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EaRL—Software for Earthquake Risk, Loss and Lifecycle Analysis

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ABSTRACT

Performance-based earthquake engineering (PBEE) has become an increasingly popular framework to design, retrofit and manage structures. This probabilistic framework integrates data from the seismic hazard, structural response, damage fragility and damage consequences to compute structural performance metrics; thereby facilitating an effective communication to building owners and stakeholders besides the engineering community. In support of PBEE, a Matlab-based computational platform/software is developed that implements state-of-the-art loss estimation and seismic lifecycle analysis methodologies. The software aims to (1) facilitate the relatively challenging PBEE computations by providing an intuitive graphical user-interface, a wide range of data visualization options and collective features that adapt to different users' preferences; and (2) provide an open-source platform for code and software development to support the continuously advancing aspects of the PBEE framework.

Code metadata

Current code version	*v1.0*
Permanent link to code/repository	https://github.com/ElsevierSoftwareX/SOFTX_2020_142
Legal Code License	*GNU GPLv3*
Code versioning system used	*None*
Software code language	*Matlab*
Compilation requirements, operating environments & dependencies	*Microsoft Windows + MATLAB runtime*
Link to developer documentation/manual	https://github.com/amaelkady/EaRL/tree/master/doc
Support email for questions	a.elkady@soton.ac.uk

Software metadata

Current software version	*v1.0*
Permanent link to code/repository	https://github.com/amaelkady/EaRL
Legal Software License	*GNU GPLv3*
Computing platform/Operating System	*Microsoft Windows*
Installation requirements & dependencies	*Microsoft Windows + MATLAB runtime* *See Installation.txt for details*
Link to user manual	https://github.com/amaelkady/EaRL/tree/master/doc
Support email for questions	a.elkady@soton.ac.uk

1. Motivation and significance

Earthquakes may cause long-lasting impact and adverse effects on the population and the economy. These include casualties and injuries as a result of collapsed/damaged structures, whereas impacts on the economy may be associated, among others, with monetary losses due to repairs in damaged structures, as well as the associated downtime. Stakeholders and building owners are interested in predicting and minimizing potential earthquake-induced economic losses to embrace seismic resilience of our built infrastructure. In this regard, the performance-based earthquake engineering (PBEE) framework has evolved since the early

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2000s [1–3]. The PBEE framework, as formulated by the Pacific Earthquake Research (PEER) center [4,5], is demonstrated schematically in Fig. 1. It aims to explicitly quantify performance decision variables (DVs), such as expected annual losses and/or downtime associated with damage repairs of infrastructure systems. These DVs can aid effective design and/or retrofit decisions early on in the conceptual design phase. The DVs can communicate challenging structural performance concepts to building owners, stakeholders and non-engineers. In brief, for a given seismic intensity measure (IM), the PBEE framework commences by quantifying a structure's seismic response; that is the engineering demand parameter (EDP) of interest at each story and/or floor. This typically requires a nonlinear numerical model and dynamic response-history analyses. Non-model-based approaches are also evolving to inform this step [6,7] in an attempt to minimize nonlinear computations. If a structure's EDPs are known for a given IM, the consequential damage can be quantified. This requires knowing the non-structural/structural building component as well as the corresponding damage fragility functions. In the final step, damage is transformed into DVs using the distribution functions of the damage consequences (e.g., monetary, downtime, casualties, injuries consequences).

The PBEE framework is assembled in a probabilistic manner. The associated aleatory and/or epistemic uncertainties are considered at each step. Practicing engineers and often researchers, find it challenging to implement the PBEE framework as part of the regular design process, which largely remains prescriptive at least for conventional structures. A number of computer-aided tools have been developed within the past decade to facilitate the PBEE process [8–12]. Most of these tools either offer a fairly limited interactive user interface or have an intricate one with limited visualization capabilities. Other software is available only for commercial use or through a cloud-based service. Moreover, a number of tools does not incorporate the current-state-of-the art in seismic lifecycle analysis of infrastructure systems.

To address the above challenges, an open-source computational platform/software, named Earthquake Risk, Loss and Lifecycle Analysis (EaRL), is developed. The new platform incorporates state-of-the-art building-specific loss estimation methodologies and a wide range of options to quantify, visualize and report the total and disaggregated losses of infrastructure systems in the aftermath of earthquakes. Several metrics are integrated in the software to facilitate needs of different users. In order to promote open-science, EaRL is complied as a standalone software with a modular design developed within the Matlab [13] programming environment, which is fairly popular within the civil engineering and research communities. It allows users modifying and improving the existing code capabilities and contributing new code and features, all prevalent of contemporary research. Platform/software development and collaborations are made available through GitHub.

