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Seismic vulnerability and dynamic response of the minaret of Sidi M'hammed Cherif Mosque: insights from a detailed finite element model

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Abstract:
This study presents a seismic assessment of a historic masonry minaret in Algeria using an integrated workflow combining Terrestrial Laser Scanning (TLS) and Finite Element Analysis (FEA). The research focuses on the minaret of the Sidi M'hammed Cherif Mosque, located in the UNESCO-listed Kasbah of Algiers, an architecturally significant structure whose dynamic behaviour and seismic vulnerability had not been quantified despite ongoing restoration initiatives. Although Algeria is exposed to a considerable seismic hazard, the seismic performance of historic masonry structures remains largely unexplored, with only a limited body of research addressing this critical issue. In contrast to the extensive literature on Turkish and Egyptian minarets, research addressing seismic assessment in the Algerian and Maghreb contexts remains scarce. We developed a restoration-oriented methodology that evaluates seismic response by combining high-resolution TLS surveys, in-situ material characterisation, and detailed finite-element modelling. Linear static, modal, and response spectrum analyses were performed to identify critical vulnerability zones, particularly at the base of the minaret and at geometric discontinuities. The numerical results show strong agreement with the observed damage patterns, validating the proposed approach. The study establishes a reproducible TLS-to-FEA framework for the seismic evaluation of slender masonry heritage structures and provides evidence-based recommendations to support conservation planning. By integrating seismic risk assessment into restoration practice, this work contributes to improved risk mitigation and more resilient heritage preservation in Algeria.

Keywords:
historic masonry minarets; seismic vulnerability; TLS-to-FEA workflow; numerical simulation; Finite Element Modelling (FEM); heritage preservation

1. Introduction

The Kasbah of Algiers has been a UNESCO World Heritage Site since 1992 [1] lies within a high seismic hazard zone along the northern margin of the Maghreb, close to the convergent boundary between the African and Eurasian tectonic plates [2]. This tectonic setting has exposed the city to recurrent seismic activity throughout its history. Several destructive earthquakes have profoundly shaped its urban evolution as well as the material and immaterial dimensions of its architectural heritage. Among these events, the 1716 earthquake stands out as the most catastrophic, causing the collapse of extensive portions of the city and resulting in more than 20,000 fatalities – nearly one-fifth of the population at the time [3].

Beyond its immediate physical destruction, this event left a lasting imprint on the cultural landscape of the Kasbah. Historians report that while the vast majority of residential and administrative buildings were completely destroyed, religious structures – particularly mosques – suffered only superficial damage, demonstrating remarkable seismic resistance [4]. This resilience results from three factors: traditional construction techniques, empirical seismic adaptations developed over generations, and regionally sourced materials [5]. Consequently, these minarets do not merely testify to architectural ingenuity; they embody tangible evidence of the capacity of traditional construction to withstand past seismic events. Their enduring presence thus serves as a testament to the collective memory of these earthquakes and to the efficacy of adaptive building traditions [6].

However, centuries of material degradation, insufficient maintenance, and uncoordinated restoration interventions have progressively undermined this inherited resistance [7]. Consequently, the minarets of the Kasbah – key visual and spiritual markers of the ancient urban skyline – have become some of the most vulnerable components of the built heritage. Their slender proportions, heterogeneous masonry composition, and limited ductility make them particularly sensitive to seismic excitation [8], while ageing and environmental exposure further compromise their stability. Ensuring their structural safety is therefore essential for public protection and the long-term preservation of Algeria's cultural identity.

Yet despite the urgency of these challenges, research on the seismic behaviour of Algerian minarets remains remarkably limited. Although the literature addressing their typology, morphology, and architectural characteristics is relatively well developed, as evidenced by studies such as Beldjilali et al. on historic minarets in northern Algeria [9], Zerari et al. on the morphological diversity of minarets in the Ziban region [10], and Benabadji et al. on the morphological identity of Ziyanid minarets [11]. Very few investigations have examined their structural or seismic performance. Advanced diagnostic and numerical approaches are particularly scarce. Among the few available contributions is a finite element stability analysis of the Sidi Belhassan Mosque in Tlemcen, which identified active cracking and informed targeted strengthening strategies [12] and a detailed numerical seismic assessment of the Mansourah minaret in Tlemcen conducted by Bourdim et al. (2013) [13].

At the international scale, research on historic minarets has contributed to the development of integrated methodologies combining architectural documentation, structural assessment, and advanced numerical modelling. Among the most influential studies on the dynamic behaviour of masonry minarets is the work of Doğangün et al. (2008), who analysed three historic minarets measuring 20 m, 25 m, and 30 m in height. These structures were modelled and assessed under seismic loading using two strong-motion records from the 1999 Kocaeli and Düzce earthquakes [14]. A second significant case study concerns the Eğri Minaret (the Leaning Minaret), which has been the subject of extensive multidisciplinary analysis. Korumaz et al. adopted an integrated approach combining terrestrial laser scanning (TLS), deviation analysis, and finite element modelling to investigate the progressive inclination of the structure, attributed to both seismic loading and wind action. The incorporation of Building Information Modelling (BIM) tools enabled a precise structural assessment and the formulation of conservation strategies tailored to the monument's specific condition [15].

Further contributions to the study of Ottoman minarets include Halil Nohutcu's (2019) research on the minaret of the Imaret Mosque (1481). By integrating 3D surveying, experimental testing, and finite element simulation, this work identified key damage mechanisms and potential buckling phenomena and allowed a systematic comparison between numerical results and empirical observations [16]. In parallel, Hökelekli et al. (2020) conducted an in-depth investigation of the Alaca minaret in Turkey using operational modal analysis (OMA) combined with finite element modelling in Abaqus. The numerical model was carefully calibrated using in-situ measurements, ensuring high accuracy in reproducing the real structural behaviour and highlighting the necessity of combining experimental data with numerical simulations for reliable seismic evaluations [17].

