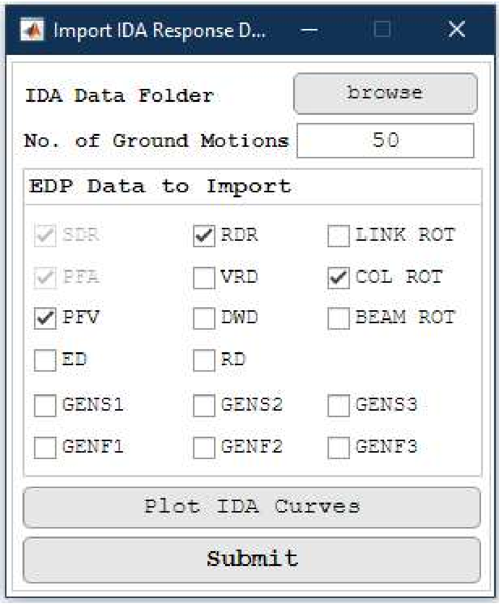


Figure 8.1. Response data module

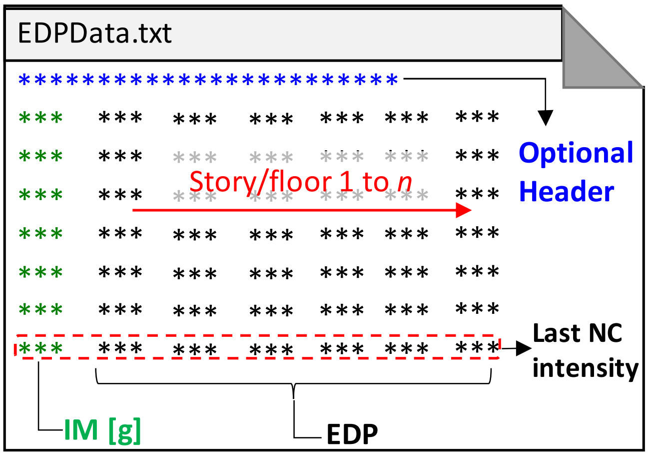
8.1 Imported Data at Multiple Seismic Intensities through Collapse

This option is used to import EDPs from single or multiple ground motion records scaled at multiple seismic intensities through collapse (i.e., IDA data). Figure 8.2a shows the module for this option. First, the user should "browse" for the folder containing the IDA data, which is organized in a pre-defined format. In particular, this folder should contain multiple subfolders; one for each of the analyzed ground motion records. There are no restrictions regarding the subfolder names. Each subfolder should include text data files for the IDA data for each EDP of interest. The names of the text files containing the IDA data for a given EDP should be named "IDA *edp*.txt", where *edp* is the EDP abbreviations (see **Error! Reference source not found.**). Figure 8.2b demonstrates the pre-defined data format of the IDA text file (e.g., "IDA SDR.txt"). In particular, the first column should contain the seismic intensity increments (spectral accelerations in units of [*g*]), at which this seismic record is scaled, in ascending order. Note that the last intensity increment (last row of data) should be the one corresponding to the non-collapse intensity that was last traced prior to the collapse occurrence. The subsequent data column(s) should contain the EDP values corresponding to each intensity level at different stories/floors, when applicable.

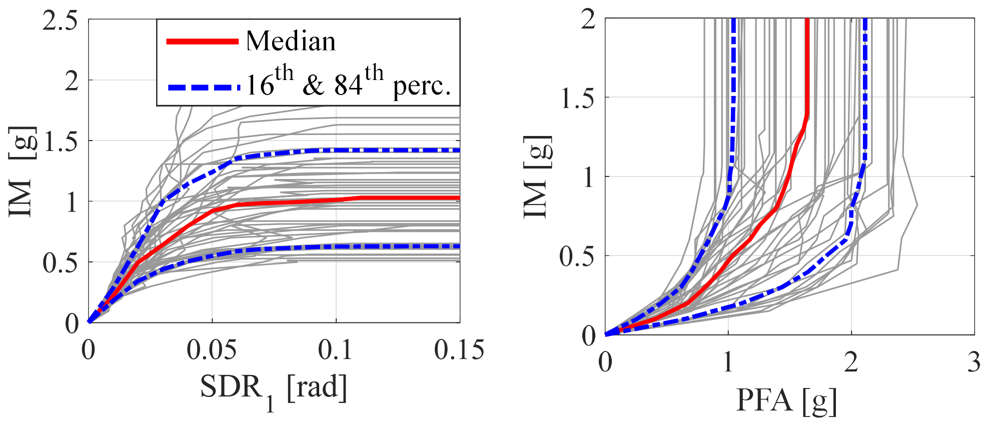
To check if the IDA data were imported correctly, the user can use the "Plot IDA Curves" button. Sample IDA plots generated by EaRL are shown in Figure 8.2c. The counted median (solid red line) as well as the 14th and 84th percentile curves (dashed red lines) are superimposed in the same figures.



(a) Module



(b) Text file format



(c) Generated IDA plots

Figure 8.2. (a) Import IDA data module; (b) Standard format of IDA text data of a single ground-motion record for a given EDP; (c) Sample IDA plots generated by EaRL

8.2 Imported Data at Multiple Stripes

This option is used to import EDP data from a number of ground motions scaled at multiple seismic intensities. This is known as multiple stripe analysis. This is commonly used in practice to evaluate response at code-based intensities, such as the service-level, design-basis and maximum considered earthquakes. The module shown in Figure 8.3a is used for this option. The user should first browse for the EXCEL file containing the data of interest. This file may have any extension type (e.g. xls, xlsx, xlsm, csv) and must have "worksheets" for each of the imported EDPs. Note that, for a given EDP, a separate worksheet should be provided for each intensity. The name of a given worksheet should be in the format *edp_ns* where *edp* is EDP abbreviation and ns is the number of the stripe (e.g., PFA_2). Each worksheet should contain the peak absolute EDP values from each seismic record at each story/floor as shown in

Figure 8.3b. The user is encouraged to use/modify the template EXCEL sheet "*Template Response Data - Multiple Stripes.xls*", which is provided in EaRL's supporting documents folder. EaRL will deduce the median and dispersion of the imported EDP values. Note again that SDR and PFA will be imported by default. Using the checkboxes in Figure 8.3a, additional EDPs can be imported based on the user's preference and the project component definition. In the same module, the user should also specify the number of stripes as well the seismic intensities, in units of *g*, corresponding to each stripe.

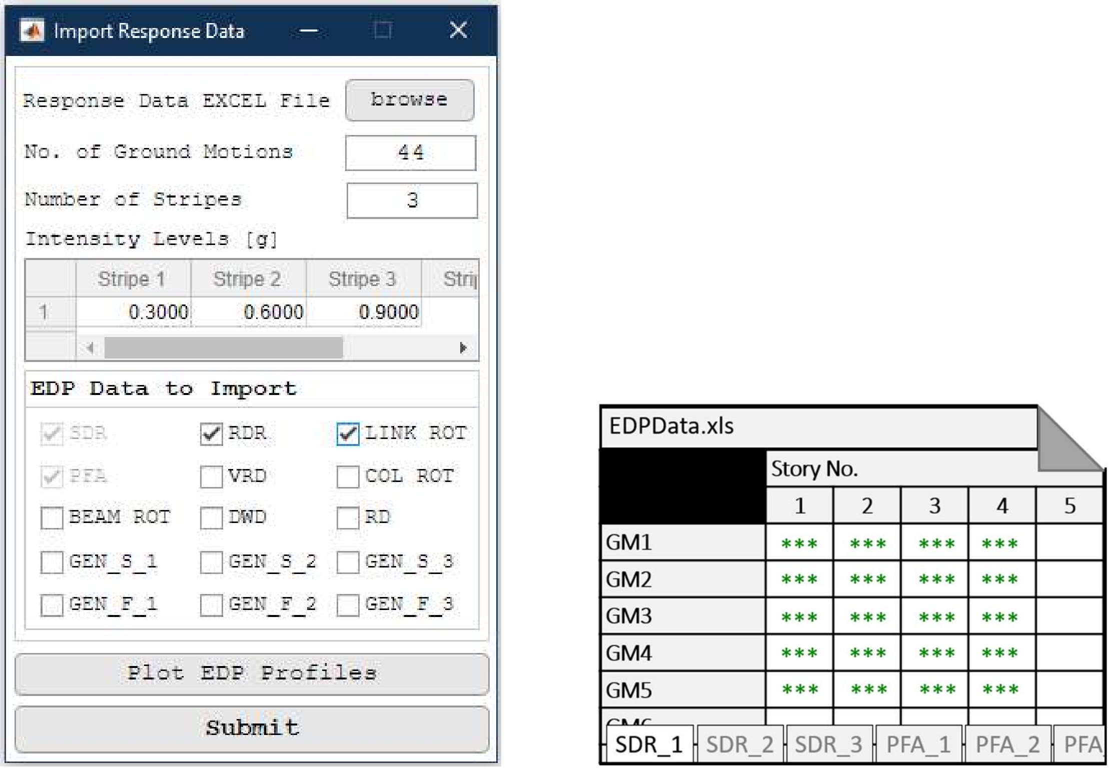
8.3 Imported Data at Single Seismic Intensity – Multiple GMs

The module shown in Figure 8.4b is used to import the structural response data at a single seismic intensity. This module is very similar to that of multiple stripes. The format of the data inside this EXCEL sheet differs based on the imported data option as follows:

In this case, the EXCEL sheet should be formatted as shown in Figure 8.4a (*bottom*), as discussed earlier. The user should specify the number of ground motion records to be imported in the "Single Intensity" module (see Figure 8.4b). For both options, the user should specify the seismic intensity, in units of [*g*], corresponding to the response data that are being imported. EaRL will then process the imported data to find the median and dispersion parameters of each EDP. Consult with the template EXCEL worksheet "*Template Response Data - Multiple GMs.xls*" that is provided in EaRL's supporting documents folder. A user may verify that the EDP data were imported properly by clicking the "Plot EDP Profiles" button. This will generate plots of the EDP profiles along the building height as shown in Figure 8.4c.

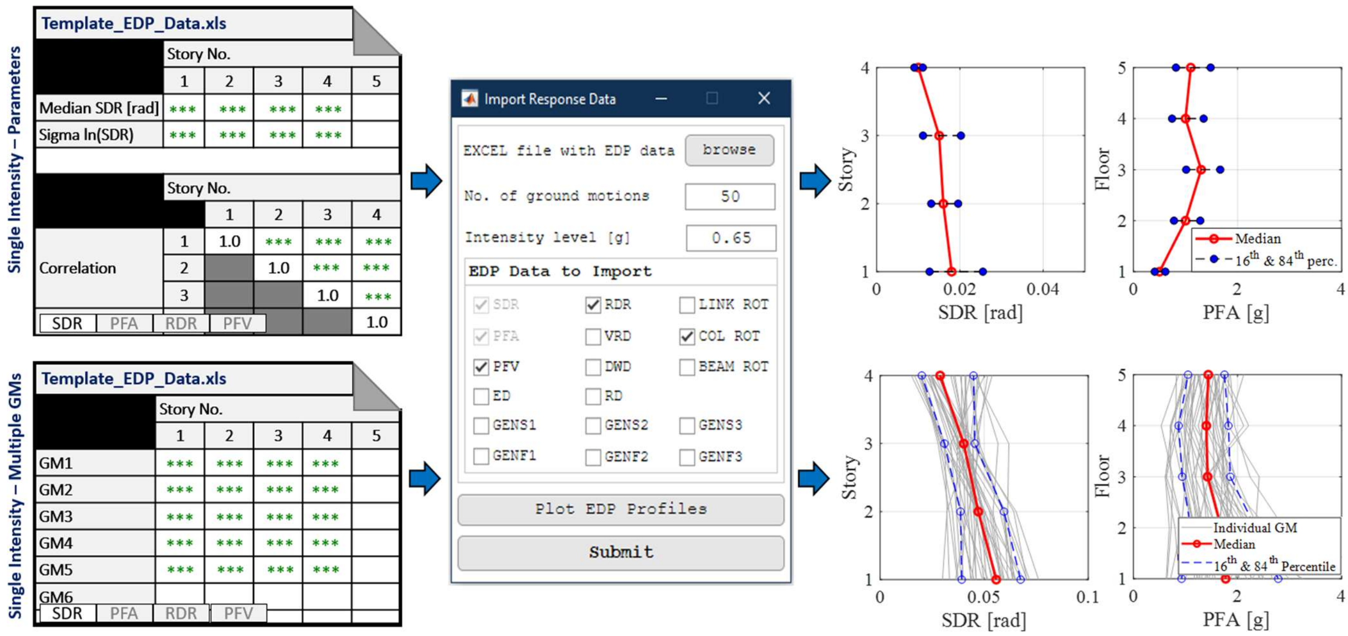
8.4 Imported Data at Single Seismic Intensity – Parameters

In this case, the EXCEL sheet should be formatted as shown in Figure 8.4a (*top*). At each story/floor, the user should specify the median and standard deviation of the logarithmic EDP values. This option is very useful particularly when non-model based approaches are used to estimate response data. Such approaches involve multiple regression equations that provide median EDP quantities and their standard deviation (uncertainty). Note that when the FEMA P-58 methodology is used for the building-specific loss estimation, the user should also define, as shown in Figure 8.4a (*top*), the correlation coefficients between the logarithmic EDP values in each story/floor. These values are used to construct the correlation matrix, which is used to generate the simulated EDP values at each realization. The correlation matrix must be symmetric positive definite.



(a) Module (b) EXCEL sheets format

Figure 8.3. Importing response data from multiple stripes



(a) EXCEL sheets format (b) Module (c) Generated plots

Figure 8.4. Importing response data from single seismic intensity (the green asterisks in (a) represent the values to be provided by the user)

8.5 Generated Data from Nonlinear Multi Degree-of-Freedom Shear Model

In this option, EDP data are automatically generated by running explicitly nonlinear response history analyses. Particularly, this option uses the open-source OpenSEES simulation platform (Mckenna 1997), to analyze a multi-degree-of-freedom (MDoF) shear model under a suite of ground motion records. The force-deformation response at each story of the MDoF system can be characterized using a range of elastic non-degrading as well as degrading models with tri-linear and peak-oriented hysteretic behavior. The MDoF system geometric and loading parameters (e.g., story heights, loads, masses) as well as the story response parameters are pre-defined in an EXCEL file (see *Template MDoF Shear Model.xls* in the supporting documents) that is then imported in EaRL using the module shown in Figure 8.5a. A number of dynamic analyses procedures can be conducted, including IDA and general NRHA at target IM or by using a constant ground motion scaling factor. This option can be very useful for conducting loss estimations using simple structural analysis models.

After running the MDoF analysis, the user is able to plot the distribution of the generated EDPs along the building height using the "Plot EDPs" button which will become active once the analysis is done. Additionally, the generated EDP data can be written to an Excel file, such that data modifications can be made by the user for instance, using the "Save to Excel" button.

8.6 Generated Data from FEMA P-58 Simplified Analysis Method

EDP data can also be generated using FEMA P-58 Simplified Analysis Method (FEMA 2012). This method uses linear models and linear static analysis to obtain elastic story drift demands. To deduce the lateral drift demands, the elastic response is corrected using supplementary multi-variate regression equations, developed by Huang et al. (2017). Knowing the peak ground acceleration (PGA), the peak floor absolute accelerations and the relative velocities can be deduced in a similar manner. To employ this method, the user is required to provide basic building information through the module in Figure 8.5b. This includes the building yield base shear force (V_y), the yield story drift ratio (SDR_y), the first-mode period (T_1), the PGA, the first mode spectral ordinate (Sa(T_1)), the spectral acceleration at 1 second (Sa(1sec)), the soil class, the structural system type and the location-basis for the ground-motion prediction equations (GMPEs). These are used to deduce the seismic acceleration spectra. The output of this method is in the form of estimates of the median SDR, RDR, PFA and PFV at each story/floor and their dispersion. The simplified method has a number of limitations, which are mainly related to the building height and extent of nonlinearity (FEMA 2012). Note that the yield base shear force can be computed using FEMA P58 approximate method by clicking on the "estimate" button.

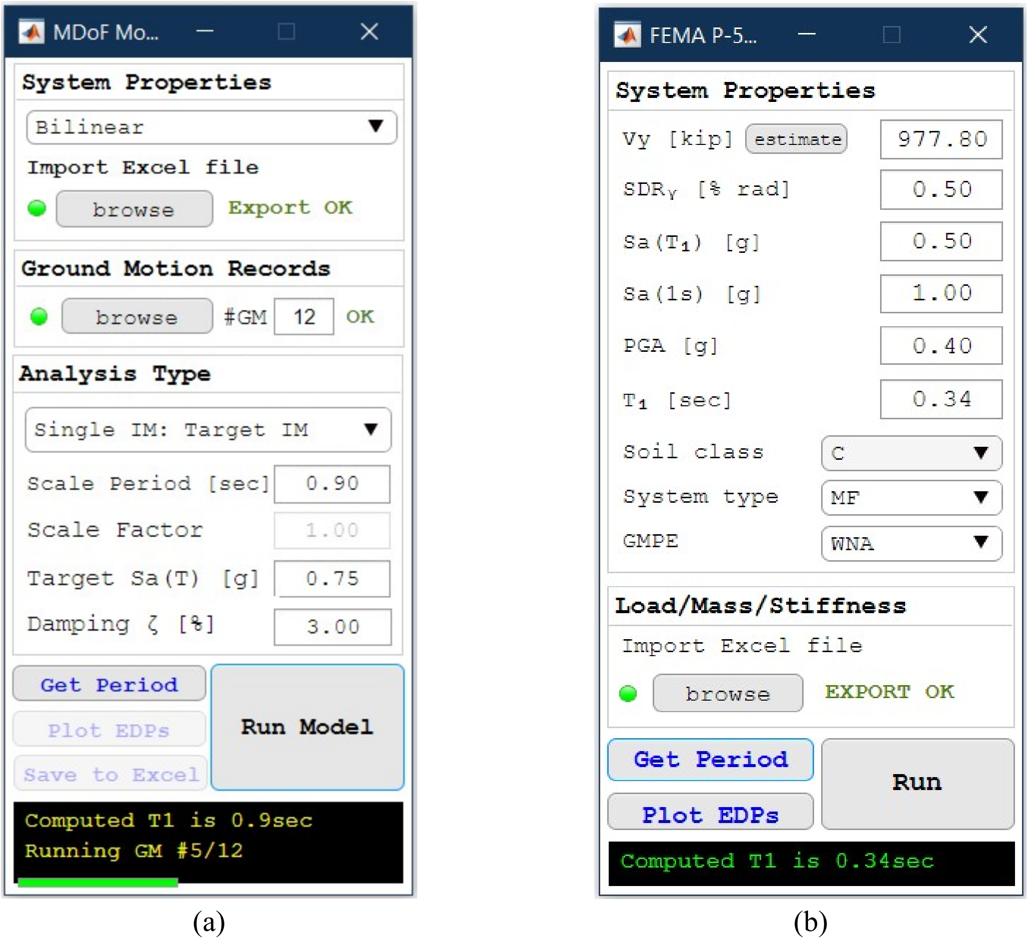
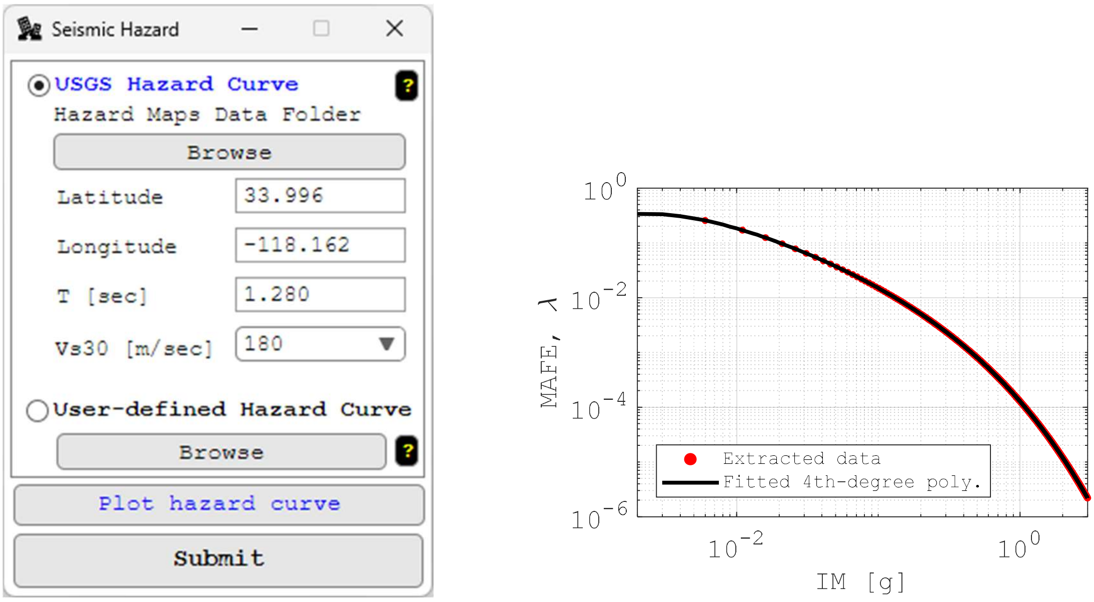


Figure 8.5. Generating response data options: (a) MDoF shear model; (b) FEMA P-58 Simplified Analysis Method

9. Seismic Hazard Module

The user can define the seismic hazard curve based on two options for a building site, as shown in Figure 9.1. These options are as follows:

17. Option 1: Import the hazard curve data directly from a text file. This file should contain two columns of data (with no headers). The first column must be <u>the intensity measure (i.e, spectral acceleration) in units of [*g*]</u> while the second column is the mean annual frequency of exceedance, λ. Because of the hazard curve fitting in the log-log space, no values in the imported text file should be set to zero.
18. Option 2: for buildings located in the US, the user can utilize the 2008 updated seismic hazard maps (Petersen et al. 2008) to extract the site-specific hazard curve. However, t<u>hese hazard curves are only provided based on the first mode spectral ordinate, $Sa(T_1)$</u>. The user should browse for the hazard maps data folder named "USGS Hazard MAT Data" that is provided within EaRL supporting files. The user should specify the *Latitude* and *Longitude* coordinates, the hazard period T_{hazard}, and the shear wave velocity of the soil *Vs30* (i.e., soil type). The discrete data points of the seismic hazard curve are then fitted internally with a fourth order polynomial function as discussed in (Eads et al. 2013). The currently integrated USGS hazard maps cover the following ranges: 24.6º ≤ *Latitude* ≤ 50º; -125º ≤ *Latitude* ≤ -100º; 0 ≤ *T* ≤ 5.0 sec; 180 m/sec ≤ *Vs30* ≤ 760 m/sec.



(a) (b)

Figure 9.1. Seismic Hazard module

10. Damage Fragility Module

EaRL contains an integrated component fragility database and allows for their modification, if needed. New univariate, bivariate, or multivariate damage state fragility functions for structural and non-structural components can also be considered through the Fragility module shown in Figure 10.1. The different features available in EaRL are discussed in this section.

