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Photogrammetry-Drone-Based Tool for Structural Vulnerability Assessment in Historic Urban Centers

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Abstract. This study presents the practical validation of a non-invasive methodology for assessing the structural vulnerability of historic masonry buildings, proposed in the previous paper by the authors (see Part 1 of this volume) and based on photogrammetric data obtained using Unmanned Aerial Vehicles (UAVs). The method is tested on nine buildings in the village of Bova in Calabria, Italy. A drone survey is conducted to acquire high-resolution nadir and oblique images, which are then processed using Structure-from-Motion (SfM) techniques to generate textured 3D models, orthophotos, and dense points clouds. Visually detectable parameters, selected as significant for structural vulnerability assessment, are extracted directly from the photogrammetric outputs and used as input for a structured, Excel-based tool. Analytic Hierarchy Process (AHP) is used to weight the parameters and Excel Visual Basic for Application (Excel-VBA), enables users to select responses for each parameter via dropdown menus. Internal automation then converts these selections into numerical scores. A vulnerability index is computed for each individual building, which is classified into three vulnerability levels.

Keywords: Drone-Based 3D Modeling · Excel-VBA Decision Tool · Masonry Buildings Aggregates

1 Introduction

Historic villages in southern Italy, like Bova (Calabria), are characterized by masonry buildings aggregates that were constructed over the years without any official design documentation. These structures, which are frequently irregular in geometry and design, are especially vulnerable to structural deterioration as a result of age, seismic exposure, climate changes and the lack of systematic upkeep. The complexity of these environments is made worse by steep topography, small streets and architectural variation, all of which provide limitations for traditional structural evaluation methodologies (Giuffrida et al., 2021).

Analytical modelling and thorough on-site investigations, even necessary for a complete structural diagnosis, are often inapplicable for preliminary screening at a large

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(urban) scale due to the difficulty of accessing historic locations (Sevieri et al., 2020). This situation highlights the need for rapid, non-invasive approaches that allow early-stage structural vulnerability mapping and prioritization methods (Pepe et al., 2022).

The current study uses and tests an interactive tool based on drone survey and visual detection on a digital twin (DT) model of the aggregate of a number of parameters selected as significant for structural vulnerability assessment of individual buildings. Analytic Hierarchy Process (AHP), as proposed by Harirchian et al. (2020), is used to handle the parameters within a structured Excel-VBA which incorporates automated grading and weighting algorithms based only on criteria viewable from drone photography, following the approach described by De Fino et al. (2023).

A sample of nine buildings in the historic center of Bova was examined. The methodology discussed here focuses on the interactive application of the aforementioned tool in real-world surveys. Data was collected using both nadir and oblique drone flights, which were adapted to improve visibility of needed structural characteristics, including façades and vertical discontinuities, as in Sammartano et al. (2023). The study's main goal is to evaluate the performance of the promoted tool under real field situations also demonstrating versatility and repeatability for structural vulnerability assessment in historical contexts. The findings also help to establish standard survey processes and decision-support strategies aimed at reducing seismic risk in vulnerable urban areas.

2 Survey Methodology and 3D modeling

2.1 UAV Photogrammetric Dataset

The first stage of the whole process was the acquisition of aerial data through a UAV-based photogrammetric survey of the entire historic center of Bova in Calabria. This survey employed a high-performance drone able to obtain high-resolution photos appropriate for structural analysis and morphological interpretation of the built environment. To this aim, flight paths were designed to provide extensive coverage of the urban setting while also reducing perspective distortion and obstructions. The flying approach emphasized low-altitude paths to provide meticulous examinations of façade components, roof configurations and typological anomalies—factors essential for structural vulnerability assessment.

Two complementary datasets were obtained:

- Nadir photos, oriented vertically with respect to the ground plane. These photographs are generally used for the creation of orthophotos and digital elevation models, in addition they allow the comprehensive planimetric reconstruction of the village.
- Oblique photos are taken with the camera's ~~a~~ focal plane positioned at approximately a 45° angle to the ground plane. These 45° flights were repeated, while keeping the same flight plan, along the cardinal direction and at different times of the day to avoid shadows and unfavorable light conditions. Such data resulted in the essential capture of vertical architectural elements, including façades, out-of-plane masonry walls deformations, fracture patterns and discontinuities in height or position of the buildings.

