Structural Vulnerability Assessment in Historic Masonry Settlements Using Drone Survey

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Abstract. This work proposes a systematic technique to carry out a structural vulnerability assessment of historic masonry structures using Unmanned Aerial Vehicle (UAV) photogrammetry. The proposed approach aims to improve structural risk mitigation efforts in small historic towns by overcoming the limits of existing on-site approaches, which are often intrusive and resource expensive, by using drone-based image data to detect peculiar structural parameters. The proposed technique formalizes observable visual parameters in orthophotos and 3D models, transforming them into a decision support system. For this purpose, 23 parameters are considered, which are divided into four macro-categories. These parameters are borrowed from official Italian Civil Protection forms, adapting them for remote analysis. Weights to the parameters are assigned using the Analytic Hierarchy Process (AHP), which is guided by experts in pairwise comparisons. The approach is implemented in an Excel-Visual Basic Application (Excel-VBA) environment, allowing users to input visual data, calculate scores, and generate a vulnerability index ranging from 1.00 (low vulnerability) to 5.00 (high vulnerability) for each individual building. The index is then framed into three vulnerability classes. This method provides a scalable, non-invasive, and reproducible methodology for guiding early vulnerability mapping and prioritization, which is especially appropriate for ancient urban centers.

Keywords: UAV Photogrammetry · Structural Vulnerability Assessment · Analytic Hierarchy Process (AHP) · Structural Vulnerability Map

1 Introduction

In the context of heritage building safeguarding, the structural safety evaluation is a needed task, especially in small towns where the preservation of heritage and safety must coexist. These urban aggregates—particularly present in southern Italy—consist of dense, irregular clusters constructed with different materials and frequently lacking structural documentation. Such situations interfere with the implementation of traditional structural safety assessment methods, which generally depend on on-site evaluations, numerical modelling, and invasive diagnostic examinations (Julià & Ferreira, 2021).

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To address the need for rapid and effective evaluation tools, recent studies have explored the use of remote sensing techniques—particularly UAV-based photogrammetry for documenting and analyzing existing buildings (Ulvi, 2021). These methods enable the production of high-resolution orthophotos and textured 3D models that can support preliminary diagnostic evaluations (Guo et al., 2022). However, despite their increased application in conservation and survey campaigns, few methodologies have formalized the obtainable outputs into structured frameworks for structural vulnerability assessment.

Some efforts have also combined photogrammetric data with GIS platforms or spatial decision-support systems to generate vulnerability maps (Leggieri et al., 2022). Others have introduced scoring-based approaches that rely on qualitative expert judgement. In this direction, Multi-Criteria Decision Making (MCDM) methods, and in particular the Analytic Hierarchy Process (AHP), have represented a systematic way to assign importance to multiple factors while ensuring logical consistency (Saaty, 1989; Saaty, 2002). Applications of AHP to vulnerability assessment have shown promising results in terms of transparency and adaptability (Shadmaan, M. S., & Popy, S. 2023; Sergiacomi, C., & Fagarazzi, C. 2020), yet often depend on field-derived data or semi-quantitative forms.

Nevertheless, in the authors' opinion, there remains a methodological gap; indeed, no current procedure provides a fully visual, photogrammetry-driven structure safety assessment system that translates image-based indicators into consistent vulnerability scores without the need for interior access or invasive surveys.

This work presents a systematic approach for the preliminary structural vulnerability evaluation of historic masonry structures, based just on using UAV photogrammetry. The methodology adapts official Italian Civil Protection forms: AeDES, GNDT and CARTIS (Baggio et al., 2007; GNDT, 1986; Zuccaro et al., 2023) for non-invasive applications and employs AHP to establish the relative significance of judgment criteria based on the visually detected parameters. The resulting operative tool, developed in a Microsoft Excel–VBA environment, is intended for use by local administrations and technical staff, facilitating the creation of vulnerability maps and digital decision-support tools for risk mitigation and building heritage preservation.

2 Methodology

The complete methodological workflow is sketched in Fig. 1. This flowchart summarizes the operational structure of the proposed method which starts with a UAV survey of the analyzed historic urban center followed by the construction of a 3D digital twin (DT) of the building aggregate. By visual inspection of the DT, the peculiar parameters affecting the structural vulnerability are then extracted for each single building. The extracted data are processed in an Excel-VBA environment where an AHP-based procedure also assigns a weight to each single parameter. Eventually, a vulnerability map of the aggregate is obtained, along with a vulnerability index associated with each single building. No comments are given on the survey procedure and the consequent construction of the DT model, both being standard procedures.

