

## **EaRL: TOOLBOX FOR EARTHQUAKE RISK AND LOSS ASSESSMENT OF BUILDING ASSETS**

Ahmed ELKADY<sup>1</sup>, Seong-Hoon HWANG<sup>2</sup>, Dimitrios LIGNOS<sup>3</sup>

### **ABSTRACT**

Infrastructure (asset) risk management is essential for a resilient environment. Several industries are concerned to improve their building asset preparedness subject to seismic hazard. To this end, the development of software tools that quantify and assess the potential risk of our assets subject to earthquakes is essential. These tools can facilitate the decision-making for appropriate pre-disaster measures based on robust risk and loss metrics. They can also facilitate the utilization of state-of-the-art building technology such that investments, that strengthen our assets, can be prioritized in such a way that human casualties, injuries, and losses are minimized.

This paper presents an interactive toolbox that facilitates story-based building-specific earthquake-induced risk and loss assessment. The toolbox builds on concepts of uncertainty quantification, and risk-based assessment methodologies within the context of performance-based earthquake engineering. It provides the loss vulnerability curves as well as expected annual losses that explicitly consider structural and non-structural repairs, losses due to collapse, and building demolition due to residual deformations in the aftermath of earthquakes. Monetary losses can be further disaggregated using a range of visualization options to help make informed design/retrofit decisions. The capabilities of the toolbox are demonstrated through an illustrative example of a conventional steel frame office building subjected to earthquake hazard.

*Keywords: Toolbox; Damage assessment; Performance-based earthquake engineering; Economic losses; Risk assessment*

### **1. INTRODUCTION**

Earthquakes can cause substantial economic impact on communities due to infrastructure damage. The performance-based earthquake engineering (PBEE) framework (Cornell and Krawinkler 2000; FEMA 2012a) aims to limit structural damage beyond the life-safety requirement specified in current building codes. This involves designing new buildings or retrofitting existing ones to achieve target performance objectives under a given earthquake scenario. Target performance objectives involve reducing casualties as well as direct and indirect monetary losses due to structural/non-structural damage and business interruption over the building's life cycle. In that respect, the PBEE framework is commonly utilized to account for the uncertainty arising from the seismic hazard, the structural response and the induced structural damage.

Due to the relative complexity associated with conducting building-specific loss assessment, its use in engineering practice is relatively limited. To that end, few computer-aided tools have been developed, e.g. MDLA (Mitrani-Reiser 2007), PEER Loss Estimation Toolbox (Ramirez and Miranda 2009), PACT (FEMA 2012b), and more recently SP3 (SP3 2017). Some of which did not have an interactive user interface or have an intricate one while others were not published or were available only for commercial

---

<sup>1</sup>Postdoctoral Research Scientist, Swiss Federal Institute of Technology, Lausanne, Switzerland, [ahmed.elkady@epfl.ch](mailto:ahmed.elkady@epfl.ch)

<sup>2</sup>Research Professor, Department of Architectural Engineering, Dankook University, South Korea, [hoonic@gmail.com](mailto:hoonic@gmail.com)

<sup>3</sup>Associate Professor, Department, Swiss Federal Institute of Technology, Lausanne, Switzerland, [dimitrios.lignos@epfl.ch](mailto:dimitrios.lignos@epfl.ch)

use. Accordingly, this paper presents a MATLAB-based toolbox with a graphical user-friendly interface for earthquake risk and loss assessment (EaRL). This toolbox allows researchers and practitioners to effortlessly conduct story-based building-specific economic loss assessment. It also provides a wide range of visualization options to facilitate the interpretation of component contributions to monetary losses. This in turn assists building stakeholders make informed design/retrofit decisions.

## 2. LOSS ESTIMATION METHODOLOGY

Under a given earthquake scenario, a building undergoes one of two events: a) *Collapse* ( $C$ ) due to increasing lateral drifts and P-Delta forces coupled with deteriorating structural strength and b) *No-Collapse* ( $NC$ ). The latter possibility can be broken down into two events as well: c) *Demolish* due to the presence of large residual deformations that render the building irreparable; hence, it needs to be demolished and d) *Repair* due to the presence of structural and non-structural components damage in the absence of large residual deformations. These three mutually exclusive events (i.e., *Collapse*, *Demolish*, and *Repair*) are illustrated in Figure 1.

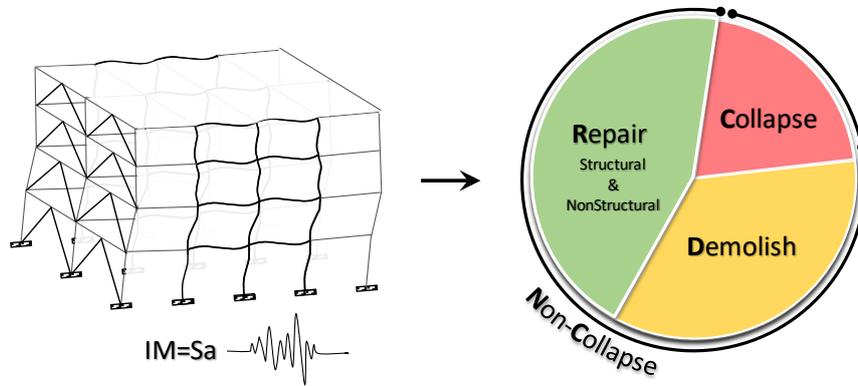


Figure 1. Illustration of mutually exclusive events in the aftermath of an earthquake