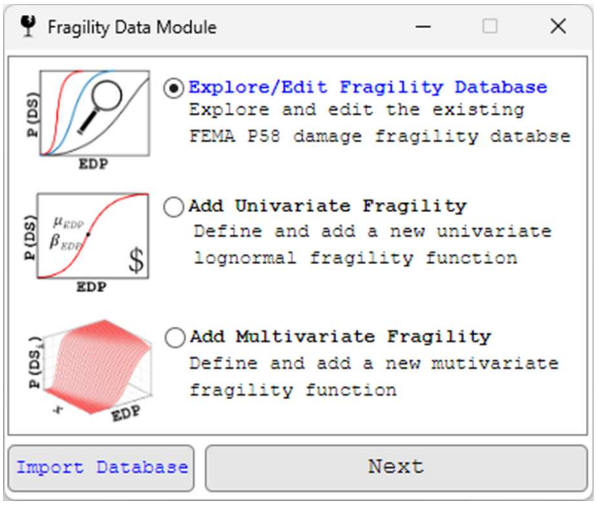
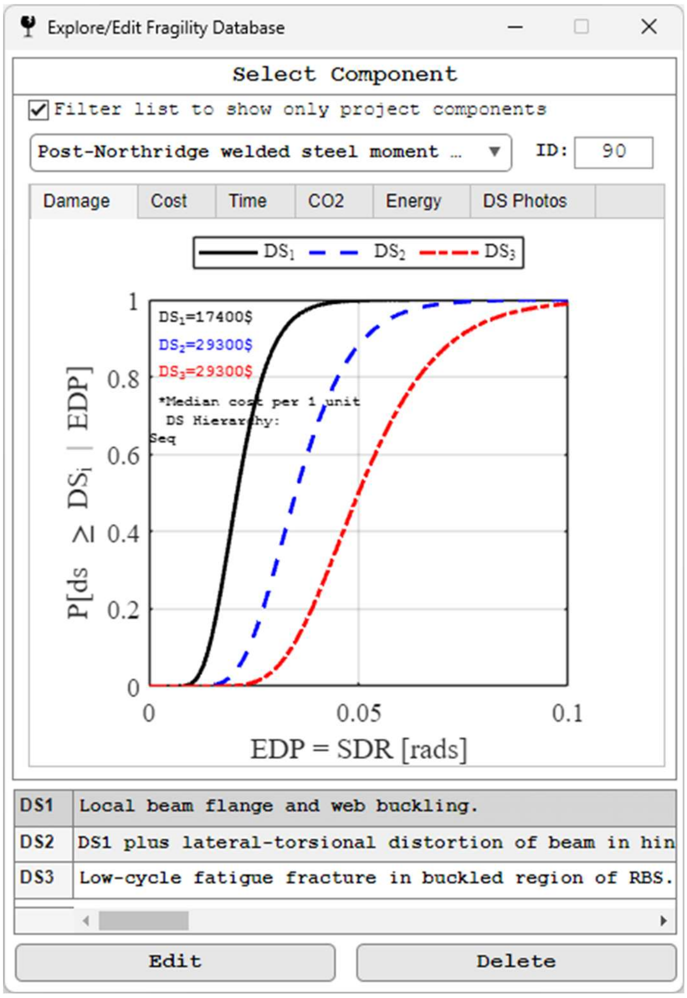


Figure 10.1. Fragility module

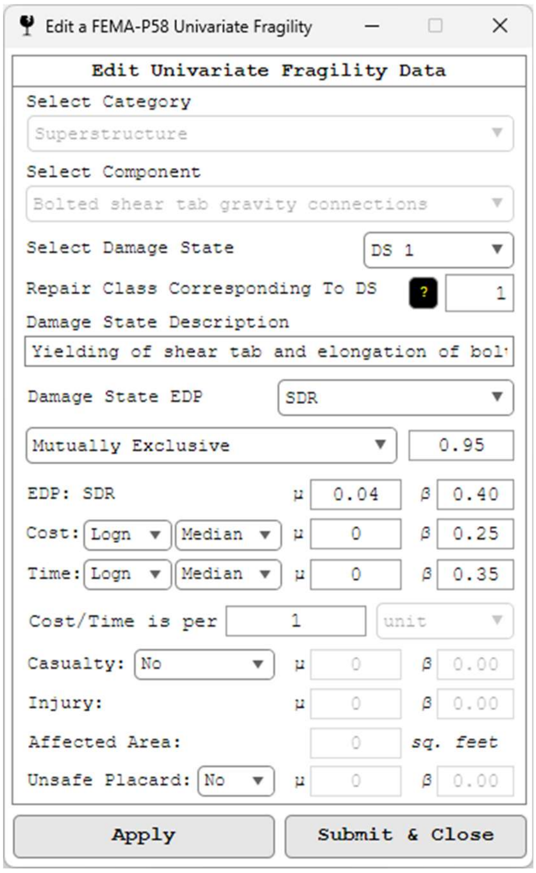
10.1 Explore/Edit Fragility Database

The full component fragility database of FEMA P-58 (Hamburger et al. 2012) is integrated in EaRL. This database comprises 764 components and their corresponding 1801 damage states. These fragility curves are either lognormal or normal univariate CDFs. This database can be explored using the module shown in Figure 10.2a. Once a component is selected from the dropdown menu, a plot of the fragility curves of all the component's damage states is generated. Text annotation showing the repair cost associated with each damage state is superimposed at the top left corner of the same plot while a description of each damage state is summarized in the table below the figure.

EaRL provides the user the ability to edit the parametric fragility data of the FEMA P-58 fragility database. Referring to Figure 10.2a, by clicking the "edit" button the "Edit FEMA-P58 Fragility" module is called (see Figure 10.2b). For a given damage state of a component, the user can edit: 1) the damage state description, 2) the controlling EDP, 3) the population parameters of a lognormal CDF, 4) the repair cost and associated cost quantity, 5) the damage state type; sequential or mutually exclusive, and 6) the associated probability of occurrence, if applicable. Using the various tabs, alternative consequences distributions can be explored, such as the repair cost, repair time, CO_2 emissions and embodied energy to restore a building to its original condition. Photos of the component damage states can also be visualized from the same module. These photos are available in FEMA P58. If any of those damage fragilities or associated consequences need to be modified by the user, the "Edit Fragility" button can be used which will prompt the user to a new window (see Figure 10.2b), where fragility parameters can be edited and saved. Note that the parameter values are updated in a copy-version of the database only inside the current project (i.e., this is not transferred to prospective projects).



(a) Exploring fragility data



(b) Editing fragility data

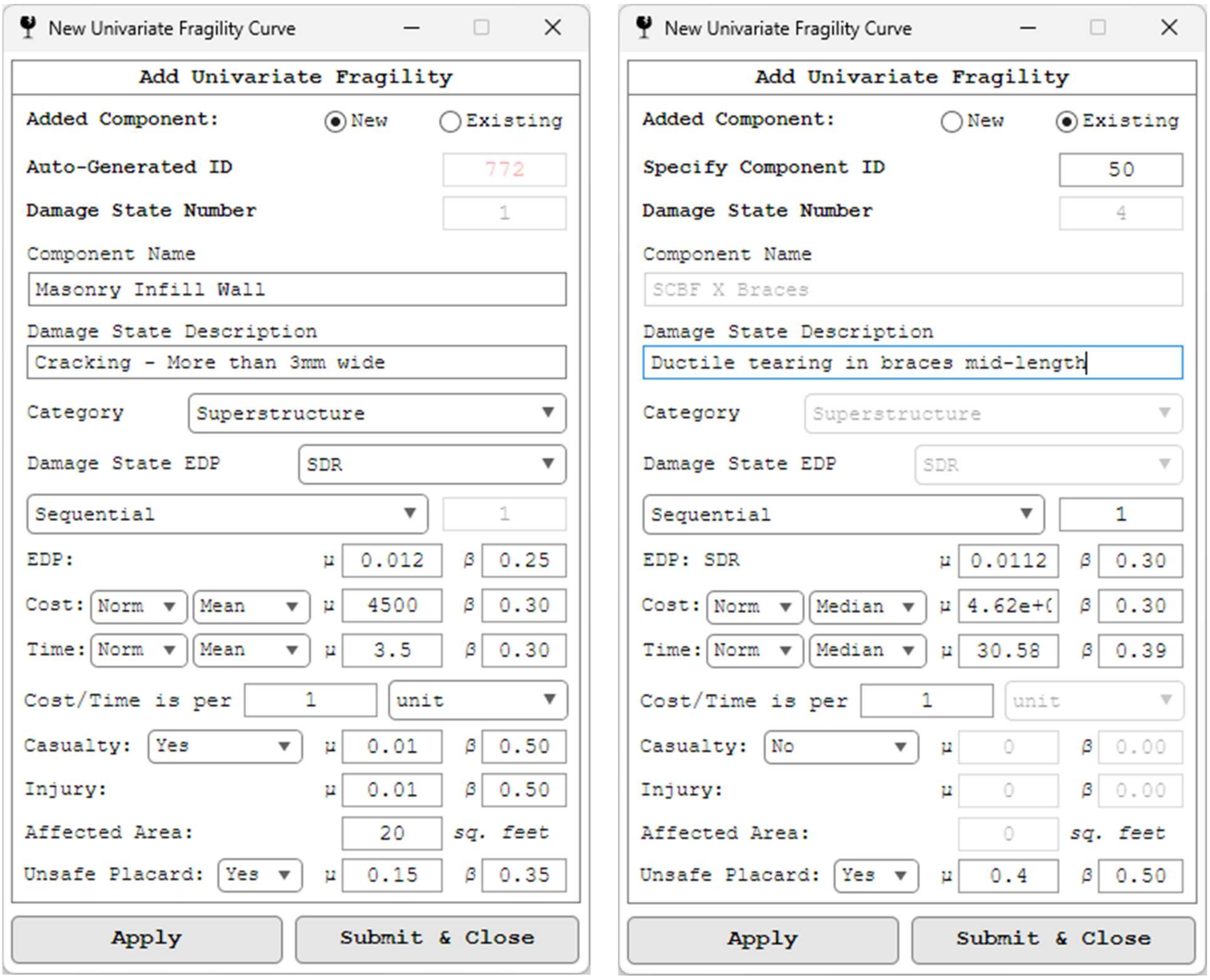
Figure 10.2. The Explore/Edit FEMA-P58 Fragility module

10.2 Add Univariate Fragility

The user has the option to add new univariate fragility curves using the module shown in Figure 10.3. The new fragility can be added to a "New" or "Existing" component in the database; this is first specified by the user using the radio buttons at the top of the module.

19. When adding a damage state to a "New" component, an ID will be automatically generated (see Figure 10.3a). This ID is used to refer to this specific component when defining the building components, or to provide additional damage state fragilities for the same building component. The user is required to fill up the module's empty fields, which includes the name and category of the component, the description of the damage state and the controlling EDP, the median and standard deviation of the lognormal CDF, the associated repair cost, cost-unit type and cost-unit value. Note that in this case (i.e., adding a damage state to a new component), the damage state number is set to 1. Additional damage state fragilities may be added to the same component by selecting the "Existing" component option and by citing the component ID generated earlier.
20. When inserting a damage state to an "Existing" component (see Figure 10.3b), the user should first specify the component ID. Once this is specified, the component name field will be automatically populated. The

damage state number field will be set to n_{DS}+1, which is the pre-defined number of damage states for this component. The remaining fields should be filled as discussed earlier.



(a) Add to New Component (b) Add to Existing Component

Figure 10.3. Add univariate fragility module

10.3 Add Multivariate Fragility

Multivariate fragility functions can be inserted through the module shown in Figure 10.4. This module can be used to define fragility functions of any form regardless of the number of controlling parameters. The module has similar fields to that of the univariate fragility module. The only difference is the "Multivariate Function" field. This is used to insert the analytical form of a fragility function. The function should be entered following the notation used in MATLAB (2019). For instance, assuming a fragility function is given by Equation 3, in which P(DS_i|SDR, P_1, P_2) is the cumulative probability of reaching or exceeding damage state i given the three controlling parameters SDR, P_1, and P_2,

$$P(DS_i|SDR, P_1, P_2) = 2.5 \cdot SDR^{-1.05} \cdot P_1^{0.675} \cdot e^{-0.02} \tag{1}$$

this function should be written as follows in the associated function field:

@(SDR, P1, P2) 2.5 * SDR^-1.05 * P1^0.675 * exp(-0.02*P2)

The following rules should be respected:

21. The function starts with "@", followed by the controlling EDP names and the independent parameters within *round brackets* and separated by *commas*. This should be followed by a single *space*, followed by the analytical expression of the fragility function. The MATLAB syntax for basic mathematical operations is summarized in Table 2.
22. Any function should have a single controlling EDP (*SDR* in this example).
23. The correct abbreviation of the EDP (i.e., *SDR*, *PFA*, *RDR*, *COL ROT*, etc.) should be used in the function. This should also be the same as the Damage State EDP selected from the dropdown menu.
24. The notation of other controlling parameters (*P1* and *P2* in this example) is flexible as long as it starts with an alphabetic character and has no special characters.

When a component, with multivariate damage state fragility, is used as part of the "Component Data" manual definition module, the user will be prompt to the "Predictor Data" module shown in Figure 10.5 to add the values of the fragility's predictor parameters *P* at each story/floor. If this component exists only in specific stories/floors, a value of *P*=0 should be specified at other stories/floors where the component does not exist.

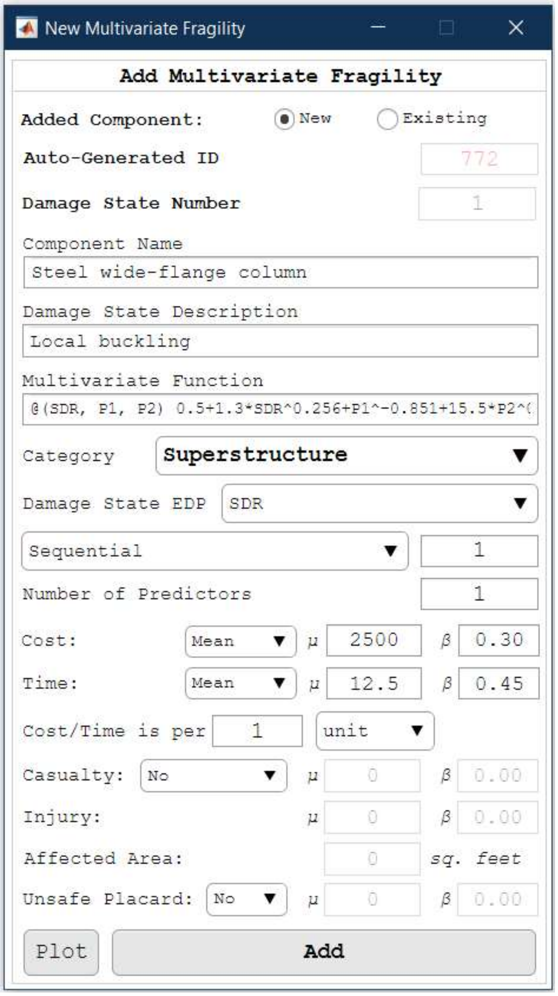


Figure 10.4. Add multivariate fragility module

Table 2. Syntax for basic mathematical operations in MATLAB

Operation	MATLAB expression	Note
$x + y$	x+y	addition
$x - y$	x-y	subtraction
x x y	x*y	multiplication
x / y	x/y	division
x^y	x^y	power operation
$\|x\|$	abs(x)	absolute
$\sqrt{x}$	sqrt(x)	square root
$\sqrt[n]{x}$	nthroot(x,n)	root to the n^{th} power
e^x	exp(x)	e to the power of x
ln(x)	log(x)	natural log (base e)
log(x)	log10(x)	common log (base 10)
sin(x)	sin(x) OR sind(x)	input in radians OR degrees
cos(x)	cos(x) OR cosd(x)	input in radians OR degrees
tan(x)	tan(x) OR tand(x)	input in radians OR degrees

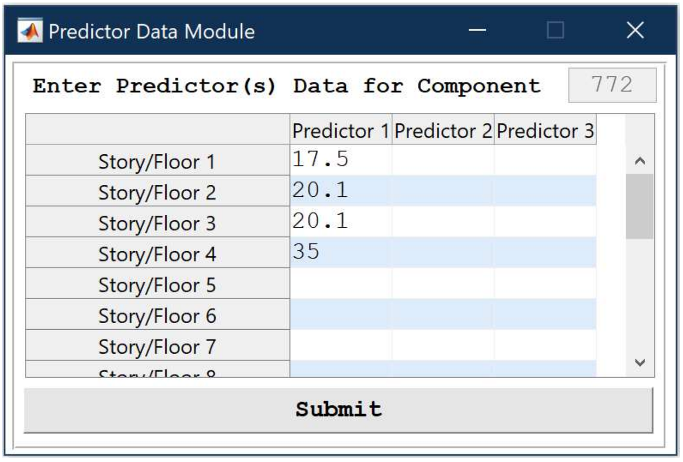


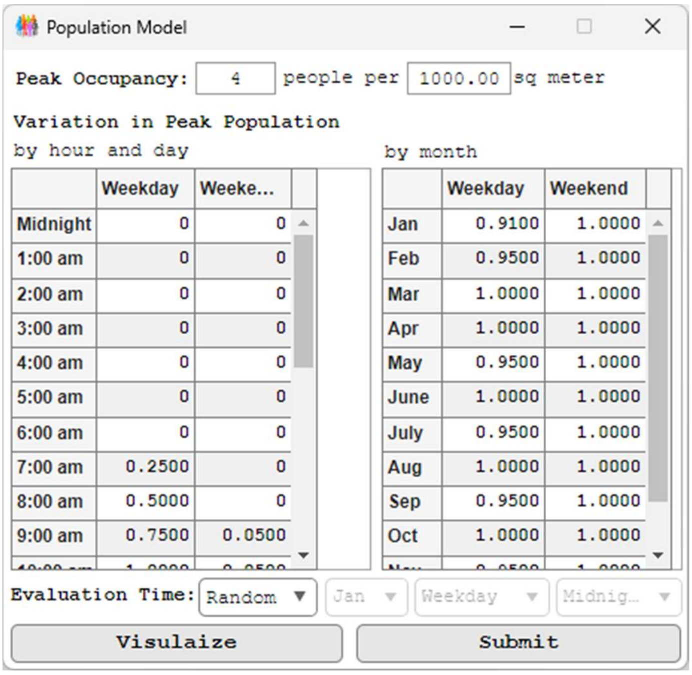
Figure 10.5. Predictor data module

10.4 Importing Fragility Database

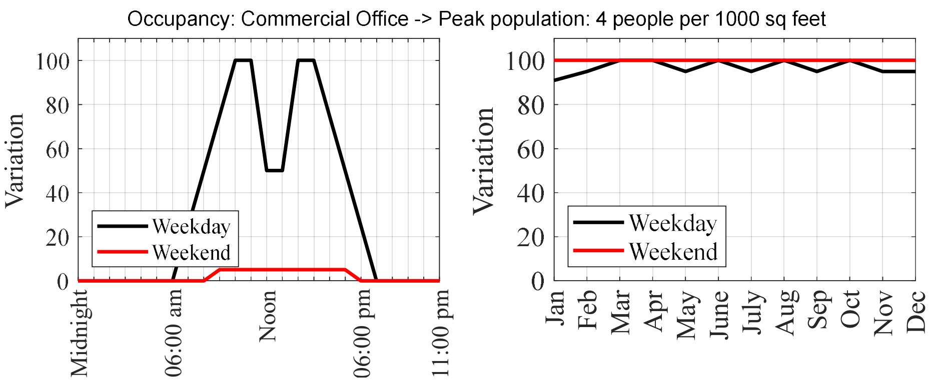
From the damage fragility main module (see Figure 10.1), the user can import an external fragility database using the “Import Database” button. In that case, the user need to specify the location of folder containing two **.mat* files: *COMPDATA.mat* and *FRAGDATA.mat*. These two files contain inside two structure variables *COMPDATA* and *FRAGDATA* where the damage fragility metadata is stored. The user can consult EaRL’s source code data where the integrated damage fragility data files can be found. The metadata description is discussed in Section 20. This option basically allows users to independently modify and amend the fragility database metadata and then simply importing it into EaRL without the need for recompiling the executable file.

11. Population Model

To compute damage consequences related to potential human injuries and casualties as a result of fallen debris from damaged components, the user should define the building population model through the module shown in Figure 11.1a. This module is accessible by clicking the "Population Model" button in Panel C of the main console (see Figure 5.1). The fields in this module are automatically populated based on the building occupancy type (e.g., commercial or residential) as defined earlier in the building data module. The population data is extracted from the population model data defined in FEMA P-58. 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. If necessary, this auto-generated population data can be modified directly through the module's data tables. The population model can be visualized by clicking the "Visualize" button, which will generate a plot similar to that of Figure 11.1b. 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.



(a) Module



(b) Visualized population model

Figure 11.1. Population model

12. Repair Time Scheme

EaRL computes several damage consequences including the downtime until repairs are complete. Two downtime assessment schemes are available as shown in Figure 12.1. The first option computes the direct time required to repair the damaged building components. The second option extends beyond the first option by calculating the total downtime until the building returns to its initial state. The specifics of the two options are described in the next sections.

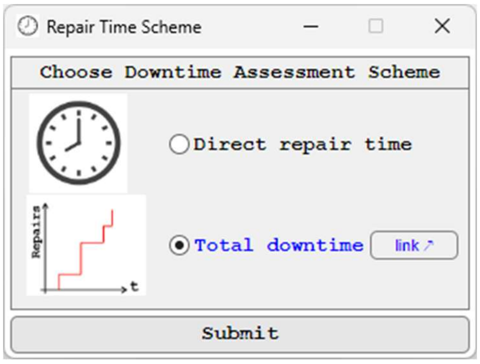


Figure 12.1. Repair time scheme options

12.1 Direct repair time

The user can control this scheme through the module shown in Figure 12.2, which can be accessed by the repair time scheme button in Panel C. This option allows the user to specify a) if different building component types should be repaired in a sequential or simultaneous manner, b) which component type groups should 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. Therefore, the user has the full control on the envisioned repair scheme.

In the case of option b (specific component type groups will be repaired simultaneously), the user need to provide the IDs of components that will be repaired simultaneously in a single rows within the module data table (see Figure 12.2). Consequent rows can be used to specify the IDs of other component groups.

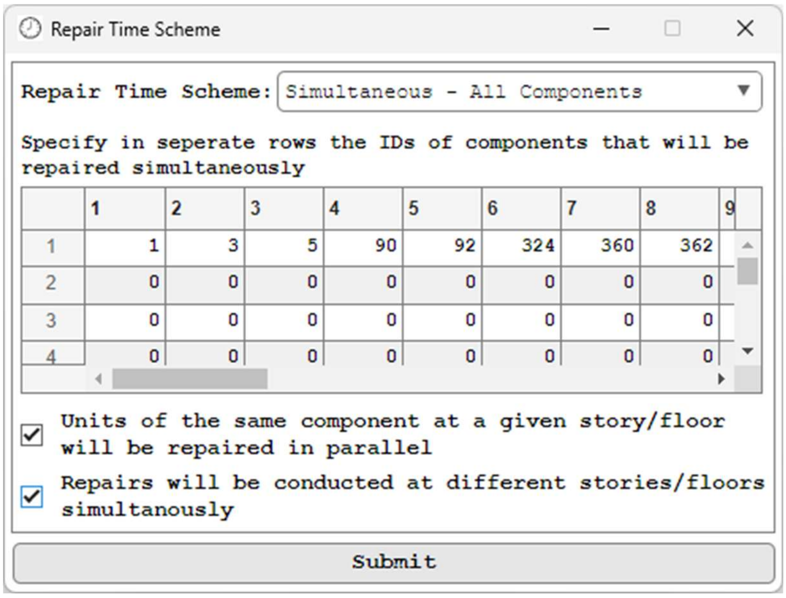


Figure 12.2. Repair time scheme module

12.2 Total downtime

This options employs the downtime assessment framework proposed by Hutt et al. (2022), along with an enhanced repair scheduling algorithm. This addition enables users to assess downtime more comprehensively: extending beyond component-level repair times alone. The total downtime module introduces impeding factor delays and simulates repair processes in real-time. It also constructs repair paths as a function of time and offers multiple visual outputs to support downtime performance evaluation. A high-level flowchart of the module is presented in Figure 12.3.