In Iran, several studies have examined the minarets of Isfahan and Yazd, focusing on their architectural typology and seismic vulnerability. A landmark contribution is the work of Mirtaheri et al. (2017), who conducted a comprehensive investigation of the Zein-o-din minaret using 3D laser scanning, in situ experimental testing, and Abaqus-based numerical modelling. The integration of geometric and mechanical data enabled a realistic reproduction of the structural response and supported well-adapted strengthening proposals [18]. In a similar direction, Wafaei Baneh Koosha et al. (2023) developed a complete methodology applied to the historic Choli minaret in Erbil, Iraq. Their study highlighted the central role of BIM in heritage conservation, especially for documenting and preserving decorative elements. Through a dedicated plug-in, the authors enhanced the association and visualisation of metadata within the digital model, offering an advanced tool for heritage management [19].

Complementary research has also been conducted in Egypt. Abdel-Wahab et al. (2024) investigated the historic Abou-Ghanam El-Bialy minaret in Cairo, using 3D laser scanning for documentation and SAP2000 software to analyse its seismic behaviour. The results demonstrated significant seismic resilience, indicating the structure can withstand dynamic loads without major risk of damage [20]. In parallel, recent studies by Badawy and El-Feky (2024) and Hassan et al. (2025) have highlighted the role of Heritage Building Information Modelling (HBIM), material diagnostics, and calibrated finite element (FE) models. These approaches are crucial for understanding geometric irregularities, restoration-induced stiffness variations, and slight tilts, all of which are key factors influencing the seismic vulnerability of Egyptian minarets [20,21].

In line with these multidisciplinary approaches, Romero-Sánchez et al. (2023) conducted a comprehensive structural assessment of the Giralda tower in Seville – historically the minaret of the Almohad Mosque. Their methodology combined 3D digitisation in Rhinoceros with advanced numerical simulations in OpenSees, calibrated using on-site experimental data. By accounting for soil–structure interaction, geotechnical parameters, and the monument's specific architectural interfaces, the authors produced robust and reliable results, further demonstrating the relevance of integrated diagnostic–numerical workflows for slender masonry towers [22].

In parallel with the development of advanced numerical modelling and integrated diagnostic approaches, recent years have witnessed the rapid emergence of artificial intelligence techniques in structural engineering and seismic assessment. Machine learning (ML) and deep learning (DL) techniques are now playing an increasingly central role in earthquake engineering research [23].

Several recent studies have demonstrated the effectiveness of these approaches for modelling highly nonlinear structural behaviour and for assessing the seismic resistance of buildings. For instance, Kong et al. (2024) proposed a hybrid framework integrating Particle Swarm Optimisation (PSO) with ensemble machine learning models (LightGBM, GBR, LSTM, and BiLSTM). This approach aims to improve ground-motion selection and predict engineering demand parameters for the development of fragility curves. Their results highlighted increased accuracy as well as a reduction in computational effort compared to traditional incremental dynamic analysis (IDA) procedures [24].

While AI-based methods offer promising capabilities, few studies have focused on the seismic assessment of historic masonry structures in Algeria, and even fewer have addressed the specific behaviour of slender minarets interacting with adjacent mosque structures. To fill this gap, the present study proposes an integrated workflow combining laser-based geometric documentation, in situ material characterisation, and finite element modelling to evaluate the seismic stability of a representative historic mosque minaret ensemble in the Kasbah of Algiers. Unlike most previous studies that treat minarets as isolated elements, this approach enables the assessment and verification of the structural interaction between the minaret and the mosque, capturing their coupled behaviour under seismic excitation. Developed and validated specifically for the local context, this workflow contributes both to the scientific understanding of slender masonry towers in interaction with their supporting structures and to the practical safeguarding of the Kasbah [25].

Building on the integrated workflow presented above, future research could incorporate artificial intelligence and scientific computing tools such as Python and MATLAB to further enhance seismic assessments. Machine learning algorithms can be trained on datasets derived from finite element simulations or in situ measurements to build surrogate models that rapidly predict the seismic response of slender masonry structures. Python's extensive libraries (e.g., TensorFlow, scikit-learn, PyTorch) offer flexible frameworks for developing such predictive models, while MATLAB provides robust capabilities for signal processing, modal identification, and optimisation [26,27].

Implementing these approaches, however, would require broadening the research team to include computer engineers, ensuring that AI tools are properly adapted to the specificities of built heritage. Such interdisciplinary collaboration would not only reduce computational costs but also improve the accuracy of vulnerability assessments and support the design of targeted strengthening interventions. Ultimately, integrating AI-driven methodologies into heritage conservation practice could significantly enhance the preventive conservation of the Kasbah's minarets and other seismically vulnerable monuments, aligning with the latest international trends in earthquake engineering.

This approach addresses a critical shortcoming that remains prevalent in restoration practices within the Algerian context, where seismic risk assessments are frequently neglected despite their fundamental role in ensuring structural safety. By providing a validated methodology specifically adapted to local construction traditions and conditions. It supports the long-term preservation of a heritage ensemble whose architectural fragility and cultural significance are closely linked.

2. Research methodology

2.1. Review of existing methodological approaches

The seismic assessment of historic masonry structures, particularly slender towers and minarets, relies on several complementary methodological approaches. These approaches differ in their theoretical background, level of intervention on the structure, and type of information obtained. In the literature, four main categories can generally be distinguished:

2.1.1. Destructive and Minor-Destructive Testing (DT/MDT)

Destructive or minor-destructive techniques provide information about material properties. These approaches involve the extraction of samples or localised interventions on the structure.

