Interreg Co-funded by the European Union

Italy – Croatia

STRENGTH

D.2.6.1
Report With Fragility for Buildings

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Executive Summary

This report presents a panoramic methodology and associated results for developing fragility curves specifically adapted for flood hazards in the Province of Ravenna, within the context of the STRENGTH project (STRategies for assessing climate change and natural hazards' impact on urban ecosystems, increasing resilience to ENvironmental hazards, and promoting territorial GrowTH). Traditionally, fragility curves have been utilized extensively to quantify structural vulnerability to earthquakes and wind hazards. However, their application to flood scenarios is limited and requires careful adaptation of methodologies, consideration of unique structural interactions, and explicit accounting for uncertainty.

Capitalising on existing methodologies from earthquake engineering, this study adapts and refines a robust fragility analysis framework suitable for flood-induced loading on masonry and concrete buildings. This adaptation includes disaggregating detailed structural data from the *CARTIS dataset* into a building level analysis, specific to the Ravenna region and employing a sensitivity analysis guided by advanced machine learning techniques. The sensitivity analysis is grounded in the approach outlined by *Milanesi et al. (2018)*, allowing for detailed consideration of parameter uncertainties that influence building vulnerability.

A key deliverable of this work is the development of a user-friendly Graphical User Interface (GUI) designed to generate flood fragility curves rapidly and intuitively. This GUI applies the methodology outlined by *Milanesi et al. (2018)* and is validated through practical examples provided within this report. The results of this work significantly amplify local authorities' capabilities to evaluate building vulnerabilities accurately, providing essential input for risk-informed decision-making processes that strengthen community resilience against flooding events.

1. Introduction

Climate change has profoundly altered the frequency and intensity of natural hazards, notably flooding, posing significant risks to urban ecosystems worldwide. The Ravenna Region in Italy is particularly vulnerable due to its low-lying geography, proximity to water bodies, and a high density of historically significant yet structurally varied buildings. Accurately assessing and mitigating the vulnerability of these structures is critical to safeguarding lives, minimizing economic losses, and preserving cultural heritage. Within the framework of the STRENGTH project, a significant objective is to develop quantitative tools to assess and manage risks associated with flooding hazards.

1.1. Fragility Curves

A fragility curve expresses the probability that a structure or system will reach or exceed a certain damage state, given the intensity of a specific hazard. The x-axis usually represents the hazard intensity (e.g., wind speed, flood depth, earthquake magnitude). The y-axis shows the probability of damage (from 0 to 1).

Different curves may represent different damage states: slight, moderate, extensive, or collapse. These curves are very important in risk analysis and can be used to evaluate resilience, guide building codes and design standards and assess economic losses and insurance needs. It can be created based on actual observed damage from past hazard events (empirical curve) or by analytical models by using structural simulations or physics-based models. For instance, for a building exposed to different flood depths, the curve could provide a 10% chance of moderate damage at 0.5m flood depth, 50% at 1.2m and 90% at 2.5m flood depth, as it seen in Figure 1.