To ensure the maximum photogrammetric quality, all photos were taken with a frontal overlap of at least 80% and a lateral overlap of 70%, following architectural photogrammetry best practices.

This survey provided a large number of high-quality photos, which are required for the creation of a thorough 3D digital model as well as structural and morphological assessments of the urban structure. Figure 1 illustrates the orthophoto of the historic center of Bova, overlaid with the UAV flight grid. The drone followed two flight paths, one highlighted in blue and the other in green, to obtain a complete view of the area, as shown by the grid.

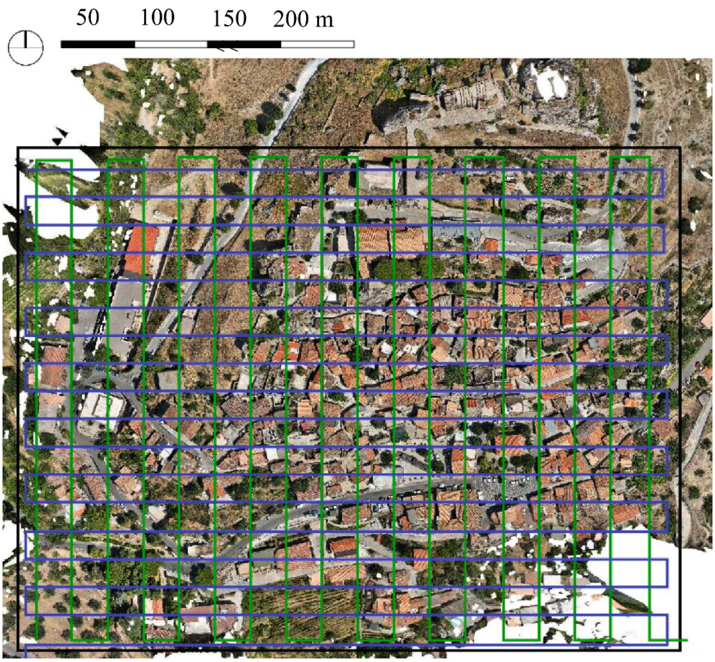

Fig. 1 . Orthophoto of the historic center of Bova with UAV flight grid overlay showing the planned paths along which both nadiral and oblique images were acquired.

2.2 3D Model Generation via Structure-from-Motion

Image data acquired from the UAV survey were processed using the Structure from-Motion (SfM) photogrammetry technique. The workflow included image alignment, generation of sparse and dense point clouds, mesh reconstruction and high-resolution texture mapping. Figure 2 shows a comparison of the dense point cloud and the final textured 3D model used.

Fig. 2. Comparison between dense point cloud generated by SfM (top image) and 3D mesh model with high-resolution texture mapping (bottom image) of Bova's historic center.

All operations were conducted in Agisoft Metashape standard version 2.2 (2025), a widely adopted platform for architectural and heritage documentation. The output dataset contains a detailed 3D model of the historic area with textures, true-scale orthophotos for flat measurements and a georeferenced points cloud for spatial referencing and additional measurements. These outputs give a complete 3D visual view of Bova's historic center which provides the geometric and visual foundation for all future steps, allowing structural and typological information.

3 Data processing and extraction

3.1 Visually detectable structural features

As said in the above quoted previous paper by the authors, the structural vulnerability assessment is grounded on the evaluation of 23 parameters, or *sub-criteria* (in the AHP logic) organized in 4 macro-categories, or *criteria.*

The sub-criteria are based on official forms provided by the Italian Civil Protection System. Precisely, reference has been made to the forms: GNDT I and II (GNDT et al., 1986), AeDES (Baggio et al., 2007) and CARTIS (Zuccaro et al., 2023) and the borrowed (here adopted) parameters were chosen for their compatibility with visual non-invasive drone photogrammetry evaluations.

Table 1 reports the criteria, the sub-criteria and the weight of each one within the process of structural vulnerability assessment.

