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AN OPEN-SOURCE TOOLKIT FOR SEISMIC VULNERABILITY ASSESSMENT

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Abstract

This study introduces an open-source numerical modeling toolkit specifically developed to assess the seismic vulnerability of building structures. Using an object-oriented approach in OpenSeesPy, the toolkit seamlessly models a wide range of building classes as multi-degree-of-freedom oscillators that effectively capture their non-linear dynamic behavior for regional seismic risk assessments. The library features several analysis methods, including linear (gravity and modal), nonlinear static (static and cyclic pushover analyses) and dynamic (i.e., cloud- or multiple-stripe based). The toolkit generates probabilistic demand-intensity models through robust regression of cloud-analysis results, linking seismic demand to building response, and derives fragility functions that estimate the probability of exceeding various damage states over a range of ground-shaking intensity levels. It also produces vulnerability functions to quantify the expected losses under different ground-shaking intensities and further compute several risk metrics. The developed toolkit is open-source, supporting transparency, reproducibility, and ongoing development within the global earthquake engineering community. The toolkit is maintained by the Global Earthquake Model (GEM) Foundation on GitHub, and benefits from continuous updates and enhancements by experts and researchers worldwide.

Keywords: Earthquake Engineering, Seismic Vulnerability Assessment, Multi-Degree of Freedom, Regional Risk Assessment, Open-Source Toolkit, Nonlinear dynamic analysis

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1. INTRODUCTION

Earthquakes pose significant threats to building structures. Over the past century, earthquakes have caused catastrophic human and economic losses, with over one million lives lost and nearly one trillion USD in damages [1]. To mitigate these impacts, reliable assessments of seismic performance and vulnerability of building portfolios remain a critical challenge in modern earthquake engineering. Addressing this issue demands open-access tools capable of delivering reliable vulnerability assessments, which not only include buildings' structural components, but also addresses their non-structural components and contents, which represent more than 50% of their value (approximately 205 trillion USD, as reported by the Global Exposure Model [2]).

Recent advancements in numerical modeling have enabled the development of robust methodologies that effectively capture complex structural behavior. Building on this foundation, researchers have aimed at modeling approaches that strike a balance between the refined multi-degree-of-freedom (MDOF) models and the simplicity of single-degree-of-freedom (SDOF) models. This balance is essential for efficiently deriving vulnerability models that relate decision variables (e.g., direct economic loss, downtime [3], fatalities [4]) to ground-shaking intensity and use them in the context of building portfolios. To achieve this, several studies have recommended using mechanical MDOF systems such as equivalent continuum structures [5], fish-bone models [6], or stick-and-mass models [7,8], which can simulate the shear response of individual stories. These simplified models represent a trade-off between accuracy and computational effort by capturing seismic demands at various story levels, making them well-suited for assessing component damage and loss. Their reliability has been consistently demonstrated in regional seismic risk assessment applications [9–11].

This study presents an open-source toolkit called "Vulnerability Modeller's Toolkit (oq-vmtk)", which integrates OpenSeesPy [10] for numerical modeling and nonlinear analyses. The toolkit also features a suite of robust methods for postprocessing non-linear analysis results, facilitating the derivation of fragility and vulnerability functions to assess damage and economic or social losses conditioned on the ground-shaking intensity. The toolkit promotes transparency, reproducibility, and flexibility in modeling. Furthermore, the toolkit's output is consistent with common earthquake catastrophe modeling open-source softwares like the OpenQuake Engine [11] that are typically used for regional risk assessments.

2. TOOLKIT STRUCTURE

2.1. Modules and Documentation

The oq-vmtk provides earthquake engineers and catastrophe modelers with a comprehensive environment for developing fragility and vulnerability models for regional risk assessment applications. A distinctive feature of the oq-vmtk is its ability to integrate all stages of seismic vulnerability assessment into one unified environment via distinct modules. Currently, the oq-vmtk consists of five core modules and two miscellaneous modules, illustrated in Figure 1.