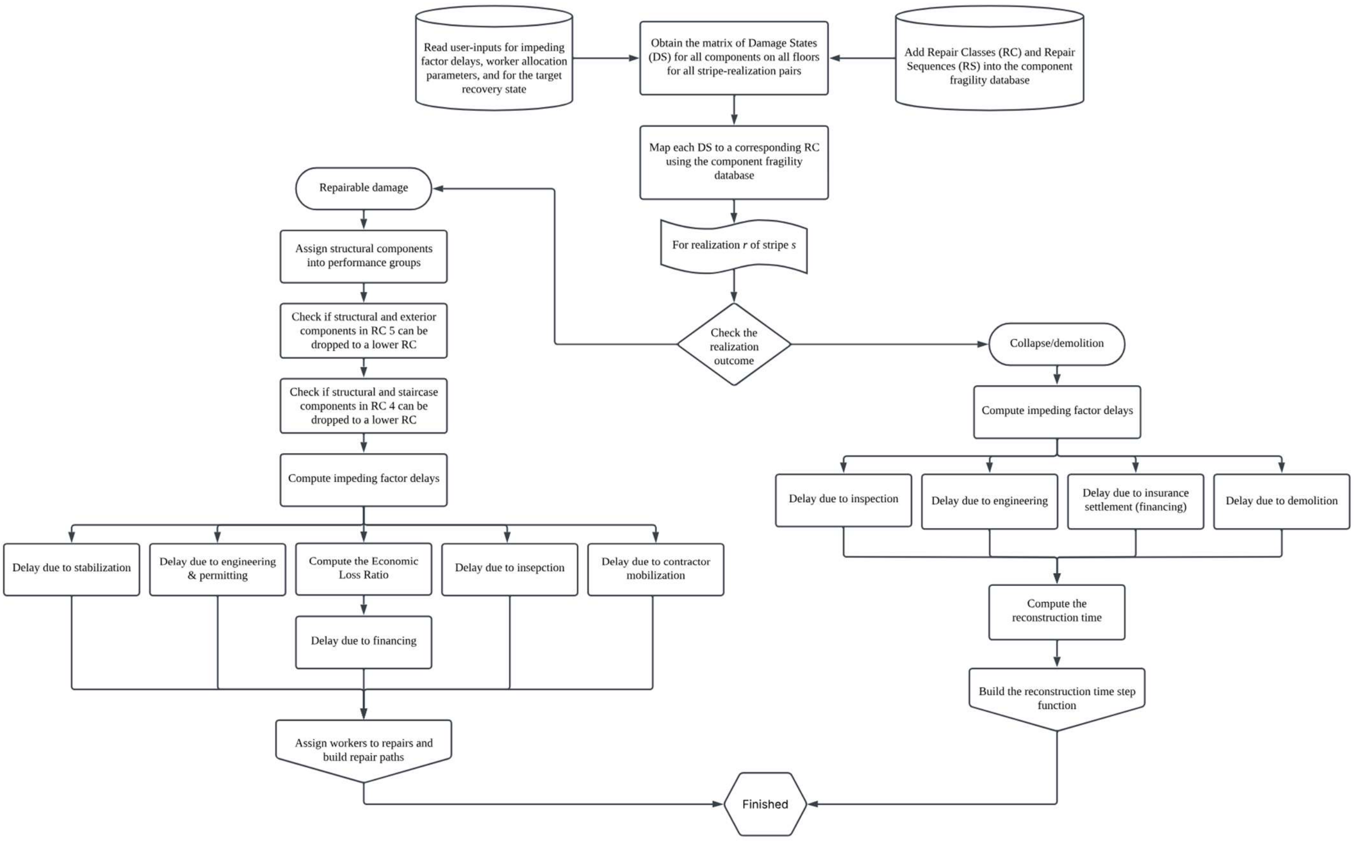


Figure 12.3. High-level flowchart of the total downtime assessment module

25. The active damage state of each component is mapped to its corresponding repair class using the component fragility database. The repair classes corresponding to each damage state of a component shall be manually defined by the user given that the current FEMA P-58 component database does not include information on repairclasses.
26. The structural components of the building are assigned to performance groups according to provisions in FEMA (2012). The performance groups are thus assigned to structural components based on their location in the building (floor number) and damaging EDP.
27. Based on Hutt et al. (2022), multiple structural or exterior components (e.g., curtain walls, exterior enclosures, ...) must be in RC 5 for the stability recovery state to be truly hindered. The program takes two user-defined thresholds as input, and checks whether the proportion of structural components in RC 5 in a single performance group exceeds the first threshold at any given story, and checks whether the proportion of structural components in RC 5 in the entire building exceeds the second threshold. The code then lowers the repair class to the next lower repair class of those structural components who do not exceed the two thresholds. The program applies the same logic for exterior components in RC 5 as well but using a single threshold for the building-wide proportion of exterior components in RC 5.
28. Based on Hutt et al. (2022),, multiple structural or staircase components must be in RC 4 for the shelter-in-place recovery state to be truly hindered. The program takes two user-defined thresholds as input, and checks whether the proportion of structural components in RC 4 exceed the first threshold at any given story, and checks whether the proportion of structural components in RC 4 in the entire building exceeds the second threshold. The code then lowers the repair class to the next lower repair class of those structural components who do not exceed the two thresholds. The program applies the same logic for staircase components using two distinct user defined thresholds.
29. Based on the chosen target recovery state, the script "turn off" the repairs of components whose repair classes do not fall within the scope of the repair classes to repair for a target recovery state. As such, the damage state, number of damaged units, repair cost, and repair time of components that are not relevant for a target recovery state are simply set equal to zero.

12.2.1 Impeding factor delays

Once the list of components to repair has been filtered, the impeding factor delays are computed. While the flowchart in Figure 12.3 explicitly branches out for realizations in which the facility is repairable, and for realizations in which collapse/demolition occurs, the algorithm evaluates all impeding factors for every realization and sets irrelevant delays to zero accordingly. For instance, contractor mobilization delays are automatically set to zero in cases of collapse or demolition. To sample from the lognormal distributions representing each impeding factor delay, the module uses default values derived from Almufti and Willford (2013) and Paul et al. (2018), tailored to conditions in the Western United States. However, all distribution parameters are fully customizable within the downtime module, allowing for adaptation to project-specific conditions. Customizing impeding-factor delays also allows users to input shorter repair times if building owners have prearranged agreements with engineers, contractors, or financial institutions, to expedite repairs following an earthquake. The impeding factor delays are then computed individually as described below.

• *Inspection*: the impeding factor is computed for all stripe-realizations pairs given that the building is inspected no matter the outcome of the realization (repairable damage or collapse/demolition). The impeding factor delay is obtained by sampling the user-defined lognormal distribution for the delay.

• *Stabilization*: the impeding factor delay is calculated by multiplying the number of damaged structural or exterior components at RC 5 by a multiplier following the same method to that described in Hutt et al. (2022). The multipliers depend on the quantity of damaged structural or exterior components in RC 5 and are subjected to uncertainty as well. The user may customize the multipliers in the input GUI to project-specific needs.

• *Financing* (for repairable damage): before the impeding factor delay due to financing can be sampled, the Economic Loss Ratio (ELR) must be determined. The ELR is defined as the sum of all repair costs divided by the replacement cost of the facility. The ELR is computed for every realization that leads to repairable damage and is used to determine the impeding factor delay based on the chosen financing type. Given the ELR and the chosen financing type, the lognormal distribution of the financing delay is sampled.

• *Contractor Mobilization*: the procedure to compute the impeding factor delay due to contractor mobilization is obtained from Hutt et al. (2022). Given that the expected delay for contractor mobilization is longer when the damage is more severe, the delay is computed as a weighted average between the delay for light damage and heavy damage. The flowchart by which the delay is computed is illustrated in Figure 12.5(a).

• *Engineering and Permitting*: the impeding factor delays due to engineering and permitting is computed similarly to the contractor mobilization delay, and the procedure is also derived from Hutt et al. (2022). The key difference is that the engineering and permitting delay is relevant for structural components only, and the total delay is comprised of the sum of the engineering and of the permitting delay. The final delay is also weighted based on the proportion of floors that experience light structural damage versus the proportion of floors that experience heavy structural damage. The flowchart by which the engineering and permitting delay is computed is illustrated in Figure 12.5(b).

• *Demolition, Insurance, and Engineering* (in case of collapse or demolition): the three impeding factor delays are sampled individually for the realizations in which collapse, or demolition occurs. The full impeding factor delay for collapse/demolition realizations is then the sum of the inspection delay, of the maximum between the demolition, insurance, and engineering delays, and of the reconstruction time.

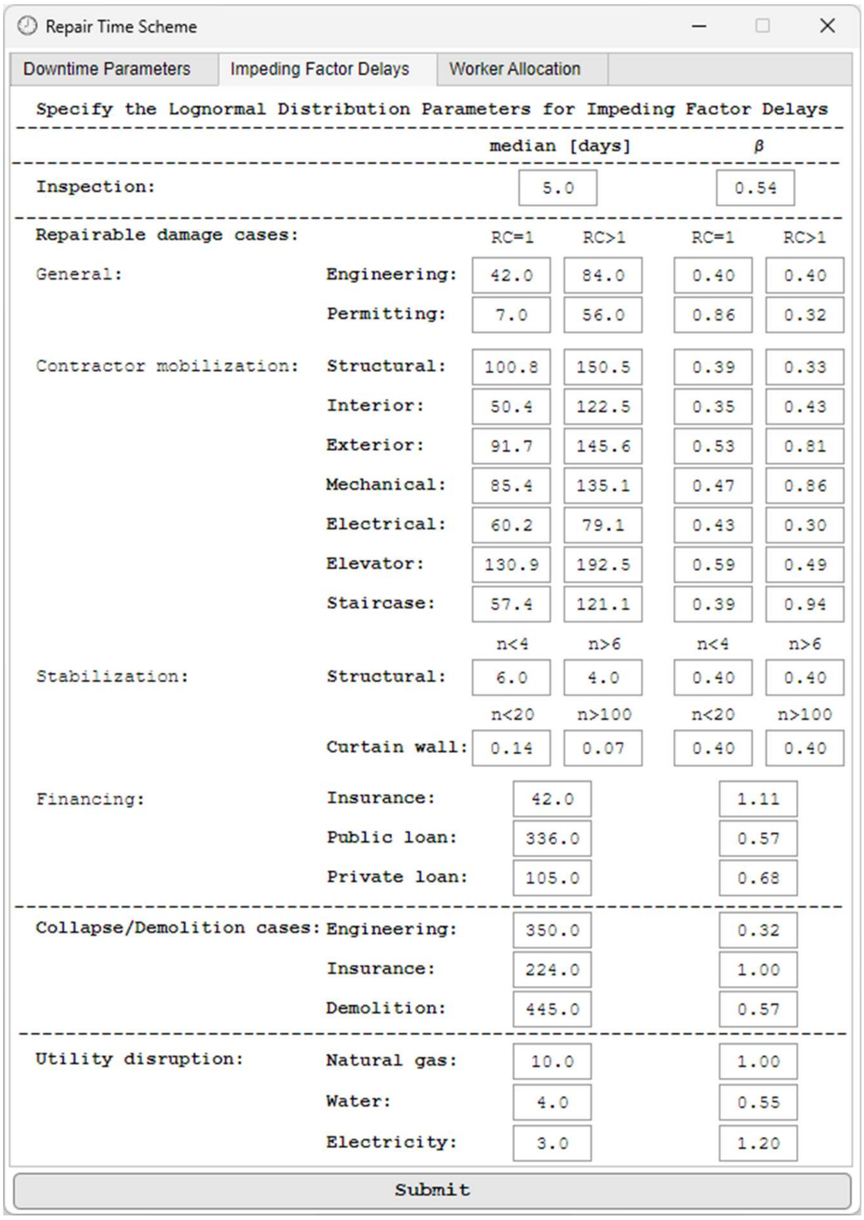


Figure 12.4. Downtime scheme module: Parameters for impeding factor delays

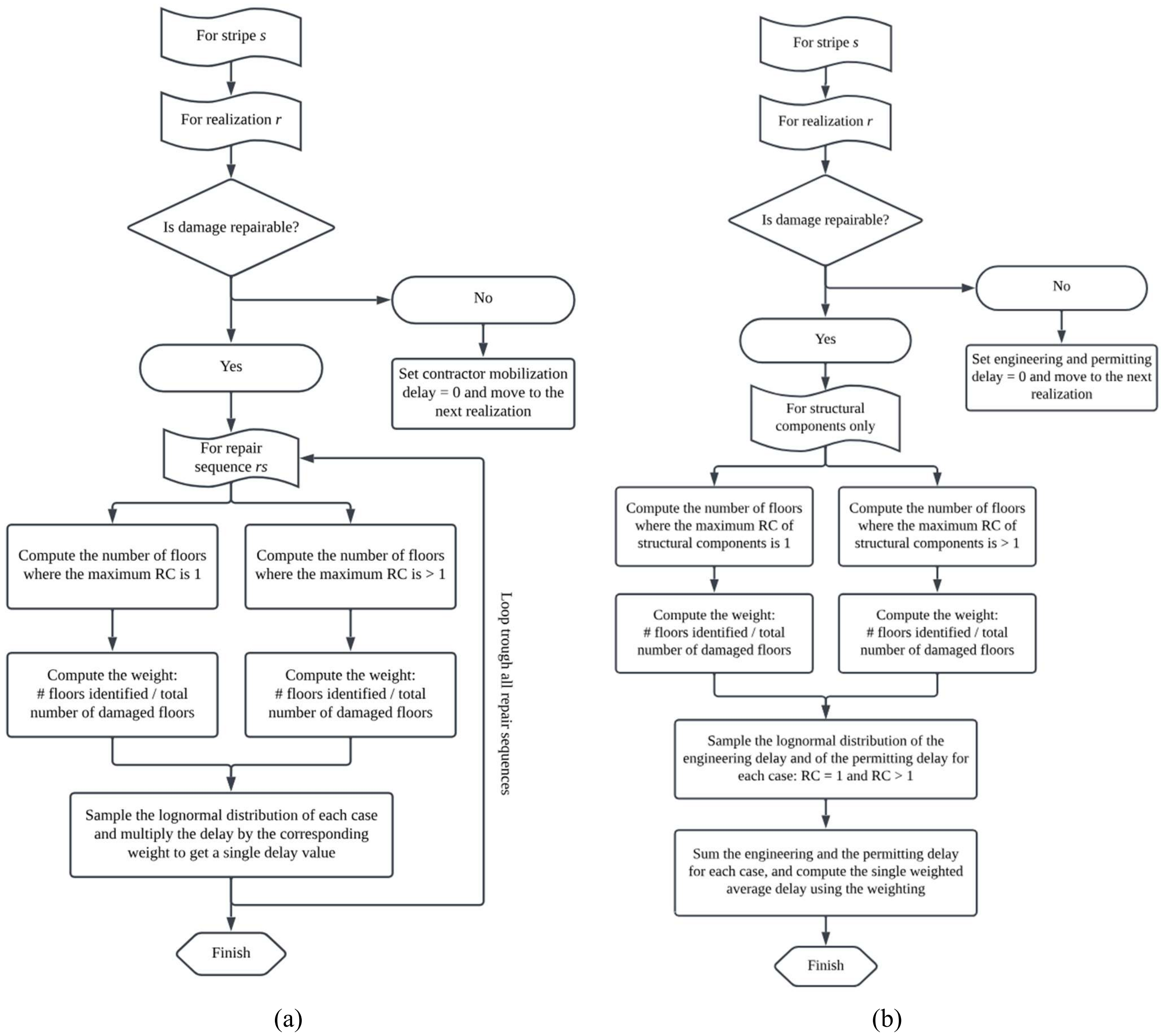


Figure 12.5. Flowchart for computing the impeding factor delay due to (a) contractor mobilization, (b) engineering and permitting

12.2.2 Worker allocation and repair path development

The procedure to simulate repairs in the facility differs from the one in Hutt et al. (2022) and employs a loop over each day of repairs instead. More precisely, the loop simulates each day from the occurrence of the earthquake until the end of repairs and allocates workers to repairs based on user-defined constraints. The new downtime module allows the user to customize most of the parameters controlling the progression of repairs. Select few customizable variables are shown in Figure 12.6.

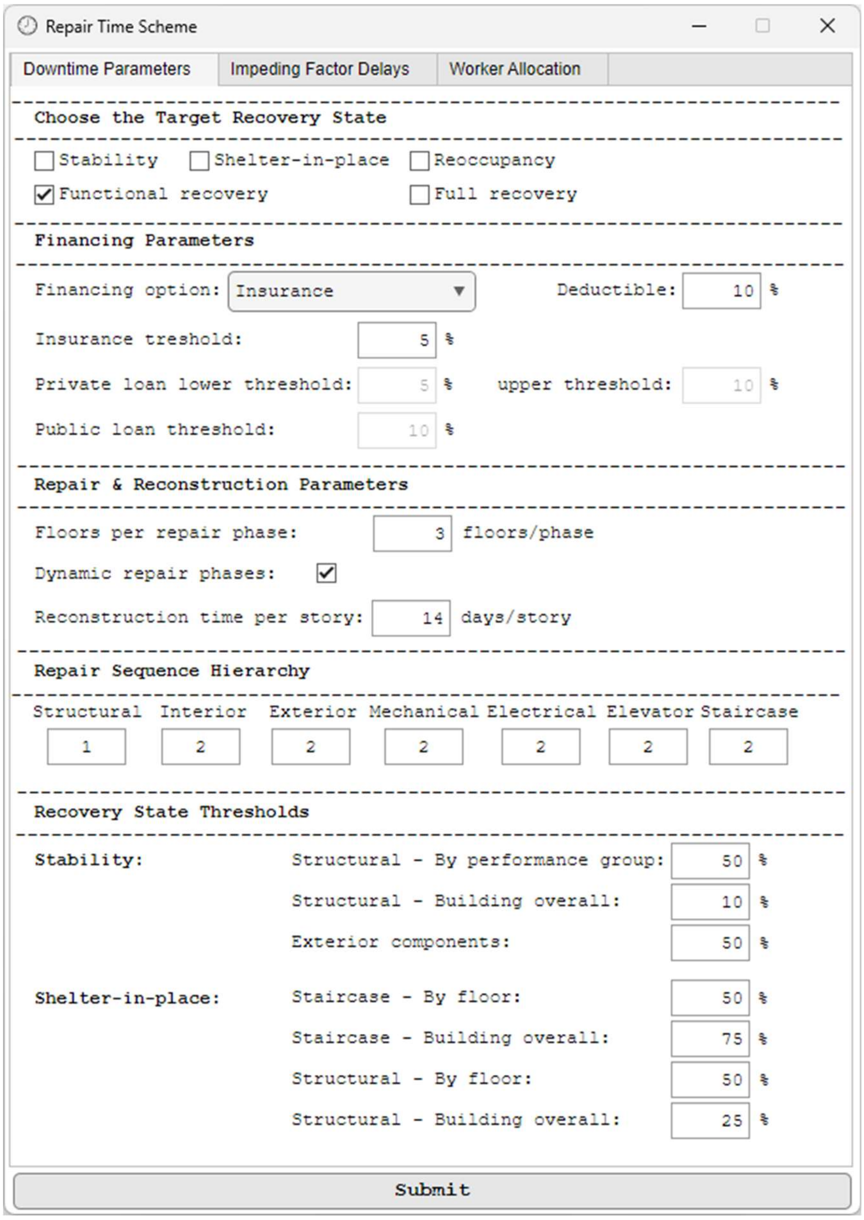


Figure 12.6. Downtime scheme module: Recovery state, financing, and repair sequencing parameters

The number of floors that are repaired simultaneously can have a large impact on the total duration of the repairs. The downtime assessment framework in Hutt et al. (2022) introduces repair phases, which is a subset of floors repaired simultaneously in the building. In-line with typical repair practices in the aftermath of the 1994 Northridge earthquake, repair phases in Hutt et al. (2022) comprise of three floors. The downtime module allows the user to customize the number of floors within a repair phase to project-specific constraints, should repair practices be different than in California.

The new downtime module also allows the user to choose between fixed and dynamic phases. In the case of fixed repair phases, each floor of a building is assigned to a repair phase before the start of the repairs. For instance, in a 9-floor building, using three floors per phase, the first 3 floors would be assigned to phase 1, floors 4-6 would be assigned to phase 2, and floors 7-9 would be assigned to phase 3. Table 5 shows an example of the progression of workers over the floors of the building using a fixed-phase logic.

Table 3. Progression of workers for a single repair sequence using fixed phases of three floors

	Floor								
Day	**1**[1]	**2**[1]	**3**[1]	**4**[2]	**5**[2]	**6**[2]	**7**[3]	**8**[3]	**9**[3]
1	**10**	**10**	**10**	0	0	0	0	0	0
2	0	0	**10**	0	0	0	0	0	0
3	0	0	**10**	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7	0	0	**10**	0	0	0	0	0	0
8	0	0	0	**10**	**10**	**10**	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

[1, 2, 3] Repair phase number

An issue that arises with said logic is that repairs progress one phase at a time, therefore, repairs could remain "stuck" in a phase given that workers will not get allocated to the next phase until all repairs are completed in the previous phase. If all floors within a phase have similar amounts of repairs, repairs in the floors within a phase will finish roughly at the same time and workers will be assigned to the next phase all at once. However, if a floor within a phase has considerably more damage than others, repairs will not progress further until the heavily damaged floor is fully repaired. This scenario leads to a period in time where there are workers present only on the last floor with ongoing repairs, which temporarily doesn' t respect the logic of having workers on multiple floors simultaneously.

To overcome this issue, the new downtime module introduces dynamic repair phases (see Figure 12.6), where on each new day of the simulations, the algorithm identifies the first n damaged floors from the bottom up. As such, the floors that are part of the active repair phase are in constant evolution, and the repairs will always progress multiple floors at a time without getting stuck in a particular phase. Table 4 shows the quicker progression of workers over the floors of the building using the alternative dynamic phase logic where the floors comprising the active phase are in constant evolution.

Table 4. Progression of workers for a single repair sequence using dynamic phases of three floors

	Floor								
Day	**1**[1]	**2**[1]	**3**[1]	**4**[2]	**5**[2]	**6**[2]	**7**[3]	**8**[3]	**9**[3]
1	**10**	**10**	**10**	0	0	0	0	0	0
2	0	0	**10**	**10**	**10**	0	0	0	0
3	0	0	**10**	0	**10**	**10**	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
7	0	0	**10**	0	**10**	**10**	0	0	0
8	0	0	0	0	0	**10**	**10**	**10**	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

In addition to the customizable phasing of the repairs, the new downtime module allows the hierarchy of repairs to be modified as well. In Hutt et al. (2022), the seven repair sequences are grouped into four repair paths which all progressed in parallel (simultaneously). Within Repair Path A, the progress is sequential as structural works must be completed before interior, mechanical, and electrical works can progress in parallel (Hutt et al. 2022). In the downtime module, the user must assign a value from 1 to 7 for each repair sequence, indicating the priority of the repairs. In the example input in Figure 12.6, structural components are assigned 1 and all other repair sequences are assigned 2, implying that on any given floor, structural repairs must finish first before all other repair sequences can progress simultaneously. This default hierarchy is consistent with the one introduced by the REDi rating system (Almufti and Willford 2013).

Regarding the allocation of workers, the user is again left in full control regarding the maximum allowable numbers of workers per repair sequence, per floor, and present in the whole building at once. The user can also choose one of two options to allocate workers to damaged units: assigning a set number of workers for each damaged component or assigning a number of workers per 1000 ft^2 of floor area. The GUI for selecting worker allocation parameters is shown in Figure 12.7.

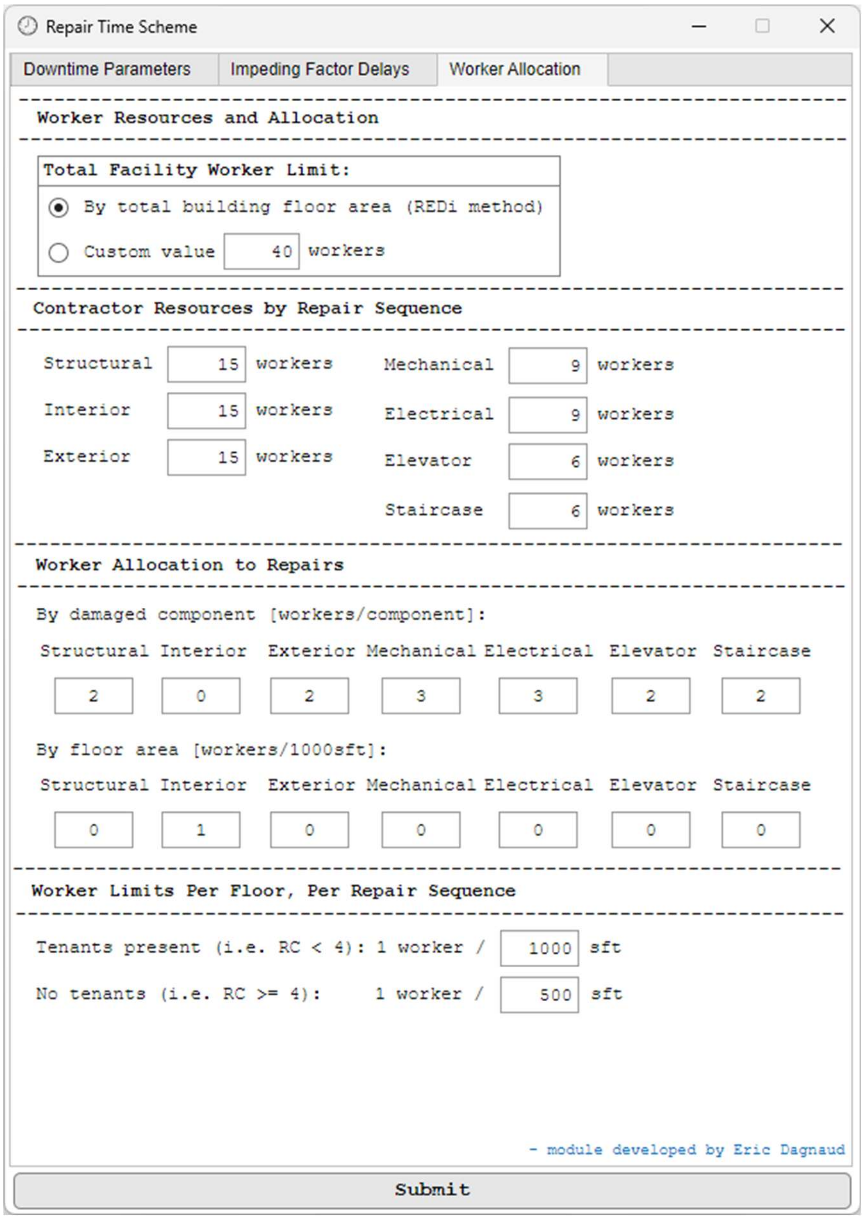


Figure 12.7. Downtime scheme module: Parameters for worker allocation

Once all repair modeling parameters are chosen, the daily simulations of the repairs progress as follows:

1. Before the daily loop, the algorithm aggregates all repairable components by repair sequence and by floor for each of the stripe-realization pairs. The resulting number of damaged units and total repair time is thus the sum of all components of a given repair sequence, on a given floor. Table 5 demonstrates how the repairable components are aggregated before the daily loop. For each repair sequence and each floor, the algorithm also computes the average repair time per component, and the average repair rate of the components, as follows:

$$RT_{\text{avg}} = \frac{\text{Total repair time [worker} - \text{days]}}{\text{Total number of damaged units [units]}} \tag{2}$$

$$RR_{\text{avg}} = \frac{1}{RT_{\text{avg}}} = \frac{\text{Total number of damaged units [units]}}{\text{Total repair time [worker} - \text{days]}} \tag{3}$$

Those two quantities are later used in the daily loop to apply repairs progressively to the components.

