DEVELOPMENT OF MULTI-HAZARD RISK INDICATORS FOR IMMOVABLE CULTURAL HERITAGE

Seismic Vulnerability Assessment

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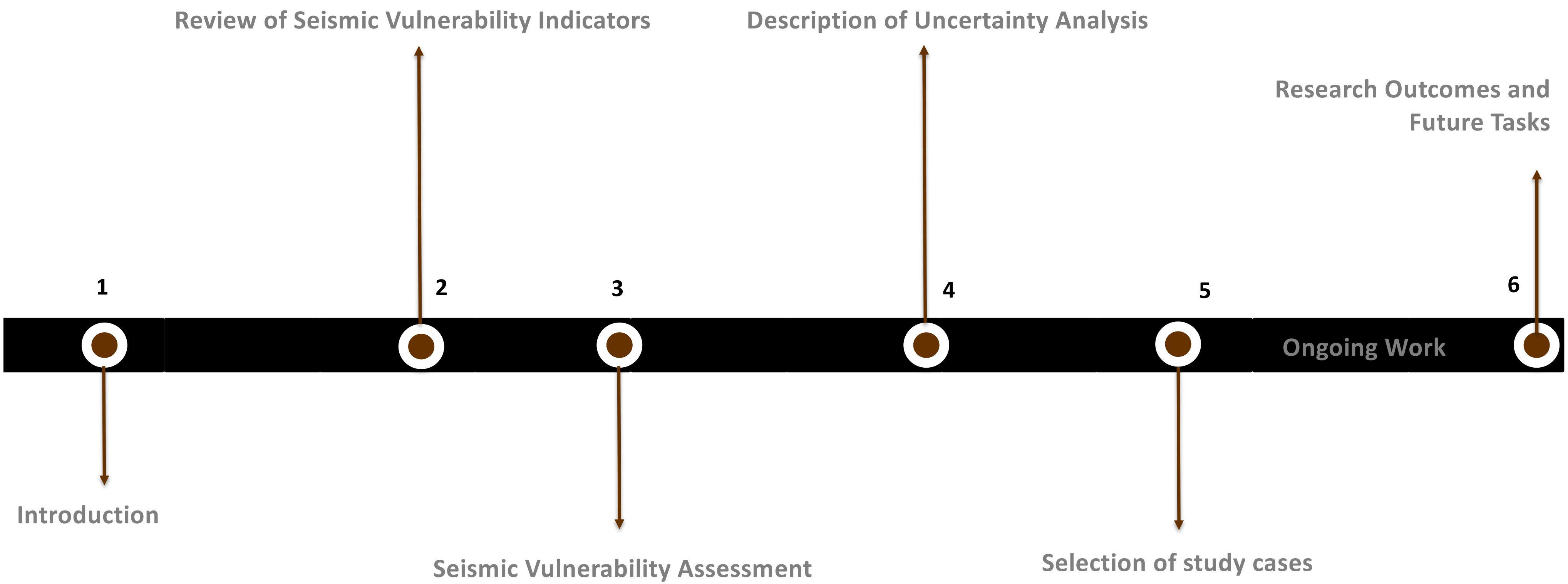
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Introduction

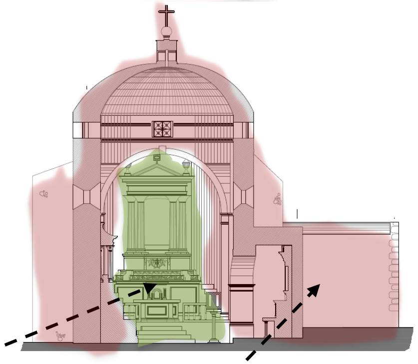
- Current indicator-based methods for immovable heritage assets, such as residential buildings in historic centres or churches, are limited to specific building types and lack a comprehensive approach.

- Some methods have been validated for residential buildings in historic centres.

- Further advancements are needed to enhance the consistency and applicability of indexing approaches. A recent development by Cescatti et al. (2023) introduces a method that formulates vulnerability indexes based on the typological characteristics of analysed churches.

Introduction

- Current indicator-based methods for immovable heritage assets, such as residential buildings in historic centres or churches, are limited to specific building types and lack a comprehensive approach.
- Some methods have been validated for residential buildings in historic centres.
- Further advancements are needed to enhance the consistency and applicability of indexing approaches. A recent development by Cescatti et al. (2023) introduces a method that formulates vulnerability indexes based on the typological characteristics of analysed churches.