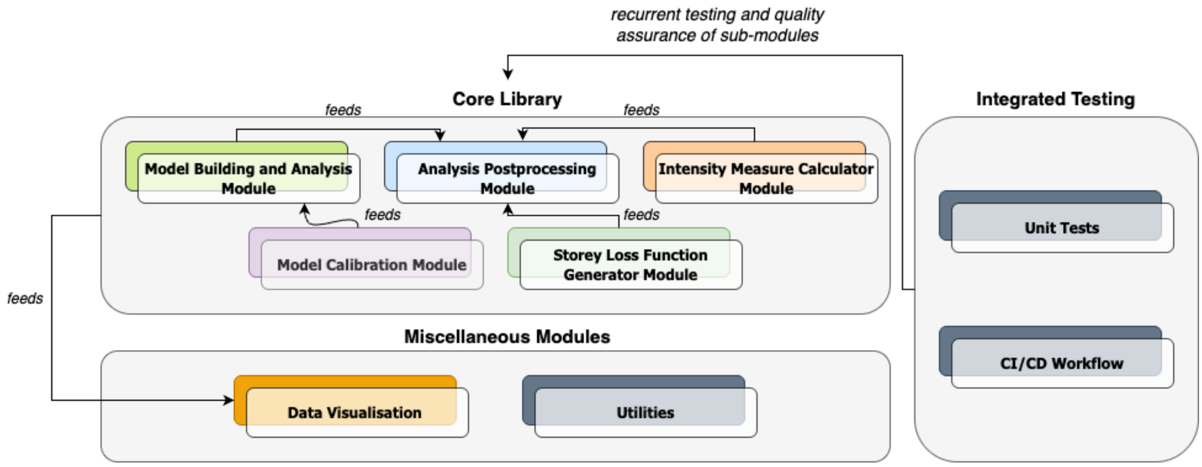

Figure 1: Code structure of the Vulnerability Modelers Toolkit repository

The oq-vmtk current modules are:

- *Intensity Measure (IM) Calculation Module*: this module processes ground-motion records and calculates various intensity measure types (e.g., peak ground velocity, spectral acceleration, average spectral acceleration, arias intensity, filtered incremental velocity, etc.), particularly useful for the derivation of a probabilistic seismic demand model. Upon initialization, the module requires an acceleration time series, a time step as inputs.
- *Model Calibration Module*: this module integrates the approach developed by Lu *et al.* [9,12] initially designed to calibrate MDOF stick models using the HAZUS database [13]. This approach aims to propagate simplistic building capacity curves expressed in terms of the spectral acceleration and spectral displacement to MDOF story-based force deformation relationships and equivalent floor mases. This module can be bypassed if users have access to direct story-force deformation relationships derived from more complex three-dimensional models, which provide a more direct and accurate solution.
- *Model Building Module*: This module compiles an OpenSeesPy *stick-and-mass* model based on basic building class information (e.g., number of stories, typical story height, structural type, floor masses) and story-based force-deformation relationships. The *stick-and-mass* MDOF systems are modelled using OpenSeesPy via a series of masses lumped at each floor's level connected by non-linear springs (i.e., zero-length elements) defining the story-level shear force versus drift behaviour. Additionally, this module performs a range of analysis methods, including gravity analysis, linear (i.e., modal analysis), static nonlinear (i.e., static and cyclic pushover analyses) and nonlinear dynamic analyses (i.e., cloud or multiple stripe analyses).