Experimental testing, such as core extraction and flat-jack tests, allows direct measurement of masonry mechanical properties, including compressive strength and in situ stress conditions [28]. These techniques have been widely used in the structural diagnosis of historic masonry structures to determine the mechanical characteristics of materials such as stone, brick, and mortar. In addition, laboratory testing on extracted samples provides valuable information on the physical and mechanical properties of masonry components. Experimental investigations have significantly contributed to the understanding of the structural behaviour of masonry under gravity and seismic loads, highlighting typical damage mechanisms and failure modes [29].

Scaled experimental studies have also contributed to understanding the seismic behaviour of slender masonry towers. Shaking-table experiments on scaled minaret models have clarified typical failure mechanisms, including overturning, shear cracking, and local collapse phenomena [30]. Despite their reliability, destructive and minor-destructive methods are often intrusive and therefore rarely applicable to well-preserved heritage monuments, where conservation requirements limit physical interventions.

2.1.2. Non-Destructive Testing (NDT) and Structural Health Monitoring (SHM)

Non-destructive testing techniques allow the investigation of structural characteristics without damaging the monument. These methods are widely used in the diagnosis of historic masonry structures. Common NDT techniques include sonic and ultrasonic pulse velocity tests, which allow the evaluation of internal defects, material heterogeneity, and degradation conditions [31]. Dynamic identification techniques, such as ambient vibration testing and modal analysis, enable the estimation of global structural parameters, including stiffness, natural frequencies, and damping ratios [32].

More advanced approaches fall within the framework of structural health monitoring (SHM), which involves continuous or periodic monitoring of structural response through sensor networks. SHM techniques allow the detection of changes in dynamic behaviour that may indicate structural damage or deterioration [33].

Although these methods provide valuable information for structural diagnosis, they generally do not directly predict seismic damage and therefore are often combined with analytical or numerical approaches.

2.1.3. Empirical vulnerability assessment methods

Empirical approaches provide simplified tools for rapidly estimating the seismic vulnerability of historic structures based on observable characteristics. One widely used methodology is derived from the Italian GNDT II framework, which evaluates vulnerability using a set of parameters that describe structural configuration and material conditions. Adaptations of this approach have been applied to slender masonry towers and minarets. For example, the method proposed by Shakya et al. (2018) evaluates twelve parameters, including material quality, slenderness ratio, soil–structure interaction, geometric irregularities, openings, and non-structural elements [34].

Each parameter is assigned a weight and score to compute a Vulnerability Index (VI), which can then be correlated with macroseismic intensity scales such as EMS-98 to estimate potential damage levels. Similar vulnerability assessments have been conducted on historic minarets in Cairo, providing useful benchmarks for densely built urban environments. Although empirical methods are relatively simple and rapid to apply, their predictive capability is limited and often depends on the quality of calibration data.

2.1.4. Numerical modelling approaches

Numerical modelling has become an essential tool for the seismic assessment of historic masonry structures, particularly when historical damage records are limited. Finite element (FE) software such as Abaqus, ANSYS, TREMURI, and DIANA enables detailed simulation of structural behaviour under seismic loading [35,36]. These models can account for material nonlinearity, geometric characteristics, and boundary conditions, allowing the prediction of potential damage mechanisms [37].

Recent studies have demonstrated the effectiveness of combining advanced surveying techniques, such as 3D laser scanning and photogrammetry, with numerical modelling to accurately represent complex historic geometries. For instance, integrated approaches have been successfully applied to the seismic assessment and retrofitting of historic bell towers and cathedral spires using point-cloud-based modelling and finite element analysis [38]. Despite these advances, numerical investigations remain relatively limited for North African historic minarets, particularly regarding the influence of dense urban surroundings on their seismic response.

2.2. Proposed integrated methodology

Building upon these foundations, this study presents the first systematic seismic evaluation of historic Algerian minarets using a comprehensive TLS-to-FE workflow. The approach is informed by seminal studies that identify stiffness, height, masonry type, and geometric transitions as key determinants of minaret vulnerability [14,39-44]. The integrated methodology combines three key components (Fig. 1):

- High-resolution geometric survey;
- Material and historical data collection;
- Numerical modelling and analysis, including modal analysis and linear static and dynamic simulations.

This approach is applied to the minaret of the Sidi M’hammed Cherif Mosque in the upper Kasbah of Algiers. This structure was selected for its exceptional heritage value and the availability of previous restoration data, which provides a crucial foundation for informing the 3D modelling and validating the structural simulations.

3. Historical and architectural context of the Sidi M’hammed Cherif mosque

3.1. Historical overview

The Sidi M'hammed Cherif Mosque is situated in the heart of the Kasbah of Algiers (Fig. 2), more precisely at the intersection of Sidi M'hammed Chérif Street and Bachara Brothers' Street. The mosque lies within a densely built quarter characterised by continuous façades, interlinked building plots, and a network of narrow alleyways typical of a traditional medina. This compact urban fabric – an outcome of incremental, organic growth – forms a distinctive component of the Kasbah's cultural identity. At the same time, such spatial configuration tends to amplify seismic vulnerability due to the reduced separation between buildings, the interaction of adjacent foundations, and the structural continuity that often exists between neighbouring constructions.