Table 1. Criteria, sub-criteria and AHP weights used for structural vulnerability assessment of the individual building. The 23 sub-criteria are divided into four macro-categories, or criteria, and are derived from official Italian Civil Protection forms. Weights were assigned according to the AHP method to represent the relative influence of each parameter on the building vulnerability index.

Criteria	Sub-Criteria	Weight (AHP)
General Characteristics	Typological position	0,98%
	Site morphology	0,84%
	Number of total floors	1,89%
	Average building height	2,08%
	Regularity in plan	1,30%
	Regularly in elevation	1,50%
	Type of aggregate	0,77%
	Type of roof	0,64%
Structural Characteristics	Type of masonry	13,70%
	Tie rods	8,55%
	Structural bow windows	3,54%
	Asymmetrical perforations	2,20%
External Envelope Feature	Surface damage	1,04%
	Irregular vertical extension	6,40%
	Presence of dangerous elements	4,01%
	Different materials at different levels	2,40%
	Presence of consolidation	2,14%
Structural Weaknesses	Visible crack	2,35%
	Type of crack	7,04%

(*continued*)

Table 1. (*continued*)

Criteria	Sub-Criteria	Weight (AHP)
	Crack orientation	4,78%
	Out-of-plane walls deformation	16,65%
	Damage at the connection between buildings	10,58%
	Roof damage	4,60%

3.2 Extraction of the parameters for structural building vulnerability assessment

Each parameter was extracted from the 3D outputs produced by UAV-based photogrammetric reconstruction. Visual interpretation was carried out using textured meshes, orthophotos and oblique images, avoiding the necessity for access to interior areas or design documents. Each building was evaluated using a structured Excel interface that included dropdown menus for parameters selection and VBA functions for automated scoring. Parameters were evaluated on a scale of 1 to 5 according to their perceived criticality. Their contributions to the building vulnerability index were weighted using the AHP model.

It is worth noting that, while orthophotos were largely used to establish a building's planimetric shape, geometric consistency and roof conditions, oblique images and façade mesh views facilitated the identification of cracks, deformations, openings, material discontinuities, and also an estimation of average building height. Particular attention was paid to texture quality and lighting conditions, which—especially in shaded areas—way occasionally limit the accurate recognition of masonry type or minor façade damage.

The tools is based on an Excel worksheet, with one row for each single building and as many columns as the number of the pertinent sub-criteria. Each metric is associated with a dropdown menu offering a limited set of predefined qualitative responses (typically between two and five), each accompanied by a brief descriptive label. For example, for the parameter "crack orientation" (within the criterion "structural weaknesses"), the available options include:

- Not present
- Vertical
- Horizontal
- Diagonal

This logic is demonstrated in Fig. 3, which shows a sample section of the interface in which four buildings are evaluated based on crack visibility and orientation. The drop-down menu makes it simpler to provide answers, resulting in a rapid and uniform compilation that is also appropriate for inexperienced operators.

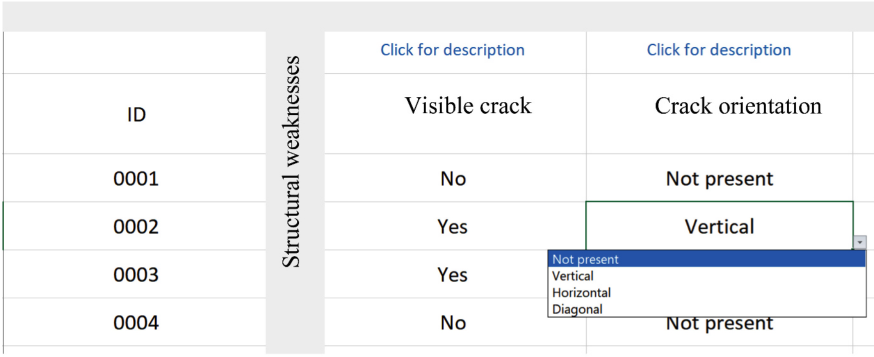

Fig. 3. Example of an Excel interface for providing parameters using a drop-down menu.