2. Software description

2.1. Software architecture

EaRL's operational outline is illustrated in Fig. 2. The outline follows four basic sequential steps to define a loss project. First, building data is defined (e.g., number of stories, floor area, replacement cost, etc.), followed by pertinent information regarding the structural system and building content data (i.e., structural and non-structural elements/contents), the structural response data (i.e., EDP along the building height) and finally, the seismic hazard data. The basic project definitions are supported by a number of supplementary modules to further define the population model (i.e., the building's occupancy and its variation with respect to time), the damage fragility (modifying existing fragilities and/or adding new ones), the repair time scheme (i.e., specifying the sequence by which repairs will be conducted for different components at different floor levels) as well as demolition and collapse fragility functions of the structure. The definition of the component data and response data steps is supported by a number options that are briefly discussed in Section 2.2.

Once a project is fully defined, story-based losses (i.e., DVs) can be computed. For this computation, EaRL incorporates the primary two building-specific story-based loss-estimation methodologies available in literature. The first methodology was originally developed within the Pacific Earthquake Engineering Research Center (PEER) framework [1,4,14,15]. This methodology computes the expected losses using the integral of the consequence functions, damage fragility functions and the response data, based on the total probability theorem. The second methodology, is the one developed by Yang [16] and implemented in FEMA P-58 [17,18]. This methodology relies on a modified Monte-Carlo method [19] to generate a large number of artificial structural response data (*realizations*) using seed data, which are then used to query damage in a building.

The main console of EaRL is shown in Fig. 3. The software interface is divided into four intuitively laid-out panels. Panel A: project file management; Panel B: basic project definitions; Panel C: supplementary project definitions and features; Panel D: computation options, results visualization and reporting. EaRL projects are saved in a single transferable and editable *.mat* file; hence simplifying project-sharing between collaborators.

2.2. Software functionalities and features

EaRL quantifies a number of DVs (i.e., loss metrics) including: (1) the probability of structural collapse and demolition; (2) the monetary cost associated with structural collapse, demolishing the building and damage repairs; (3) the time required to conduct direct damage repairs to the building structural/non-structural components; (4) the expected number of injuries and casualties due to structural damage; (5) the potential of issuing an *unsafe placard* at significant damage levels; and (6) time-based decision variables such as the expected annual losses (EALs) and the mean annual rates of exceeding given repair cost and/or time thresholds.

EaRL comprises of a number of new and useful features to aid with the loss project definition; some of the main ones are highlighted as follows:

- **Component data:** two options are available for defining the building content:
  - Explicit definition, where a user manually defines the type, number and location of each component in the building. This process is simplified with an intuitive and interactive interface. It is also supported by the integrated component fragility database of FEMA P-58 [18], which comprises more than 750 different component fragility functions.
  - Implicit definition using story-based Loss-EDP functions. Two such functions are incorporated in EaRL; those developed by Ramirez and Miranda [9] and Papadopoulos [20] for reinforced concrete and steel buildings, respectively. Other Loss-EDP functions can also be defined by the user.

- **Response data:** structural response data, i.e., EDPs, can be obtained from different types of dynamic analysis procedures as well as non-model-based approaches. In this regard, EaRL provides six different ways to import or generate such data, most notably:

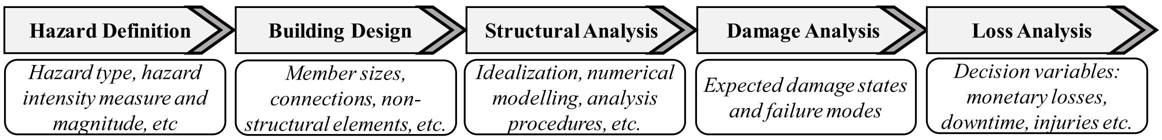

Fig. 1. Overview of the performance-based Earthquake Engineering framework.