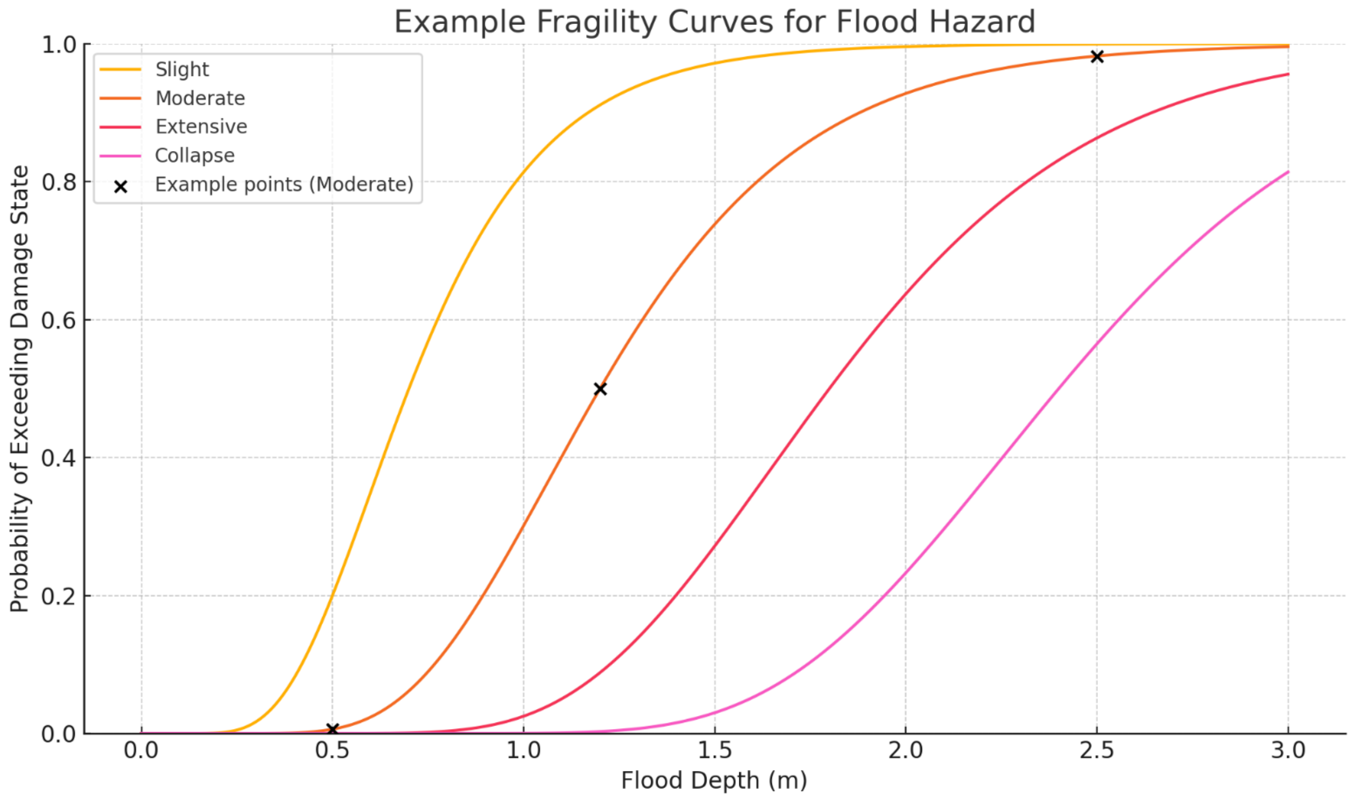

Figure 1 Different curves that represent different damage states for a building exposed to different flood depths.

1.2. Overview and Importance of Fragility Curves for Flooding and Seismic Hazards

Fragility Curves have proven invaluable in earthquake and wind engineering. However, their direct application to flood hazards is not straightforward, given the distinct nature of flood-induced structural loads, such as hydrostatic and hydrodynamic pressures and the varied structural responses depending on building typology. To effectively bridge these gaps, this deliverable presents two clearly delineated and independently developed methodologies: one applying advanced machine learning-based sensitivity analysis, outlined by *Dabiri et al. (2022)* to earthquake scenarios, and the other employing a simplified structural model specifically developed for flood vulnerability analysis based on *Milanesi et al. (2018).* Each approach rigorously addresses uncertainties and provides tailored insights relevant to distinct hazard scenarios.
The earthquake-focused methodology uses detailed data from the *CARTIS dataset* specific to Ravenna, combined with machine learning techniques to systematically quantify

uncertainties affecting structural vulnerability predictions. In parallel, the flood-focused approach utilizes structural mechanics concepts to capture unique flood load characteristics, including hydrostatic and hydrodynamic pressures, particularly targeting masonry buildings prevalent in Ravenna.
Complementing these methodological advances, the developed GUI tool significantly enhances practical application by enabling intuitive generation and exploration of fragility curves. This ensures that sophisticated analytical capabilities are accessible to decision-makers, emergency management authorities, and urban planners, thereby supporting informed and proactive risk management strategies.
Ultimately, this report provides a foundational and broadly applicable approach to building vulnerability assessment, laying the groundwork for subsequent application to specific community scenarios such as the Mezzano area in Ravenna, detailed in a subsequent deliverable.

2. Adaptation of Methodology

2.1. Earthquake Vulnerability Assessment Using Machine Learning

The first methodological approach employs advanced machine learning techniques to assess building vulnerability to earthquake hazards. The analysis begins with the disaggregation of the detailed *CARTIS dataset* for the Ravenna region. This dataset contains comprehensive structural data on various building typologies, including material properties, age, geometric dimensions, and structural features. Parameters such as building height, plan area, material types, and opening fractions were defined following standard recommendations from *FEMA P-58 (2012)*, which provides guidelines on typical structural parameters and damage states, and *HAZUS-MH MR4 (2015)*, which outlines procedures for estimating seismic vulnerabilities based on common structural typologies and occupancy classifications.
Inspired by the recent literature *Dabiri et al. (2022): "A machine learning-based analysis for predicting fragility curve parameters of buildings"* this approach involved training predictive models that link structural parameters to damage states using historical earthquake data and expert elicitation. According to this paper, the most effective parameters on the target outputs are defined as input variables including construction material, building plan area, building height, damage state, buildings' period and soil classification. β and μ were

estimated utilizing various ML-based techniques. To quantify uncertainties and systematically assess the sensitivity of fragility curves, a sensitivity analysis based on machine learning algorithms was conducted. The output of these ML models provided probabilistic assessments of damage states, facilitating the construction of accurate and robust fragility curves.