Table 5. Aggregation of repairable units and repair times by repair sequence.

Stripe	Realization	Floor	RS	# Units	RT
1	1	1	Structural	4	45.2
1	1	1	Interior	26	10.8
1	1	1	Exterior	0	12
1	1	1	Mechanical	3	2.6
1	1	1	Electrical	2	2.2
1	1	1	Elevator	1	12.7
1	1	1	Staircase	1	2.1
1	1	2	Structural	8	84.6
⋮	⋮	⋮	⋮	⋮	⋮

2. At the start of the daily loop, and on each day, the algorithm determines which repair sequences, and which floors are eligible to have workers assigned to them. Four conditions must apply for a floor to be eligible for repairs. The first condition is that all floors remain ineligible as long as an impeding factor delay is ongoing. The second condition is that the floor must have remaining repairs. The code thus keeps track of the remaining repairs for each floor, repair sequence, and stripe-realization pair. The third condition is that higher-priority repairs, as defined by the hierarchy of the repair sequences, must be finished on a floor before lower-priority repairs can begin. Finally, a floor must be part of the active repair phase to be eligible to obtain workers. The final output is Boolean matrix which either "turns on" or "turns off" the floors of the building for each repair sequence. Table 6 shows the active floors and repair sequences on an arbitrary day where elevator and staircase impeding factor delays are still ongoing and all other repairs have begun to progress.

Table 6. Activation of floors for repair worker allocation.

RS	1	2	3	4	5	6	7	8	9
Structural	F	F	F	T	F	T	T	F	F
Interior	F	T	T	F	F	F	F	F	F
Exterior	F	T	T	F	F	F	F	F	F
Mechanical	T	F	F	F	F	F	F	F	F
Electrical	T	F	F	F	F	F	F	F	F
Elevator	F	F	F	F	F	F	F	F	F
Staircase	F	F	F	F	F	F	F	F	F

3. Once eligible floors are identified, the code assigns a trial number of workers to the repairs. The trial number of workers is obtained by assigning a set number of workers to each damaged component or by floor area, based on the user's choice. The trial number of workers is the theoretical number of workers needed for the repairs if limits on the maximum number of workers did not apply.
4. For each floor of each repair sequence, the algorithm then caps the number of workers by floor if it exceeds the user-defined congestion limit. The algorithm therefore never assigns more workers per repair sequence and per floor than the permissible amount.
5. The algorithm then checks whether the total number of workers present in the facility exceeds the contractor's resources. If the limit is exceeded, the workers are scaled down proportionally based on the number of workers present on each floor.
6. The algorithm then checks whether the total number of workers present in the facility is within the permissible limit. If the limit is exceeded, the algorithm progressively removes workers starting from the lowest-priority repair sequences to the highest- priority repair sequences. If multiple repair sequences share the same hierarchy, the algorithm removes workers from the repair sequence with the most assigned workers first. In every case, the algorithm removes workers from the highest active floor and moves downwards if necessary.
7. Next, the algorithm rounds the number of workers to whole units. To yield reasonable crew sizes per floor and per repair sequence, the algorithm implements specific rules to round the number of workers. For repair sequences in which workers are assigned by number of damaged components:
    - The workers per floor and per repair sequence are rounded up to the minimum crew size (number of workers assigned per damaged component) if the number of workers on a given floor is below this value.
    - The crew size is arbitrarily rounded if the crew size per floor, per repair sequence, exceeds the minimum crew size.

    For repair sequences in which workers are assigned by floor area:

    - The crew size is rounded up if it is below three workers.
    - The crew size is rounded arbitrarily if it exceeds three workers.

    The minimum limit of 3 workers per floor and per repair sequence when the workers are assigned by floor area is based on personal judgment and relies on the assumption that crew sizes under three workers are rather rare. The methodic rounding of the workers may lead to the total number of workers present in the facility on a given day exceeding the maximum permissible limit. However, on average, the rounding produces total workers counts within the permissible limits.

8. Using the final number of assigned workers, the algorithm applies repair work and updates the remaining quantity of repairs for each floor and for each repair sequence, as follows:

$$\Delta_{\text{repairable components}} = \text{Assigned workers} \times RR_{\text{avg}} \times \text{dt} \tag{4}$$

where dt is set to 1 day and RR_{avg} is the average repair rate computed prior to the daily loop.

9. If repairs are finished on a floor, the algorithm checks if the floor below it is repaired as well. If both conditions are met, the algorithm marks the new floor as completed and adds a new point to the repair step function. By also checking if the floor below is repaired, the algorithm enforces a strictly increasing step function, similar to the repair paths in Hutt et al. (2022) and Cook et al. (2022).

While the new daily loop implements the detailed algorithm described above, most parameters governing the progression of repairs remain fully customizable. Users can adjust the facility-wide worker limit, contractor resource constraints, and worker limits per floor and per repair sequence through the new user interface, particularly when default values from Almufti and Willford (2013), Hutt et al. (2022), and Paul et al. (2018) are not appropriate for a given project. Additional customizable parameters include the number of floors per repair phase, the choice between fixed or dynamic repair phases, the reconstruction time in case of collapse/demolition, and the prioritization hierarchy among repair sequences. All key parameters can thus be tailored to reflect project-specific constraints and practices.

13. Demolition Fragility Module

The demolition fragility module is shown in Figure 13.1c. This module can be accessed using the “Demolition” button in the main console. The user can specify the fragility function for demolition loss computations. The following options are available:

No Demolition: No demolition takes place, and subsequently there is no demolition loss, regardless of the potential residual deformations along the building height. This is the default option.

Univariate Demolition Fragility: Demolition losses are defined by specifying a lognormal univariate fragility CDF, which is a function of the horizontal residual story drift ratio (RDR) as given by Equation 10. The user should specify the population parameters of the lognormal CDF fragility function. Particularly, μ and σ represent the central tendency (median) of the *RDR* dataset (i.e., μ_{RDR}) and the standard deviation of the associated normal distribution of ln*RDR* (i.e., σ_{lnRDR}). The user may then visualize the fragility curve by clicking the “Show Demolition Fragility” button. A sample univariate demolition fragility curve is shown in Figure 13.1b. The user should provide the RDR data through the “Response Data” module.

$$P[\mathrm{D}|RDR] = \Phi\left(\frac{\ln(RDR) - \ln\,(\mu_{RDR})}{\sigma_{\ln RDR}}\right) \tag{5}$$

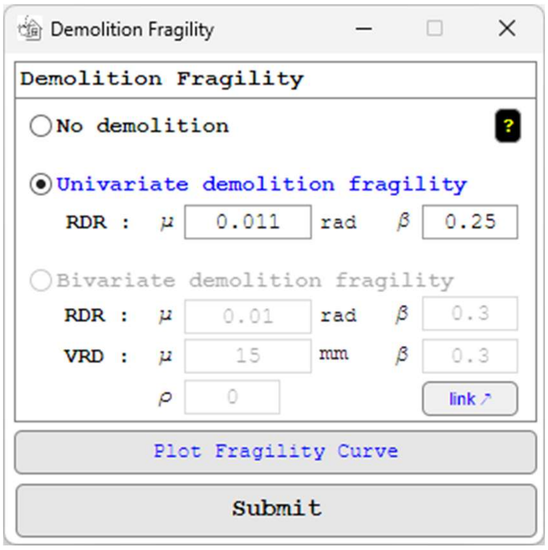
Bivariate Demolition Fragility: Demolition loss is considered by specifying a lognormal bivariate fragility CDF, which is a function of the horizontal residual drift ratio (*RDR*) and the vertical residual deformation (*VRD*), as proposed by Elkady et al. (2020). The user should specify the population parameters of the fragility function; that is the μ and σ of the individual *RDR* and *VRD* fragilities as well as the correlation coefficient between the two EDPs. The bivariate fragility curve may be visualized by clicking the “Show Demolition Fragility” button. A sample bivariate demolition fragility is shown in Figure 13.1c. On the left, the figure shows the bivariate demolition probability density function (PDF). In the center, a 2-D plan view of the PDF surface is shown. The PDF is represented by Equation 11.

$$f(\text{Demolition} \mid RDR, VRD) = \frac{1}{2\pi \cdot RDR \cdot VRD \cdot \sigma_{\ln RDR} \cdot \sigma_{\ln VRD}\sqrt{1-\rho^2}} \cdot e^{-\frac{q}{2}} \tag{6}$$

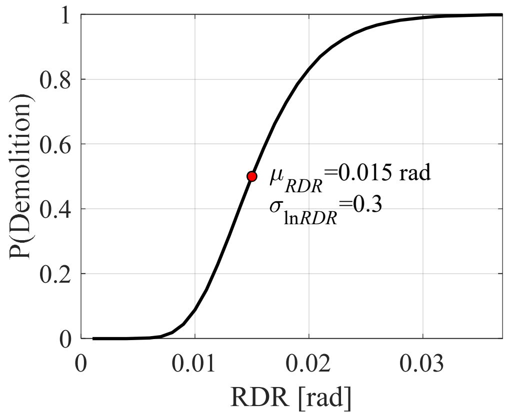
where, q is given by Equation 4.

$$q = \frac{1}{1-\rho^2} \cdot \left[\left(\frac{\ln(RDR) - \mu_{\ln RDR}}{\sigma_{\ln RDR}}\right)^2 - 2\rho\left(\frac{\ln(RDR) - \mu_{\ln RDR}}{\sigma_{\ln RDR}}\right)\left(\frac{\ln(VRD) - \mu_{\ln VRD}}{\sigma_{\ln VRD}}\right) + \left(\frac{\ln(VRD) - \mu_{\ln VRD}}{\sigma_{\ln VRD}}\right)^2\right] \tag{7}$$

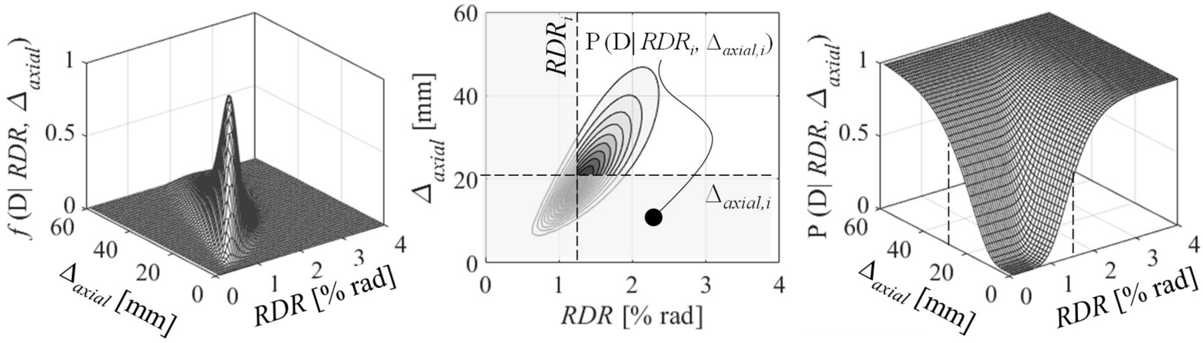
In which, $\mu_{\ln RDR}$ and $\sigma_{\ln RDR}$ are the mean and standard deviation of the normally distributed variable ln*RDR*, respectively; $\mu_{\ln VRD}$ and $\sigma_{\ln VRD}$ are the mean and standard deviation of the normally distributed variable ln*VRD*, respectively; and ρ is the population product-moment correlation coefficient between ln*RDR* and ln*VRD*. Tthe same figure shows the bivariate demolition cumulative distribution function (CDF), which is obtained by numerically integrating the PDF.



(a) Module



(b) Sample plot of the lognormal univariate demolition fragility curve



(c) Sample plot of lognormal bivariate demolition fragility curve (Elkady et al. 2020)

Figure 13.1. Demolition fragility definition

14. Collapse Fragility Module

The Collapse Fragility module is shown in Figure 14.1. This module can be loaded through the “Collapse” button in the main console. From this module, the user can specify the fragility function used for collapse loss computations. The following options are available:

No Collapse: This option assumes that there will be no collapse event, and subsequently no collapse losses. This is the default option.

IDA-Based Collapse Fragility: The collapse fragility curve is deduced from the IDA data that is provided by the “Response Data” module. The collapse intensities are sorted and the empirical distribution function is deduced. A lognormal CDF is fitted to the empirical distribution (i.e., the median and dispersion of the CDF). The collapse fragility curve can be viewed by clicking the “Show Fragility” button (see Figure 14.2a).

Define collapse fragility using μ and β: The user specifies directly the population parameters, μ and β, of the lognormal CDF. The fragility curve can be viewed as shown in Figure 14.2b.

Define collapse fragility using fragility point and β: The user should specify the dispersion, β, of the lognormal CDF as well as the data for a single fragility point [SA_i, P(Collapse|SA_i)]. EaRL identifies the μ value that satisfies the user-defined data point as shown in Figure 14.2c.

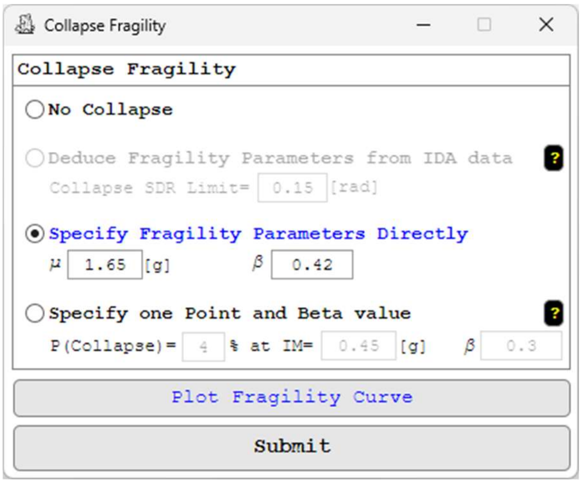


Figure 14.1. Collapse fragility module

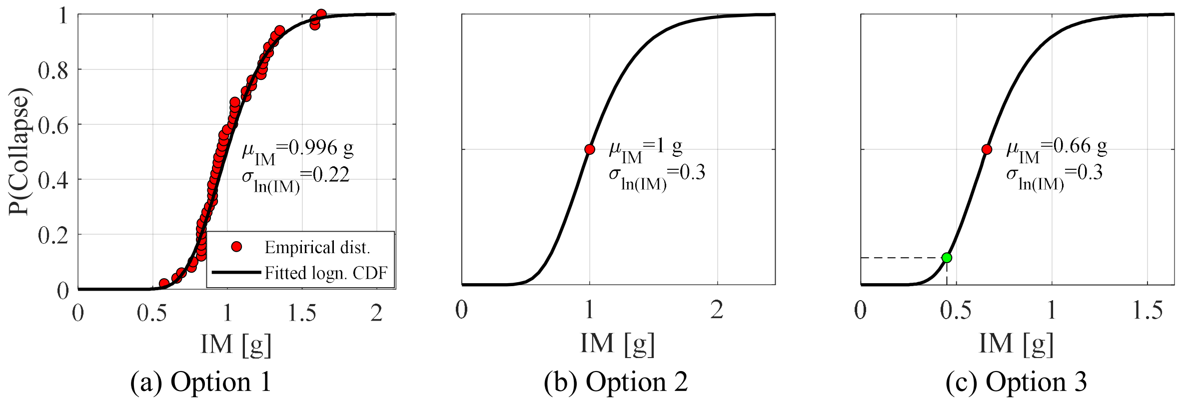


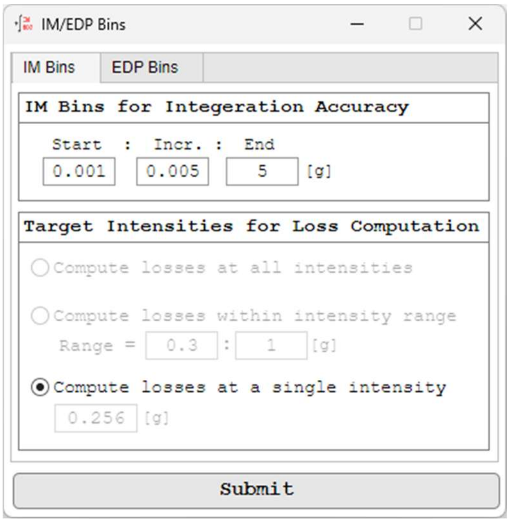
Figure 14.2. Sample lognormal collapse-fragility curves deduced based on the different options

15. IM/EDP Bins Module

Loss computations according to the PEER methodology, involves analytical and numerical integration through seismic intensity and EDP ranges. The IM/EDP bins module shown in Figure 15.1 can be used to control the accuracy of these integration ranges. In particular, the user can specify the range of the intensity levels as well as the incremental step size. Figure 15.1a shows that the integration will be conducted from 0.001g to 5.0g with an incremental step of 0.005g, which is the default/recommended IM range. Losses will then be evaluated at a total of 1000 intensity increments/levels. Repair loss computations can be time consuming (see Section 21). For this reason, the user may conduct this computation at all intensities, or at a subset of the intensity range, or at a single intensity. These options are only available if the structural response has already been defined at multiple intensities.

Referring to Figure 15.1b, the EDP ranges can be set by the user from the IM/EDP Bins module. These ranges should cover the maximum expected value for a given EDP. The default values are the recommended ones. Larger bin values and/or lower maximum range values can be specified with caution, as they may affect the integration accuracy.

(a)



(b)

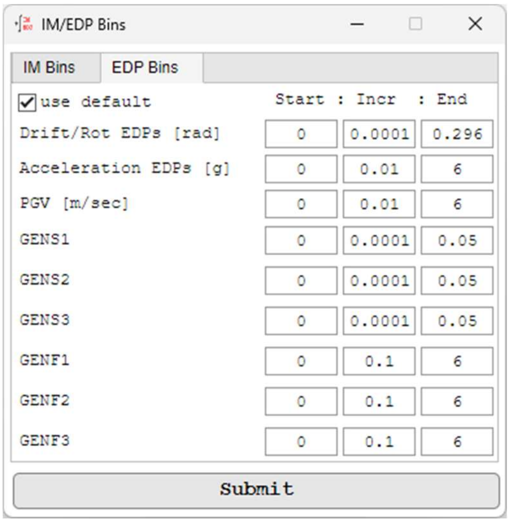


Figure 15.1. IM/EDP bins module

16. Methodology Options

After fully-defining the project; loss analysis can be conducted by pressing the “Compute” button. The user will then be prompted to the module in Figure 16.1 to specify which methodology to be utilized for this analysis; the PEER or the FEMA P-58 methodology. For the former, the user need to only specify the cost value to be used in the analysis (mean, median, 10th percentile or 90th percentile) while for the latter, the user must specify the total number of realizations to be generated, per analysis stripe. Optionally, the user can specify additional uncertainty value to represent the uncertainty in the modeling parameters used to obtain the seed EDP data. Also, the user may choose to check for the potential of issuing an unsafe placard. Note that checking for unsafe placard leads to a relatively longer computation time because this computation requires treating each unit of the same components independently when querying damage.

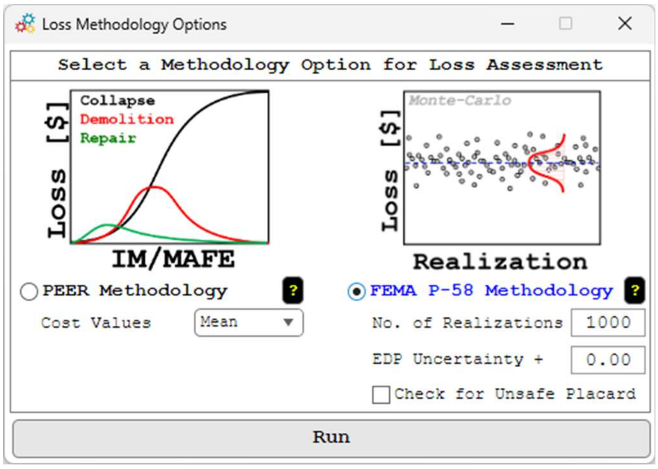


Figure 16.1. Loss methodology options

17. Visualization Options

The visualizations options differ based on the selected loss estimation methodology and the project definitions. The availability of each of these plot options depends on the project definition as summarized in Table 7.

Table 7. Available visualization options based on project definition

Methodology	PEER				FEMA P-58			
Component Definition	Manual Definition		Loss-EDP Functions		Manual Definition		Loss-EDP Functions	
Seismic Intensity	IDA	Other	IDA	Other	IDA	Other	IDA	Other
Seismic Hazard	Yes	No	Yes	No	Yes	No	Yes	No
Monetary loss vulnerability curves	•	NA	•	NA	NA	NA	NA	NA
Repair cost versus realization number	NA	NA	NA	NA	•	•	•	•
Repair time versus realization number	NA	NA	NA	NA	•	•	•	•
Monetary loss breakdown by event	•	•	•	•	•	•	•	•
Repair cost Profile by component type	•	•	•	•	•	•	•	•
Repair time Profile by component type	NA	NA	NA	NA	•	•	NA	NA
Repair cost profile by component name	•	•	NA	NA	•	•	NA	NA
Repair time profile by component name	NA	NA	NA	NA	•	•	NA	NA
Repair cost breakdown by component name	•	•	NA	NA	•	•	NA	NA
Expected annual losses	•	NA	•	NA	NA	NA	NA	NA
Annual rate of exceeding repair cost	NA	NA	NA	NA	•	NA	•	NA

17.1 PEER Methodology Visualizations

The visualization module, shown in Figure 17.1, provides the user with a variety of options to present and comprehend the loss distribution. In particular, six different main plot types are available in EaRL v2.0. In the visualization module, the user should first specify the target seismic intensity (*Sa*) or hazard level at which the loss data should be visualized. The loss units should also be specified; that is “Absolute” for absolute dollar values or “Normalized” for losses normalized by the building total replacement cost. The six main plot options within the visualization module are described below.

Loss Vulnerability Curves: These are plots of the expected monetary loss versus the IM or the hazard level expressed by the mean annual frequency of exceedance (MAFE). The expected loss can be expressed either in absolute dollar values (by selecting the “Absolute” radio button) or normalized by the building replacement cost (by selecting the “Normalized” radio button). Sample vulnerability curves disaggregated into Collapse, Demolition, and Repair are shown in Figure 17.2.

Loss Disaggregation by Event: This shows the disaggregated loss distribution among the three main events in the form of a bar or pie chart as shown in Figure 17.3. Note that the Repair event is disaggregated into three sub-events: 1) Repair of structural components (noted in the plot as SC), 2) Repair of drift-sensitive non-structural components (noted in the plot as NSC-SDR), and 3) Repair of acceleration-sensitive non-structural components (noted in the plot as NSC-ACC). This is evaluated at a single seismic intensity (i.e., spectral acceleration or hazard level), which should be specified first at the top of the Visualization Options module (see Figure 17.1).

Repair Cost Profile: The repair loss distribution along a building’s height can be disaggregated with respect to the “component type” (i.e., SC, NSC-SDR, and NSC-ACC) or the “component name” (e.g. Beams, Drywalls, Sprinklers, etc.) as shown in Figure 17.4a and 6.4b, respectively. For the latter, only components that contribute, in sum, to 95% of the total repair cost are plotted. This is intentionally done to avoid overcrowded plots.

Repair Cost Disaggregation by Component Name: This is a bar or a pie chart, depending on the user’s selection, of the repair loss disaggregation with respect to the component names as shown in Figure 17.5.

Expected Annual Losses: This shows a bar chart of the total expected annual losses disaggregated with respect to the five events: Collapse, Demolition, SC, NSC-SDR, and NSC-ACC as shown in Figure 17.6.

Summary Plots: These differ depending on the utilized loess estimation methodology. For the PEER methodology, the summary plot, shown in Figure 17.7, displays four main plots: a) the vulnerability curves, (b) the EaRL bar chart, (c) the total loss breakdown at a given IM, and (d) the repair loss profile disaggregation with respect to the component type at a given IM. Using the slider controller at the bottom of the window, the user can scroll to the seismic intensity of interest.