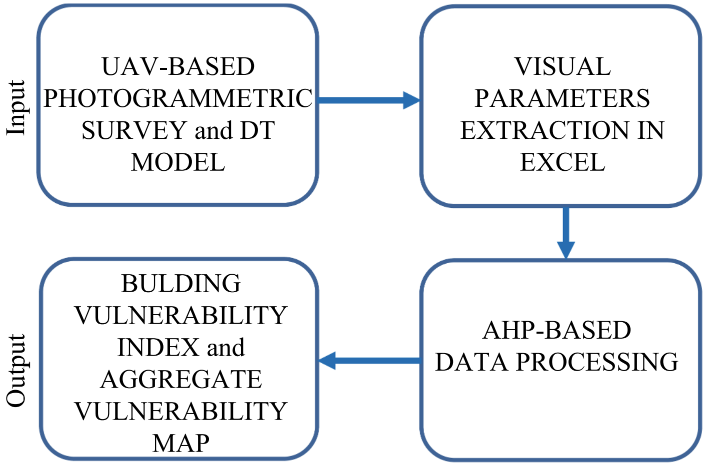

Fig. 1. Workflow of the proposed methodology, from UAV-based data acquisition to vulnerability index calculation via AHP and Excel–VBA automation.

2.1 Selection and Structuring of the Visual Detectable Parameters

The selection of the peculiar parameters is based on official documentation issued by the Italian Civil Protection Department for seismic damage and vulnerability assessment. The reference sources include the forms AeDES, GNDT and CARTIS (Baggio et al., 2007; GNDT, 1986; Zuccaro et al., 2023). Only parameters that are externally observable and reliably interpretable through UAV-based photogrammetry were considered. Parameters requiring invasive inspections, interior access, or unavailable documentation have been excluded.

The selected significant parameters have resulted in 23, and they have been grouped in 4 *evaluation criteria*, precisely:

- **General Characteristics:** typological position; site morphology; number of total floors; average building height; regularity in plan; regularity in elevation; type of aggregate; type of roof.
- **Structural Characteristics:** type of masonry; tie rods; structural bow windows; asymmetrical perforations.
- **External Envelope Feature:** surface damage; irregular vertical extension; presence of dangerous elements; different materials at different levels; presence of consolidation.
- **Structural Weaknesses:** visible crack; type of crack; crack orientation; out-of-plane walls deformation; damage at the connection between buildings; roof damage.

All the selected parameters were verified for compatibility with visual analysis conducted on orthophotos, 3D textured meshes, and oblique/nadir views generated via Structure-from-Motion (SfM) photogrammetry.

2.2 Hierarchical Weighting Model Based on AHP

The weighting process was structured according to a three-level hierarchy:

- Level 0: *Overall objective* that is the structural vulnerability assessment.
- Level 1: 4 criteria.
- Level 2: 23 Sub-criteria (distributed within the criteria).

Pairwise comparisons were conducted following Saaty's 1–9 scale (Saaty, 1989; Saaty, 2002). Five pairwise comparison matrices were constructed using expert judgment.

One matrix comparing the four criteria; Four matrices comparing the sub-criteria within each criterion.

For each matrix, the Consistency Index (*CI*) and Consistency Ratio (*CR*) were computed to verify internal coherence. All matrices yielded *CR* values < 0.10, confirming the reliability of the judgments. The *CI* and *CR* were calculated according to Saaty's method (Saaty, 1989) to assess the reliability of the judgments provided in each pairwise comparison matrix. The *CI* is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Where n is the number of elements in the matrix and λ_{max} is the principal eigenvalue. The *CR* is computed as:

$$CR = \frac{CI}{RI} \tag{2}$$

Where *RI* is the Random Consistency Index, which depends on the order of the matrix. A *CR* value less than 0.10 is generally considered acceptable. If *CR* exceeds this threshold, the pairwise judgments are considered inconsistent and should be reviewed. Table 1 shows *RI* for n =1, 2, ...,12.

Table 1. Random Consistency Index

n	1	2	3	4	5	6
RI	0	0	0.58	0.90	1.12	1.24
n	7	8	9	10	11	12
RI	1.32	1.41	1.45	1.49	1.52	1.54

The hierarchical structure adopted in this study is illustrated in Fig. 2. It reflects the decomposition of the overall objective into four criteria, each further divided into sub-criteria.