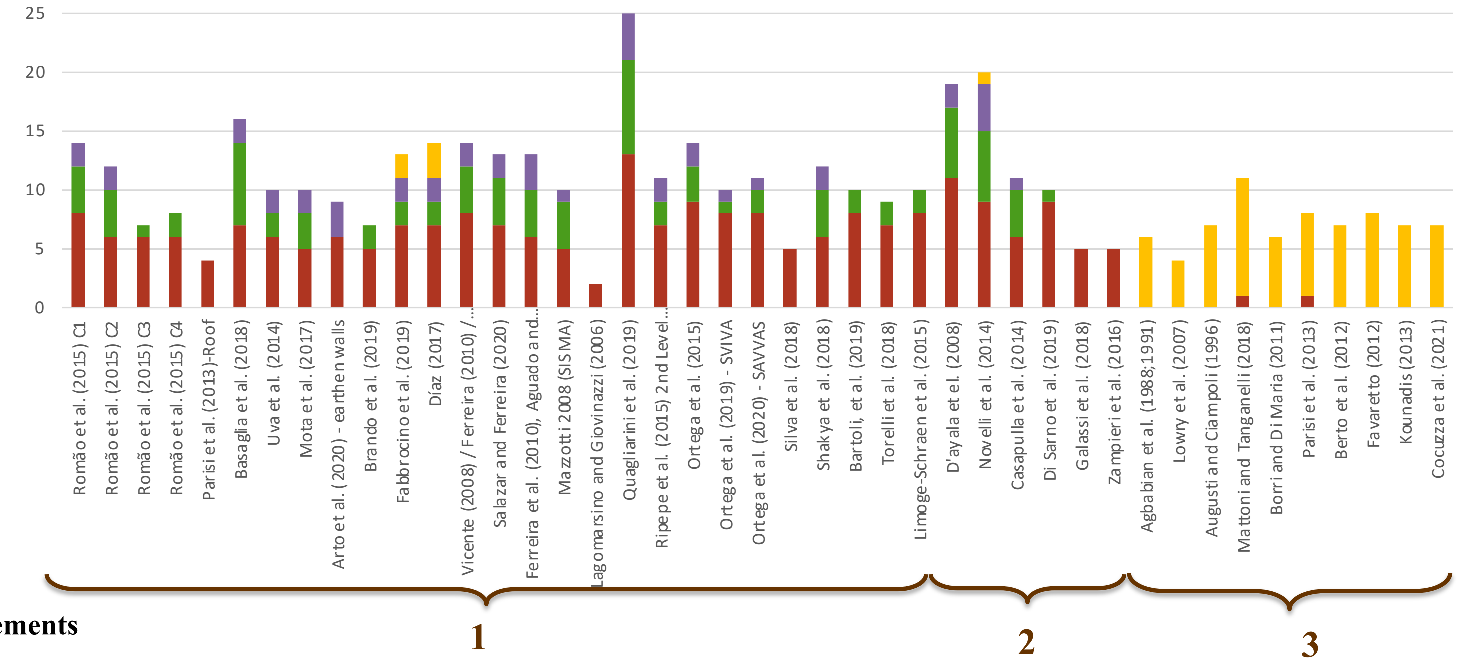
Objective

Propose a simplified method for the seismic vulnerability analysis of **historic buildings** that:
- Considers the presence of **valuable contents**.
- Accounts for the **uncertainty** in the assessment/scoring of the indicators that are involved due to the type of information that might be used (e.g., off-site surveys)

Review of Methods to identify relevant Seismic Vulnerability Indicators

Indicators identified

Literature Reviewed on Seismic Risk Assessment: 43 references



- Structural building system
- Irregularities and global interaction
- Conservation and non-structural elements
- Emergency preparedness

1. Vulnerability assessment methods for immovable assets at a larger scale

2. Vulnerability simulation methods involving limit analysis modelling

3. Vulnerability assessment methods for artworks

Review of Methods to identify relevant Seismic Vulnerability Indicators

Indicators identified

Structural building system
- Type of global structural system
- Type of masonry of the walls
- Lateral strength
- Maximum distance between walls
- Height of the construction
- Soil conditions and foundations
- Type of floor structural system
- Type of roof structural system