The EaRL toolbox computes the economic losses arising from each event by utilizing the building-specific story-based loss estimation methodology discussed in detail Ramirez and Miranda (2012). This methodology extended the scope of preceding methodologies (Deierlein 2004; Krawinkler and Miranda 2004; Aslani and Miranda 2005) by explicitly accounting for the possibility of building demolition due to large residual story deformations. The total expected economic loss arising from all events at a given intensity measure (IM),  $E[L_T|IM]$ , is expressed using Equation 1.

$$E[L_T | IM] = E[L_C | IM] + E[L_D | NC, IM] + E[L_R | NC \text{ and } ND, IM] \quad (1)$$

in which,  $E[L_C|IM]$  is the expected loss due to collapse,  $E[L_D|NC, IM]$  is the expected loss due to building demolition given *No-Collapse*, and  $E[L_R |NC \text{ and } ND, IM]$  is the expected repair losses given *No-Collapse* and *No-Demolition*. Figure 2 shows a flowchart outlining the procedure for calculating the total economic monetary loss for a building. In summary,  $E[L_C|IM]$  is calculated as the product of the collapse fragility curve and the building replacement cost. The collapse fragility curve provides the probability of collapse at a given intensity level,  $IM=im$ . This curve can be deduced from incremental dynamic analysis (IDA) data as shown in Figure 2. Similarly,  $E[L_D|IM]$  is calculated as the product of the demolition fragility curve and the cost of demolishing and replacing the building. The demolition fragility curve can be deduced by integrating the cumulative distribution function describing the probability of demolition given the residual drift demand  $P(Demolish|RDR)$  over the density function relating the probability of residual drift demand and the intensity level  $im$ ,  $f(RDR|im)$ . The  $E[L_D|NC, IM]$  can be then deduced by multiplying  $E[L_D|IM]$  by the complementary probability of collapse,  $1-P(Collapse)$ , (i.e., probability of *No-Collapse*). Finally, the repair losses,  $E[L_R|IM]$ , are calculated as the summation of individual damage state losses for each structural/non-structural component at each story.

The loss due to a single damage state is calculated as the product of the damage state (*DS*) fragility given *im*,  $P(DS|im)$ , and the associated repair cost. The damage state fragility,  $P(DS|im)$ , can be deduced by integrating the cumulative distribution function describing the probability of being in a given damage state given the associated engineering demand parameter (EDP),  $P(DS|EDP)$  over the probability density function relating EDP and *im*,  $f(EDP|im)$ . The  $E[L_R/NC \text{ and } ND, IM]$  can be then deduced by multiplying  $E_R$  by the complementary probabilities of demolition and collapse,  $1-P(Demolish)$  and  $1-P(Collapse)$ .