This hierarchical structure enabled the calculation of a *global weight* (i. e., the weight of the single criterion within the four) and a *local weight* (i. e., the weight of each single sub-criterion within the criterion to which it belongs). A *final weight* of each sub-criterion (i. e., its weight within the 23) is simply obtained by multiplying the local by the global weight and it is used to compute the vulnerability index for each assessed building based on its visually detected features.

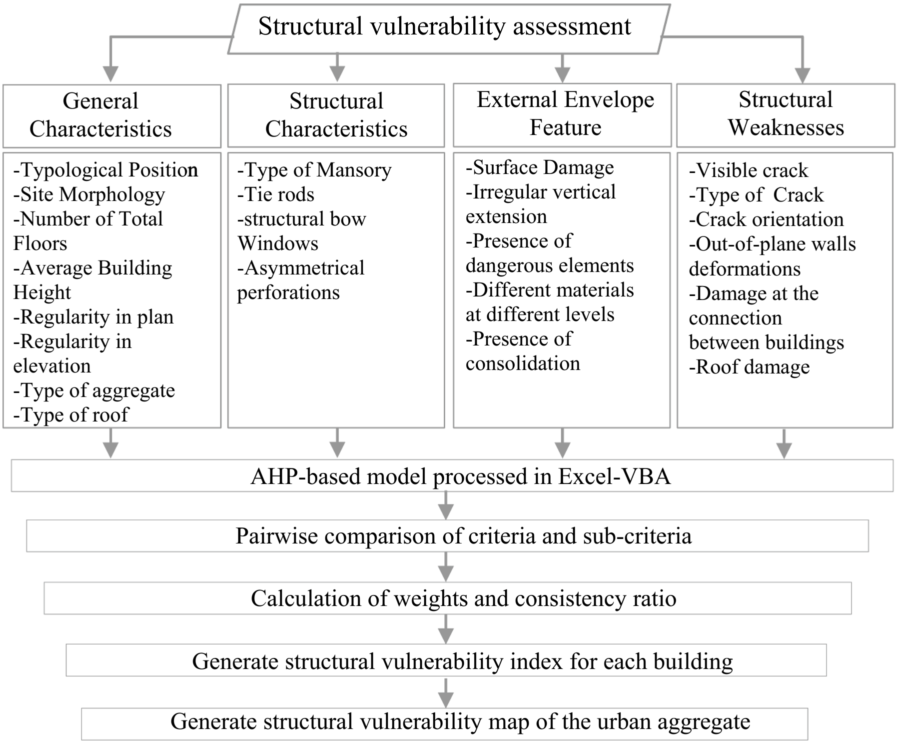

Fig. 2. AHP hierarchical structure used for criteria weighting and individual building vulnerability index computation.

2.3 Implementation in Excel-VBA

The methodology was implemented in Microsoft Excel, choosing it for its structured interface, accessibility and integrated automation support through Visual Basic for Applications (VBA). The spreadsheet is modular and includes the following core components:

- Pairwise comparison modules for entering the AHP judgement matrices at both criteria and sub-criteria levels.
- Automated processing blocks, executing matrix normalization, consistency checks, and hierarchical weight propagation.
- Building evaluation forms are used to input the observed peculiar characteristics (i. e., the discussed parameters or sub-criteria) of each examined building.

Each sub-criteria is associated with a closed list of possible answers, defined according to visual attributes identifiable in the 3D model or orthophotos. Each answer is assigned a score on a 1–5 ordinal scale as shown by Alizadeh et al. (2018), the validity of this scale stems from its capacity to convert subjective perceptions into consistent numerical values within a defined weighting system. The choice to implement a 1–5 scale was driven by the variability in the number of answer possibilities across sub-criteria: a few provide just two or three alternatives, while others present four. Employing a five-point scale facilitates a more equitable differentiation in the scoring system and mitigates excessive result variability that may develop with extended scales, where:

- 1 indicates a favorable condition (a low contribution to structure vulnerability).
- 5 indicates a critical condition (high contribution to structure vulnerability).

The scoring criteria follow two predefined classification frameworks based on national technical standards once again, reference is made to the forms: AeDES GNDT and CARTIS above quoted. The method facilitates the concurrent processing of numerous buildings within a single worksheet. For each building, the selected answers for each sub-criteria are converted into numerical scores, which are subsequently combined utilizing the weighted AHP model to get the building vulnerability index.