Irregularities and global interaction
- Interaction with other constructions
- In-plan configuration
- Regularity in elevation
- Alignment of wall openings

Conservation and non-structural elements
- Conservation state
- Hazards due to non-structural elements

Emergency preparedness
- Preventive measures for movable artwork
- Cultural value

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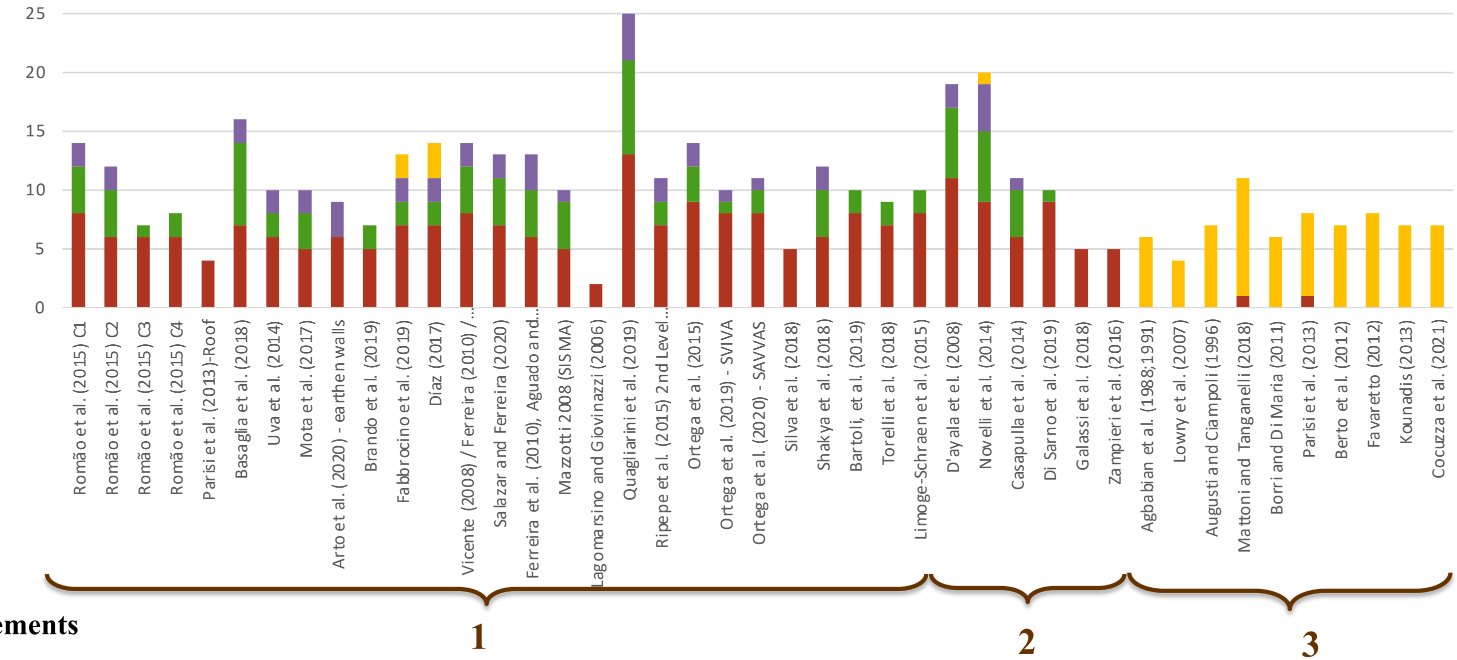

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Simplified Seismic Vulnerability Assessment

Romão, et al. (2015)

Fragility index *IFS*

$$IFS = \frac{\sum_{i=1}^{14} C_i \cdot p_i}{650}$$

$$0 \leq IFS \leq 1.0$$

Fragility index *IFS* and indicators involved in its quantification

Parameters		Fragility Class C_i				Weight, p_i
		A	B	C	D	
P1	Type of global structural system	0	5	20	50	0.75
P2	Type of masonry of the walls	0	5	20	50	1.00
P3	Lateral strength	0	5	20	50	1.50
P4	Maximum distance between walls	0	5	20	50	0.50
P5	Height of the construction	0	5	20	50	1.50
P6	Soil conditions and foundations	0	5	20	50	0.75
P7	Interaction with other constructions	0	5	20	50	1.50
P8	In-plan configuration	0	5	20	50	0.75
P9	Regularity in elevation	0	5	20	50	0.75
P10	Alignment of wall openings	0	5	20	50	0.50
P11	Type of floor structural system	0	5	20	50	1.00
P12	Type of roof structural system	0	5	20	50	1.00
P13	Conservation state	0	5	20	50	1.00
P14	Hazards due to non-structural elements	0	5	20	50	0.50