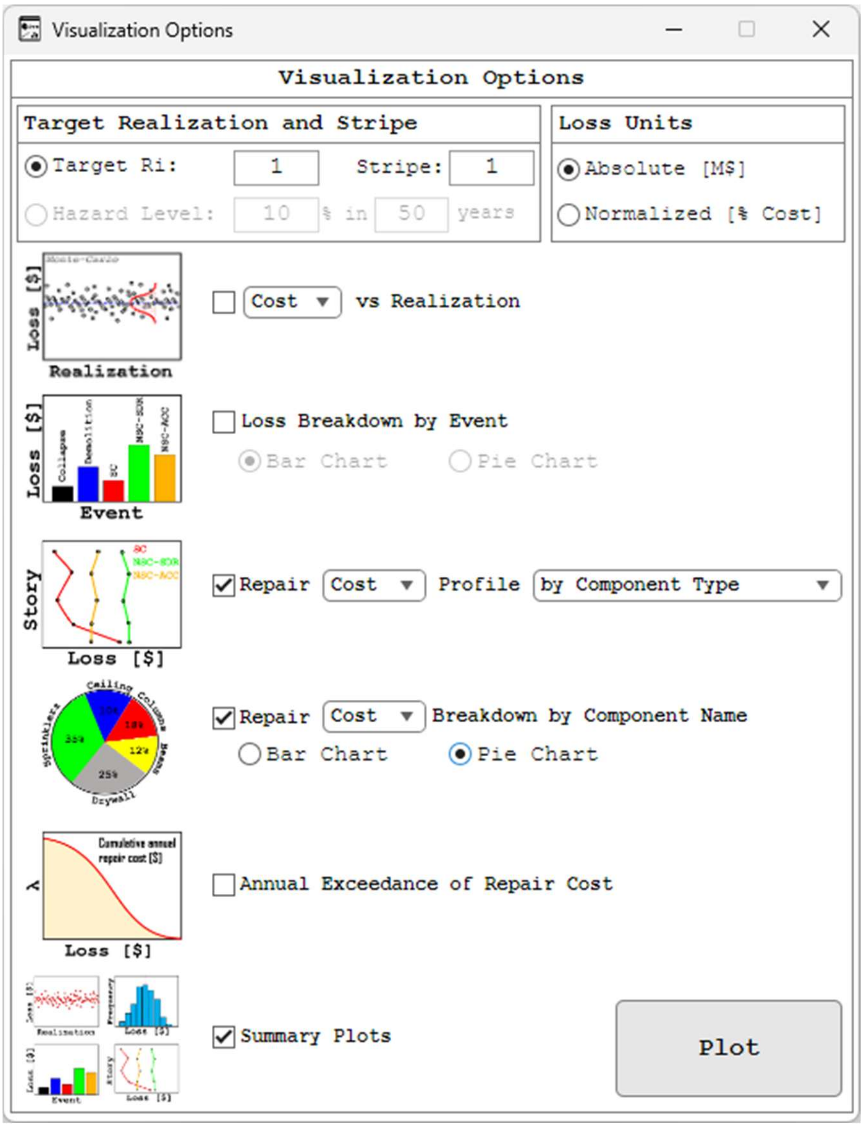
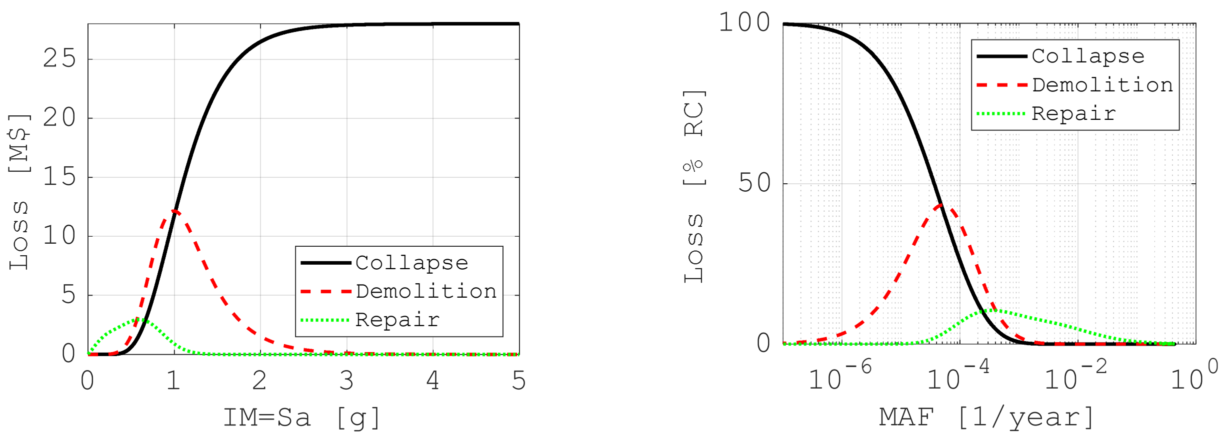


Figure 17.1. Visualization options module the PEER option



(a) vs IM

(b) vs MAFE

Figure 17.2. Loss vulnerability curves

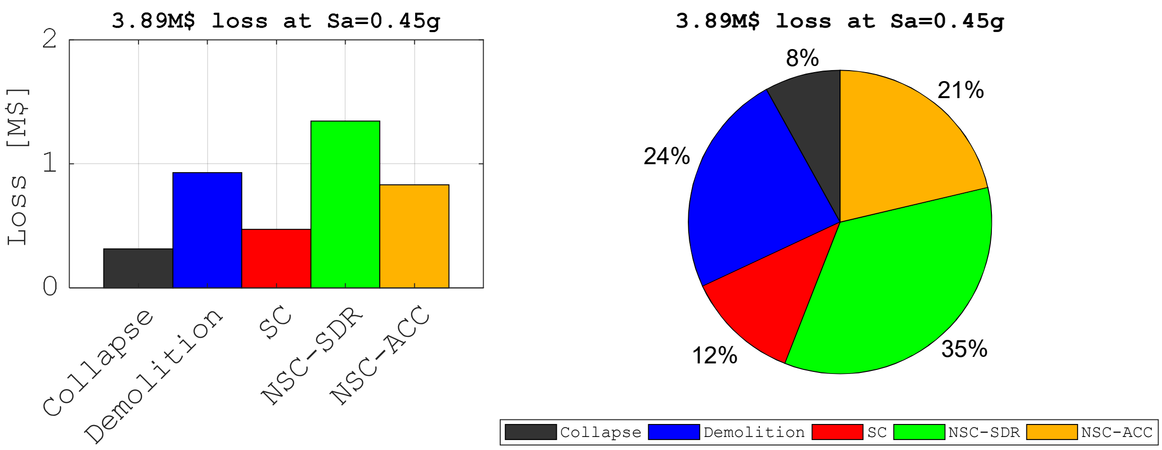
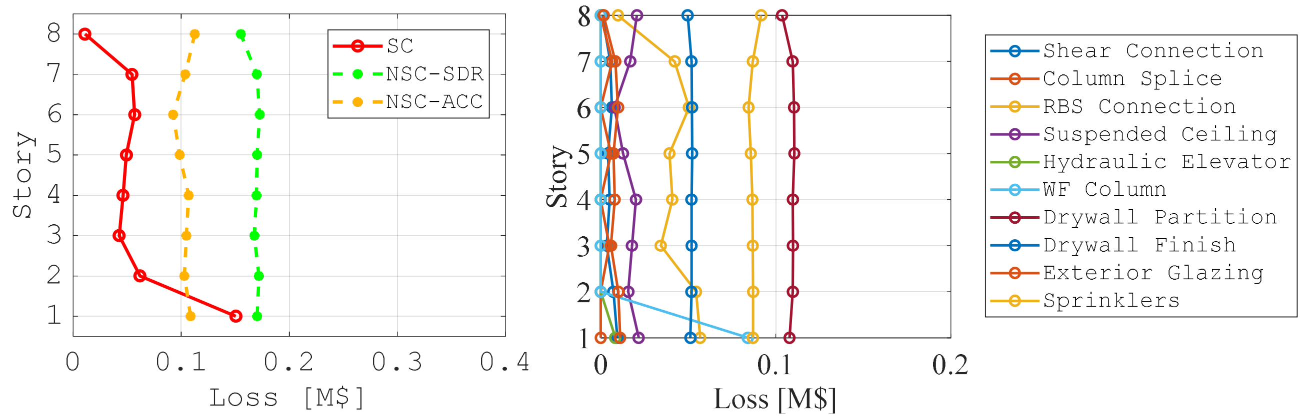


Figure 17.3. Loss breakdown by event



(a) by Component Type (b) by Component Name

Figure 17.4. Repair loss profile

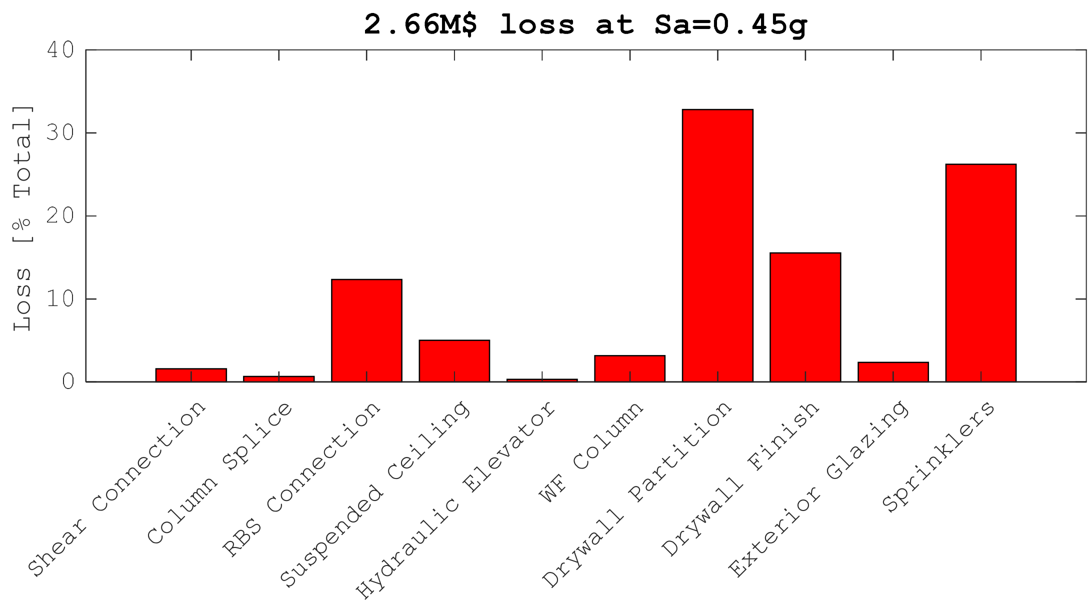


Figure 17.5. Repair loss disaggregation by component name

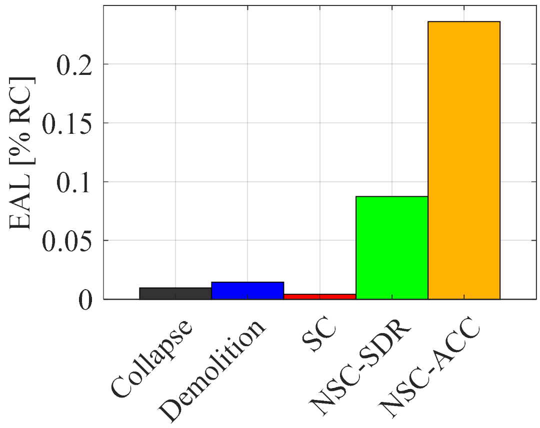


Figure 17.6. Expected annual losses

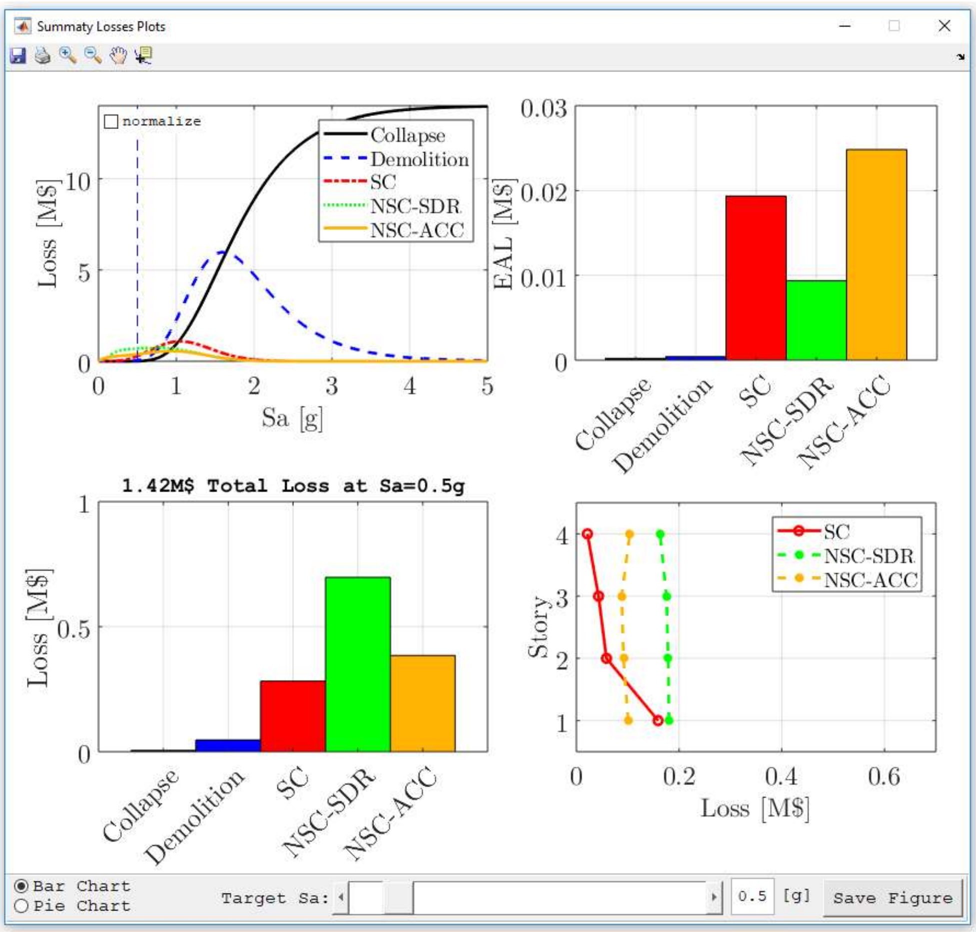


Figure 17.7. Summary plot for PEER methodology simulations

17.2 FEMA P-58 Methodology Visualizations

Referring to Figure 17.8, for the FEMA P-58 option, six different main plot types are available in EaRL v2 to visualize the loss distributions along the building height. The availability of each of the six plot options depends on the project definition as summarized in **Error! Reference source not found.**.

Loss versus realization: This shows the scatter of repair cost or time with respect to the number of realizations as shown in Figure 17.9.

Annual Exceedance of Repair Cost: This shows a plot of the annual rate of exceeding the repair cost as shown in Figure 17.10.

Summary Plot: Referring to Figure 17.11, four main plots are displayed under the "Loss Distribution" tab: a) a scatter plot of the repair cost for each realization (note that this plot excludes realizations where collapse or demolition took place), (b) the histogram distribution of the repair costs (this figure can be transformed into the normally distributed CDF by checking the "CDF checkbox" at the top right corner), (c) the total loss breakdown for a given realization at a given intensity stripe, and (d) the repair loss profile breakdown with respect to the component type at a given realization and at a given intensity stripe (assuming multiple intensity stripes were defined in the response module). Using the knob at the bottom left corner of the window, the user can select the intensity stripe of interest. Similarly, the slider and spinner controllers may be used interchangeably to select the realization of interest.

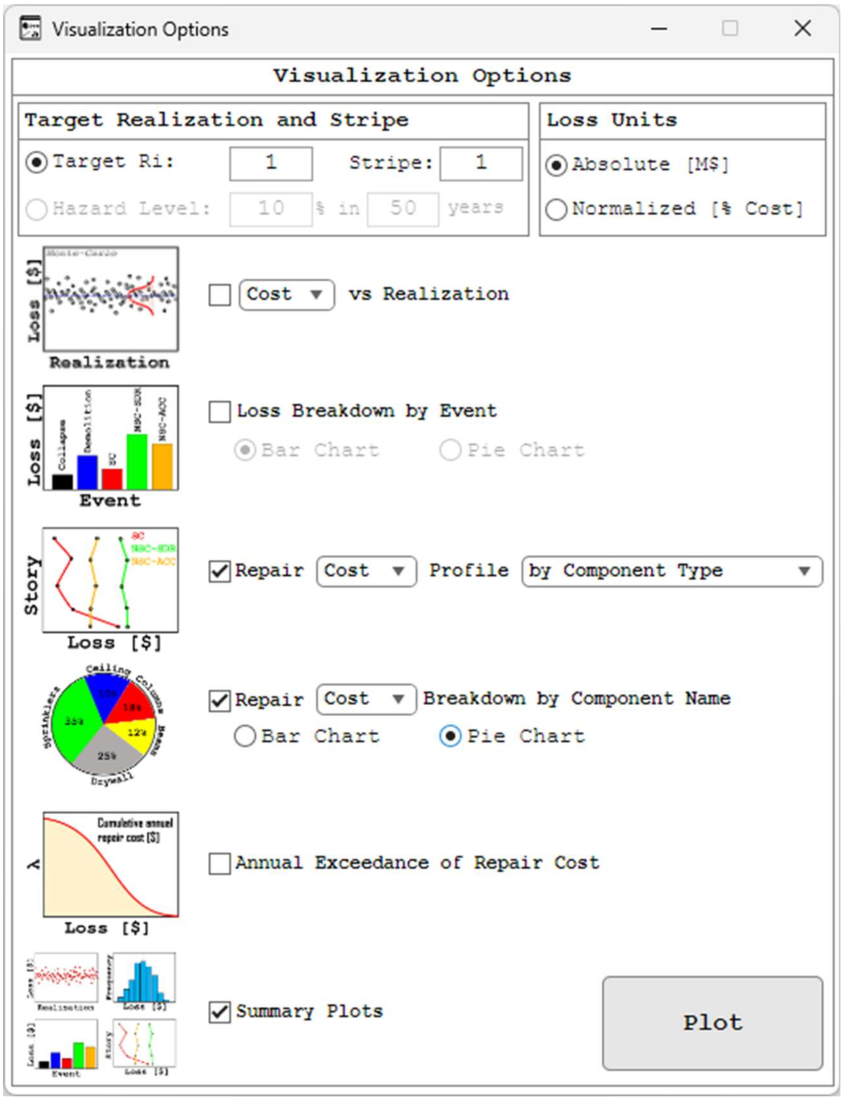


Figure 17.8. Visualization options module for FEMA P-58

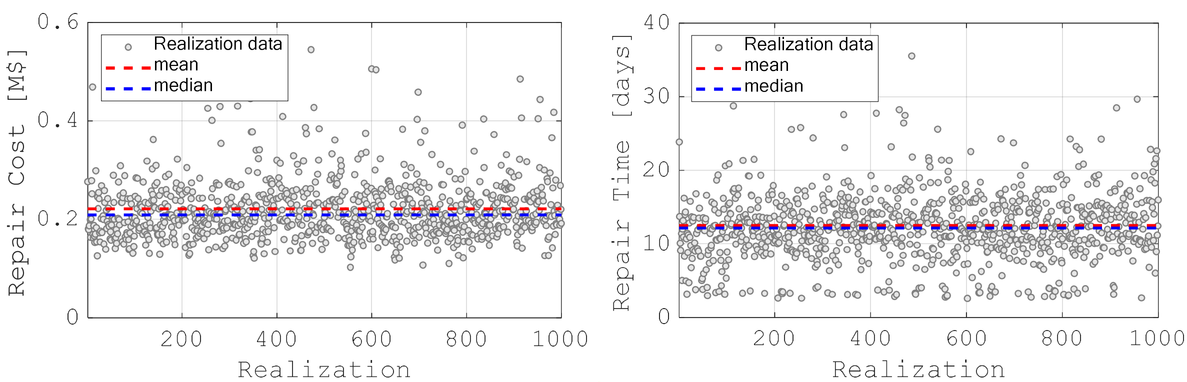


Figure 17.9. Repair cost and time loss versus realization

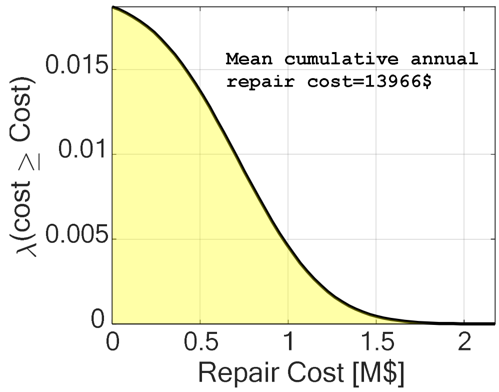


Figure 17.10. Annual exceedance of repair cost

(a) 

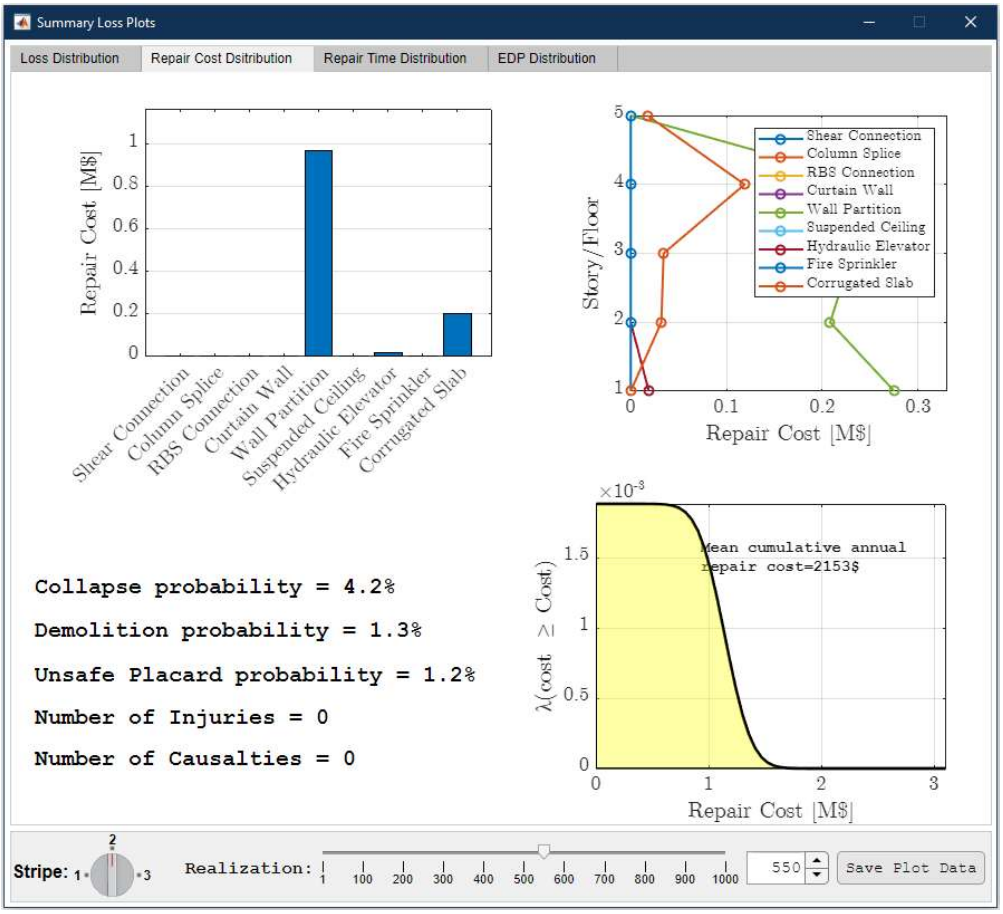
(b) 