2.2. Flood Vulnerability Assessment Using Structural Mechanics

The second methodological approach focuses explicitly on flooding hazards, using a simplified structural model derived from the work of *Milanesi et al. (2018)*. This approach captures the fundamental mechanisms of structural failure in masonry buildings due to flood-induced loads, specifically hydrostatic and hydrodynamic pressures.
This structural model incorporates key parameters such as wall thickness, wall density, building geometry, opening fraction, and boundary conditions. Sensitivity analyses were performed systematically to quantify the impact of uncertainties on the generated fragility curves, enabling a clear understanding of which parameters significantly influence structural vulnerability.
The outcomes from this analysis were integrated into a custom-developed Graphical User Interface (GUI), designed to simplify the generation and visualization of flood fragility curves. The GUI allows users to input specific structural parameters and generates tailored fragility curves, significantly improving the accessibility and practical applicability of these analytical tools.
This dual methodological adaptation ensures comprehensive vulnerability assessments for buildings in Ravenna, addressing both earthquake and flooding hazards with scientifically robust and practically useful tools.

3. Preliminary Research: ML-based Building's Seismic Vulnerability

3.1. Ravenna CARTIS Dataset Disaggregation

The initial phase of this research focused on the systematic analysis and disaggregation of the *CARTIS dataset* specifically for the Ravenna region. CARTIS provides extensive attributes for buildings, including:

- Building Height: Essential for determining dynamic structural responses to seismic events.
- Construction Period: Reflects general material standards and construction practices but does not explicitly define structural periods.
- Plan Area: Important for assessing structural mass and stiffness distribution.
- Material Type: Defines essential mechanical characteristics such as strength, stiffness, and ductility.

However, the Ravenna *CARTIS* dataset lacks two crucial parameters directly required by standard fragility analyses:

- Soil Type: Needed to incorporate local amplification effects of seismic waves.
- Building Structural Period: Critical for defining dynamic seismic response but not directly provided by *CARTIS*.

To overcome these limitations, standard engineering guidelines and empirical relationships were employed to estimate missing attributes, specifically the building structural periods based on building height according to common seismic design standards.

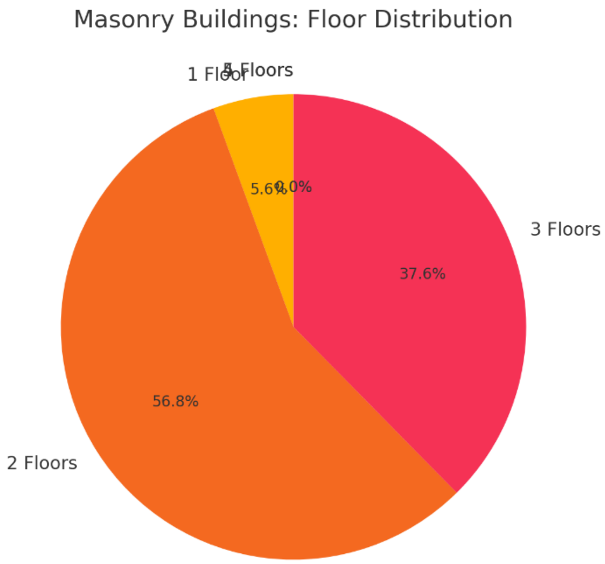

Figure 2 Floor Distribution - Ravenna Cartis Dataset

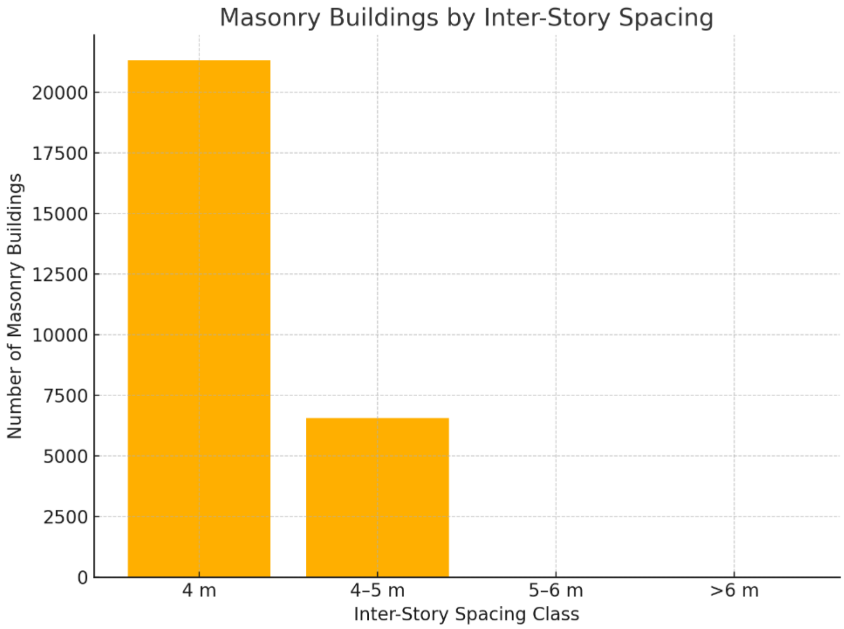

Figure 3 Inter-Story Spacing Class for Masonry Buildings

3.2. Reference Methodology

The methodology adopted in this analysis closely follows the framework established by *Dabiri et al. (2022)* in their paper titled *"A machine learning-based analysis for predicting fragility curve parameters of buildings."* The authors present a structured approach for estimating fragility curve parameters (μ, β) systematically integrating uncertainties associated with various structural and environmental attributes. Their methodology explicitly considers several essential parameters including:

- Building Height
- Structural Period of Buildings
- Material Type
- Plan Area
- Soil Type

The authors developed empirical equations derived from a detailed sensitivity analysis conducted via advanced machine learning algorithms. These equations quantify how each parameter, individually and in combination, influences the resulting fragility parameters, allowing explicit representation and quantification of uncertainties.

3.3. ML-based Approach and Results

In the adapted approach of this report, we utilized the empirical equations from the sensitivity analysis conducted by *Dabiri et al. (2022)*, directly applying these equations to the *Ravenna CARTIS dataset* rather than retraining new machine learning models. This adaptation was necessary due to limitations in available dataset attributes. The following structured steps were executed:

Step 1 - Attribute Estimation:

- Structural periods were estimated for each building based on building heights using empirical relationships from standard seismic design codes, recognizing that the dataset lacked explicit building period information.
- To address the absence of soil type information, separate fragility curves were generated considering all standard soil classifications, providing a comprehensive range of seismic vulnerability scenarios.

Step 2 - Parameter Calculation with Uncertainty:

- Fragility curve parameters (μ, β) were calculated using the empirical equations provided by *Dabiri et al. (2022)*, explicitly incorporating uncertainties.
- Uncertainty ranges were included particularly for parameters such as building height, reflecting realistic variability and uncertainty inherent in these measurements.

Step 3 - Fragility Curve Generation:

- Individual fragility curves were generated for both concrete and masonry buildings, with each curve representing seismic vulnerability probabilistically.
- Uncertainty envelopes around the mean fragility curves were computed, clearly visualizing the sensitivity of seismic vulnerability to variations in μ and β parameters.

<u>Detailed Description of Results</u>

The generated fragility curves, exemplified in figures 4,5 illustrate clear probabilistic distributions of building failure under varying seismic intensities (expressed as Peak Ground Acceleration - PGA). The mean fragility curve is represented by a solid black line, while uncertainty envelopes for μ (blue dashed lines and shaded area) and β (red dashed lines and shaded area) clearly demonstrate the range of possible vulnerabilities arising from parameter uncertainties.

Specifically, the curves indicate the probability of structural failure under incremental seismic loading conditions. Buildings with lower uncertainty envelopes suggest higher confidence in predicted performance, while wider envelopes highlight areas needing more precise data or further investigation. Figures provided distinctly illustrate these conditions for different building typologies, explicitly differentiating between masonry and concrete structures.
This structured methodology, emphasizing uncertainty quantification and clear visualization, provides a rigorous yet practically applicable toolset for earthquake vulnerability assessment in Ravenna region. It supports decision-making by highlighting both expected seismic performance and associated uncertainty ranges, thereby significantly enhancing regional resilience strategies.