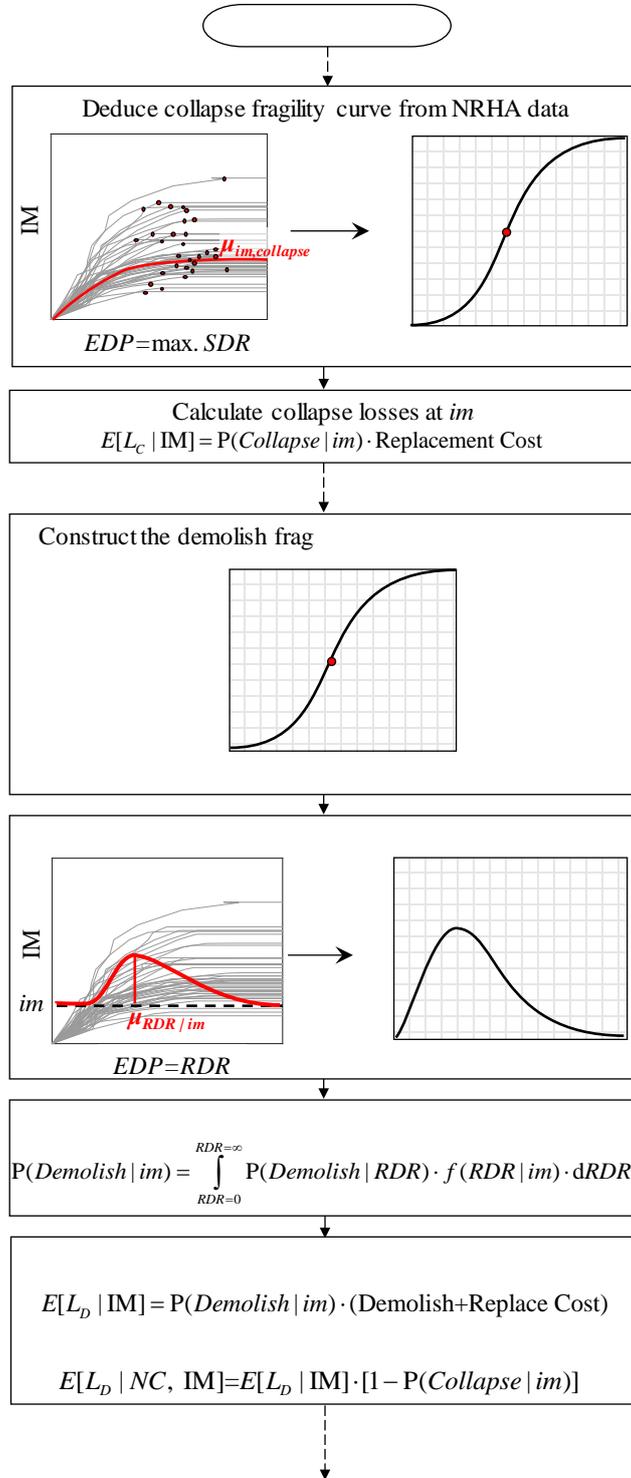


Figure 2. Procedure outline for monetary loss calculation

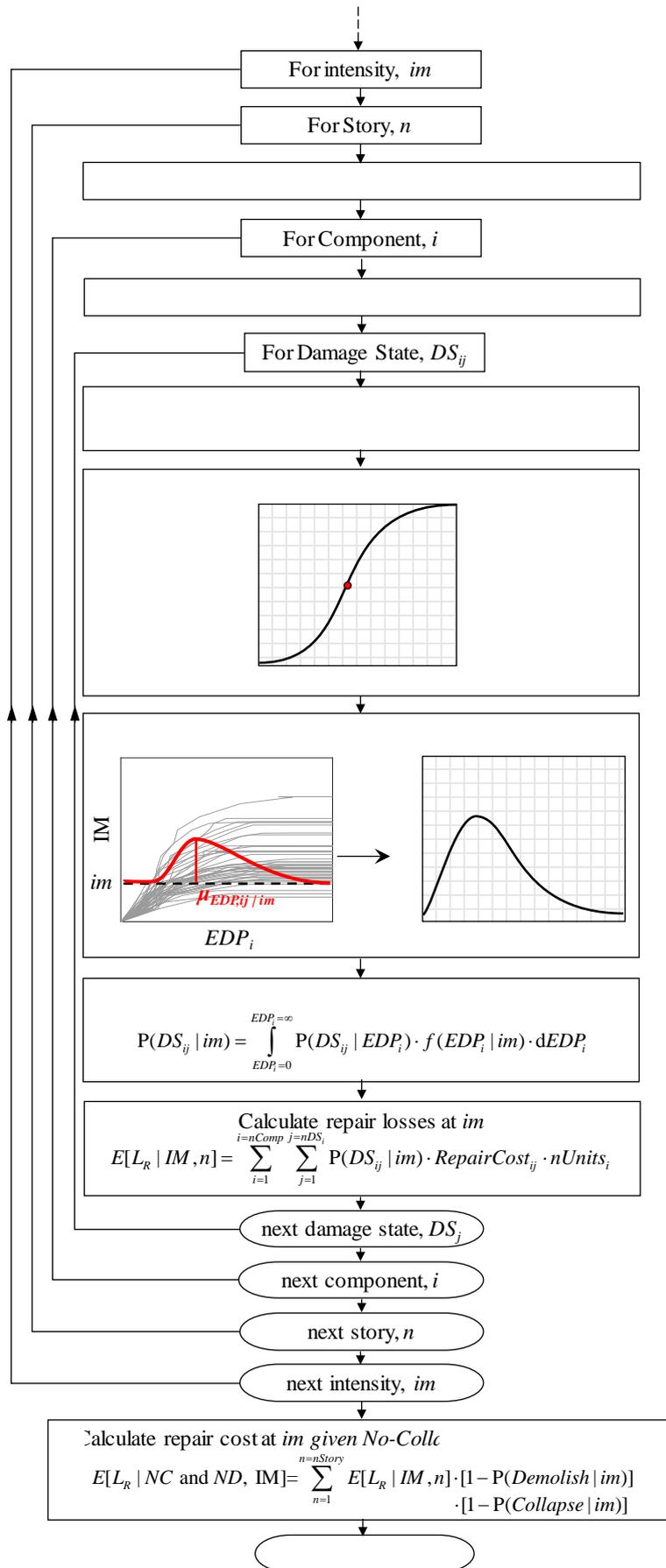


Figure 2. Procedure outline for monetary loss calculation (*continue*)

### 3. DESCRIPTION OF THE TOOLBOX MODULES

The main console of the EaRL toolbox is shown in Figure 3. The current console consists of six main modules. For any given project, loss assessment can be performed by defining the three main modules: Building Data, Component Data and Response Data. The remaining modules are optional. The scope and features of each module are discussed in the following subsections.

#### 3.1 Building Data Module

The first step of a new project is to define the building main characteristics and attributes. This data is entered through the Building Data module shown in Figure 4. This includes the building construction material(s) and the lateral load-resisting structural system(s). This information is used to filter the large component and fragility databases integrated into the toolbox; hence, simplifying the subsequent steps of selecting the building's components as well as reducing the processing time for repair cost calculations. Other building data include the number of stories and the story height, the foot print area, the total floor area, as well as the cost and time associated with demolishing and replacing the building. This data can also be used to auto-generate structural response EDPs or to directly estimate story-based losses as discussed in subsequent sections.

#### 3.2 Component Data Module

In the Component Data Module shown in Figure 5, the building content in terms of the structural (SC) and non-structural (NSC) components, allocated at each story, are defined. Two options are available in this module. The first option represents the simplified approach where functions that directly relate expected monetary losses (i.e., DV: decision variable) at a given story to the story EDPs, can be utilized. These DV-EDP functions are commonly known as the “story-loss functions”. The toolbox currently 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 frames, respectively. To use this option, only few additional information regarding the building typology need to be provided by the user.

The second option represents the more rigorous approach where the inventory of individual components at each story/floor needs to be explicitly defined by the user. For this purpose, the component data module integrates the full FEMA P-58 (FEMA 2012a) fragility database, which comprises of a total of 764 different components and a corresponding total of 1784 damage states. For each damage state, the database provides the controlling EDP (e.g. story-drift ratio, floor acceleration, and local member rotation), median and standard deviation (i.e., population parameters) of the lognormal/normal damage fragility function, and the associated repair cost. The data can be entered individually for each component using dropdown menus or collectively using a preformatted EXCEL file (see Figure 5). The user can explore the fragility curves for each component through the Fragility Data module as shown in Figure 6a. Other options provided by the Fragility Data module are discussed in the next section.