The VBA system automates the fundamental computational processes of the AHP-based evaluation methodology, including:

- Normalization of judgement matrices and computation of local priority vectors.
- Calculation of λ_{max}, *CI* and *CR* for each matrix.
- Application of the weights through the hierarchy and calculation of the weighted scores which are aggregated across all sub-criteria.
- Computation of a vulnerability index for each individual building.

The final output is a synthetic building vulnerability index, ranging from 1.00 (minimum vulnerability) to 5.00 (maximum vulnerability). The obtained values of the vulnerability index are finally grouped into three vulnerability classes:

- Low Vulnerability: 1.00–2.33
- Medium Vulnerability: 2.34–3.66
- High Vulnerability: 3.67–5.00

This classification, via the resulting vulnerability maps of the entire urban aggregate, supports decision-making by enabling intuitive comparison, spatial mapping, and prioritized technical inspections.

3 Results, Preliminary Validation and Discussion

The Analytic Hierarchy Process (AHP) indicated that the two criteria. “Structural Characteristics” and “Structural Weaknesses” have the greatest impact on the overall vulnerability assessment. Among the 23 sub-criteria, the most significant ones were out-of-plane walls deformation, type of masonry, damage at the connection between buildings and type of crack; such results correspond indeed with established literature on failure mechanisms in historic masonry structures.

The results of the AHP weighting process are summarized in the following tables.

In particular:

- Table 2 reports the pairwise comparison matrix for the 4 criteria assumed. All values were assigned using Saaty’s fundamental scale. According to this scale, a score of 1 indicates equal importance between two criteria, while scores of 3, 5, 7, and 9 represent increasing levels of importance (moderate, strong, forceful, and extreme,

Table 2. Pairwise comparison matrix for the 4 criteria, with derived global weights and consistency indicators.

Criteria	General Characteristics	Structural Characteristics	External Envelope Feature	Structural Weaknesses	Global Weight
General Characteristics	1	1/3	1/2	1/4	10%
Structural Characteristics	3	1	2	1/2	28%
External Envelope Feature	2	1/2	1	1/3	16%
Structural Weaknesses	4	2	3	1	46%
λ_{max}	4,03				
CI	0,01				
CR	0,01				

Table 3. Pairwise comparison matrix for the sub-criteria within the "Structural Characteristics" Local and Final weights of the sub-criteria.

Structural Characteristics	Type of Masonry	Tie Rods	Structural Bow Windows	Asymmetrical Perforations	Local Weight
Type of Masonry	1	2	4	5	48,96%
Tie rods	1/2	1	3	4	30,54%
Structural Bow Windows	1/4	1/3	1	2	12,64%
Asymmetrical perforations	1/5	1/4	1/2	1	7,86%
Final Weight	13,70%	8,55%	3,54%	2,20%	
λmax	4,04				
CI	0,01				
CR	0,01				

respectively). Reciprocal values (e.g., 1/3, 1/5) are applied when the compared criterion is considered less important. The weights are expressed as percentages. The Consistency Ratio (*CR*) confirms the matrix is within acceptable consistency limits ($CR < 0.10$).

- Table 3 presents the sub-criteria comparison matrix for the "Structural Characteristics" criterion, just as a representative example. The same pairwise comparison procedure and scoring system based on Saaty's scale was applied to derive the relative weights.

Table 4. Final weights for each sub-criteria.

Criteria and Sub-Criteria	Local Weight	Final Weight
General Characteristics (10%)		
Typological position	9,77%	0,98%
Site morphology	8,38%	0,84%
Number of total floors	18,87%	1,89%
Average building height	20,76%	2,08%
Regularity in plan	13,09%	1,30%
Regularly in elevation	14,98%	1,50%
Type of aggregate	7,72%	0,77%
Type of roof	6,43%	0,64%
Structural Characteristics (28%)		
Type of masonry	48,96%	13,70%
Tie rods	30,54%	8,55%
Structural bow windows	12,64%	3,54%
Asymmetrical perforations	7,86%	2,20%
External Envelope Feature (16%)		
Surface damage	6,50%	1,04%
Irregular vertical extension	40,00%	6,40%
Presence of dangerous elements	25,10%	4,01%
Different materials at different levels	15,00%	2,40%
Presence of consolidation	13,40%	2,14%
Structural Weaknesses (46%)		
Visible crack	5,10%	2,35%
Type of crack	15,30%	7,04%
Crack orientation	10,40%	4,78%
Out-of-plane walls deformation	36,20%	16,65%
Damage at the connection between buildings	23,00%	10,58%
Roof damage	10,00%	4,60%