Illustrative assessment of an indicator – P11

Vulnerability Classification of P11 in case of vaulted floors

Description of the type of floor	Class	
	Baseline value	Deficient conservation state found in the supports
Vaulted floor supported by walls with buttresses or ties (Figure a) to ensure its stability or supported by walls that are thick enough.	A	B
Vaulted floor supported by walls where the starting angle is greater than 45º (Figure b), without any buttresses or ties to secure it.	C	D
Vaulted floor supported by walls where the starting angle is less than 45º(Figure c), without any buttresses or tie rods to secure it.	D	D

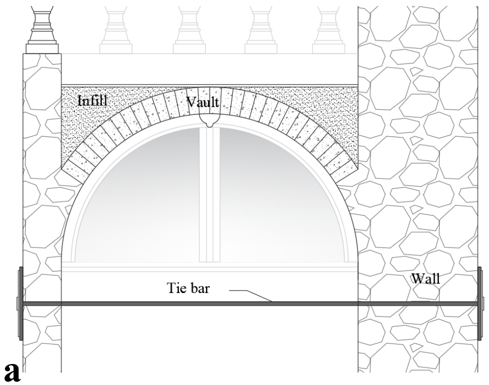

Figure a

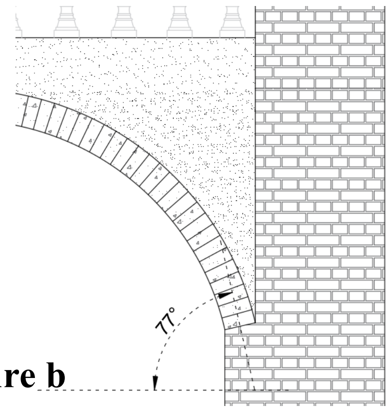

Figure b

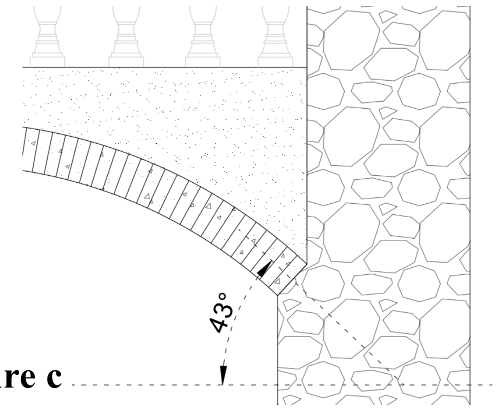

Figure c

Simplified Seismic Vulnerability Assessment

Romão, et al. (2015)