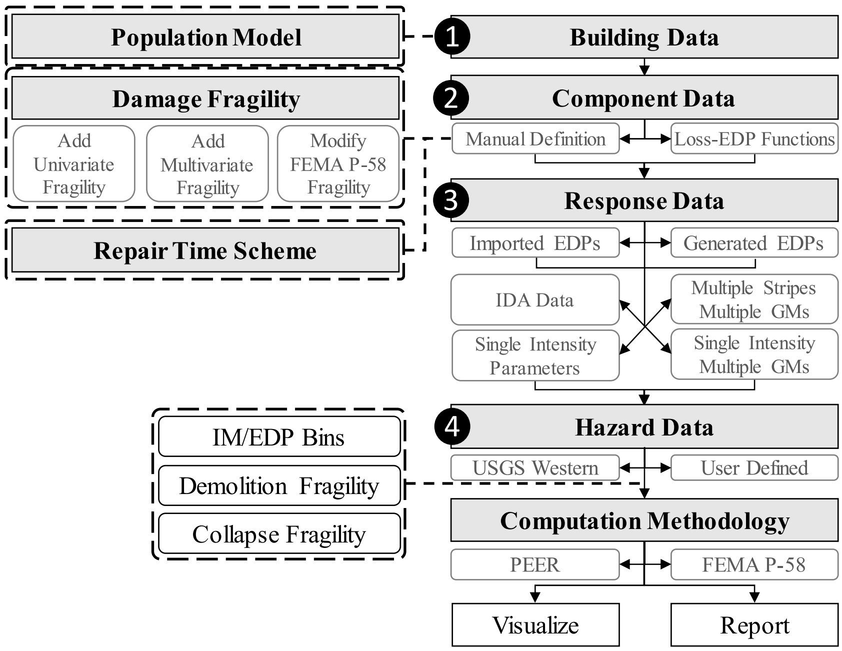

Fig. 2. Outline of EaRL's operational procedures.

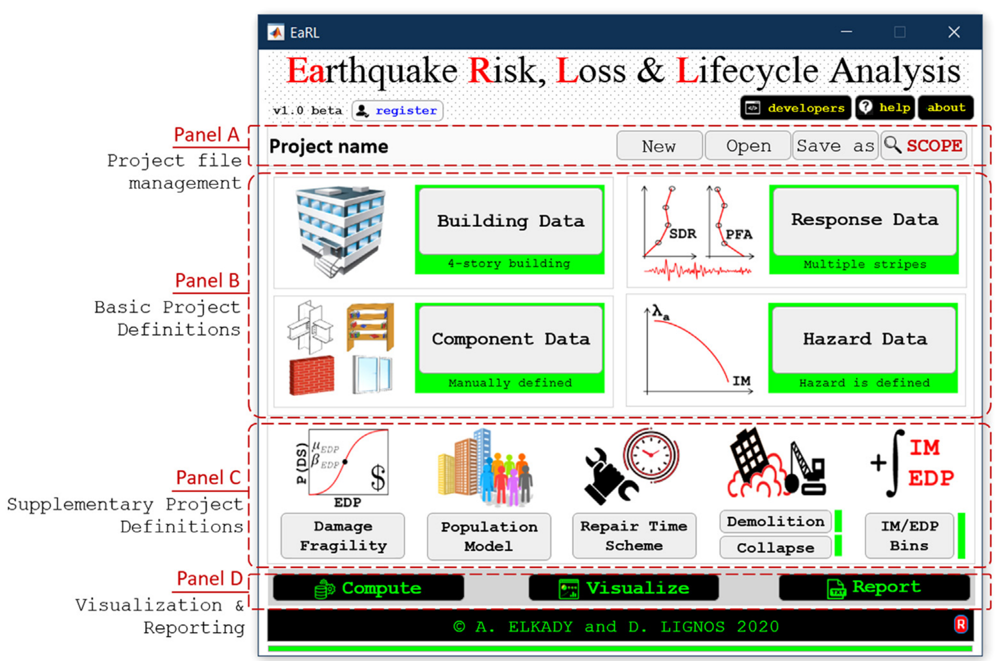

Fig. 3. EaRL's main console.

– Existing EDP data can be simply imported into EaRL through pre-formatted EXCEL sheets. These are provided together with the software. EaRL supports data generated by different analysis procedures including incremental dynamic analysis [21] and nonlinear response-history analyses at single or multiple seismic intensity levels.