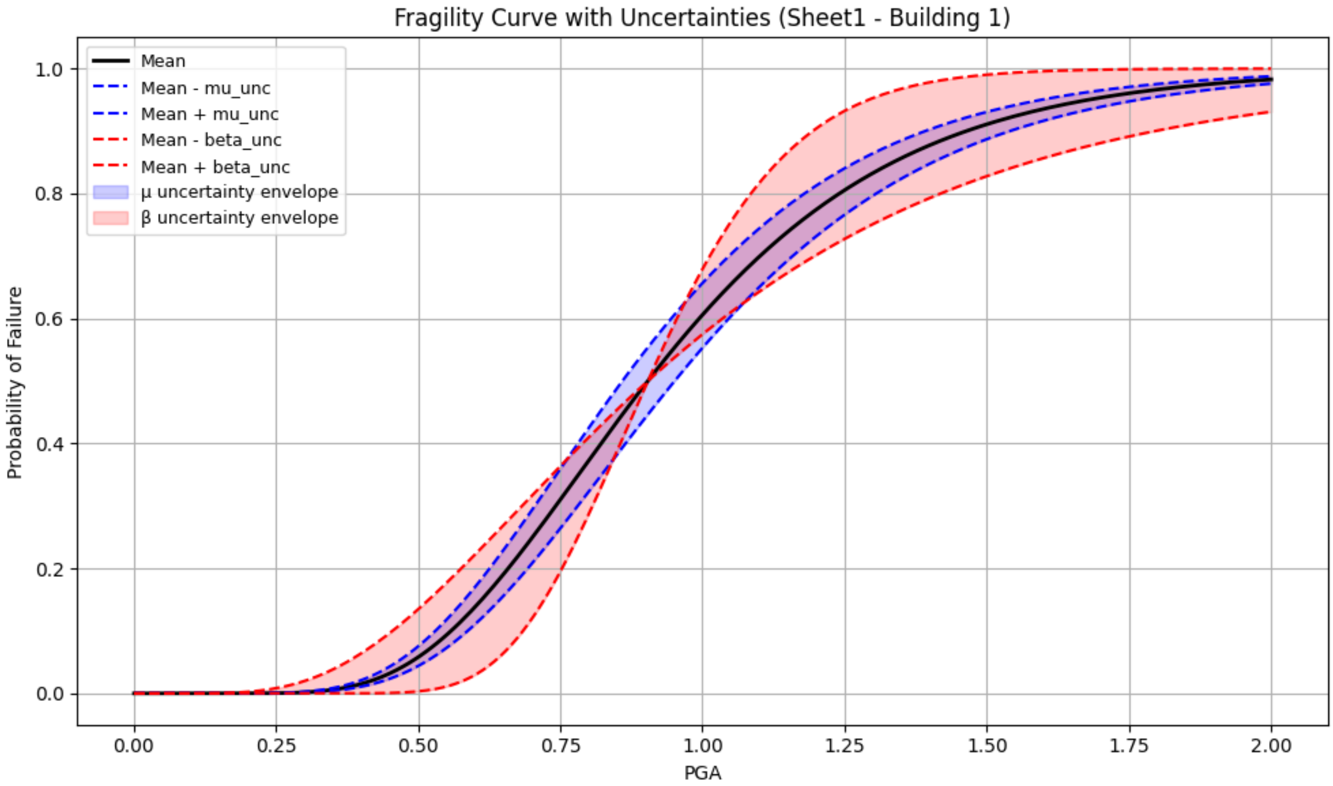

Figure 4 Masonry Building Fragility Curve with Uncertainty

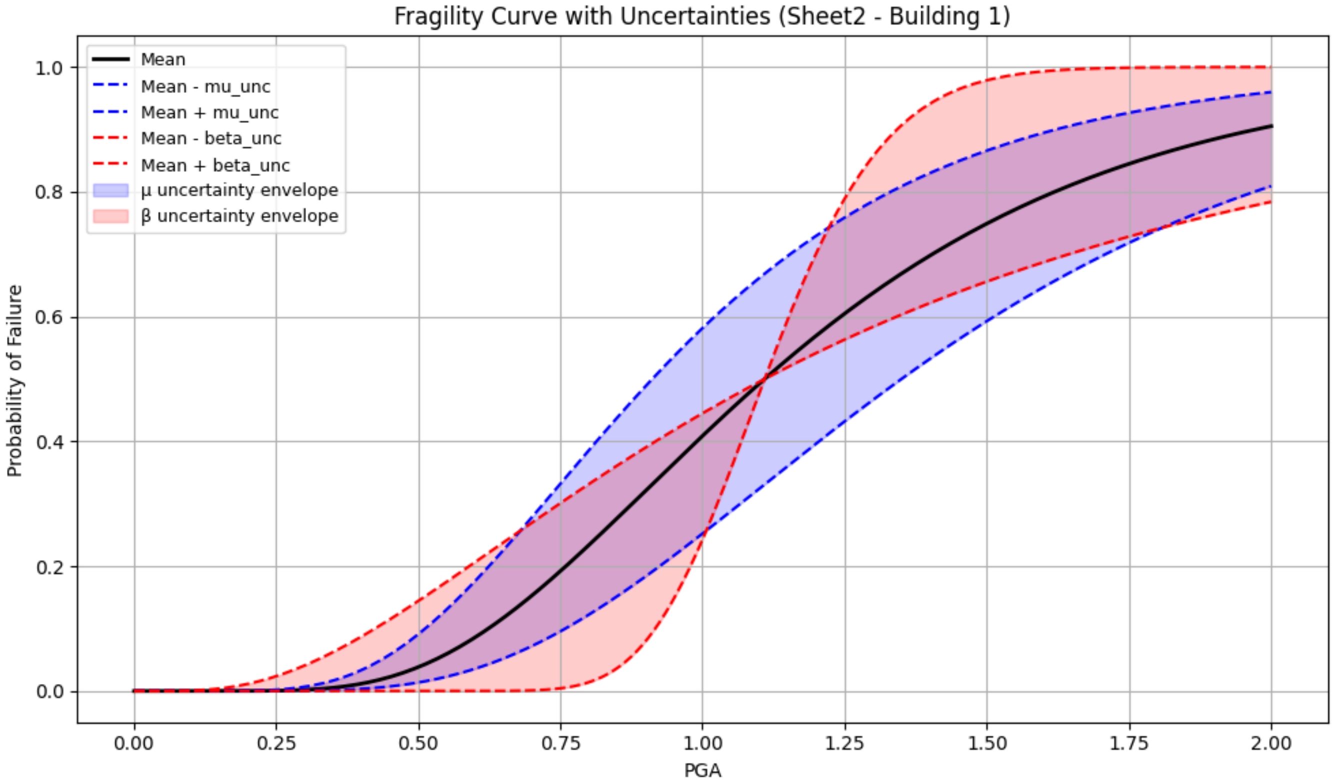

Figure 5 Reinforced Concrete Bulding Fragility Curve Example with Uncertainty

4. Flood Fragility Curves for Buildings using the Milanesi Approach and GUI Tool

4.1. Theoretical Background: Milanesi Approach

The fragility assessment for flood hazards presented in this section follows the methodology developed by *Milanesi et al. (2018)*. This structural mechanics-based model specifically addresses masonry buildings, characterizing their vulnerability to flooding-induced loading, such as hydrostatic and hydrodynamic pressures. The Milanesi approach calculates collapse mechanisms of a masonry wall considering:

- Wall thickness
- Wall density
- Building height

- Opening fraction (percentage of openings in the wall)
- Boundary conditions (P1-P4 mechanisms depending on edge supports)

These parameters directly influence the building's resistance against flooding loads, where the collapse condition is evaluated through an equilibrium between overturning moments (flood loads) and stabilizing moments (wall weights and vertical loads).

4.2. GUI Tool Development and Description

To facilitate the practical implementation of the Milanesi approach, a specialized *Graphical User Interface (GUI)* was developed. This GUI serves as an accessible analytical tool, allowing stakeholders (urban planners, engineers, and decision-makers) to efficiently generate flood fragility curves.

Key features of the GUI include:

- Interactive Parameter Input: Users can input critical parameters such as wall thickness, wall density, building height, opening fraction, and select boundary conditions.
- Real-time Fragility Curve Generation: The GUI rapidly processes inputs based on the Milanesi equations, generating immediate graphical outputs of fragility curves.