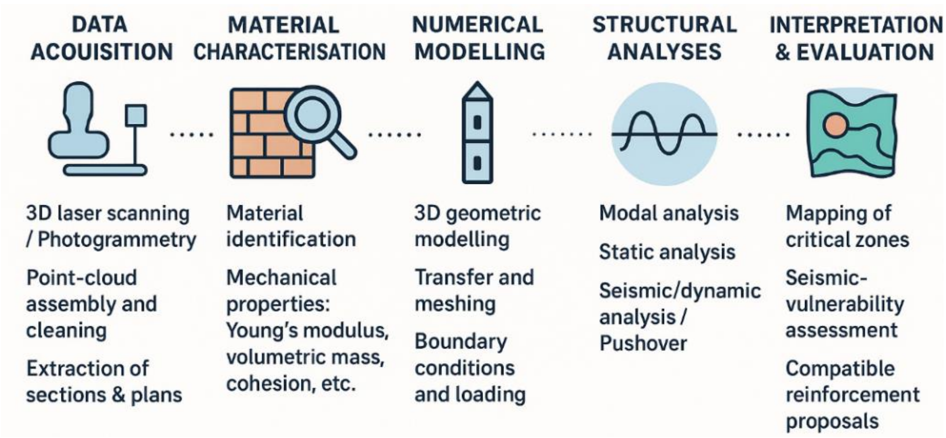


Fig. 1. Flowchart of the numerical seismic assessment methodology, source: the authors

Fig. 2. The entrance of the Sidi M'hammed Cherif Mosque, source: the authors

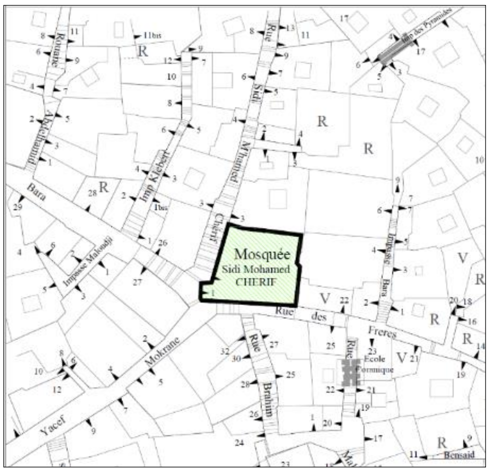


Fig. 3. Site plan of the Sidi M'hammed Cherif Mosque, source: the authors, 2018

The religious complex comprises several interrelated components: the mosque, a zāwiya (or marabout) dedicated to the eponymous saint Sidi M'hammed El-Cherif, and an adjoining Qur'anic school (madrasa) [45]. The ensemble dates from the Ottoman period, with the saint's tomb housed within the Qubba. The exact construction date of the mosque remains uncertain owing to the absence of surviving foundation documents [45]. Historical sources suggest that the marabout constituted the earliest nucleus of the site, preceding the expansion of the mosque and its ancillary spaces. Over time, the place of worship grew around this original funerary sanctuary through successive additions and incremental modifications.

During the French colonial period, the complex underwent several alterations, particularly after 1855, including the construction of a Qur'anic school and additional service rooms intended for religious teaching and the accommodation of worshippers [46]. One of the most distinctive architectural elements of the site is the large fountain located opposite the mosque's entrance porch (Fig. 3). Bearing the inscription "Aïn Sidi M'hammed Ech-Cherif" (Fountain of Sidi M'hammed Ech-Cherif), it not only highlights the name of the sanctuary but also underscores the symbolic and practical role of water in the spiritual, architectural, and urban organisation of the complex [47].

3.2. Architectural description of the mosque

The Sidi M'hammed Cherif Mosque is a distinguished example of religious architecture in the Kasbah of Algiers, combining both liturgical and educational functions. The adjoining Qur'anic school consists of vaulted rectangular chambers decorated with polychrome ceramic tiles, arranged around a central courtyard equipped with latrines and ablution facilities.