+1 Indicator

To consider a criteria for valuable contents in the historic building

P15 – Preventive measures for movable artwork

Fragility index *IFS* and indicators involved in its quantification

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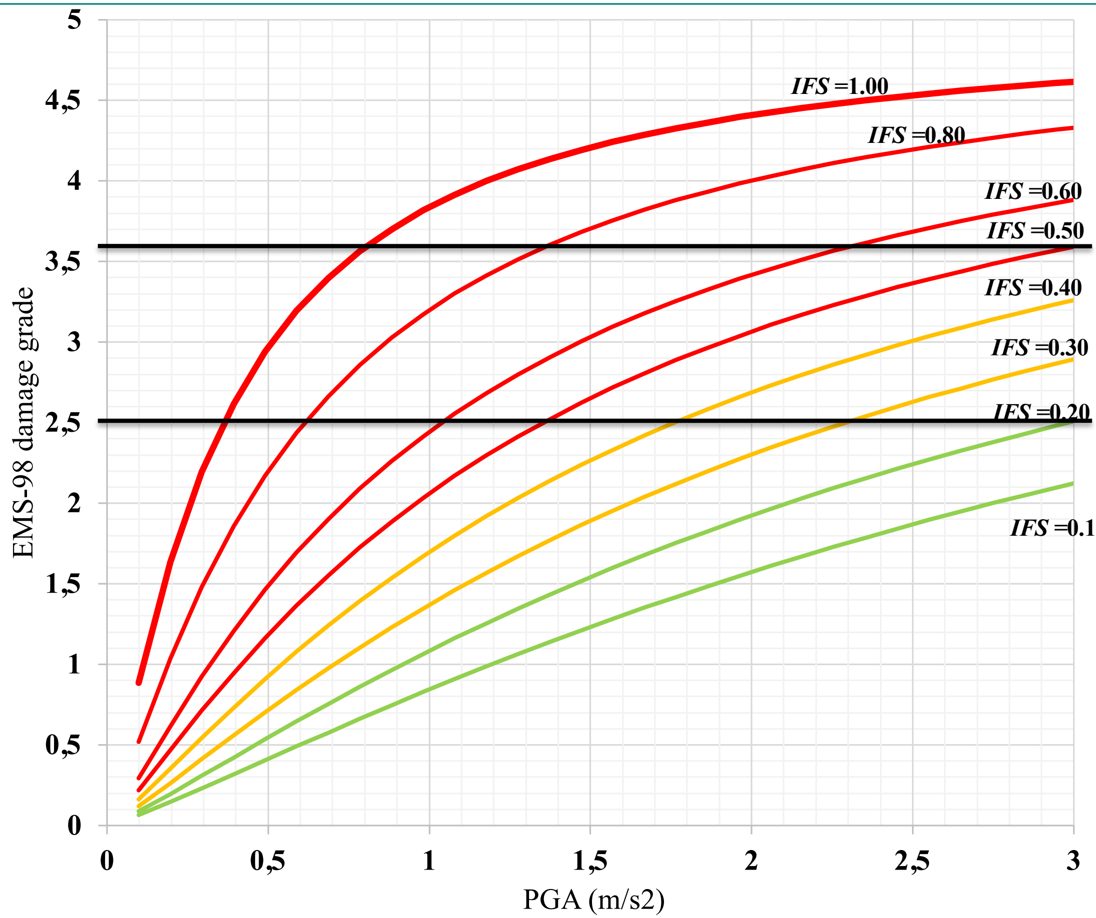
Simplified Seismic Vulnerability Assessment

A fragility class is assigned according to the IFS value.

$IFS \leq 0.20$	→	Low
$0.20 < IFS \leq 0.50$	→	Moderate
$IFS > 0.50$	→	High

The framework defines three levels of expected damage based a relation with EMS-98 damage grades. These damage grades are then correlated with peak ground acceleration values and assigned to a 3-level expected damage scale using a colour-coded system.



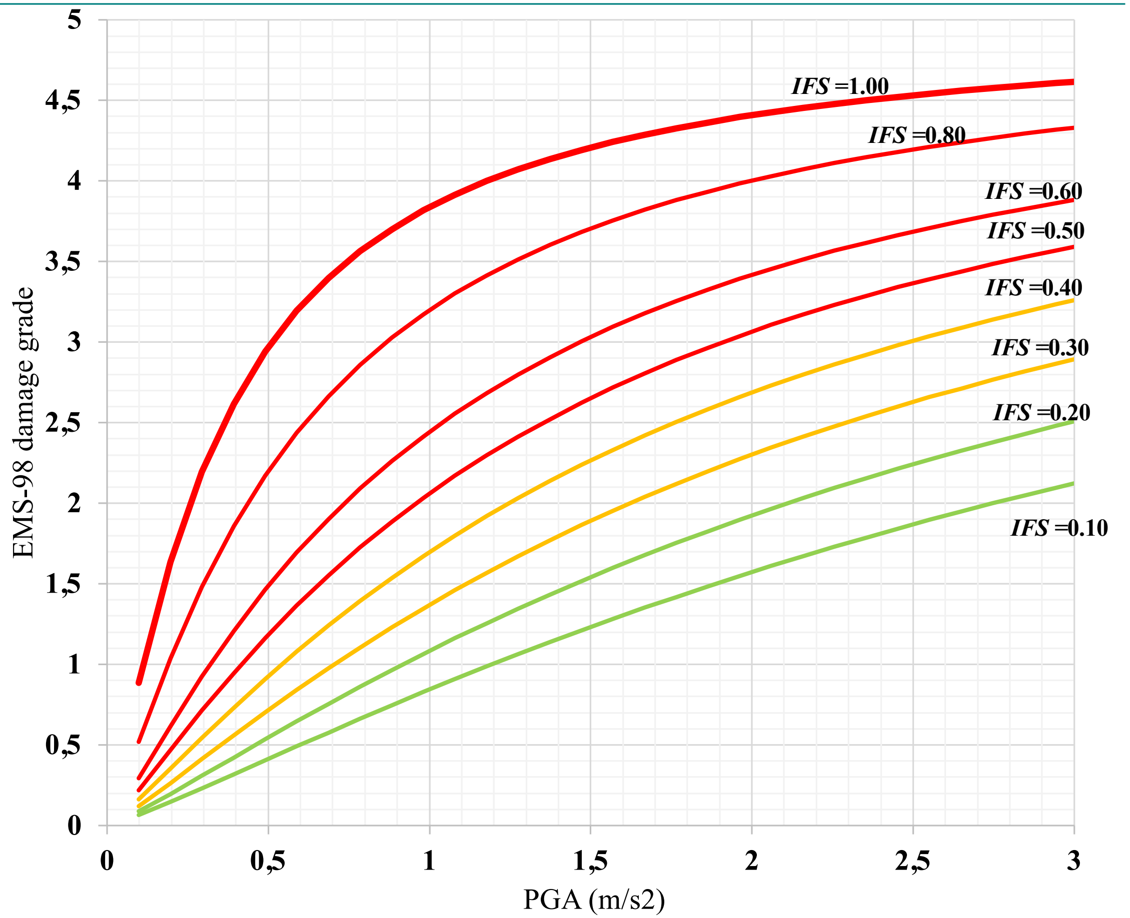
Simplified Seismic Vulnerability Assessment