- Table 4 summarizes the local and final weights for all sub-criteria.
- Table 5 illustrates the calculation procedure for determining the vulnerability index combining the AHP-derived weights with the answer scores assigned to each sub-criterion. For every sub-criteria, the selected answer corresponds to a predefined score from 1 to 5. This value is multiplied by the sub-criteria's final weight to obtain the *sub-criteria weighted score.* For instance, the choice "neighboring" under the criterion Typological Position corresponds to a score of 3; multiplied by its final

weight of 0.98%, the result yields a weighted score of 0.03. The vulnerability index of the building is finally obtained as the sum of all sub-criteria weighted scores. The table reports only a selection of parameters for clarity, while the complete evaluation considers the entire set of criteria.

Table 5. Example of weighted score calculation for a sample building. The vulnerability index results from the sum of each sub-criteria's weight multiplied by the assigned answer score.

Criteria	Final Weight	Answer	Answer Score	Sub-criteria weighted score
Typological Position	0,98%	Isolated	1	0,03
		neighboring	3	
		connection	5	
Type of Masonry	13,70%	I don't know	0	0,00
		Regular masonry	1	
		Rough masonry	3	
		Irregular masonry	5	
Number of Total Floors	1,89%	1	1	0,09
		2	3	
		≥3	5	
…	…	…	…	…
		…	…	
Roof damage	4,60%	Yes	5	0,05
		No	1	
Sub-criteria weighted score = Final Weight X Answer Score				
Building vulnerability index = ∑ (Sub-criteria weighted score)				

Table 5 also includes cases where the selected response is "I don't know". In these situations, the corresponding sub-criteria is excluded from the evaluation, and its weight is proportionally redistributed among the remaining sub-criteria within the same criterion. For instance, when the type of masonry is not identifiable—frequent in drone-based surveys—the weight associated with that sub-criteria is reallocated across the other sub-criteria within the structural characteristics criterion.

To facilitate a cross-comparison among buildings of different typologies and state of preservation within the examined urban aggregate, the vulnerability index has been classified into *three vulnerability levels,* or *classes*. To this end the index range was divided into three equal intervals corresponding to *low*, *medium*, and *high vulnerability classes*, each associated with a specific color code and interpretation, as shown in Table 6.

Table 6. Classification of the vulnerability index. The index range is divided into three vulnerability classes, each associated with a color and a qualitative interpretation to support decision-making and prioritization of actions.

Vulnerability Class	Index Range	Color Code	Interpretation
Low	1.00 - 2.33	Green	The building has no visible structural weaknesses. No immediate intervention is required.
Medium	2.34 - 3.66	Yellow	Some vulnerabilities are present. Further inspection is recommended.
High	3.67 - 5.00	Red	The structure shows significant damage or instability. Priority intervention and detailed assessment are advised.

A colored structural vulnerability map of the entire urban aggregate can then be provided for a quick and easy consultation.

The preliminary application of the promoted tool has been implemented on a limited dataset that included masonry structures with diverse morphologies, materials and damage states. Precisely, as pilot test, the village of Bova, Reggio Calabria, Italy, was chosen. The village of about 500 inhabitants. The tool exhibited reliable performance, categorizing well-preserved and geometrically regular structures as low vulnerability while recognizing buildings with structural deterioration or geometric irregularities as medium or high vulnerability. The test affirmed the methodological effectiveness, structural vulnerability, and scalability for expedited assessment in historic urban environments.

4 Concluding Remarks

This study proposes a systematic and reproducible approach for evaluating the structural vulnerability of historic masonry structures, using only UAV-derived photogrammetric data. The methodology combines visual parameters obtained from official Italian national forms AeDES, GNDT and CARTIS with a multi-criteria weighting mechanism using the Analytic Hierarchy Process. The model is executed in a completely automated Microsoft Excel-VBA environment, guaranteeing methodological transparency and accessibility for non-specialist users.

The proposed method allows a non-invasive evaluation of buildings' structural vulnerability at the urban level, helping in the first identification of vulnerable buildings and guiding the prioritization of subsequent inspections or interventions. A pilot test validated the consistency and operational reliability of the tool.

Subsequent efforts will concentrate on expanding the application of the promoted tool to more extensive case studies, also incorporating the methodology into geospatial platforms or digital twin systems for enhanced planning and structural vulnerability management in historic built environments.

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