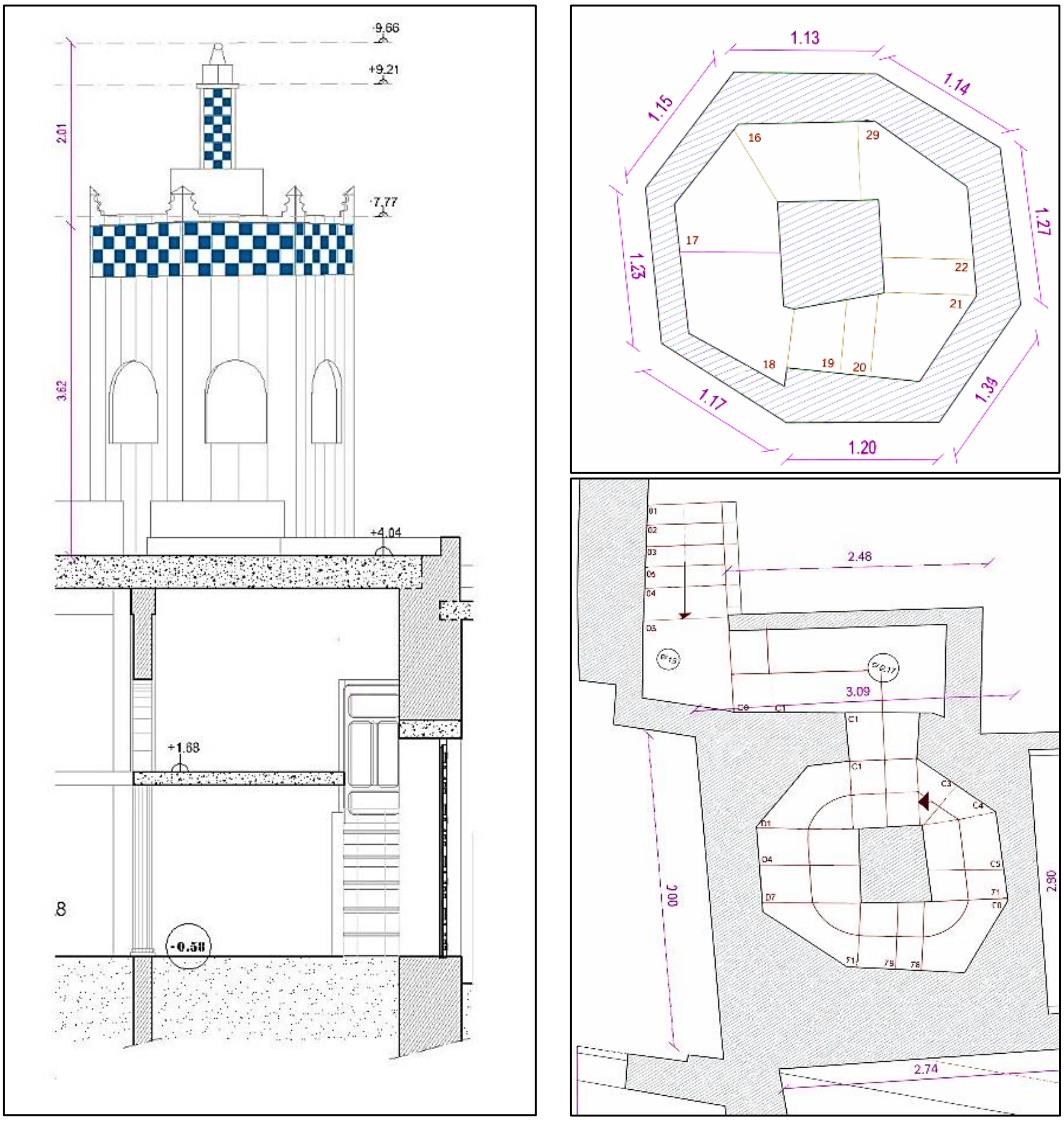
The mosque follows a restrained and harmoniously ordered plan (Fig. 4), centred on a rectangular prayer hall divided into two parallel naves by a colonnade supporting semicircular arches and articulated into three bays. The entire structure is covered by a flat roof made of thuya beams and compacted earth. The mihrab, embedded in the qibla wall, features discreet ornamentation consistent with the overall sobriety of the interior and is crowned by a richly decorated stucco half-dome.

Access to the prayer hall is provided through a central corridor, ensuring a smooth spatial transition from the main entrance. Opposite the prayer hall lies a rectangular zaouia housing the tomb of Sidi M'hammed Cherif. This annex is surmounted by an elegant octagonal dome adorned with refined stucco work, completing the architectural ensemble and reinforcing the dual spiritual and educational character of the complex.

Fig. 4. Plan of the Sidi M'hammed Cherif Mosque, source: the authors, 2018

The octagonal minaret, accessed directly from the prayer hall, is organised around a spiral staircase that winds around a solid central core, a configuration characteristic of Ottoman architecture in Algiers. The exterior façades are articulated with niches topped by horseshoe arches, while the upper register is adorned with two friezes of black-and-white ceramic tiles and crowned by a row of sawtooth merlons. The structure is topped by a small octagonal lantern surmounted by a truncated dome (Fig. 5).

The complex also includes a small residence for the imam, accessed via a staircase located to the left of the corridor leading to the prayer hall. This upper-floor dwelling comprises two rooms, a kitchenette, and sanitary facilities. At the basement level, several rooms facing Frères Bachagha Street serve as commercial shops. These spaces form part of the waqf endowment, with their rental income dedicated to the mosque's maintenance and upkeep.



Section through the hall prayer

The plan of the minaret

Fig. 5. Detail of the Minaret of the Sidi M'hammed Cherif Mosque, source: the authors, 2018

3.3. Current state of conservation

The Sidi M'hammed Cherif Mosque, like many monuments in the Kasbah, is in poor condition of conservation, attributable to the cumulative effects of time, inadequate maintenance, and prolonged environmental exposure. In response, the Ministry of Culture and the Arts initiated a restoration program, entrusted to an engineering office specialised in heritage conservation. Although diagnostic studies – including masonry assessment and structural analysis – were completed, the study process was delayed, and the interval between the completion of the diagnostics and the start of restoration works extended over four years, during which deterioration continued, further compromising the structural and material integrity of the mosque.

On-site inspections revealed multiple structural pathologies affecting various components of the complex. External renders are partially detached or eroded, exposing the underlying masonry. Vertical and diagonal cracks (Fig. 6 and Fig. 7), generally superficial but occasionally structurally significant, are visible on the main façades, particularly in the lower sections that formerly housed ancillary spaces. Paint layers are flaking, and the combined effects of rising damp and water infiltration have caused significant deterioration of surface finishes (Fig. 8).

At terrace level, decay includes detachment of tiles, blistering of surface coatings, appearance of vegetation within cracks and above lintels, and mortar disintegration (Fig. 9). These disorders are compounded by previous inappropriate interventions using incompatible modern materials such as cement and reinforced concrete, notably in the madrasa annexes and the imam's residence, which introduce additional mechanical stresses and exacerbate crack propagation (Fig. 10 and Fig. 11)

Deterioration results from material ageing, water ingress, urban vibrations, and insufficient maintenance. Collectively, these factors have progressively undermined structural cohesion (Fig. 12), reducing the building's capacity to resist external loads, particularly seismic actions – a critical issue in Algiers' moderate-to-high seismic hazard zone [34].

Numerical simulations integrating metric surveys, terrestrial laser scanning, and finite element modelling were undertaken to evaluate dynamic behaviour and seismic performance, identifying vulnerable zones. This approach is especially significant for the minaret – the slenderest and structurally sensitive component – whose stability is fundamental to the preservation of the monument.