Figure 17.11. Summary plot for the FEMA P-58 option

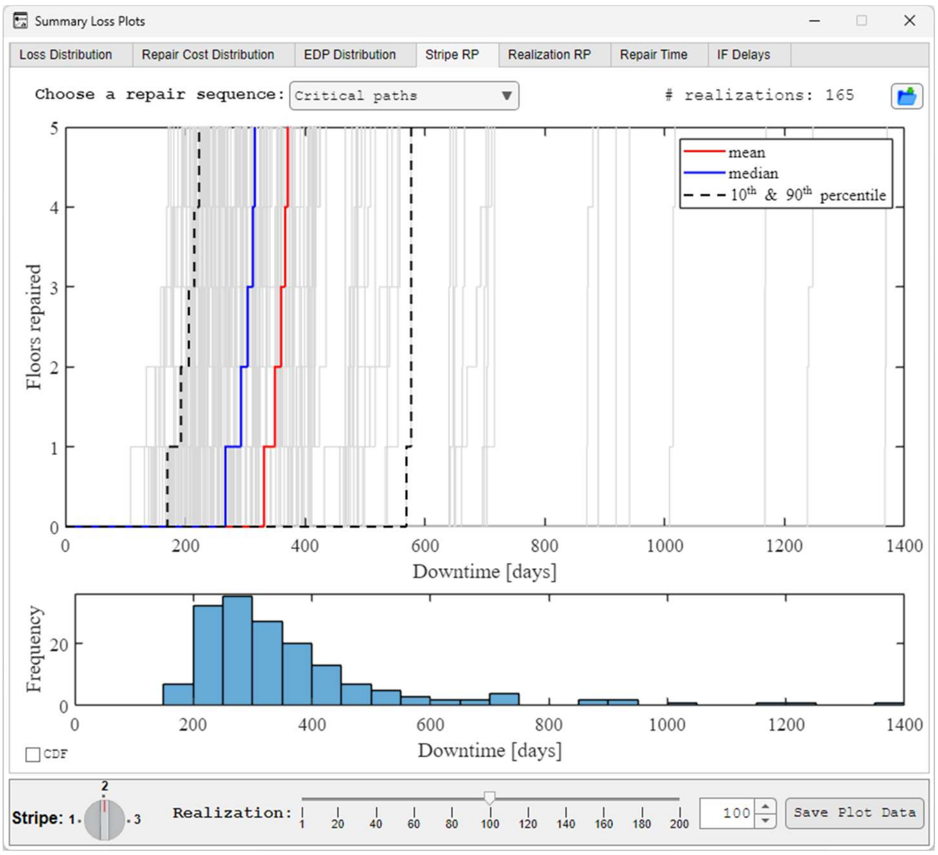


Figure 17.12. Downtime profile and histogram plots for a given analysis stripe

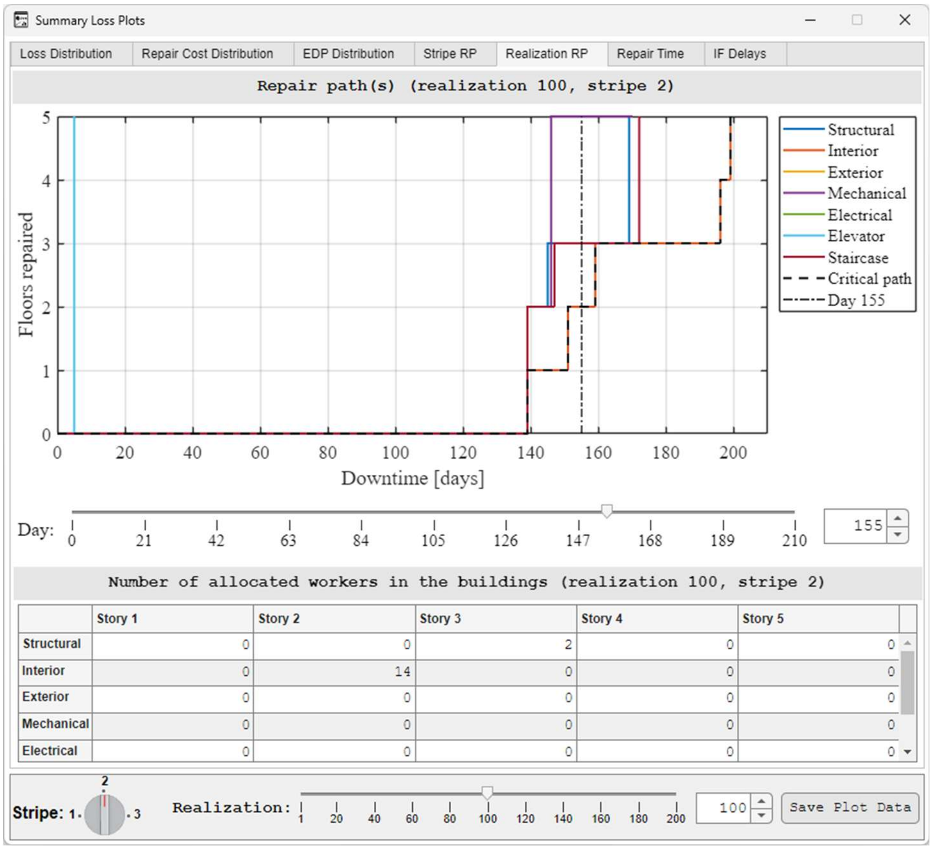


Figure 17.13. Downtime repair path(s) for different component categories and active workers at a given time for a given realization/stripe

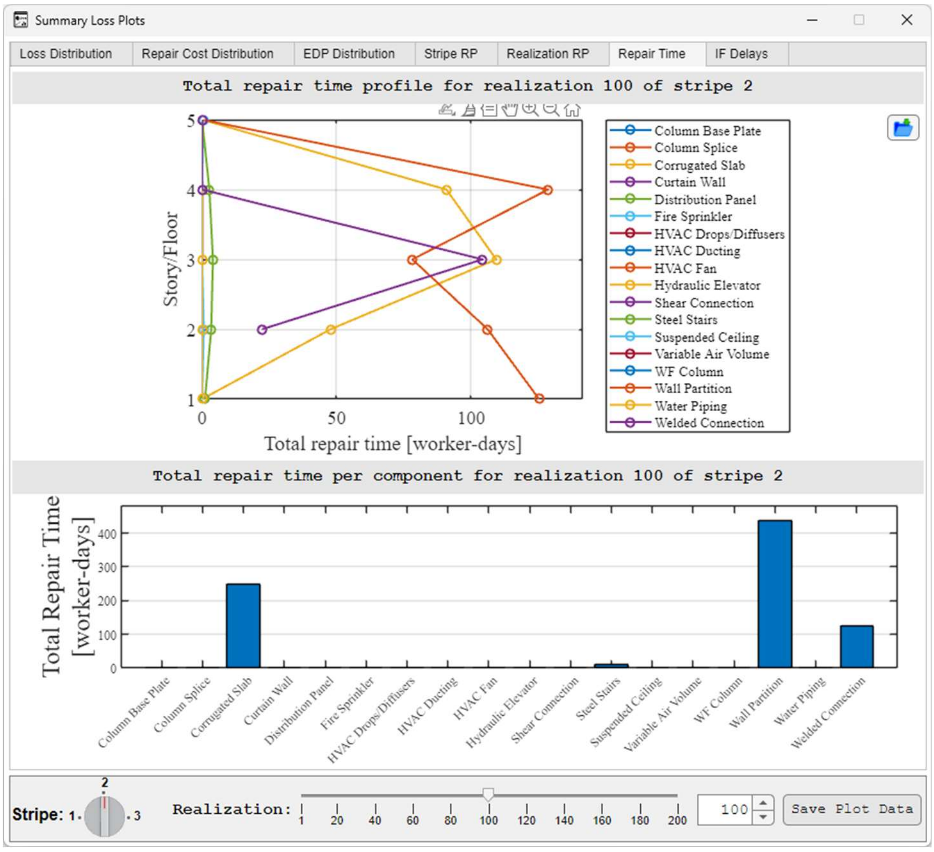


Figure 17.14. Total repair time profiles for the different components for a given realization/stripe

18. Project Inspector

The user can verify the defined project components and parameters by using the "scope" button located in the project file management panel (see Figure 5.1). This button will open a window that provides a summary of the current project definition as shown in Figure 18.1.

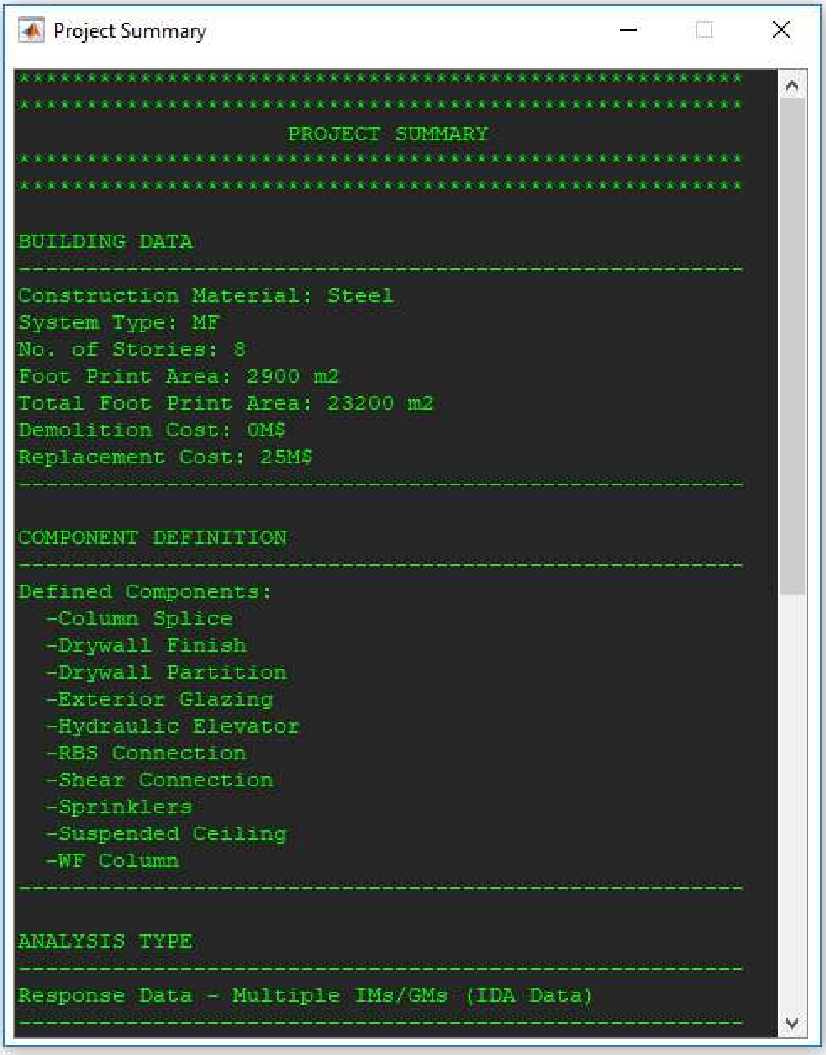


Figure 18.1. Project summary window

19. Reporting Results

All the data that can be plotted through the Visualization module can be saved into a text file through the "Report" module shown in Figure 19.1. This module is accessible by clicking the "Report" button, which becomes active after the loss computations. In this module, similar to the Visualization module, the user should first specify the target seismic intensity or hazard level at which loss data will be reported as well as the loss units (i.e., absolute dollar values or normalized by the building replacement cost). Once the "Generate Report" button is clicked, the user should select a folder to save the generated text files. The available data for reporting depends on the project definition, as discussed earlier. Figure 19.2 shows how the output data is organized within the text file of the various report options.

To allow the user to manage the data independently and process it in their own way, EaRL provides the option to save MATLAB files (*.mat) summarizing the results. These can be produced by clicking the "Save summary MAT files" button. In the case of the FEMA P-58 methodology, a MATLAB file named *Summary_Results_MAT_Files.mat* is created. This file, when opened in MATLAB, will include the following variables:

9. **REALIZATIONS_EDP_DATA**: a structured variable containing the EDP data of all the imported/generated realization and stripes.
10. **DEAGGREGATED_LOSS_DATA**: a matrix with the full disaggregated loss data for each component, at each story/floor, at every realization and at each seismic intensity. The number of columns in the matrix depends on the project definition. Each column is described in a cell variable named **DEAGGREGATED_LOSS_DATA_Titles** that is saved with the main matrix.

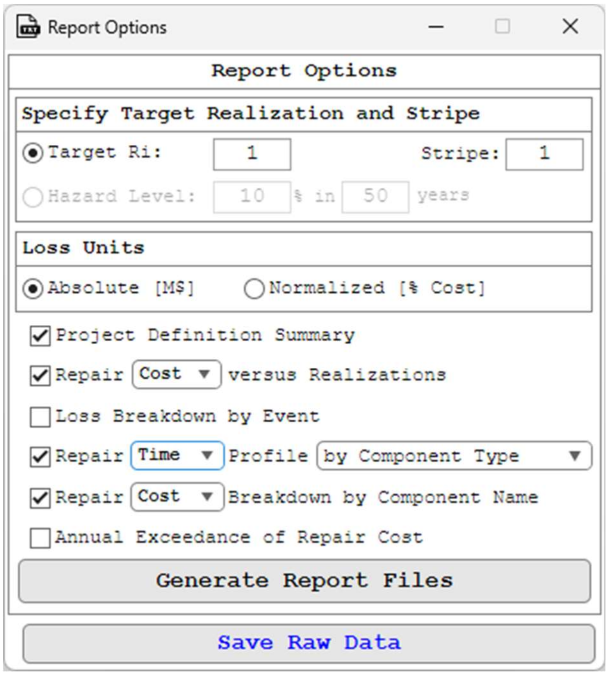


Figure 19.1. Report options module

SA [g]	COLLAPSE	DEMOLITION	SC	NSC-SDR	NSC-ACC
0.001000	0.000000	0.000000	0.079225	0.000000	0.003130
0.006000	0.000000	0.000000	0.055334	0.000000	0.025117
0.011000	0.000000	0.000000	0.042881	0.000000	0.044283
0.016000	0.000000	0.000000	0.036597	0.000003	0.060693
0.021000	0.000000	0.000000	0.032952	0.000056	0.075039
0.026000	0.000000	0.000000	0.030565	0.000361	0.087787
0.031000	0.000000	0.000000	0.028834	0.001526	0.099260
0.036000	0.000000	0.000000	0.027473	0.004575	0.109688
0.041000	0.000000	0.000000	0.026334	0.010299	0.119245
0.046000	0.000000	0.000000	0.025335	0.018742	0.128063
0.051000	0.000000	0.000000	0.024430	0.029462	0.136243
0.056000	0.000000	0.000000	0.023590	0.041893	0.143870
0.061000	0.000000	0.000000	0.022798	0.055453	0.151009

(a) Vulnearability curves vs IM

0.26M$ Repair Loss for IM=0.751g, Ri #250

EVENT	LEVEL-1	LEVEL-2	LEVEL-3	LEVEL-4	LEVEL-5
SC	0.000000	0.000000	0.000000	0.000000	0.000000
NSC-SDR	0.012181	0.075483	0.063484	0.039201	0.068459
NSC-ACC	0.000000	0.000000	0.000000	0.000000	0.000000

(b) Repair cost profile breakdown by component type

0.26M$ Loss for IM=0.751g, Ri #250

COMPONENT NAME	Repair cost [M$]
Shear Connection	0.000000
Column Splice	0.000000
RBS Connection	0.000000
Curtain Wall	0.000000
Wall Partition	0.063329
Suspended Ceiling	0.000000
Hydraulic Elevator	0.000000
Fire Sprinkler	0.000000
Corrugated Slab	0.195478

(c) Repair cost breakdown by component name

16.6 days repair time for IM=0.751g, Ri #1

COMPONENT NAME	Repair Time [days]
Shear Connection	0.000000
Column Splice	0.000000
RBS Connection	0.000000
Curtain Wall	0.000000
Wall Partition	9.863425
Suspended Ceiling	0.000000
Hydraulic Elevator	0.000000
Fire Sprinkler	0.000000
Corrugated Slab	39.834354

(d) Repair time breakdown by component name

1.43M$ Loss at Sa=0.5g

EVENT	LOSS [M$]
Collapse	0.006018
Demolition	0.050325
SC	0.291013
NSC-SDR	0.698948
NSC-ACC	0.387234

(e) Loss breakdown by event

0.05M$ Expected Annual Total Loss
0.05M$ Expected Annual Repair Loss

EVENT	EAL [M$]
Collapse	0.000205
Demolition	0.000419
SC	0.019346
NSC-SDR	0.009360
NSC-ACC	0.024825

(f) EAL breakdown per event

Realization	Repair Cost [M$]
1	0.228699
3	0.359993
4	0.196874
5	0.464963
6	0.281480
7	0.244406
9	0.654547
11	0.220088
12	0.222718
13	0.575992

(g) Repair cost versus realization number

Figure 19.2. Sample report text files output

20. Developers

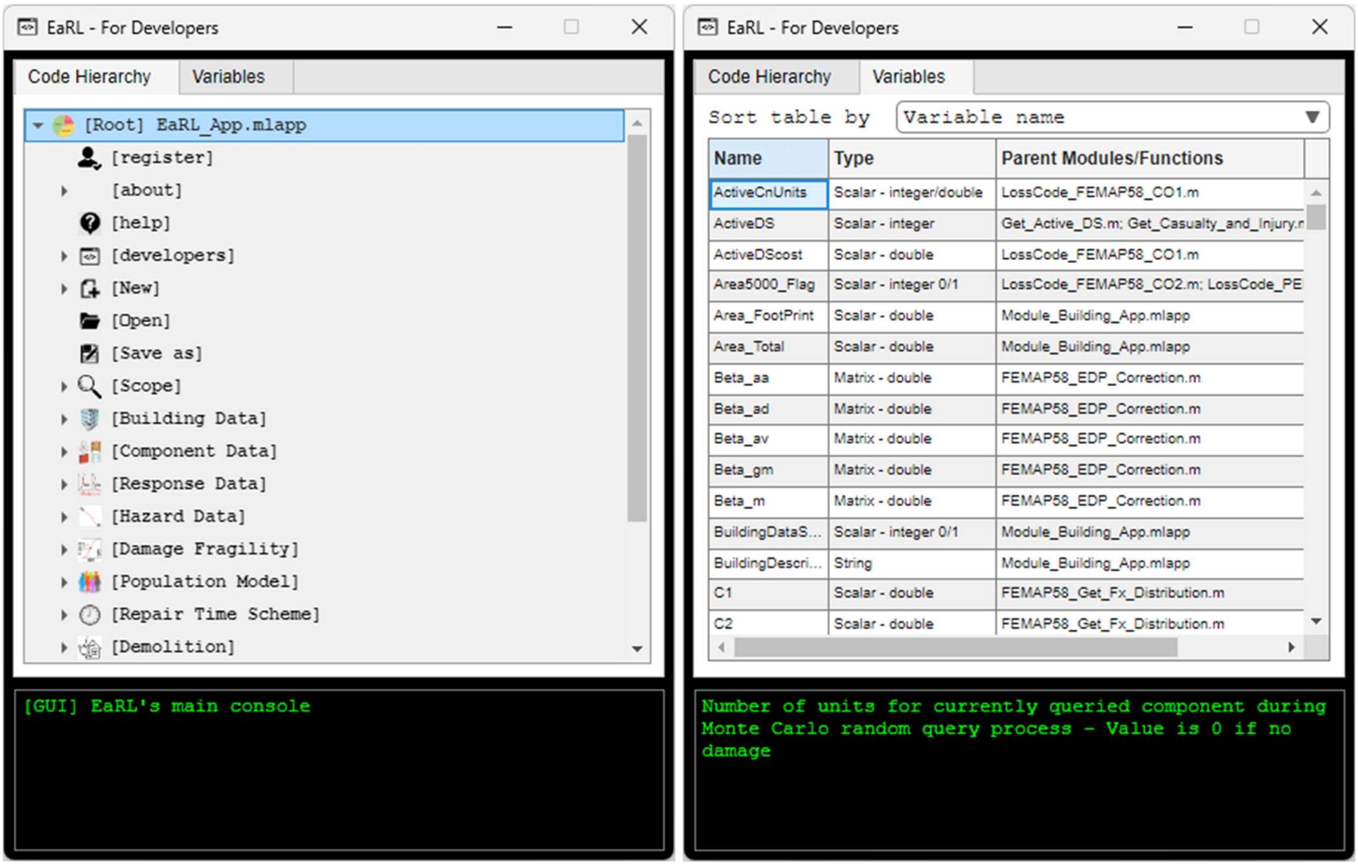
EaRL platform is fully developed in Matlab. The entire source code is a combination of Matlab's **.mlapp* graphical user interface (GUI) files and **.m* function files. The source code is available in the online GitHub repository inside the folder named *src*. Users who are interested in further developing EaRL are able to do so through the GitHub platform. In brief, the user should 1) Create an account on GitHub.com, 2) Download and install the GituHub Desktop application, 3) Fork EaRL's repository (i.e., take a parallel copy of EaRL's code on the user's local computer) and 4) finally, further developing and expanding the source code. Proposed changes to the code should then be publically shared with other users, under the GPLv3 license. The user can "commit" any changes to the online repository where they will be vetted and validated before being patched to the master code. Credit will be given to any user contributions in newly compiled executables. Consult the GitHub quick start guide here: https://help.github.com/en/github/getting-started-with-github/quickstart.

To help users understand the source code, the Matlab script code within the **.m* function files is well commented and organized. Furthermore, by clicking the "developers" button in EaRL's main console, the interface shown in Figure 20.1 will be opened. This interface comprises two tabs:

(a) Code Hierarchy tab, see Figure 20.1a, shows the code's organizational tree. By expanding the branches of this tree list, the user can inspect the dependency and the relation between the different source code GUI and function files. Additionally, by clicking on a specific element (GUI or function name) within this code tree, a full description of this element is displayed in the tip window at the bottom of the interface. The description also includes the names of the output variables generated by a specific function.

(b) Variables tab, see Figure 20.1b, which lists the details of all the variables used within the source code, including their name, type (scalar, vector, matrix, structure, etc.) and the parent module(s) or function(s) where this variable is used and defined. By clicking on a given variable name, a full description of the variable will be displayed in the tip window.

These tools are aimed to help the user comprehend the source code. As such, the user is potentially able to navigate the source code and modify/add specific functions accordingly.



(a) (b)

Figure 20.1. Developers summary window

21. Indicative Computation Time

The computational time for loss calculations varies depending on the project definition and the range/accuracy of the IM bins. Table 8 summarizes the indicative simulation time for performing different types of project definitions for a 4-story office building. The run time is based on a 64-bit Windows machine with Intel i7 (4GHz) CPU, 16 GB of RAM and an SSD disk. Note that an increased simulation time (~four times larger) would occur if the user chooses to compute the probability of issuing an Unsafe Placard in accordance with the FEMA P-58 methodology. This is because such computation requires treating units of the same structural/non-structural component as uncorrelated (i.e., independent damage occurrence in each unit).

Table 8. Indicative computation time based on project definition [in seconds]

		Single Intensity	Three Stripes	1000 Intensities
PEER	Manual Definition (10 Components per story)	3	6	70
	Loss-EDP Functions	4	5	40
FEMA P-58 1000 realizations	Manual Definition (10 Components per story)	11	52	NA
	Loss-EDP Functions	6	14	NA

22. Step by Step Practical Example

In this section, a step-by-step example of defining a loss project in EaRL is described. This example is also covered in the dedicated YouTube playlist. This example involves a 4-story office building with perimeter special moment frames (SMFs) designed in Los Angeles, California as per ASCE (2010). Figure 22.1 shows plan and elevation view of the building as well as the basic seismic design parameters. This building is based on the archetype steel moment frame buildings that were first designed as part of the NIST (2010) report as per the ASCE (2006) building code. A nonlinear 2-dimensional concentrated-plasticity model of the building, in the East-West direction, is built and analyzed in OpenSEES using state-of-the-art component deterioration models and considering the composite floor action and the gravity framing effects. The full details of the building and numerical model can be found in Elkady and Lignos (2014, 2015). The numerical model is also publicly available at the following GitHub repository https://github.com/amaelkady/OpenSEES_Models_SMF. The 44 ground motion records of the Far-Field set, specified in FEMA (2009), were used in this analysis. This ground motion set can also be found in EaRL supporting documents. Nonlinear response-history analysis was conducted by scaling the record set at three intensity stripes (first-mode spectral acceleration equal to 0.3g, 0.6g and 1.1g) representing the service-level, design-level and maximum considered earthquakes at the building location. In Figure 22.1, a summary of the various types of structural and non-structural components in the building are summarized as well as their number and location. Other buildings contents, such as office furniture, projector and computer, are not considered in this example for simplicity.

In this example, losses will be quantified at the three seismic intensity levels (multiple stripes) using the FEMA-P58 methodology. The steps for the project definition are summarized below.