– EDP data can be automatically generated through two options. The first one uses the integrated open-source

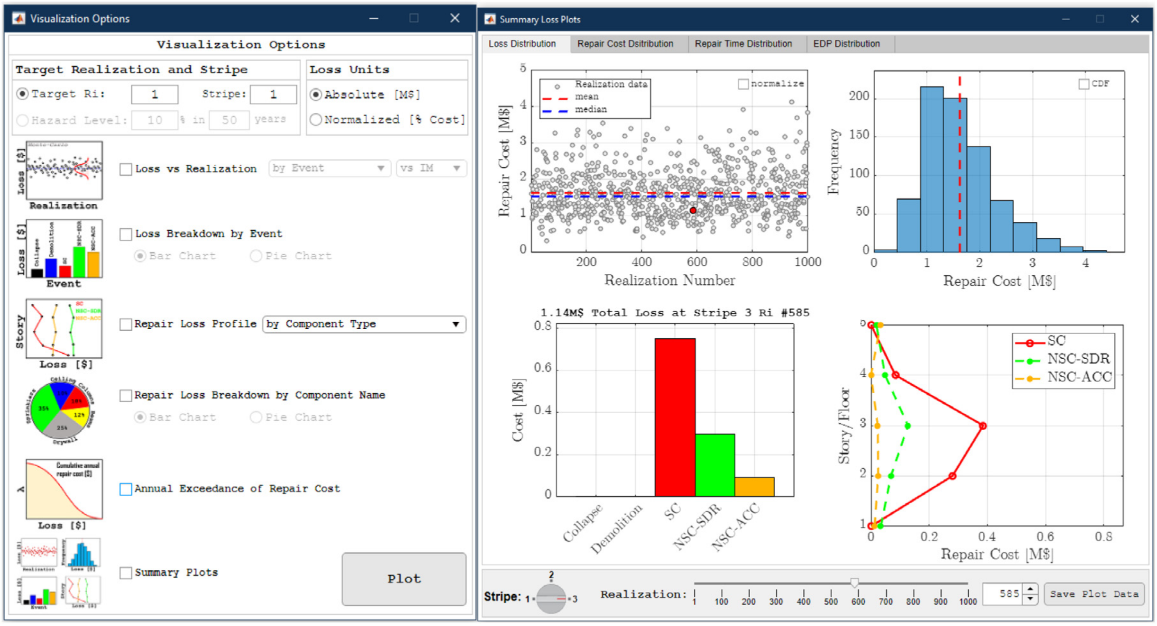

Fig. 4. One of EaRL's visualization options modules and interactive interfaces for visualizing summarized results.

OpenSEES simulation platform [22], to analyze a multi-degree-of-freedom shear model under a suite of seismic records. The second option utilizes the FEMA P-58 Simplified Analysis Method [23], which features linear numerical models of a building, static analysis and supplementary regression equations.

- **Damage fragility:** Component data definition is supported by a comprehensive interactive module to explore and modify the integrated fragility database parameters and/or adding new univariate and multivariate damage fragility functions and associated consequences.
- **Demolition fragility:** EaRL includes a recent methodology developed by the authors for quantifying building demolition loss-based on bivariate fragility functions that consider both lateral and vertical residual drifts [24].
- **Visualization and reporting:** Comprehensive modules are incorporated to communicate loss analysis results in the form of figures with a vector-graphics format as well as text file reports. Fig. 4 shows one of the many visualization features of EaRL. One of the interactive result–summary interfaces is also illustrated in the same figure. Essentially, the user is able to choose alternative ways to visualize and disaggregate the economic loss results for scenario based loss assessment. The loss analysis data, organized in a titled-table format, can be extracted for further independent processing by the user.

3. Impact and conclusions

This paper introduces a new Matlab-based computational platform/software named Earthquake Risk, Loss and Lifecycle Analysis (EaRL) that provides an interactive and user-friendly platform for evaluating the consequences of natural hazards on the built environment and communities, in support of the performance-based earthquake engineering framework. It is envisioned that this software platform, will in turn, assist stakeholders, (re-)insurers and building owners to make informed design/retrofit decisions to mitigate the impact of earthquake hazard on our built infrastructure and potentially optimize the seismic lifecycle performance of infrastructure assets. Being an open-source software, EaRL notably paves the way for researchers and practicing engineers worldwide to collaborate and contribute to its metadata, functionalities and interactive features. The choice of the Matlab and GitHub environments, in addition to the platform's well-documented technical details and codebase, will hopefully stimulate further developments in support of performance-based design. The full technical manual is available in the platform GitHub repository, including illustrative step-by-step examples. Comprehensive video tutorials are also available at a dedicated YouTube playlist: https://www.youtube.com/playlist?list=PLz_XdUL-6Y_nbmyXU7Pcdg_XDwvwgGXjF.