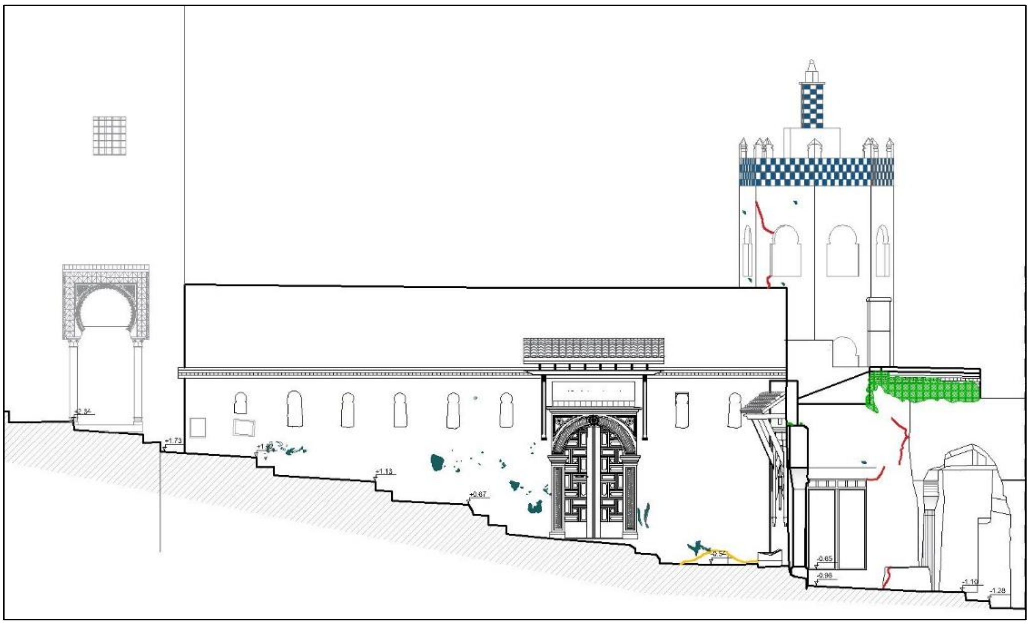


Fig. 6. Deterioration of the main façade, source: the authors, 2018

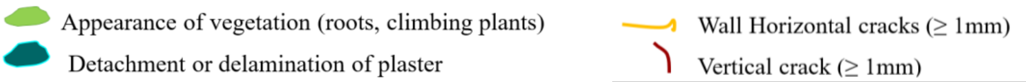


Fig. 7. Recorded deteriorations in the prayer hall and basement shops, source: the authors, 2018

Fig. 8. Moisture-related deterioration inside the building (plaster removed), source: the authors, 2018

Fig. 9. Vegetation growing on the façades and at the terrace level, source: the authors, 2018

Fig. 10. Cracks and structural damage observed on the exterior of the mosque, on the minaret and prayer hall sides, source: the authors, 2018

Fig. 11. Cracks recorded on the exterior and interior of the minaret, source: the authors, 2018

Fig. 12. Incompatible materials used to patch cracks and other defects in the mosque, source: the authors, 2018

4. Seismic analysis of the mosque

4.1. Architectural survey

Developing a reliable structural model requires accurate geometric characterisation of the building. For the Sidi M'hammed Cherif Mosque, the architectural survey was conducted using a combined approach that integrated conventional topographic techniques with terrestrial laser scanning (TLS).

The primary geometric survey was carried out using traditional instruments, including a theodolite and a laser distance meter (Fig. 13). This phase established the overall layout of the mosque and enabled the accurate measurement of its main structural components, such as load-bearing walls, arches, and floor levels.