#### 3.3 Fragility Data Module

Component damage-fragility curves are being developed/updated regularly. Therefore, the EaRL toolbox provides the user with the option to define his/her own fragility and add it to the existing database. This is accomplished through the Fragility Data module shown in Figure 6. This module comprises of two main options. The first one allows for the user to define a new lognormal univariate fragility curve as shown in Figure 6b. In this case, the user defines the component name, type (SC or NSC), the damage state description and number, the controlling EDP, the damage state lognormal population parameters ( $\mu_{EDP}$ ,  $\sigma_{EDP}$ ), and the associated repair cost and time. The toolbox enables the user to define a wide range of story-based EDPs as well as local EDPs (e.g., plastic rotation) in structural members such as columns, beams, and dissipative links.

The second option allows for the user to define other-than-lognormal univariate fragility functions as

well as multivariate fragility functions. Multivariate fragilities typically consider material, geometric, and loading parameters that influence the extent of component damage. Hence, they can provide a more accurate estimation of damage compared to univariate ones. Some examples of such fragilities can be found literature involving steel braces and infill walls (Lignos and Karamanci 2013; Chiozzi and Miranda 2017). In this case, the user directly provides the multivariate fragility function in addition to the basic fragility data discussed earlier as shown in Figure 6b. This feature is commonly seen in currently available loss-estimation toolboxes.