- Visualization and Analysis: Provides clear visualization of probabilistic collapse depths, enabling intuitive understanding and comparison of structural vulnerabilities.

4.3. GUI Workflow and Functionality

The GUI tool operates through the following simplified workflow:

1. Input Structural Data: Users define the building characteristics through clearly marked input fields.
2. Boundary Conditions Selection: Users choose the appropriate boundary condition type (P1 to P4) based on building configurations.
3. Generate Fragility Curve: Upon input, the GUI calculates fragility curves using the equilibrium-based Milanesi methodology.
4. Review and Export Results: Results, including probabilistic fragility curves, are displayed graphically for immediate analysis and can be exported for further use in reports and presentations.

The Graphical User Interface (GUI), as illustrated in Figure 6, provides an intuitive platform for generating flood fragility curves specifically for masonry buildings, following the structural mechanics approach of *Milanesi et al. (2018).* Users input essential parameters, including total building height, estimated floor height, base area, perimeter (optional), wall thickness, wall density, wall opening fraction, and flood loading direction. Users also specify the boundary conditions (mechanisms P1–P4) and the preferred curve type (empirical with lognormal fitting). Upon entering these parameters, users generate customized fragility curves instantly, clearly illustrating the building's probabilistic vulnerability to different flood depths.

The GUI prominently features a visual schematic that clearly delineates the four possible boundary conditions (P1–P4 mechanisms), helping users accurately select the most representative boundary condition based on actual building conditions. This schematic visualization enhances user understanding, promoting accurate and practical use of the tool.