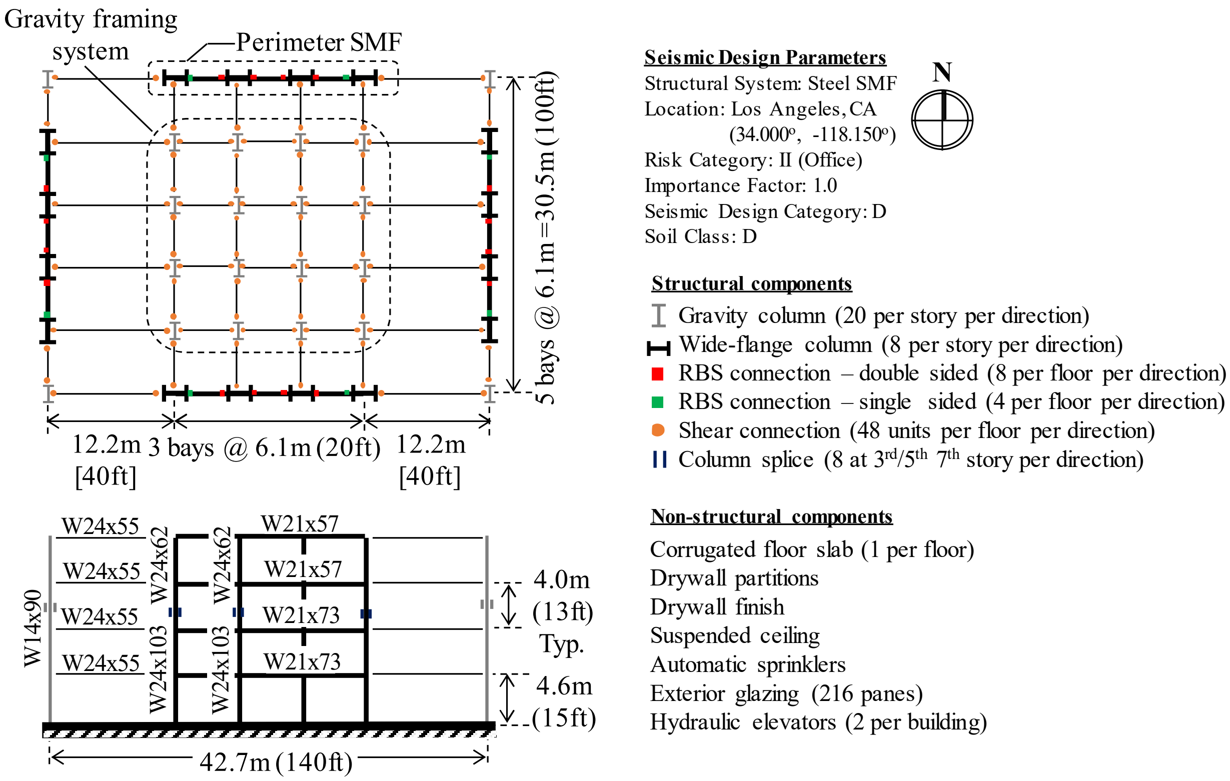


Figure 22.1. Plan view of the 4-story building

From EaRL's main console, a "New" project is initiated under the name "Example Project" using "Imperial" units. At this point, only the "Building Data" button is active on the main console since should be the first project component to be defined.

Building Data: First, the building data is defined by clicking the "Building Data" button. The data are defined in the building data module as shown in Figure 22.2. In particular, the foot print area is equal to 14000 ft^2 (140 ft x 100 ft) and the total floor area is 56000ft^2 (4 floors x 14000 ft^2). The building replacement cost is 15 million US dollars and the cost for demolition is 2 million dollars. The building occupancy is set as a "Commercial Office".

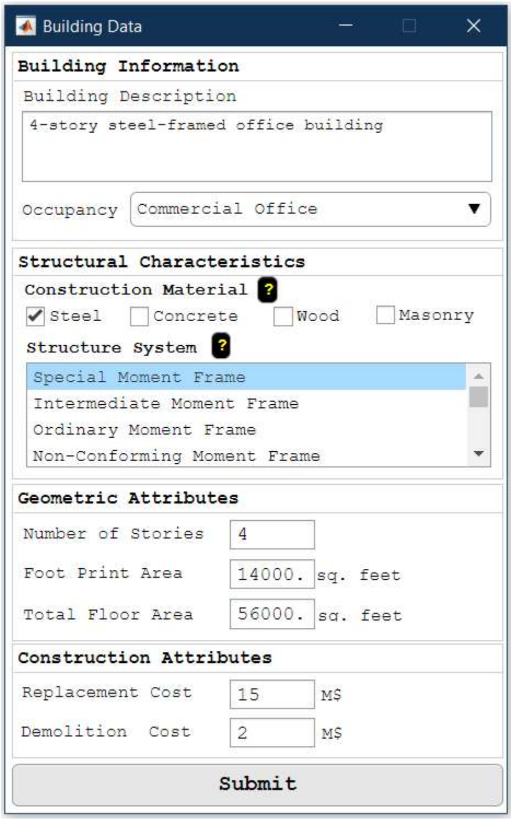


Figure 22.2. Building data definition

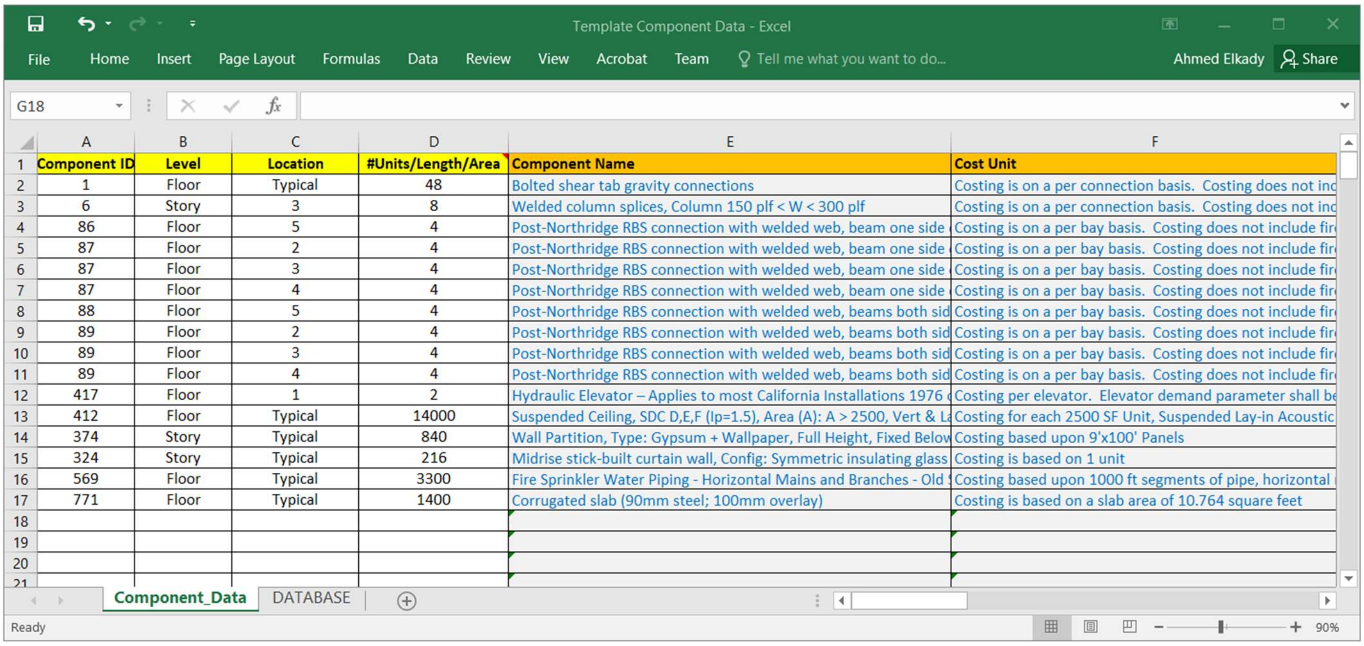
Component Data: The building component data are defined using the "Manual Definition" option. In particular, instead of using the drop-down menus (see Figure 7.3) to define and add each component individually, the component data are defined in a preformatted EXCEL sheet as shown in Figure 22.3. Note that the components are defined in the first four columns of this EXCEL sheet named as discussed in detail in Section 7.1. The data for this specific example are defined in the "*Template Component Data.xls*" file that is provided within EarL's supporting documents folder.

Few key things to note based on the data in Figure 22.3:

11. For the *suspended ceiling* component (component ID: 412), the repair cost of each damage state is associated with a unit area (specifically, 2500 ft^2; see FEMA-P58 database). Therefore, since the *suspended ceiling* covers the entire floor area in this example, a value of 14000 ft^2 (must be in the same units of the project) is assigned in the fourth column in the EXEL sheet. Consequently, EaRL will compute the number of

components units as the specified area value divided by the unit area associated with the damage state repair cost (i.e., number of units=14000/2500; see Section 7.1). Note that a user may specify a different value than the building floor area, if needed. This is actually the case for the *corrugated slab* component (component ID: 771) where a lower value of 1400 is specified (representing only the potentially affected area around the columns rather than the entire floor area).

12. For the *wall partition* component (component ID: 374), the repair cost of each damage state is associated with a unit length (specifically, 100 ft partition panel; see FEMA-P58 database). Therefore, since the *wall partition* is considered to cover all the grid lines in the East-West direction, a value of 840 ft (represents 6 gridlines x 140ft; see plan view) is assigned in the fourth column in the EXEL sheet. Consequently, the number of wall partition units will be computed by EaRL as 840/100 = 8.4 panels.
13. For the *hydraulic elevator* component (component ID: 417), the repair cost of each damage state is associated with a single component unit. Therefore, a value of 2 is specified in the fourth column representing directly the number of elevator units in the building. The component (Elevator) location is set to 1 in the third column since this component damage is associated with PGA which is relevant to the ground floor (i.e., floor #1).



Component ID	Level	Location	#Units/Length/Area	Component Name	Cost Unit
1	Floor	Typical	48	Bolted shear tab gravity connections	Costing is on a per connection basis. Costing does not inc
6	Story	3	8	Welded column splices, Column 150 plf < W < 300 plf	Costing is on a per connection basis. Costing does not inc
86	Floor	5	4	Post-Northridge RBS connection with welded web, beam one side	Costing is on a per bay basis. Costing does not include fir
87	Floor	2	4	Post-Northridge RBS connection with welded web, beam one side	Costing is on a per bay basis. Costing does not include fir
87	Floor	3	4	Post-Northridge RBS connection with welded web, beam one side	Costing is on a per bay basis. Costing does not include fir
87	Floor	4	4	Post-Northridge RBS connection with welded web, beam one side	Costing is on a per bay basis. Costing does not include fir
88	Floor	5	4	Post-Northridge RBS connection with welded web, beams both sid	Costing is on a per bay basis. Costing does not include fir
89	Floor	2	4	Post-Northridge RBS connection with welded web, beams both sid	Costing is on a per bay basis. Costing does not include fir
89	Floor	3	4	Post-Northridge RBS connection with welded web, beams both sid	Costing is on a per bay basis. Costing does not include fir
89	Floor	4	4	Post-Northridge RBS connection with welded web, beams both sid	Costing is on a per bay basis. Costing does not include fir
417	Floor	1	2	Hydraulic Elevator – Applies to most California Installations 1976	Costing per elevator. Elevator demand parameter shall be
412	Floor	Typical	14000	Suspended Ceiling, SDC D,E,F (Ip=1.5), Area (A): A > 2500, Vert & La	Costing for each 2500 SF Unit, Suspended Lay-in Acoustic
374	Story	Typical	840	Wall Partition, Type: Gypsum + Wallpaper, Full Height, Fixed Below	Costing based upon 9'x100' Panels
324	Story	Typical	216	Midrise stick-built curtain wall, Config: Symmetric insulating glass	Costing is based on 1 unit
569	Floor	Typical	3300	Fire Sprinkler Water Piping - Horizontal Mains and Branches - Old	Costing based upon 1000 ft segments of pipe, horizontal
771	Floor	Typical	1400	Corrugated slab (90mm steel; 100mm overlay)	Costing is based on a slab area of 10.764 square feet

Figure 22.3. Building component data definition in EXCEL

Once the component data are fully defined and saved in the EXCEL file, the “Import from EXCEL” button is used to import the data into the module. The table in the “Manual Definition” module is populated with the component data as shown in Figure 22.4. Note that modification and additions to this table of components can be made. Once the component data is submitted, the edge color around the “Component Data” button on the main console turns from red to green. The “Response Data” button becomes active.

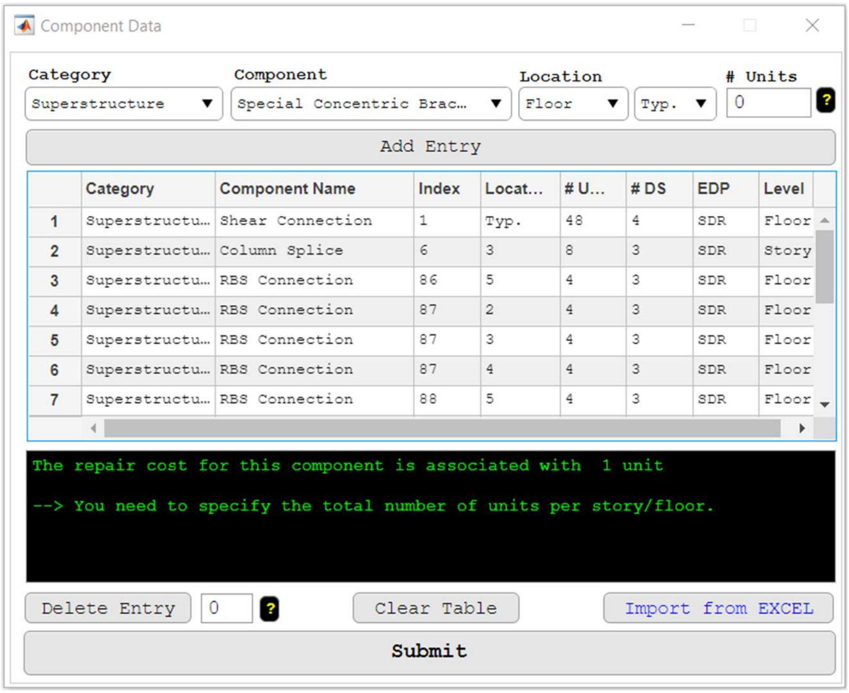


Figure 22.4. Building component data populated in the "Manual Definition" module

Response Data: Losses are to be evaluated at a three seismic intensities. Accordingly, we will opt to select the "Data at Multiple Stripe" option from the "Response Data" module (refer to Figure 8.1). For that option, we will provide the structural response data directly in the form of story/floor-based EDP median values for each of the 44 ground motion record at each intensity (stripe). As demonstrated in Figure 22.6, the data is organized in the pre-formatted EXCEL file "*Template Response Data –Multiple Stripes.xlsx*" that is provided with EaRL's supporting documents folder (refer to Section 8.2). In particular, we shall provide the data for *SDR* or *PFA* (both EDPs are mandatory by default) since the damage fragility functions of the considered building components in this project depends on either one of them. Additionally, because we would like to evaluate the loss associated with building demolition due to lateral residual drift ratios, we should also provide the *RDR* data.

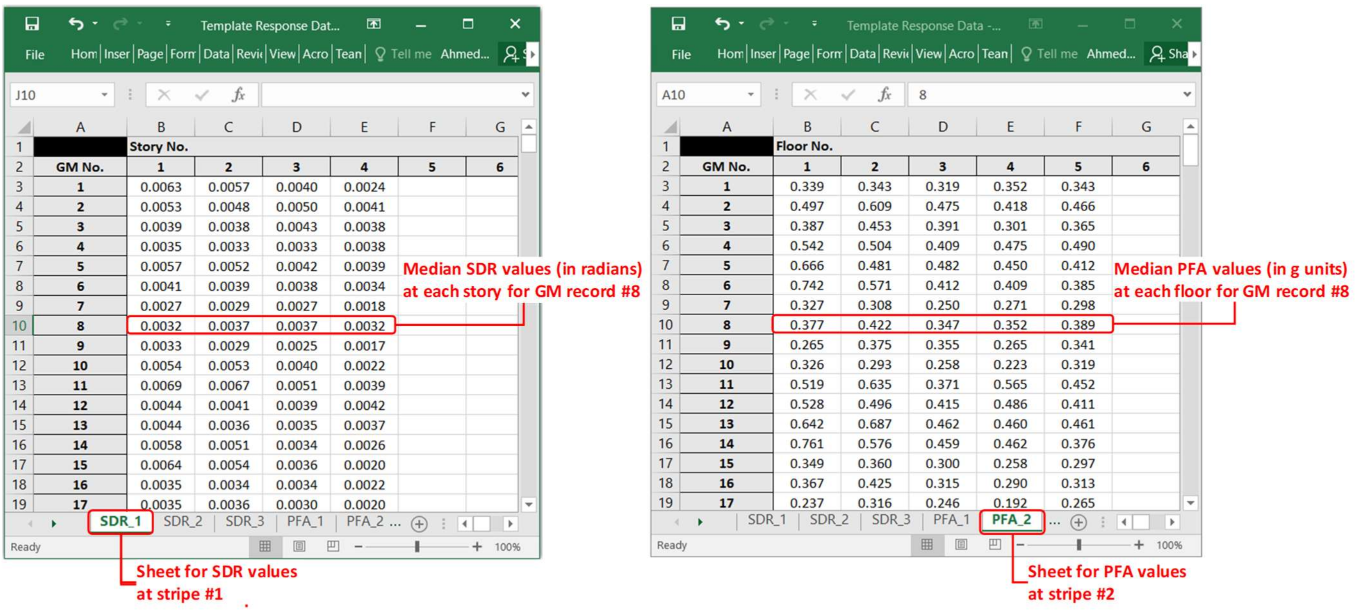


Figure 22.5. Tabulated EDPs values in the pre-formatted EXCEL file based on multiple stripe analyses

Through the response data definition module shown in Figure 22.6, the EXCEL file is then imported using the “browse” button, and then the number of ground motions and analysis stripes are specified as well as the associated intensity levels. Using the “Plot EDP profiles” button, we can verify that the data is correctly imported as shown in Figure 22.7. In this case, 9 plots are generated: 3 stripes x 3 defined EDP (*SDR*, *PFA* and *RDR*). Once the response data is submitted, the color surrounding the “Response Data” button on the main console will turn from red to green.

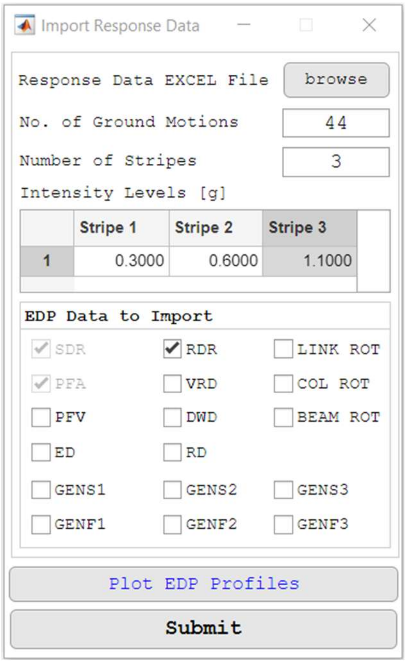
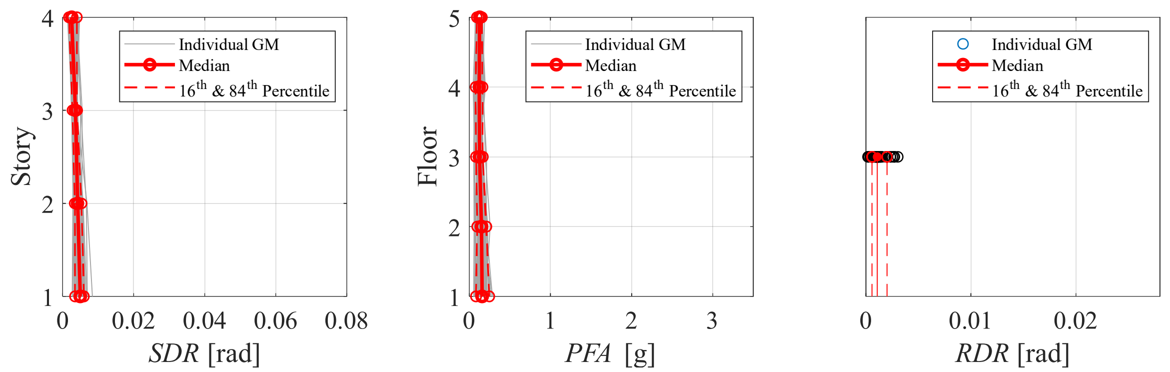
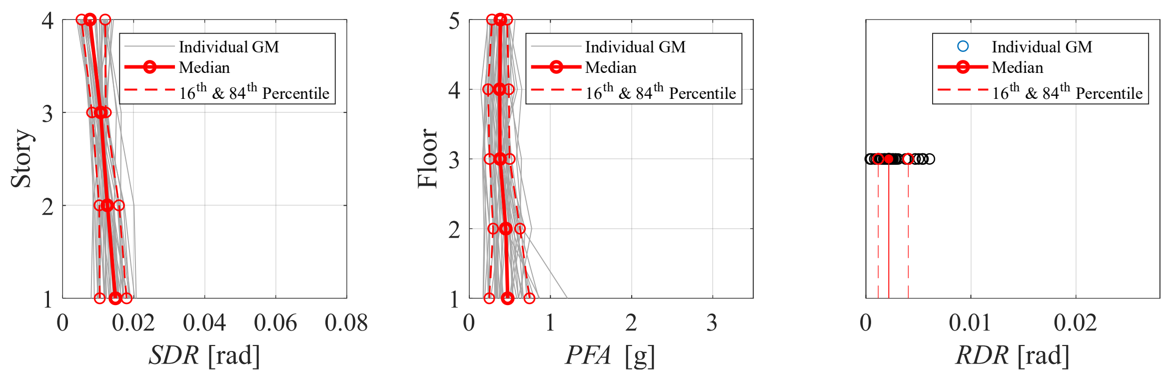


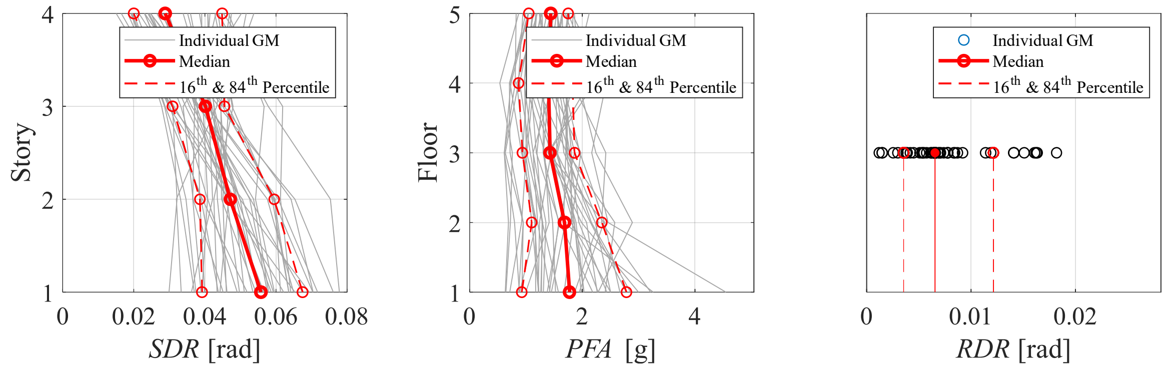
Figure 22.6. EDP data definition in the multiple stripes analysis module



(a) Stripe #1



(b) Stripe #2



(c) Stripe #3

Figure 22.7. Profiles of imported EDPs along the building height at three different stripes

Hazard Data: The seismic hazard curve for the building location is imported from the text file "*Template Hazard Curve.txt*" that is provided in EaRL's supporting documents folder.

Demolition: In the "Demolition" module, the univariate demolition fragility option is selected as shown in Figure 22.8. The following fragility population parameters are specified: for the *RDR* μ=0.011 rad and $\sigma_{\ln RDR}$ =0.25. These values represent the common practice for steel frame building demolition in North America based on the recent recommendation by Elkady et al. (2020).

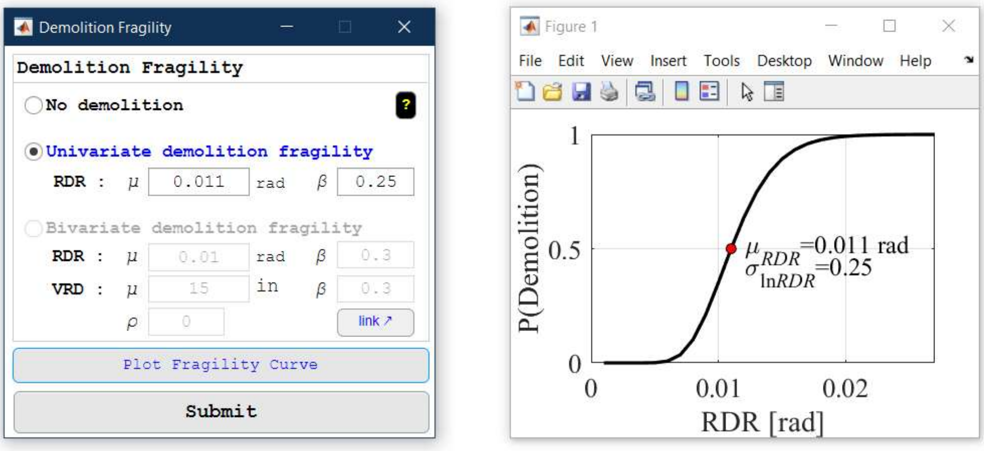


Figure 22.8. Demolition fragility curve definition

Collapse: In the "Collapse" module, the univariate collapse fragility option is selected as shown in Figure 22.9. The collapse fragility curve is defined by specifying a point on the curve and the dispersion parameter. In particular, a probability of collapse equal to 6% at *IM*=1.1g (i.e., maximum considered earthquake intensity). Note that this value can be inferred from the nonlinear response-history analyses by counting the number of GM records that causes collapse at a given intensity. The collapse fragility curve dispersion is taken as $\sigma_{\ln IM}$ =0.40 which is a typical value expected from record-to-record variability (NIST 2010; Elkady and Lignos 2014, 2015).