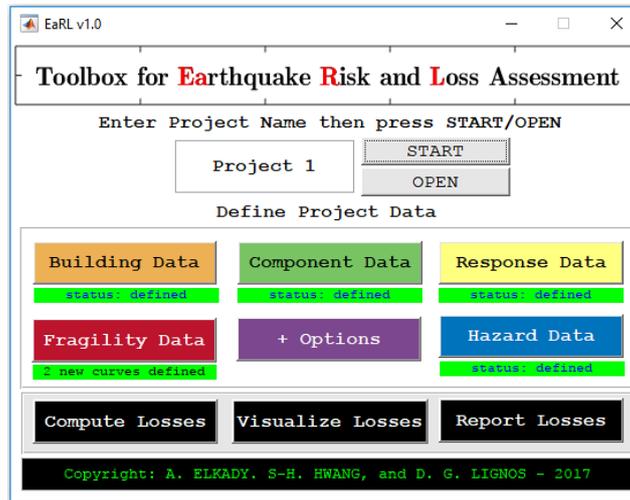


Figure 3. Main console of EaRL v1.0

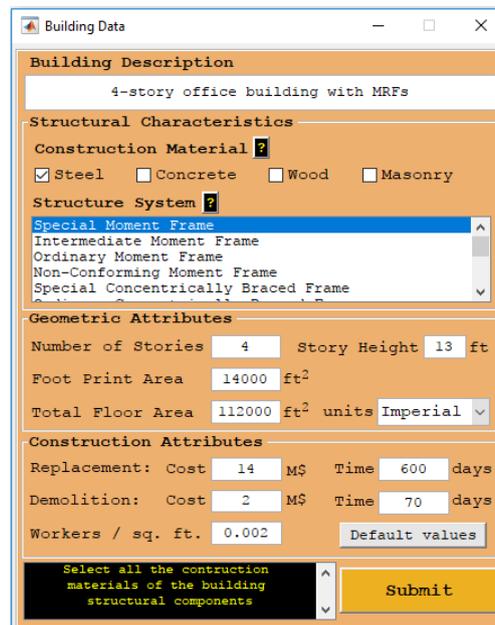


Figure 4. Building Data module

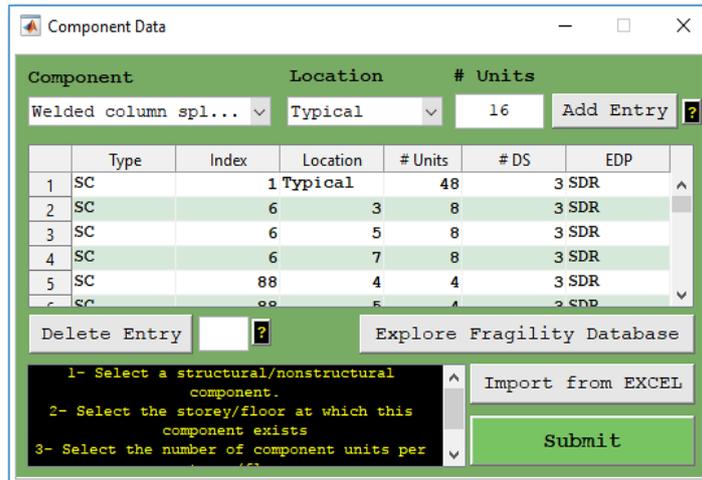


Figure 5. Component Data module

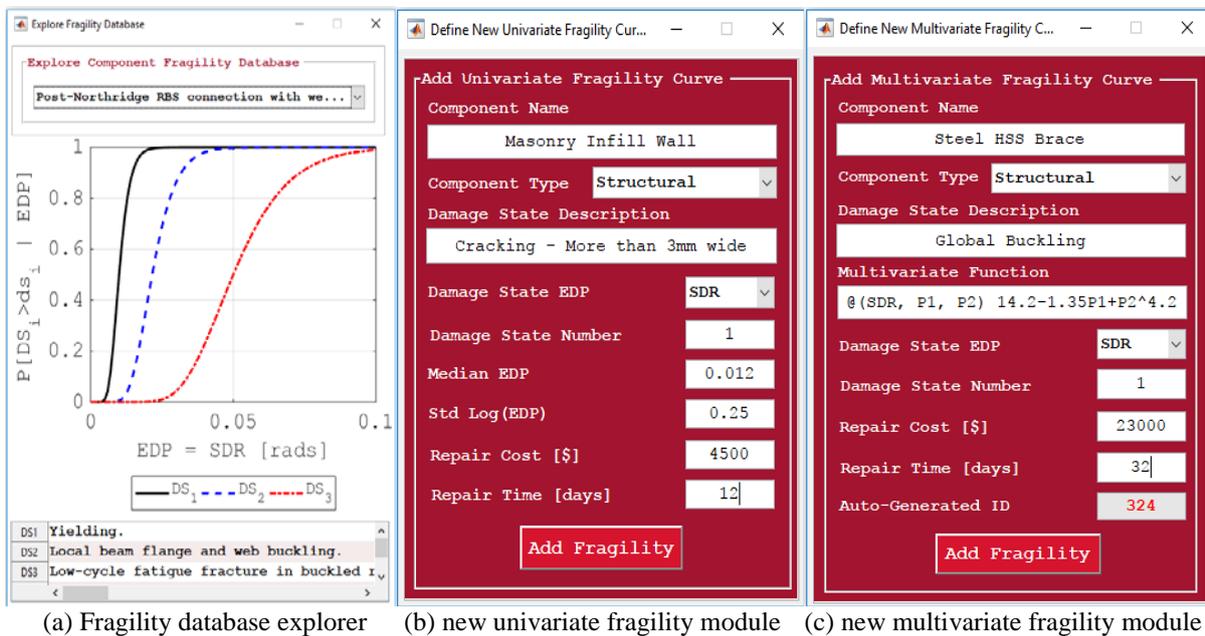


Figure 6. Fragility Data module options

### 3.4 Response Data Module

The last main step in defining a project is to input the structural response in terms of the EDPs at each story/floor. This type of data is typically obtained from nonlinear-response history analysis (NRHA) or FEMA-P58 simplified method. Other data-driven non-model based approaches could be utilized (Hwang and Lignos 2017) as part of this step. Four options are available to input such data through the Response Data module as shown in Figure 7a. *Option 1* represents the most general case, where EDPs data are available from multiple ground motions scaled at multiple seismic intensities. This type of data is typically produced when IDA (Vamvatsikos and Cornell 2002) is conducted. The input data in this case are processed to deduce the median and lognormal standard deviation of the collapse fragility curve and the story-based EDPs at a given *im*. *Option 2* represents the case where EDPs data are available from multiple ground motions scaled at a single intensity. This is typically the case in engineering practice that a building is analyzed under a set of ground motion records at a target seismic intensity/hazard of interest (e.g. design-basis and maximum considered earthquake intensities). *Option 3* represents the case where EDP data are available from a single ground motion analysis at a single seismic intensity. In this option, the user directly provides story-based EDP values. These are assumed

to be median values with zero dispersion. For *Options 2* and *3*, the data are entered using a pre-formatted EXCEL file. In all three options, the toolbox reads the EDP data, conducts basic sanity checks, and informs the user of any possible mistakes. Within the same module, the user can further check if the data was imported correctly by visualizing for instance the EDP distributions along the building height (see Figure 7b). Finally, *Option 4* can be used to auto-generate EDP data based on the FEMA P-58 Simplified Method (FEMA 2012a). This method generates EDP data at multiple intensities using an equivalent single-degree-of-freedom approximation of the structure and a predefined static pushover curve (Vamvatsikos and Cornell 2006; Baltzopoulos et al. 2017).

### 3.5 Hazard Data Module

To calculate the expected annual losses (EAL), the vulnerability loss curves (i.e., expected loss as a function of IM) should be integrated over the seismic hazard curve. For this purpose, the seismic hazard data (i.e., mean annual frequency of exceedance,  $\lambda$ , versus the seismic intensity,  $S_a$ ) need to be defined. This data can be entered manually using a pre-formatted EXCEL file. Alternatively, for buildings situated in the US, the user can utilize the 2008 updated seismic hazard maps (Petersen et al. 2008), which are integrated in the toolbox, to extract the hazard curves. In this case, the user only provides the building's latitude and longitude coordinates, its period  $T$ , and the shear wave velocity of the soil  $V_{s30}$  (i.e., soil type) as shown in Figure 8a. The discrete data points of the seismic hazard curve are then fitted with a fourth order polynomial function as suggested by Eads et al. (2013). This polynomial function is used for the numerical integration of the hazard curve. Within the same module, the imported/extracted hazard curve data and the fitted polynomial can be visualized as shown in Figure 8b.

### 3.6 Options Module

The toolbox enables the user to control the loss calculation for the collapse and demolition events. Through the Options module shown in Figure 9, the user may choose to include or exclude collapse- and demolition- related losses. To deduce the collapse fragility curve, three options are available. The first option deduced the collapse fragility curve directly from the input IDA data (this option is only valid for Response Data *Option 1*). The user can also enforce an SDR limit, at which collapse occurs, different from that assumed in the IDA simulations. In the second option, the median collapse intensity and dispersion of the collapse fragility curve can be specified directly. Finally, in the third option, collapse fragility can be defined by specifying a single point on the curve (e.g. probability of collapse at maximum-considered earthquake intensity) and the dispersion. Furthermore, by controlling the IM range and bin size, the user can control the numerical integration accuracy as well as the speed of the loss calculation process.