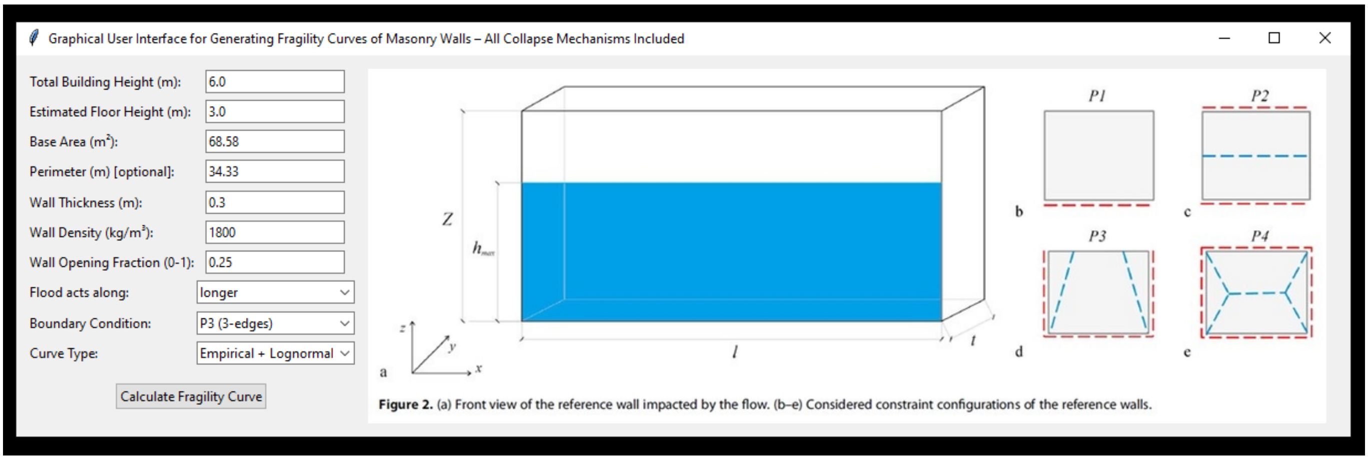

Figure 6 Preview of GUI tool

4.4. Practical Benefits and Applications

The GUI significantly streamlines the otherwise complex analytical procedures required by the Milanesi approach, reducing barriers to its application. It empowers stakeholders to:

- Quickly identify the most critical structural parameters influencing vulnerability.
- Easily evaluate multiple scenarios, aiding comprehensive risk assessments.
- Support proactive decision-making and planning for flood resilience enhancement in vulnerable urban areas such as Ravenna.

This section illustrates how the *Milanesi-based GUI tool* provides an intuitive, accessible, and robust method for generating and applying flood fragility curves to real-world structural assessments, thereby strengthening community resilience strategies against flooding hazards.

Figure 7 presents the visual sensitivity analysis output from the GUI, demonstrating fragility curves for a standard masonry building (height 6.0 m, floor height 3.0 m, two floors) analyzed under four distinct boundary condition mechanisms (P1–P4). Each fragility curve provides the probability of collapse as a function of flood height, clearly distinguishing between mechanisms:

- Mechanism P1 (1-edge support): This curve demonstrates the simplest overturning scenario with a relatively lower stability threshold, showing a higher probability of collapse at lower flood heights.
- Mechanism P2 (2-edges support): The fragility curve reveals enhanced stability compared to P1, reflecting the additional top-edge constraint, resulting in a moderate increase in the collapse threshold.
- Mechanism P3 (3-edges support): This scenario, representing the presence of lateral supports, indicates significantly improved structural stability, thus shifting the fragility curve to higher flood heights and lower collapse probabilities at intermediate levels.
- Mechanism P4 (4-edges support): Exhibits the highest stability, clearly highlighted by the furthest shift of the fragility curve to the right, indicating substantially lower collapse probabilities at equivalent flood heights compared to other mechanisms.

This *visual sensitivity analysis* enables users and decision-makers to immediately grasp the critical importance of accurately characterizing boundary conditions and structural constraints when evaluating building vulnerabilities. The GUI tool thus not only facilitates practical and rapid assessment but also significantly contributes to informed decision-making and targeted structural improvements for flood resilience.