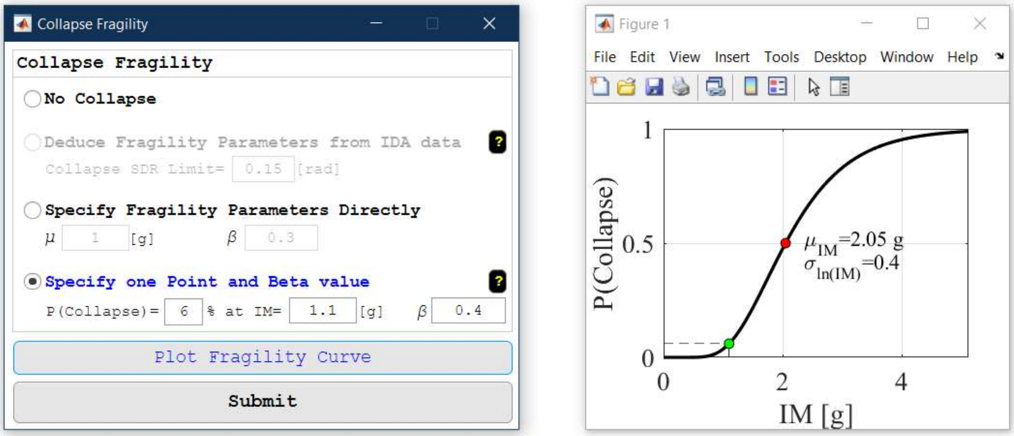


Figure 22.9. Collapse fragility curve definition

Population Model: No modifications are specified to the "Population Model". Therefore, the default model as per FEMA-P58 will be used.

Repair Time Scheme: In this example, all the building components are set to be repaired simultaneously. This scheme is selected as shown in Figure 22.10. Also, the units of the same component as well as components in different stories or at different floors will be repaired in parallel.

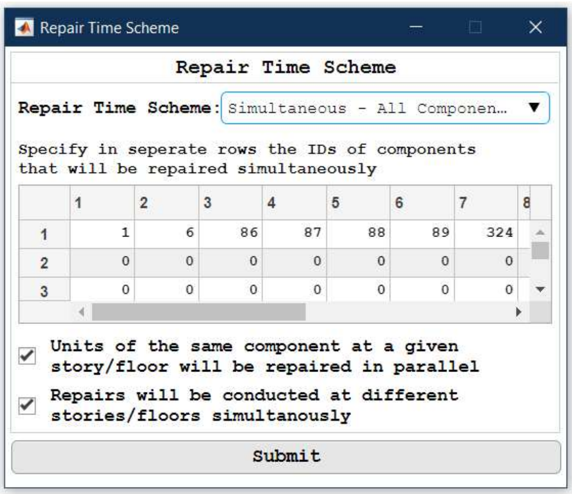


Figure 22.10. Repair time scheme definition

IM/EDP Bins: No modifications are specified to the "IM/EDP Bins". Therefore, the default ranges and values will be used.

Methodology option: Now that the project is fully defined, we press the "Compute" button. This prompts the "Methodology Options" module, as shown in Figure 22.11 where the FEMA P-58 methodology is selected for this example. A total of 1000 realizations, per stripe, are specified. An additional uncertainty of 0.2 is specified; represent the uncertainty in the numerical modeling parameters used to obtain the seed EDP data. The box for computing unsafe placard potential is selected.

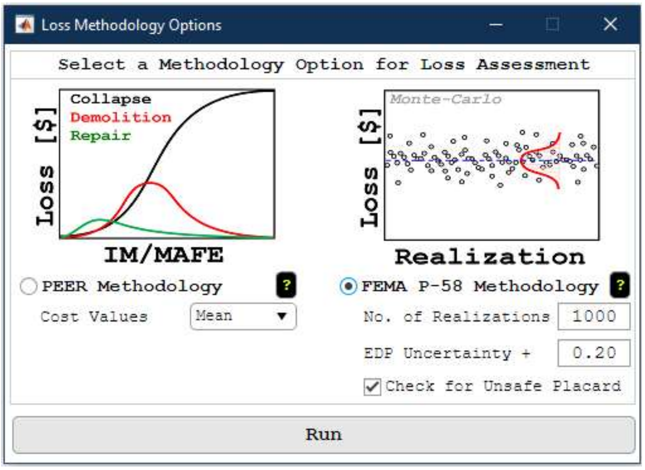
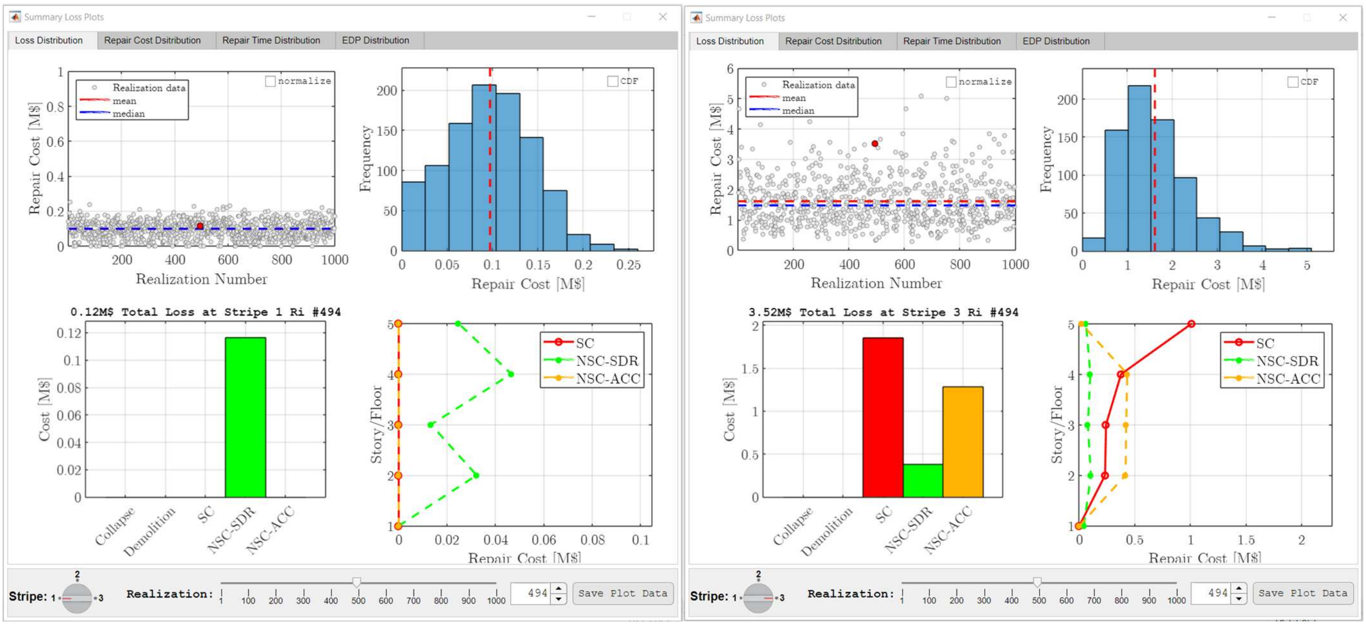
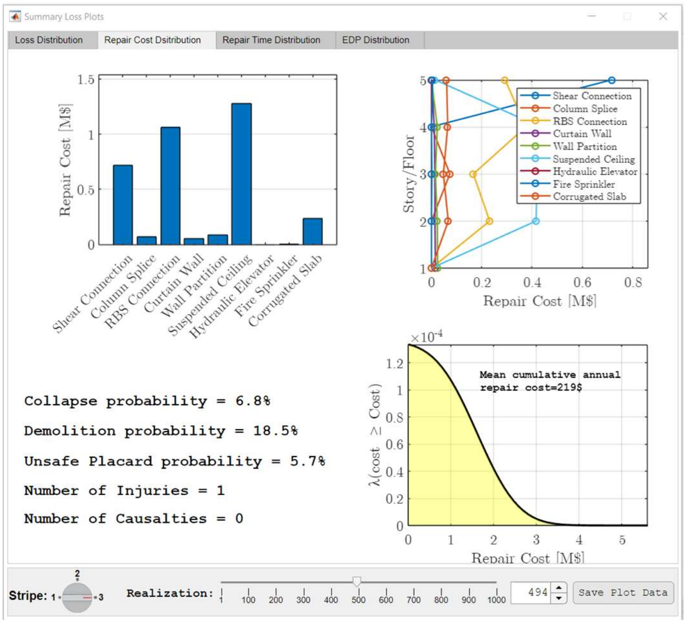


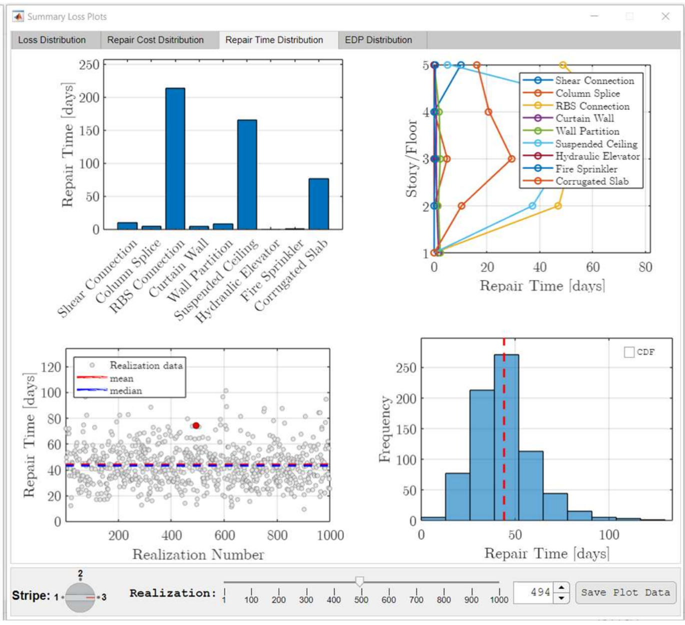
Figure 22.11. Loss methodology option used for the loss estimation

The elapsed time for this computation is about 5 minutes. The relatively longer computation time is because of the inclusion of the unsafe placard computation. After the completion of the computations, the "Visualize" and "Report" buttons become active in the main console. A number of plots are available in the visualization module for this example (refer to **Error! Reference source not found.** and Figure 17.8). Here, we are going to go through the results presented in the "Summary Plots" interface shown in Figure 22.12. Based on the summarized loss distribution data (first tab; see Figure 22.12a-b), we observe a mean repair cost of about 0.1 M$ for stripe #1 (*IM*=0.3g). This repair cost goes up to about 1.5 M$ for stripe #3 (*IM*=1.1g). From the summarized repair cost distribution data (second tab; see



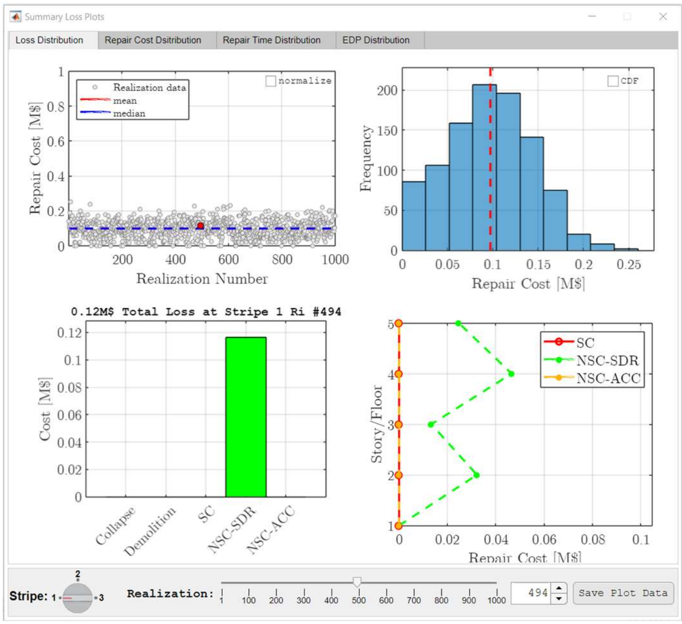
(a) (b)

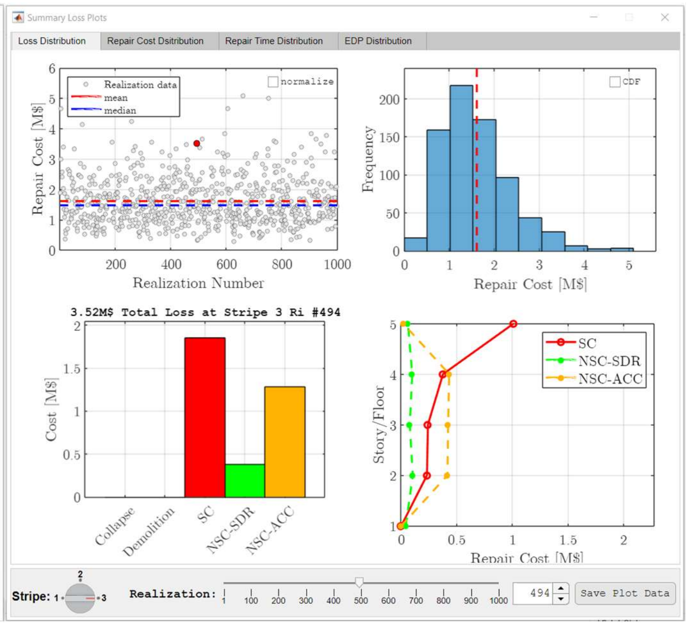




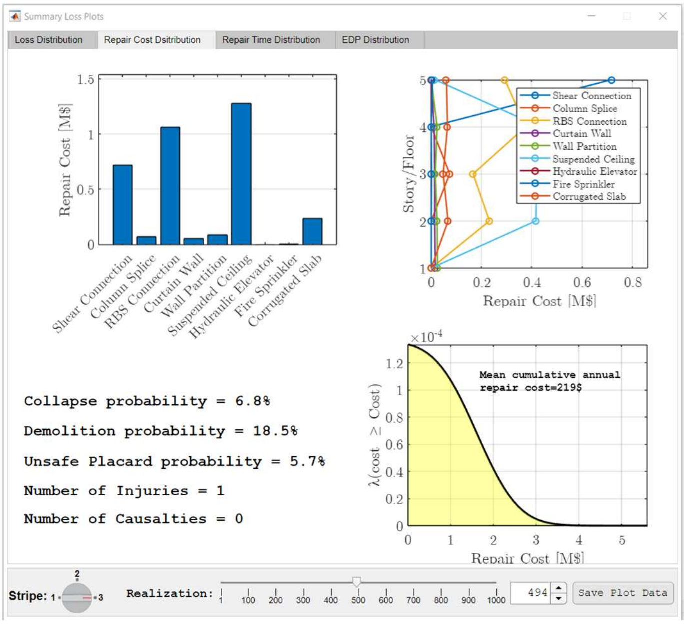
(c) (d)

Figure 22.12c), we can observe the disaggregation of repair cost among the different building components for a particular realization. For instance, it appears that most losses (most damage) is contributed by the *suspended ceiling*, the *corrugated slab* and the *steel frame connections*. From the second tab, we can also find the that the collapse and demolition probabilities are 6.8% and 18.5%, respectively at stripe #3. No casualties are expected even at highest seismic intensity, however, a single injury is to be expected as well as a 5.7% probability of issuing an unsafe placard. From the summarized repair time distribution data (third tab; see Figure 22.12d), we find that a mean repair time of 43 days is expected at the highest seismic intensity (stripe #3).

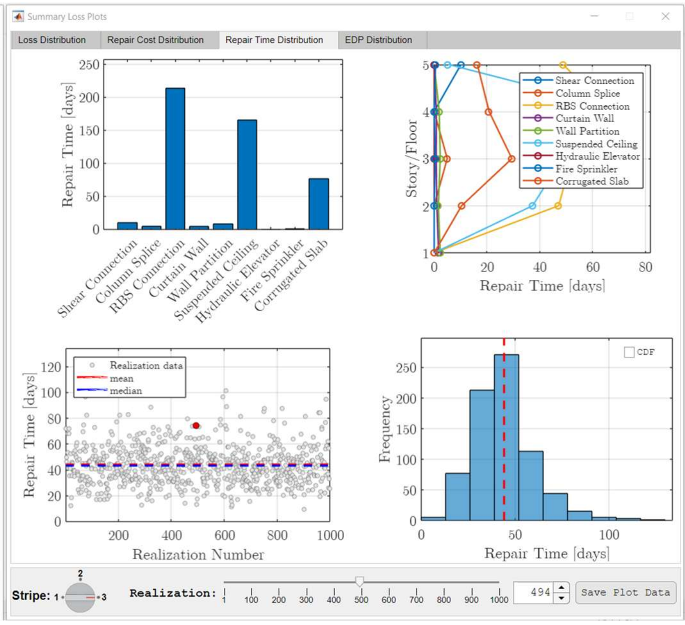




(a) (b)



(c)



(d)

Figure 22.12. Project summary loss plots

23. References

Almufti, I., and Willford, M. (2013). "REDi™ rating system: Resilience-based earthquake design initiative for the next generation of buildings." *Arup Co*, DOI:

ASCE (2006). "Minimum Design Loads for Buildings and Other Structures." *ASCE/SEI 7-05*, Reston, VA.

ASCE (2010). "Minimum Design Loads for Buildings and Other Structures." *ASCE/SEI 7-10*, Reston, VA.

Aslani, H., and Miranda, E. (2005). "Probabilistic Earthquake Loss Estimation and Loss Disaggregation in Buildings." *Report No. 157*Stanford, CA.

Clifton, C., Bruneau, M., MacRae, G., Leon, R., and Fussell, A. (2011). "Steel Structures Damage from the Christchurch Earthquake Series of 2010 and 2011." *Bulletin of the New Zealand Society for Earthquake Engineering*, 44(4), 297-318, DOI:

Comerio, M. C., and Blecher, H. E. (2010). "Estimating Downtime from Data on Residential Buildings After the Northridge and Loma Prieta Earthquakes." *Earthquake Spectra*, 26(4), 951-965, DOI:

Cook, D. T., Liel, A. B., Haselton, C. B., and Koliou, M. (2022). "A framework for operationalizing the assessment of post-earthquake functional recovery of buildings." *Earthquake Spectra*, 38(3), 1972-2007, DOI: 10.1177/87552930221081538.

Cornell, C. A., and Krawinkler, H. (2000). "Progress and Challenges in Seismic Performance Assessment." *PEER Center News*, 3(2), 1-3, DOI:

Deierlein, G. G. (2004). "Overview of a Comprehensive Framework for Earthquake Performance Assessment." *PEER Report 2004/05*, University of California, Berkeley, Berkeley, CA, USA, 15-26.

Eads, L., Miranda, E., Krawinkler, H., and Lignos, D. G. (2013). "An Efficient Method for Estimating the Collapse Risk of Structures in Seismic Regions." *Earthquake Engineering & Structural Dynamics*, 42(1), 25-41, DOI: 10.1002/eqe.2191.

Elkady, A., Güell, G., and Lignos, D. G. (2020). "Proposed Methodology for Building-Specific Earthquake Loss Assessment Including Column Residual Axial Shortening." *Earthquake Engineering and Structural Dynamics*, 49(4), 339-355, DOI: 10.1002/eqe.3242.

Elkady, A., and Lignos, D. G. (2014). "Modeling of the Composite Action in Fully Restrained Beam-to-Column Connections: Implications in the Seismic Design and Collapse Capacity of Steel Special Moment Frames." *Earthquake Engineering & Structural Dynamics*, 43(13), 1935-1954, DOI: 10.1002/eqe.2430.

Elkady, A., and Lignos, D. G. (2015). "Effect of Gravity Framing on the Overstrength and Collapse Capacity of Steel Frame Buildings with Perimeter Special Moment Frames." *Earthquake Engineering & Structural Dynamics*, 44(8), 1289–1307, DOI: 10.1002/eqe.2519.

FEMA (2000). "Prestandard and Commentary for the Seismic Rehabilitation of Buildings." *Report FEMA-356*, Federal Emergency Management Agency, Washington, DC.

FEMA (2009). "Quantification of Building Seismic Performance Factors." *Report FEMA-P695*, Federal Emergency Management Agency, Washington, DC.

FEMA (2012). "Seismic Performance Assessment of Buildings." *Report FEMA P-58-1*, Federal Emergency Management Agency, Washington, DC.

Ghosh, S. K. (1995). "Observations on the Performance of Structures in the Kobe Earthquake of January 17, 1995." *PCI journal*, 40(2), 14-22, DOI:

Goltz, J. (1994). "The Northridge, California Earthquake of January 17, 1994: General Reconnaissance Report." *Report NCEER-94-0005*, National Center for Earthquake Engineering Research (NCEER), New York, USA.

Hamburger, R. O., Rojahn, C., Heintz, J. A., and Mahoney, M. G. (2012). "FEMA P58: Next-Generation Building Seismic Performance Assessment Methodology." *Proc., 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.

Huang, Y.-N., Whittaker, A. S., and Hamburger, R. O. (2017). "A Simplified Analysis Procedure for Performance-Based Earthquake Engineering of Buildings." *Engineering Structures*, 150, 719-735, DOI: 10.1016/j.engstruct.2017.07.048.

Hutt, C. M., Vahanvaty, T., and Kourehpaz, P. (2022). "An analytical framework to assess earthquake-induced downtime and model recovery of buildings." *Earthquake Spectra*, 38(2), 1283-1320, DOI: 10.1177/87552930211060856.

Krawinkler, H., and Miranda, E. (2004). "Performance-Based Earthquake Engineering." *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*, 9, 9-1-9-59, DOI:

MATLAB (2019). *version 9.13.0 (R2022b)*, The MathWorks Inc., Natick, Massachusetts, USA.

Mckenna, F. T. (1997). "Object-Oriented Finite Element Programming: Frameworks for Analysis, Algorithms and Parallel Computing." Ph.D., University of California.

Metropolis, N., and Ulam, S. (1949). "The Monte Carlo Method." *Journal of the American Statistical Association*, 44(247), 335-341, DOI:

Moehle, J., and Deierlein, G. G. (2004). "A Framework Methodology for Performance-Based Earthquake Engineering." *Proc., 13th World Conference on Earthquake Engineering*, Vancouver, Canada.

NIST (2010). "Evaluation of the FEMA P695 Methadology for Quantification of Building Seismic Performance Factors." *NIST GCR 10-917-8*, NEHRP consultants Joint Venture.

Papadopoulos, A. N., Vamvatsikos, D., and Kazantzi, A. (2017). "Development of FEMA P-58 Compatible Story Loss Functions: Steel Office Buildings in Highly Seismic Regions." *Proc., 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, Rhodes Island, Greece.

Paul, N., Lee, J. S., Mieler, M., and Almufti, I. (2018). "Improving Estimates of Earthquake-Induced Downtime in Individual Buildings Using the REDi Methodology." *Proc., Structures Congress 2018*, Fort Worth, Texas, USA, 77-86.

Petersen, M. D., Frankel, A. D., Harmsen, S. C., Mueller, C. S., Haller, K. M., Wheeler, R. L., Wesson, R. L., Zeng, Y., Boyd, O. S., and Perkins, D. M. (2008). "Documentation for the 2008 Update of the United States National Seismic Hazard Maps." Geological Survey (US).

Porter, K. A. (2003). "An Overview of PEER's Performance-Based Earthquake Engineering Methodology." *Proc., 9th International Conf. on Applications of Statistics and Probability in Civil Engineering*, San Francisco, USA.

Ramirez, C. M., and Miranda, E. (2009). "Building-Specific Loss Estimation Methods and Tools for Simplified Performance-Based Earthquake Engineering." *Report No. 171*, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.

Saatcioglu, M., Tremblay, R., Mitchell, D., Ghobarah, A., Palermo, D., Simpson, R., Adebar, P., Ventura, C., and Hong, H. (2013). "Performance of Steel Buildings and Nonstructural Elements During the 27 February 2010 Maule (Chile) Earthquake." *Canadian Journal of Civil Engineering*, 40(8), 722-734, DOI: 10.1139/cjce-2012-0244.

SEAOC (1995). "Performance Based Seismic Engineering of Buildings." Structural Engineers Association of California (SEAOC), Sacramento, California.

Vamvatsikos, D., and Cornell, C. A. (2002). "Incremental Dynamic Analysis." *Earthquake Engineering & Structural Dynamics*, 31(3), 491-514, DOI: 10.1002/eqe.141.

Yang, T. Y., Moehle, J., Stojadinovic, B., and Der Kiureghian, A. (2009). "Seismic Performance Evaluation of Facilities: Methodology and Implementation." *Journal of Structural Engineering*, 135(10), 1146-1154, DOI: 10.1061/(ASCE)0733-9445(2009)135:10(1146).