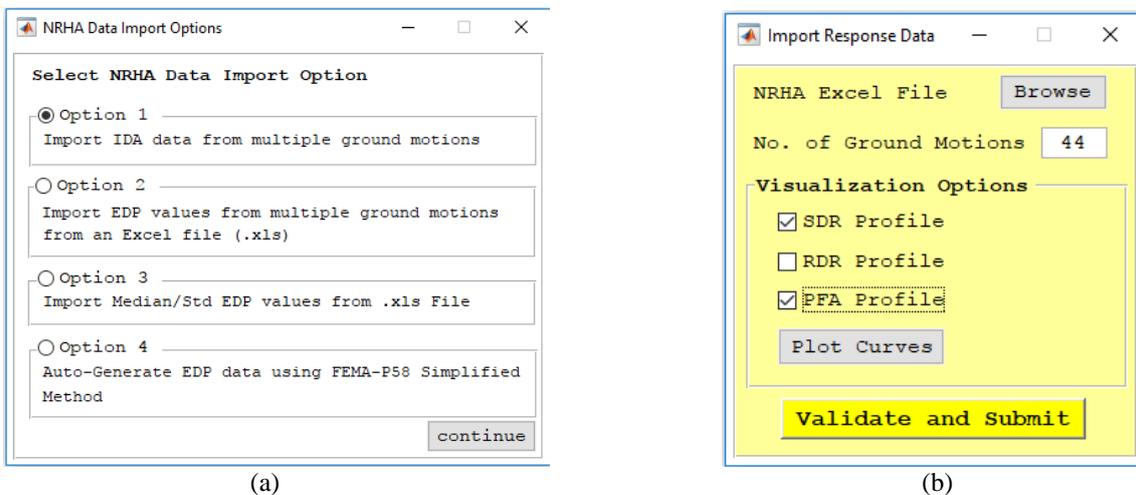
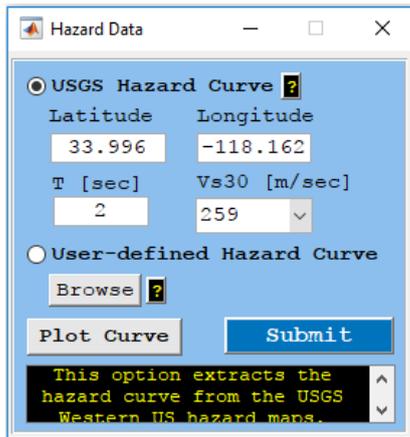
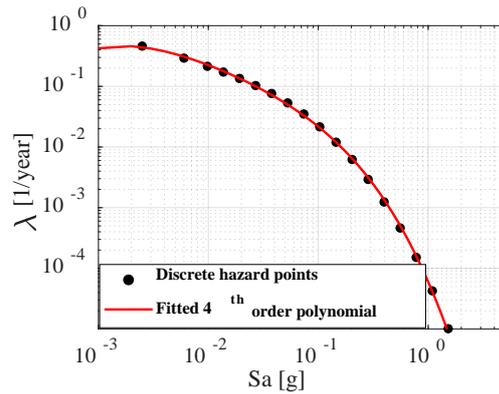


Figure 7. The different options within the NRHA Data module



(a)



(b)

Figure 8. Hazard Data module

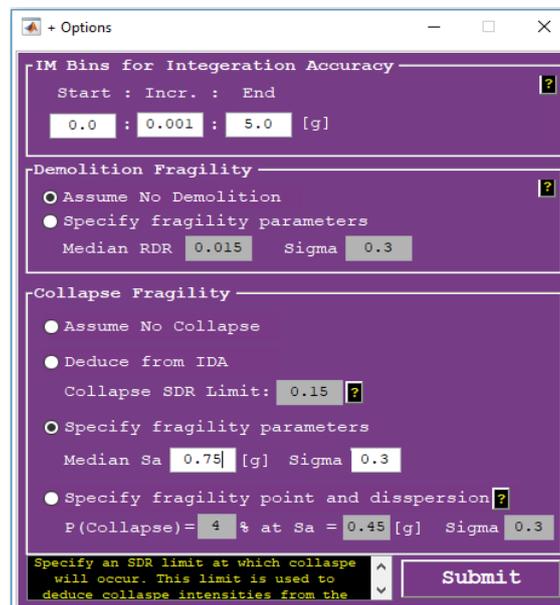


Figure 9. Options module

#### 4. ILLUSTRATIVE CASE STUDY

A 4-story steel frame building is used to demonstrate the visualization capabilities of the EaRL toolbox. The building has a rectangular plan with special moment resisting frames at its perimeter as shown in Figure 10. The building is located in downtown Los Angeles, California and designed per the 2010 seismic provisions in the US (AISC 2010; ASCE 2010) as discussed in Elkady and Lignos (2015). Other design parameters are summarized in Figure 10. The building's damageable components are listed in Table 1 for reference. Increment dynamic analysis was conducted through collapse (i.e., *Option 1*) in the building EW direction. Hence, it was possible to compute losses at all seismic intensities (i.e., vulnerability curves) and the corresponding expected annual losses.

The toolbox provides several options to visualize losses some of which are shown in Figure 11a. This includes loss vulnerability curves, expected annual losses, and repair cost profiles along the building height. The main loss summary window is shown in Figure 11b. This interactive window allows the user to explore the expected losses at different seismic intensities. Referring to Figure 12c, other visualization options allow the user to disaggregate the losses at a given seismic intensity/hazard

component by component. Such illustrations facilitate the component identification with the most contributions to earthquake-induced losses; hence, informed design/retrofit decisions can be taken.