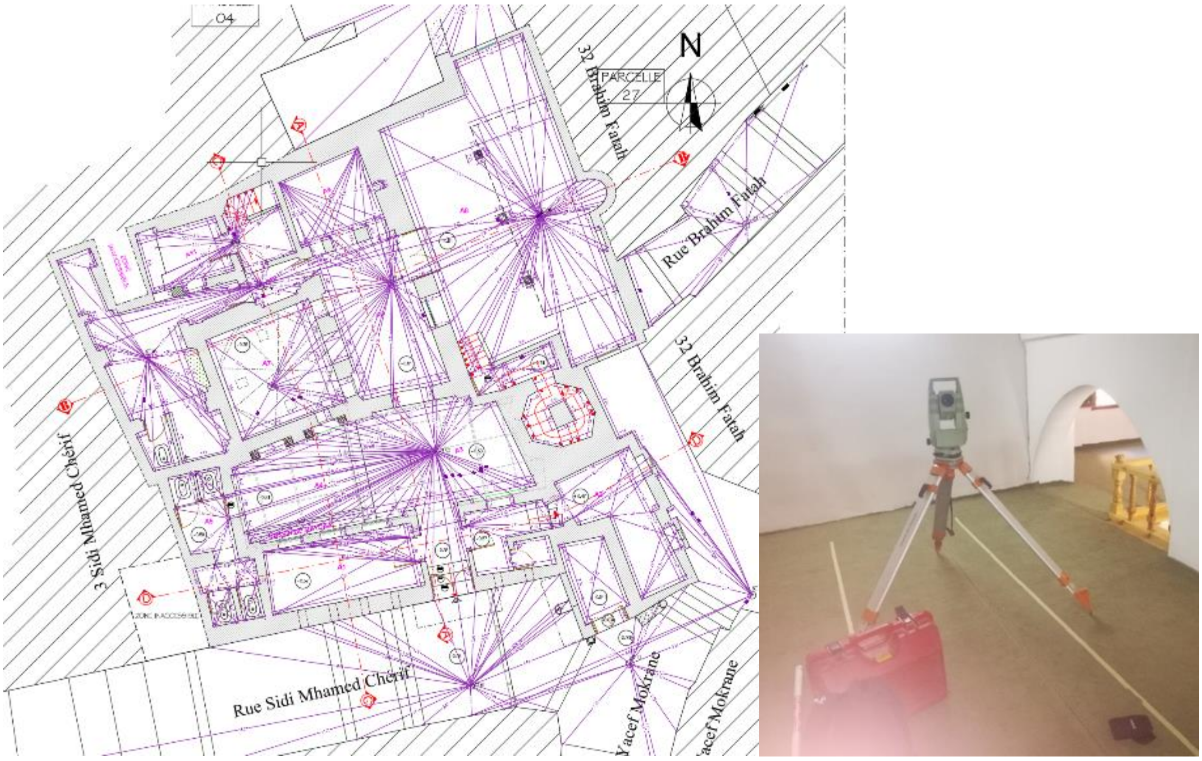


Fig. 13. Use of the theodolite for the survey, source: the authors. 2018

To complement these measurements and capture the detailed geometry of the architectural features – particularly those with complex ornamentation – a terrestrial laser scanning (TLS) survey was subsequently performed using a FARO laser scanner. The TLS acquisition focused primarily on the main façade and the minaret, where the geometric intricacy and decorative elements necessitated high-resolution documentation.

Given the complexity of the façade and the spatial constraints imposed by the surrounding urban environment, the survey strategy relied on 3D laser scanning to ensure complete and accurate data acquisition (Fig. 14). The scanning campaign began at the upper part of the site along Sidi M'hammed Cherif Street, which is situated at a higher elevation, and proceeded toward the lower section along Frères Bachara Street. Approximately 10 scanning stations were strategically positioned around the façade to ensure full coverage, with additional stations on the terrace to capture the minaret's geometry from an elevated perspective.

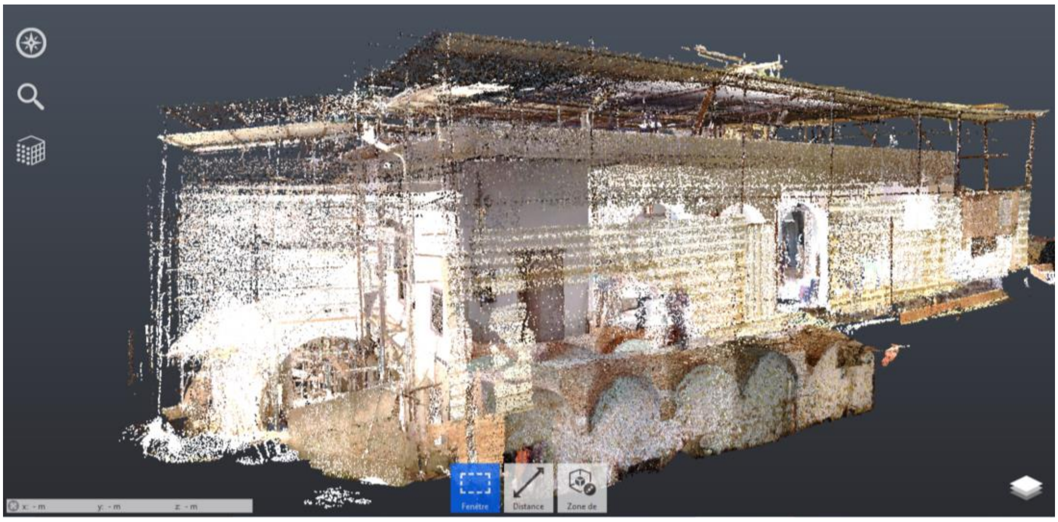


Fig. 14. Exterior of the mosque recorded using a 3D laser scanner in ReCap, source: the authors, 2018

The acquired scans were subsequently processed by removing irrelevant points and unwanted elements from the raw point clouds. The cleaned scans were then registered and merged using Autodesk ReCap software to generate a coherent three-dimensional point cloud model. This consolidated dataset was imported into AutoCAD for further geometric interpretation and architectural reconstruction.

From the processed point cloud, several vertical and horizontal sections were extracted (Fig. 15). These were combined with measurements obtained during the conventional survey to reconstruct architectural drawings and define the complete geometry of the building. This process enabled the production of the plans and geometric documentation presented in this study, which served as the foundation for the subsequent structural analysis.