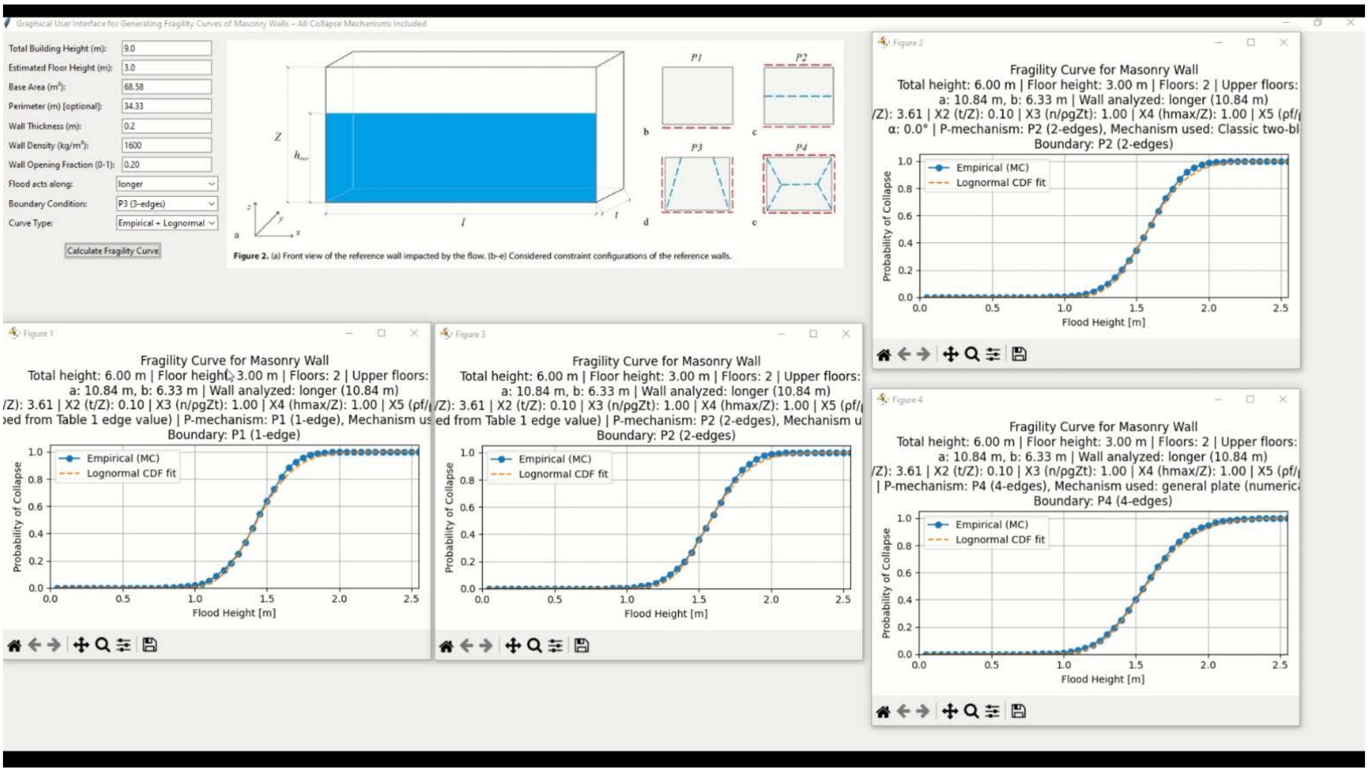

Figure 7 Visual Sensitivity Analysis for Standard Buildings Attributes by 4 Boundary Condition Mechanism (P1-P4)

5. Discussion

5.1 Strengths and Limitations of the Applied Methodology

The methodologies presented in this report provide robust and comprehensive frameworks for evaluating building vulnerabilities to earthquake and flooding hazards. A significant strength of the ML-based seismic fragility approach is its ability to systematically incorporate uncertainty, offering probabilistic insights and flexibility when addressing a range of structural typologies and soil conditions. Similarly, the flood fragility assessment using the Milanesi methodology demonstrates clear applicability to masonry buildings, explicitly accounting for key structural parameters and their impact on building stability under flood loads. The accompanying GUI tools substantially enhance usability and accessibility for practitioners and decision-makers.

However, some limitations should be recognized. The earthquake ML approach depends heavily on the availability and quality of input data; uncertainties in input data or gaps in the dataset may affect the accuracy of the predictive models. In addition, the structural mechanics approach for flooding, though rigorously validated, primarily applies to masonry buildings and may require significant modifications for other construction types, such as reinforced concrete or steel structures.

5.2 Comparison with Earthquake and Wind Hazard Fragility Assessments

Fragility curve methodologies have traditionally focused heavily on earthquake and wind hazards, where structural responses and loading conditions are comparatively well-studied and documented. Earthquake fragility assessments typically emphasize dynamic response characteristics such as natural periods and damping ratios. In contrast, wind fragility assessments focus on aerodynamic effects and structural responses to fluctuating pressures and uplift forces.

The methodologies presented here effectively adapt earthquake-based frameworks to seismic and flooding hazards. However, the simplified structural mechanics model for flooding distinctly differs from typical dynamic seismic analyses, emphasizing hydrostatic and hydrodynamic pressures rather than dynamic responses. This difference necessitates unique parameter selection and modelling strategies, highlighting the importance of specific vulnerability functions tailored to distinct hazard types.

5.3 Recommendations for Future Refinement

For future refinement, the following recommendations are suggested:

- Data Enhancement: Expand and refine the *CARTIS dataset*, ensuring comprehensive and high-quality input parameters to enhance the accuracy and reliability of ML-based predictive models.
- Extension of Structural Typologies: Broaden the applicability of the flood vulnerability approach beyond masonry structures by developing analogous structural mechanics frameworks for reinforced concrete, steel, and composite structures.
- Validation and Calibration: Continuously validate and calibrate predictive models and fragility curves against empirical data from historical hazard events, ensuring ongoing accuracy and relevance.
- Enhanced GUI Capabilities: Improve GUI functionalities to include automated scenario analyses, batch processing of multiple buildings, and direct integration with existing Geographic Information Systems (GIS) for broader spatial risk analysis.

6. Conclusions

This deliverable has successfully presented and implemented two innovative methodologies tailored for seismic and flood fragility assessment of buildings within the Ravenna region, aligned with the objectives of the STRENGTH project. The ML-based seismic vulnerability assessment offers a robust framework for capturing uncertainties and delivering probabilistic vulnerability analyses, while the Milanesi-inspired structural mechanics approach provides clear guidance on flood vulnerability for masonry buildings.

The practical outcomes, strengthened by intuitive GUI tools, ensure accessibility and usability for urban planners, local authorities, and stakeholders. By enhancing the ability to perform rigorous yet practical vulnerability assessments, these methodologies significantly contribute to informed risk management and decision-making, ultimately supporting increased resilience of urban ecosystems to climate-induced hazards.

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