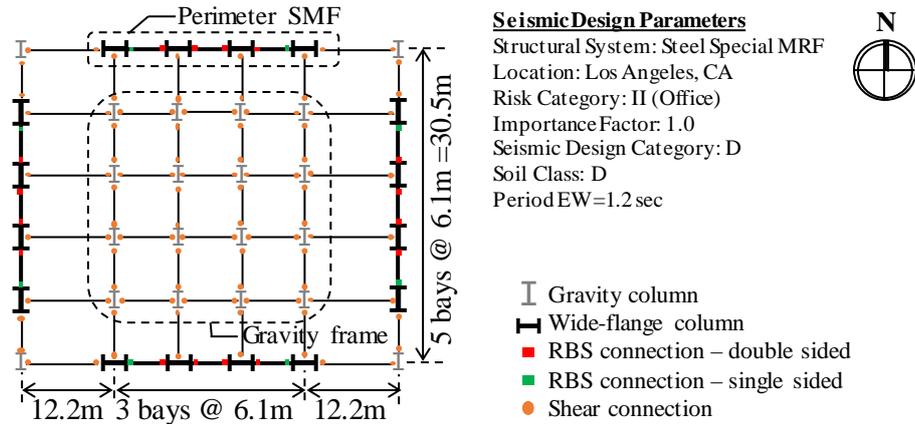


Figure 10. Plan view of the analyzed 4-story building

Table 1. Summary of damageable components in the 4-story steel office building

Type	Component name	Location	Unit/location	# DS	EDP*
SC	Steel shear connection	Typ. story	48	3	SDR
SC	Steel wide-flange column	Typ. story	8	4	SDR
SC	Steel column splice	3 <sup>rd</sup> story	8	3	SDR
SC	RBS connection – double sided	Typ. story	4	3	SDR
SC	RBS connection – single sided	Typ. story	4	3	SDR
NSC	Concrete slab	Typ. floor	1	3	SDR
NSC	Dry wall partition	Typ. story	5.9 m <sup>2</sup>	2	SDR
NSC	Dry wall finish	Typ. story	5.9 m <sup>2</sup>	2	SDR
NSC	Suspended ceiling	Typ. floor	EA	3	PFA
NSC	Exterior glazing	Typ. story	5.9 m <sup>2</sup>	2	SDR
NSC	Automatic sprinkler	Typ. floor	1.1 m <sup>2</sup>	1	PFA
NSC	Hydraulic elevator	Typ. story	2/building	1	PFA

\* SDR: story drift ratio; PFA: peak floor absolute acceleration; PGA: peak ground acceleration

## 5. SUMMARY

This paper presented the first version of EaRL; a MATLAB-based toolbox to calculate story-based building-specific earthquake-induced economic losses. The toolbox features an interactive interface that simplify data entry on the user's end. Options to auto-generate structural response data, story-based losses based on building typology, and to extract the seismic hazard curve based on the design location are made available. This makes rapid loss assessment possible with minimal effort. The option for user-defined univariate and multivariate damage fragility functions is provided in support of rigorous building-specific loss assessment projects. The toolbox also provides a range of visualization options to advance the user's understanding regarding the variation of expected losses along the height of a building at a given seismic intensity. Losses can be further disaggregated by component type contributions (structural and non-structural). This can help researchers and practitioners identify critical components and stories within a building that contribute most to earthquake-induced losses. Accordingly, informed design/retrofit decisions can be taken. The toolbox is regularly updated to include the latest developments in building-specific loss assessment methodologies. The authors are in the process of extending the scope of the toolbox to perform loss assessment at city-scale.