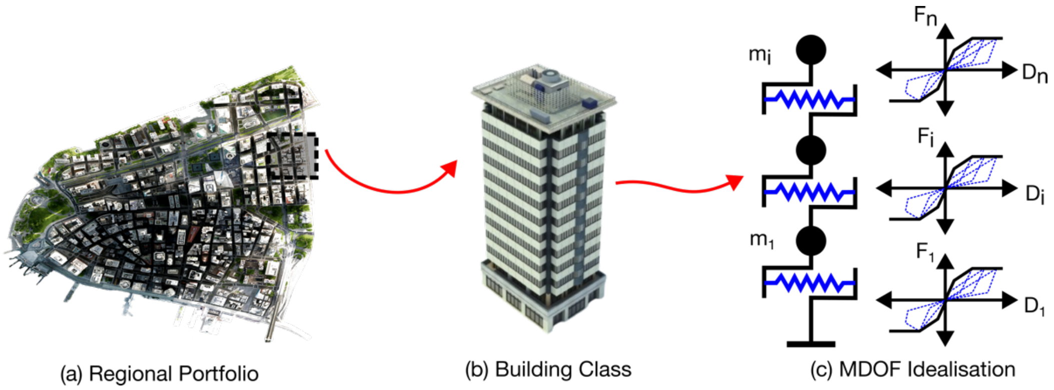

Figure 2: Idealised multi-degree-of-freedom systems for regional risk assessment applications using the Model Building Module

- *Postprocessing Module*: this module provides a comprehensive set of functions for deriving fragility and vulnerability models based on nonlinear time-history analysis (NLTHA). It requires three key inputs: IM levels corresponding to ground-shaking records, engineering demand parameters (EDPs) obtained from NLTHA (e.g., peak interstory drifts), and damage state thresholds defined in terms of EDPs. The module offers multiple postprocessing methods, including cloud analysis regression using least squares or maximum likelihood estimation (MLE) to characterize probabilistic seismic demand models, as well as multiple stripe analysis processed via MLE. Both methods generate fragility functions modeled as lognormal cumulative distribution functions with median and dispersion parameters, allowing optional rotation around a user-defined percentile (e.g., 20th percentile) and supporting generalized linear models (e.g., logit, probit, ordinal). Additionally, the module facilitates the computation of mean vulnerability functions and their variability in loss ratio given an IM through convolution of fragility functions with user-defined consequence models or literature-based damage-to-loss models [14–17]. By integrating these methods, the module enables a robust seismic risk assessment framework based on NLTHA results.

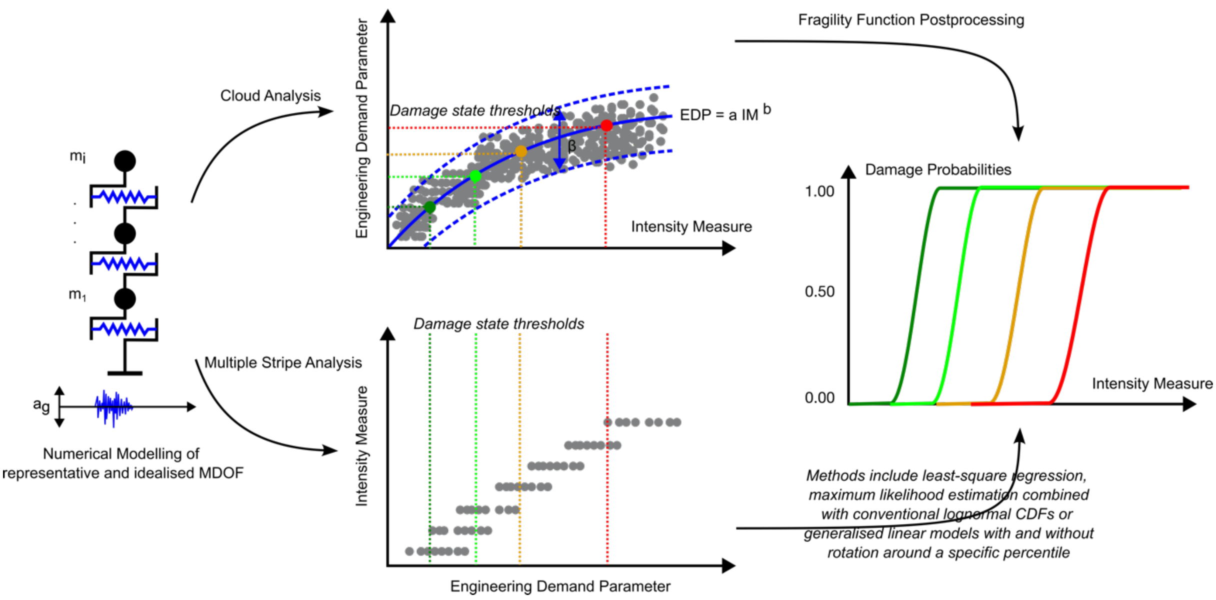

Figure 3: Illustration of different NLTHA dynamic approaches applied to representative MDOF models for fragility function derivation