PGA must be converted to macroseismic intensity values I_{MCS} through the logarithmic relation established by Guagenti and Petrini (1989).

$$I_{MCS} = \frac{\ln(PGA) + 7.073}{0.602}$$

To convert the values to the MSK scale, which is equivalent to the EMS-98 scale, the following equation is used, presented by Margottini et al. (1992).

$$I_{MsK} = 734 + 0.814 \times I_{MCS}$$



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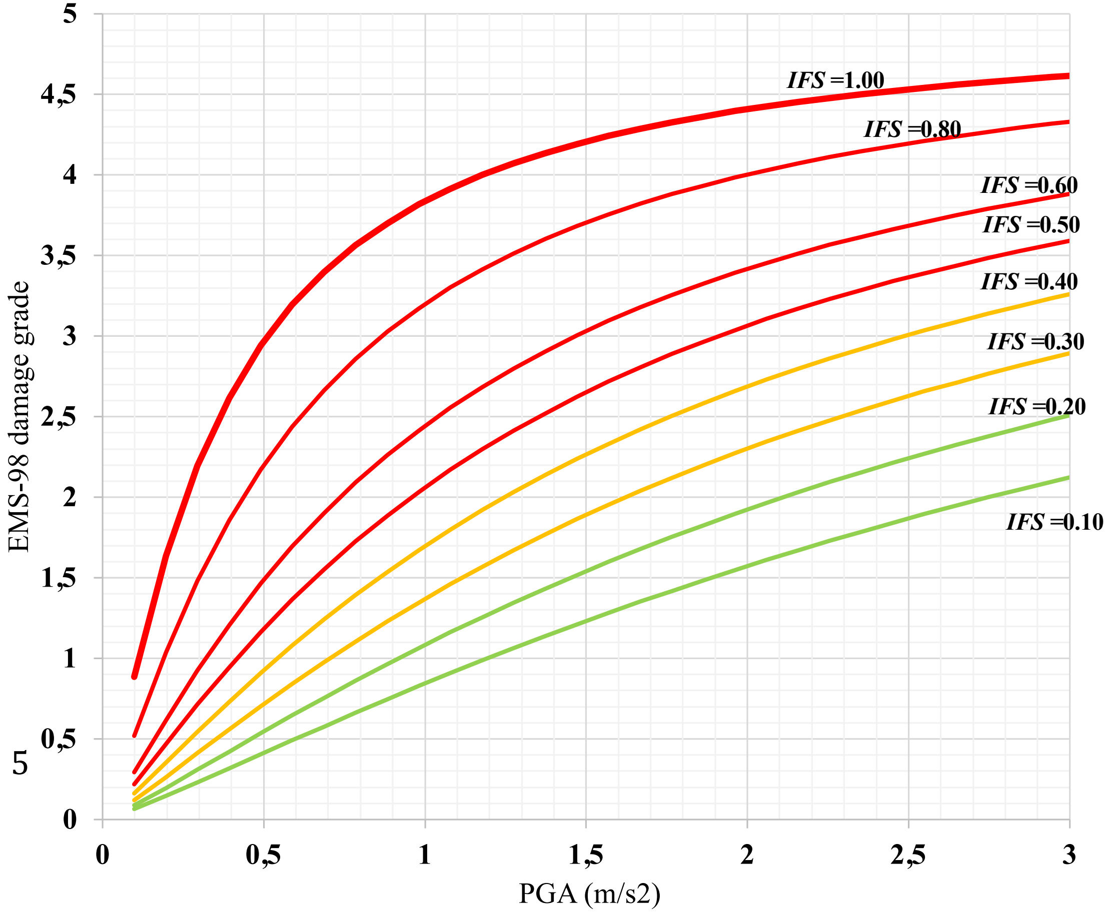
The damage grades (μ_D) are correlated using the value of I_{MsK}= I_{EMS-98} and IFS using the following equations:

$$\mu_D = 2.5 \times \left[1 + \tanh\left(\frac{I_{EMS-98} + 6.25 \times V - 13.1}{Q}\right)\right]; 0 \leq \mu_D \leq 5$$

$$V = 0.592 + 0.0057 \times IFS$$



Simplified Seismic Vulnerability Assessment

- The assessment/scoring of each indicator might involve some uncertainty due to the source of information that is used, and it is possible that more than one fragility class could be assigned as a result of this uncertainty
- To reflect this uncertainty, the different fragility classes that could be assigned for each indicator are associated to a probability that reflects the level of confidence that the surveyor has given the available data

San Agustin Church in Trujillo, Perú

Example:
indicator (P_2)

$$\mathbf{P}(P_2 = Class\ A \therefore 0) = 0$$

$$\mathbf{P}(P_2 = Class\ B \therefore 5) = 0.15$$

$$\mathbf{P}(P_2 = Class\ C \therefore 20) = 0.15$$

$$\mathbf{P}(P_2 = Class\ D \therefore 50) = 0.70$$

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Which type of Masonry?

San Agustin Church in Trujillo, Perú

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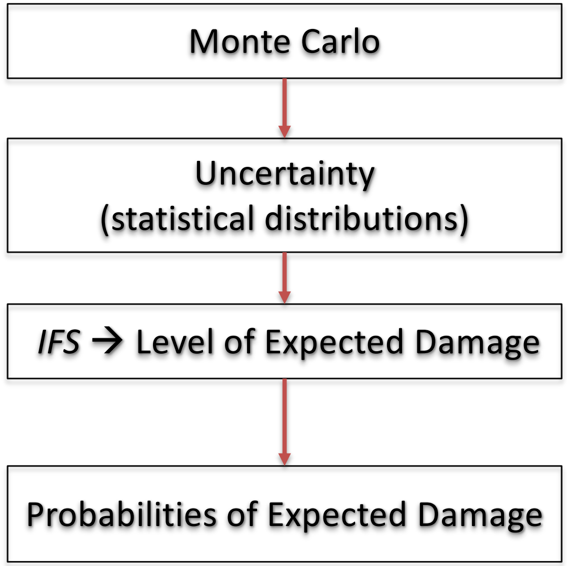
$\mathbf{P}(P_2 = Class\ D \therefore 50) = 0.70$

Simplified Seismic Vulnerability Assessment

- The probabilities of the fragility classes assigned to each indicator are combined using Monte Carlo simulation
- A statistical distribution for the fragility index *IFS* is established, reflecting the underlying uncertainty
- This uncertainty is propagated from *IFS* to the level of expected damage
- The probabilities for each level of expected damage are defined based on the statistics of *IFS* (e.g., how many value below the threshold for low damage)



Example:

Level of Expected Damage

Low	Medium	High
20%	45%	35%

Addressing Uncertainty: Future tasks

To validate the proposed approach for integrating and propagating the uncertainty about the classifications of indicators, it will be applied to simulate the seismic vulnerability assessment of 6 churches damaged from the 2009 L'Aquila earthquake for which the damage levels are known:

- Simulate different scenarios of uncertainty in the information used to score/assess the indicators and analyse the variability of the expected damage levels in comparison with the actual damage levels caused by the earthquake

- Calculate the *IFS* and the expected damage level considering the best available data and compare with the actual damage levels caused by the earthquake

Study Cases

The city of L'Aquila, Italy, suffered an earthquake in 2009. It is in the central part of the Apennines in the Abruzzo region, where a significant portion of the cultural heritage was severely damaged.