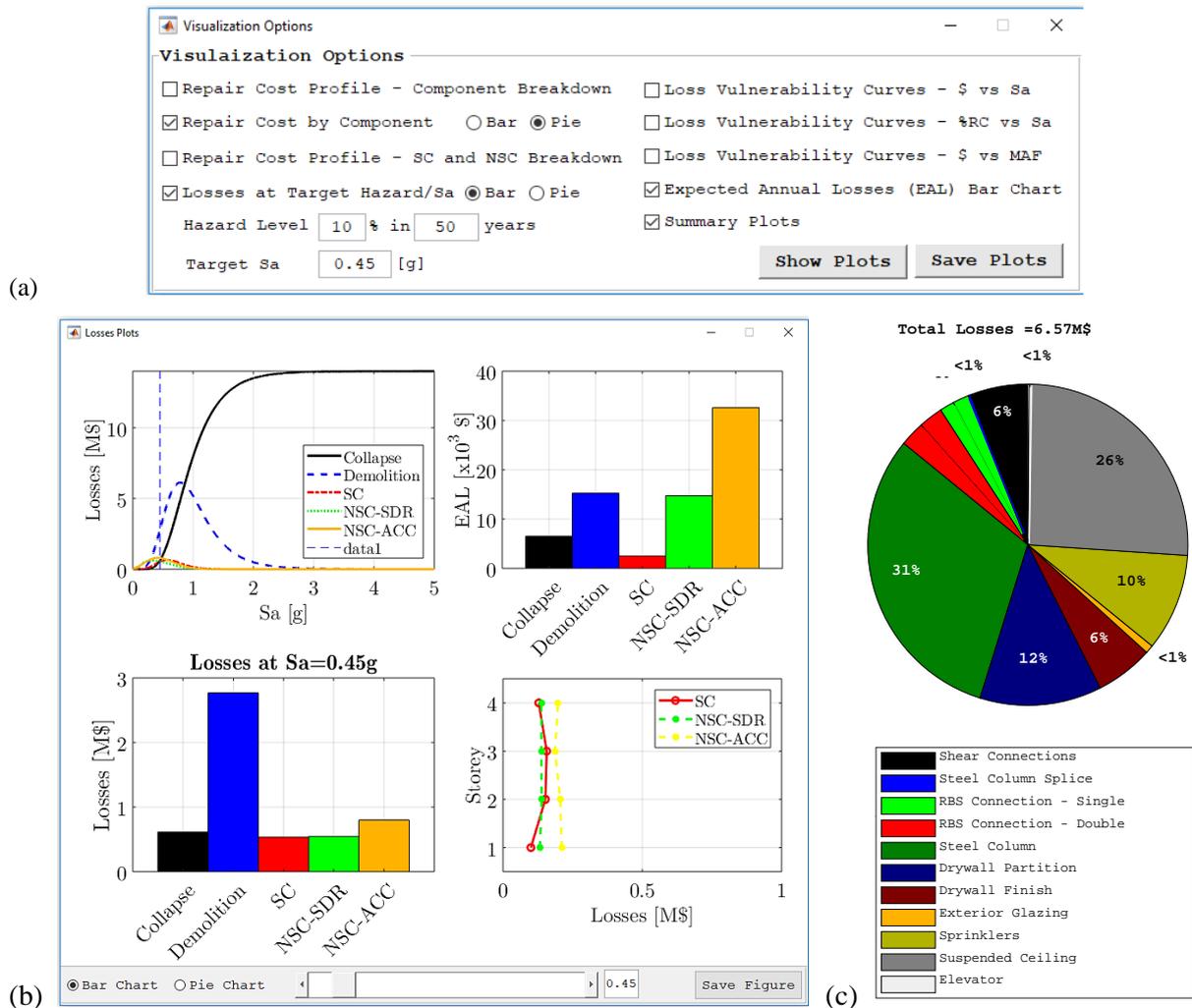


Figure 11. Loss visualization

## 6. ACKNOWLEDGMENTS

This work is financially supported by the Swiss National Science Foundation (Award No. 200021\_169248) and the Resilient Steel Structures Laboratory at Ecole Polytechnique Fédérale de Lausanne (EPFL). This financial support is gratefully acknowledged.

## 7. REFERENCES

- AISC (2010). Seismic provisions for structural steel buildings. *ANSI/AISC 341-10*, Chicago, IL.
- ASCE (2010). Minimum design loads for buildings and other structures. *ASCE/SEI 7-10*, Reston, VA.
- Aslani, H., Miranda, E. (2005). Probabilistic earthquake loss estimation and loss disaggregation in buildings. *Report No. 157*, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, CA.
- Baltzopoulos, G., Baraschino, R., Iervolino, I., Vamvatsikos, D. (2017). SPO2FRAG: Software for seismic fragility assessment based on static pushover. *Bull Earthquake Eng*, 15(10): pp 1-27.
- Chiozzi, A., Miranda, E. (2017). Fragility functions for masonry infill walls with in-plane loading. *Earthquake Engineering & Structural Dynamics*, 46(15): pp 2831-2850.

- Cornell, C. A., Krawinkler, H. (2000). Progress and challenges in seismic performance assessment. *PEER Center News*, 3(2).
- Deierlein, G. G. (2004). Overview of a comprehensive framework for earthquake performance assessment. *Performance-Based Seismic Design Concepts and Implementation, Proceedings of an International Workshop*, University of California, Berkeley, Berkeley, CA, USA, pp 15-26.
- Eads, L., Miranda, E., Krawinkler, H., Lignos, D. G. (2013). An efficient method for estimating the collapse risk of structures in seismic regions. *Earthquake Engineering & Structural Dynamics*, 42(1): pp 25-41.
- Elkady, A., 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 Dynamic*, 44(8): pp 1289–1307.
- FEMA (2012a). Seismic performance assessment of buildings. *Report FEMA P-58-1*, Federal Emergency Management Agency, Washington, DC.
- FEMA (2012b). Seismic performance assessment of buildings - volume 3 - performance assessment calculation tool (PACT), version 2.9.65. Federal Emergency Management Agency, Washington, DC, USA, Washington, DC, USA.
- Hwang, S.-H., Lignos, D. G. (2017). Assessment of structural damage detection methods for steel structures using full-scale experimental data and nonlinear analysis. *Bull Earthquake Eng*, pp 1-29.
- Krawinkler, H., Miranda, E. (2004). Performance-based earthquake engineering. *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*, 9: pp 1-9.
- Lignos, D. G., Karamanci, E. (2013). Drift-based and dual-parameter fragility curves for concentrically braced frames in seismic regions. *Journal of Constructional Steel Research*, 90: pp 209-220.
- Mitrani-Reiser, J. (2007). An ounce of prevention: Probabilistic loss estimation for performance-based earthquake engineering. *Ph.D. Thesis*, California Institute of Technology, Pasadena, CA, USA.
- Papadopoulos, A. N., Vamvatsikos, D., Kazantzi, A. (2017). Development of fema p-58 compatible story loss functions: Steel office buildings in highly seismic regions. *Proceedings of the 6<sup>th</sup> ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 15-17 June, Rhodes Island, Greece.
- 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., Perkins, D. M. (2008). Documentation for the 2008 update of the United States national seismic hazard maps. Geological Survey (US).
- Ramirez, C. M., 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.
- Ramirez, C. M., Miranda, E. (2012). Significance of residual drifts in building earthquake loss estimation. *Earthquake Engineering & Structural Dynamics*, 41(11): pp 1477-1493.
- SP3 (2017). Seismic performance prediction program, version 2.6, Haselton Baker Risk Group, LLC. Chico, CA, USA.
- Vamvatsikos, D., Cornell, C. A. (2002). Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, 31(3): pp 491-514.
- Vamvatsikos, D., Cornell, C. A. (2006). Direct estimation of the seismic demand and capacity of oscillators with multi-linear static pushovers through IDA. *Earthquake Engineering & Structural Dynamics*, 35(9): pp 1097-1117.