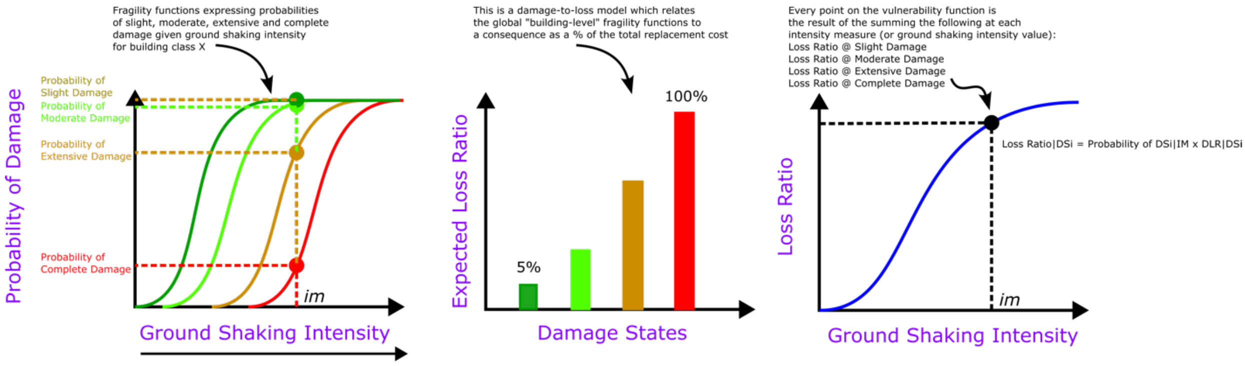

Figure 4: Illustration of fragility function and consequence model convolution for vulnerability function derivation

Storey-Loss Function Generation Module: This module generates story-loss functions (SLFs) based on component-based fragility, consequence and quantity data. SLFs were first proposed by Ramirez and Miranda [18] as an alternative to the computationally expensive component-based approach highlighted in FEMA P-58 [19,20]. SLFs establish a direct relationship between the expected loss at a specific story and the EDP as illustrated in Figure 5. This module implements a probabilistic approach outlined in Shahnazaryan *et al.* [21] leveraging Monte Carlo simulations to model damage, assess the associated losses and consequently determine its distribution within a story, considering a user-defined inventory of damageable components. The main advantage of this approach is its ability to directly account for losses at the story- rather than building-level, using story demands like floor acceleration or inter-story drifts. Shahnazaryan *et al.* [22] amongst others [23–25] demonstrate the key benefits of integrating SLF-based methods with building-specific and regional loss applications by demonstrating that the SLF-based method offers a more comprehensive way to compute and communicate loss contributions across different element groups such as structural, non-structural, and contents as well as individual stories along the building height.

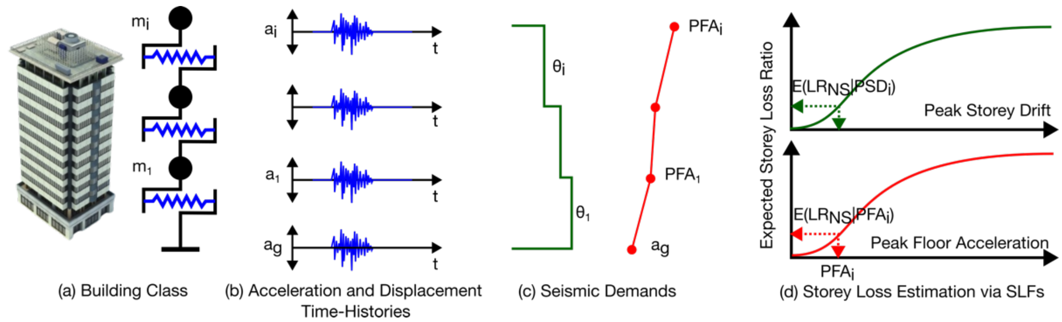

Figure 5: Storey-based loss estimation integrating seismic demands (e.g., peak floor acceleration and peak storey drifts) with storey-loss functions