Each textual response is internally linked to a fixed numerical score, ensuring consistency across evaluations.

The Excel-based tool is fully automated through VBA functions, which convert qualitative inputs into quantitative scores and apply pre-assigned AHP weights. Once all values are entered for a given building, the tool computes the overall structural vulnerability index as a weighted sum of the individual scores. Eventually, the tool assigns the building to one of three *vulnerability classes* using fixed threshold intervals, namely:

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

This fully visual and automated process enables rapid, consistent assessments of building structural vulnerability, while maintaining compliance with the underlying AHP model. Final scores can be exported or integrated into external platforms for mapping at urban-scale prioritizations so resulting a very useful decision support.

4 Results on the Pilot Test and Discussion

To evaluate the operational effectiveness of the proposed methodology, a pilot test was conducted on nine buildings located in the historic center of Bova (Calabria). The building structural vulnerability assessment was independently performed by three trained operators using the Excel-based evaluation tool above described. Each operator extracted visual parameters from the photogrammetric model and classified them through the guided dropdown interface, generating a final vulnerability index for each building.

Table 2 shows the structural vulnerability scores assigned by each operator at each of the nine examined buildings as well as the resulting classes.

Table 2. Structural vulnerability index and class assigned by three independent operators to the 9 benchmark buildings.

ID BUILDING	Operator 1	Operator 2	Operator 3
0001	2,30	2,83	3,17
0002	2,24	0,00	3,23
0003	2,13	2,05	2,43
0004	1,86	2,22	2,55
0005	2,50	3,20	2,97
0006	1,52	1,94	2,20
0007	3,51	2,79	2,90
0008	2,68	2,47	2,78
0009	1,99	2,15	2,04
vulnerability classes		Low: 1.00–2.33	
		Medium: 2.34–3.66	
		High: 3.67–5.00	

The results showed a consistent distribution of scores across the three evaluations, with all buildings falling within the low- to medium-vulnerability classes. Particularly, none of the structures were classified as highly vulnerable by any operator, in agreement with field observations confirming the general structural integrity of the samples. Minor variations were observed in the scores—particularly between the first and third operators—but the resulting indices remained within comparable ranges. These differences likely reflect varying interpretation thresholds, with some operators applying more conservative evaluation criteria. Nonetheless, the consistency of the final classifications confirms the method's robustness and limited sensitivity to subjective variation in judgement.

In one case (Building ID: 0002), an operator encountered difficulties in identifying specific façade features due to limited image quality and lighting conditions. This highlights a key challenge for future applications: improving image coverage, particularly in narrow alleyways and shaded areas where drone access or visibility may be limited. To address these limitations, UAV surveys might be scheduled at different times of day to mitigate lighting-related issues or supplementary ground-level image acquisition, using low-cost devices such as GoPro cameras, might be performed.

5 Concluding Remarks

This study showed the first practical use of a method for a rapid structural vulnerability assessment of historic masonry buildings based only on drone survey. The method was tested on a sample of nine buildings in the historic center of Bova (Calabria), extracting visually detectable parameters from textured 3D models, orthophotos and oblique facade views of the entire village. The tool, set up in a structured Excel format with automatic scoring and AHP weighting, showed outstanding reliability in sorting buildings into vulnerability classes using a completely non-invasive, image-based method.

The pilot test, conducted by multiple operators, yielded consistent results, confirming the method's robustness and adaptability under realistic survey conditions. No structures were classified as highly vulnerable, a result aligned with direct visual assessments and in-situ field knowledge. Minor discrepancies between operators' judgements brought attention to the need for high image quality and completeness, particularly in constrained urban environments.

Future development efforts will focus on enhancing dataset accuracy through optimized UAV flight planning, multi-time-of-day image acquisition, and the incorporation of ground-level photogrammetry using lightweight, low-cost equipment, such as GoPro cameras to be used in the areas inaccessible by drone.

Overall, the proposed methodology offers a technically sound and user-friendly solution for structural vulnerability screening in historic urban areas. Its future use in GIS environments and digital twin platforms shows great potentialities for practical application also being an effective decision-support tool for risk reduction strategies.

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