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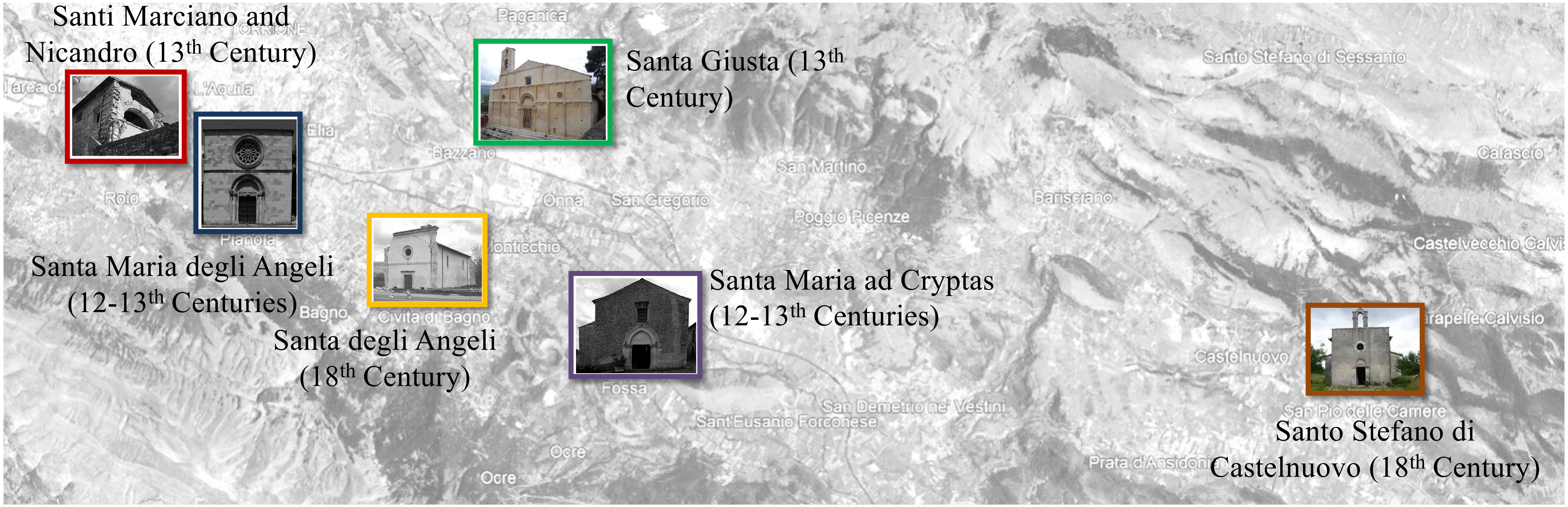

Research Products and Future Tasks

Conference papers (22/23)

- **Salazar, L. G. F., Romão, X., Figueiredo, R., Bertolin, C., Foti, P., Boccacci, G., & Siani, A. M. (2023). Indicator-based Fire Vulnerability Assessment of the Ringebu and Heddal Stave Churches in Norway. In ESICC Conference 2023 - Energy Efficiency, Structural Integrity in Historical and modern buildings facing Climate Change and Circularity (Presented in July 2023). Lisbon, Portugal.**

- **Salazar, L. G. F., Figueiredo, R., Romão, X. (2023). A hybrid approach for the assessment of flood vulnerability of historic constructions and their contents. In 13th International Conference on Structural Analysis of Historical Constructions SAHC 2023 (Accepted to be presented in September 2023). Kyoto, Japan.**

Research Products and Future Tasks

Research Articles (23/24) in Scientific journals

“One step at a time”

- **Fire damage index for vulnerability assessment in cultural heritage**
- **Performance of fire vulnerability assessment method in historic centre of Guimarães**

- **Review of vulnerability indicators for flood risk assessment in cultural heritage**
- **Hybrid flood vulnerability assessment for historic buildings and their valuable content**

- **Uncertainty analysis for simplified seismic assessments in historic buildings**

THANK YOU FOR YOUR ATTENTION

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