Declaration of competing interest

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

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References

[1] Cornell CA, Krawinkler H. Progress and challenges in seismic performance assessment. PEER Center News 2000;3(2):1–3.
[2] FEMA. Prestandard and commentary for the seismic rehabilitation of buildings. Report FEMA-356, Washington, DC: Federal Emergency Management Agency; 2000.
[3] SEAOC. Performance based seismic engineering of buildings. Sacramento, California: Structural Engineers Association of California (SEAOC); 1995.
[4] Moehle J, Deierlein GG. A Framework methodology for performance-based earthquake engineering. In: 13th World conference on earthquake engineering. 2004; Vancouver, Canada.

[5] Porter KA. An overview of PEER's performance-based earthquake engineering methodology. In: 9th international conference on applications of statistics and probability in civil engineering. 2003; San Francisco, USA.

[6] Hwang S-H, Lignos DG. Nonmodel-based framework for rapid seismic risk and loss assessment of instrumented steel buildings. Eng Struct 2018;156:417–32. http://dx.doi.org/10.1016/j.engstruct.2017.11.045.

[7] Bravo-Haro MA, et al. Drift and rrotation demands in steel frames incorporating degradation effects. Bull Earthq Eng 2018. http://dx.doi.org/10.1007/s10518-018-0389-6.

[8] Mitrani-Reiser J. An ounce of prevention: Probabilistic loss estimation for performance-based earthquake engineering. Pasadena, CA, USA: California Institute of Technology; 2007.

[9] Ramirez CM, Miranda E. Building-specific loss estimation methods and tools for simplified performance-based earthquake engineering. Report No. 171, Stanford, CA: The John A. Blume Earthquake Engineering Center, Stanford University; 2009.

[10] FEMA. Seismic performance assessment of buildings - Volume 3 - Performance assessment calculation tool (PACT), version 2.9.65. Report P-58-3.1, Washington, DC, USA: Washington, DC, USA: Federal Emergency Management Agency; 2012.

[11] SP3. Seismic performance prediction program. Chico, CA, USA: Haselton Baker Risk Group, LLC; 2017.

[12] Zsarnoczay A, et al. NHERI-SimCenter/PBE. Zenodo; 2019.

[13] MATLAB. Natick, Massachusetts, USA: The MathWorks Inc.; 2019.

[14] Krawinkler H, Miranda E. Performance-based earthquake engineering. In: Earthquake engineering: From engineering seismology to performance-based engineering, Vol. 9. 2004, p. 9–1–9–59.

[15] Ramirez CM, Miranda E. Significance of residual drifts in building earthquake loss estimation. Earthq Eng Struct Dyn 2012;41(11):1477–93. http://dx.doi.org/10.1002/eqe.2217.

[16] Yang TY, et al. Seismic performance evaluation of facilities: Methodology and implementation. J Struct Eng 2009;135(10):1146–54.

[17] Hamburger RO, et al. FEMA P58: Next-generation building seismic performance assessment methodology. In: 15th world conference on earthquake engineering. 2012; Lisbon, Portugal.

[18] FEMA. Seismic performance assessment of buildings. Report FEMA P-58-1, Washington, DC: Federal Emergency Management Agency; 2012.

[19] Metropolis N, Ulam S. The Monte Carlo method. J Amer Statist Assoc 1949;44(247):335–41.

[20] Papadopoulos AN, et al. Development and application of FEMA P-58 compatible story loss functions. Earthq Spectra 2019. http://dx.doi.org/10.1193/102417eqs222m.

[21] Vamvatsikos D, Cornell CA. Incremental dynamic analysis. Earthq Eng Struct Dyn 2002;31(3):491–514. http://dx.doi.org/10.1002/eqe.141.

[22] Mckenna FT. Object-oriented finite element programming: Frameworks for analysis, algorithms and parallel computing, in department of civil engineering. University of California; 1997.

[23] Huang Y-N, et al. A simplified analysis procedure for performance-based earthquake engineering of buildings. Eng Struct 2017;150:719–35. http://dx.doi.org/10.1016/j.engstruct.2017.07.048.

[24] Elkady A, et al. Proposed methodology for building-specific earthquake loss assessment including column residual axial shortening. Earthq Eng Struct Dyn 2020;49(4):339–55. http://dx.doi.org/10.1002/eqe.3242.