- *Plotting Module*: This module offers a comprehensive library of visualization functions designed to support the graphical interpretation of various stages in the probabilistic vulnerability modeling methodology. Specifically, it allows users to visualize key metrics, such as

peak story drift and peak floor acceleration distributions associated with a set of ground-motion records. By directly utilizing output variables from different methods in oq-vmtk, users can create a diverse range of visualizations, including cloud and multiple stripe analysis plots, seismic demand profiles (i.e., peak story drift and peak floor acceleration distributions along the building height for a given set of ground-motion records), as well as fragility and vulnerability functions while accounting for uncertainties;
- *Utilities Module*: This module contains a miscellaneous set of functions used for variable handling and create, read, update, and delete (CRUD) operations

The toolkit, including source code and demos is hosted in a publicly available GitHub repository, accessible here: https://github.com/GEMScienceTools/oq-vmtk. For comprehensive documentation and user guidance on utilizing the toolkit for vulnerability modeling—including installation steps, essential features, and sample workflows, please visit: https://gemscience-tools.github.io/oq-vmtk.

2.2. Quality Assurance and Continuous Integration Testing

Unit tests are crucial for managing large open-access repositories and ensuring the quality of derived outputs and their compliance with the underlying science. They also ensure that new contributions do not break existing functionality and play a key role in continuous integration and deployment (CI/CD) pipelines. By enhancing developer productivity, unit tests save time by allowing code validation without manual testing, enabling developers to focus on feature development rather than debugging. The unit tests associated with each module of the oq-vmtk package are available in https://github.com/GEMScienceTools/oq-vmtk/openquake/vmtk/tests whereas the CI/CD pipelines were integrated were set up in the repository's GitHub Actions.

2.3. Demos

The oq-vmtk repository provides a comprehensive collection of Jupyter Notebook demos, accessible at https://github.com/GEMScienceTools/oq-vmtk/tree/main/demos, offering step-by-step guidance on its various functionalities. These interactive notebooks showcase end-to-end applications, including ground-motion record processing for intensity measure types, the generation of story-loss functions using an example inventory of damageable building components, and the modeling of MDOF systems followed by NLTHA with fragility and vulnerability derivation. By covering different aspects of vulnerability modeling—such as data processing, function development, and loss assessment—these demos offer practical, real-world examples that help both new and experienced users deepen their understanding of the tool's capabilities. Furthermore, they support seamless experimentation and customization, making it easier to integrate *oq-vmtk* into a wide range of research and industry applications.

6. CONCLUSION

This study presented an open-source numerical modeling toolkit designed for assessing the seismic vulnerability of building structures. The toolkit named Vulnerability Modellers Toolkit (oq-vmtk) is hosted on GitHub by the Global Earthquake Model (GEM) Foundation and benefits from ongoing contributions and updates from researchers and experts worldwide. Built using an object-oriented framework in OpenSeesPy, it enables seamless modeling of diverse building classes as multi-degree-of-freedom oscillators, accurately capturing their nonlinear dynamic behavior for regional seismic risk evaluations. The toolkit includes various analysis methods, such as linear (gravity and modal), nonlinear static (static and cyclic pushover), and dynamic approaches (cloud- and multiple-stripe-based). By applying robust mathematical models to cloud or multiple-stripe analysis results, it establishes probabilistic demand-intensity models that link seismic demand to structural response. It also implements multiple options for generating fragility functions to estimate the probability of exceeding different damage states across ground-shaking intensities and develops vulnerability functions to quantify expected losses and calculate key risk metrics. As an open-source resource, the toolkit promotes transparency, reproducibility, and continuous advancement within the earthquake engineering community [26].

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