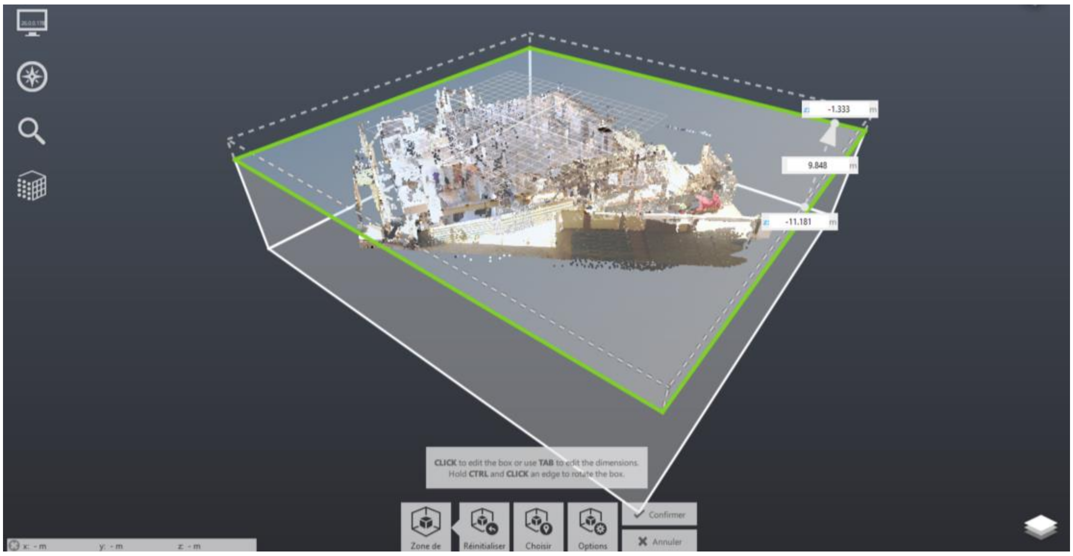


Fig. 15. Sections of the point cloud in ReCap, source: the authors, 2018

The analysis of the TLS-derived point cloud also facilitated the extraction of key geometric parameters of the structure. In particular, the minaret was found to have a total height of approximately 9.50 m, a base width of about 2.80 m, and an average wall thickness of 0.4 m. These geometric characteristics were directly used to define the structural model implemented in the finite element analysis.

4.2. Numerical simulation in Robot Structural Analysis

Numerical simulations are necessary for assessing historic buildings, especially in protected areas such as the Kasbah of Algiers, where destructive testing is prohibited. We selected Autodesk Robot Structural Analysis for its compatibility with AutoCAD and Revit models, enabling a streamlined workflow from survey to structural analysis.

The main goal is to evaluate both static and seismic stresses on the mosque and minaret while preserving the historic fabric. Analyses follow the Algerian seismic regulations (RPA 2024) to ensure reliable and comparable results. This method also allows the study of interactions between the minaret and adjacent walls, which is innovative in this context.

4.2.1. Geometric modelling

While the primary focus of the study is the minaret, the entire mosque was reconstructed to account for global structural interactions. The process began with the creation of 2D AutoCAD drawings to establish a reference grid along the X, Y, and Z axes. Walls, arches, floors, and vaults were then generated according to measured dimensions, incorporating minor deviations in alignment and thickness to faithfully represent the irregularities inherent in historic construction.

The octagonal shaft of the minaret was meticulously represented to capture its complex geometry. Smaller architectural features, such as cornices and niches, were simplified to optimise computational efficiency while preserving the accuracy necessary for reliable structural analysis.

A comprehensive BIM-based 3D model was produced that integrates both global structural elements and local architectural features relevant to seismic response assessment.

4.2.2. Material properties and boundary condition:

Accurately defining material properties and boundary conditions is essential for developing reliable finite element models. The construction system of the Sidi M'hammed Cherif Mosque, typical of Ottoman-period architecture in the Kasbah of Algiers, was identified through on-site observations and previous studies of similar buildings [48]. The load-bearing walls are composed of traditional rubble masonry made of fired bricks bonded with lime mortar. In structurally sensitive areas, such as corners and highly loaded zones, horizontal ashlar blocks are used to improve structural cohesion and enhance resistance to lateral forces, as illustrated in Fig. 16.

Fig. 16. Masonry of one of the walls of the Qur'anic school and the basement Shops, source: the authors, 2018

The floor system consists of thuya wood beams embedded into the masonry walls. These beams support a traditional layered filling composed of wooden planks, compacted earth mixed with brick and tile fragments, and mortar layers [49,50]. This construction technique, commonly used in the historic buildings of the Kasbah, contributes to the structural system's relative lightness and flexibility.

The analysis of the TLS-derived point cloud enabled the identification of the main geometric characteristics of the structure. The results reveal a global inclination of the minaret estimated at approximately 1% from the vertical axis. This deviation may be attributed either to torsional effects developed over time or to construction imperfections, considering that the mosque was built using traditional local craftsmanship.

The mechanical properties assigned to the masonry in the numerical model were derived from published data on similar historic structures in the Kasbah [51] and complemented by values recommended in international guidelines for historic masonry in the Italian Building Code (52). The following average values were adopted:

- Compressive strength of brickwork (f_m): 5 MPa
- Modulus of elasticity (E): 2500 MPa
- Unit weight (γ): 18 kN/m³
- Poisson's ratio (ν): 0.2

These parameters reflect the typical mechanical behaviour of historic masonry, which is generally characterised by high compressive capacity but very limited tensile strength. For modelling purposes, the masonry was considered a homogeneous and isotropic material, a common simplification adopted in global structural analyses of heritage structures.

Regarding boundary conditions, the base of the minaret was assumed to be fully fixed, representing a conservative approximation of the interaction between the foundation and the ground. Permanent loads corresponding to the self-weight of the structure were automatically generated from the assigned material densities. Seismic actions were defined in accordance with the Algerian seismic regulations (RPA 2024).

4.2.3. Meshing and finite elements

The finite element mesh was generated from the 3D model in Autodesk Robot Structural Analysis to ensure geometric continuity and efficient load transfer. A regular mesh was adopted with local refinements at geometric discontinuities – such as openings, wall thickness variations, and the minaret base junction – to balance accuracy and computational efficiency.

Shell elements were employed to model masonry walls under combined bending, shear, and compression (Fig. 17), enabling realistic global behaviour representation with a manageable number of elements. The average mesh size was set to 0.25m, sufficient to capture local deformations while maintaining numerical stability. Convergence tests confirmed result independence from mesh density, and element connections were modelled as fully continuous, reflecting the cohesive behaviour observed in masonry joints. The final model provided a consistent and reliable representation of the minaret's global seismic response, with realistic stress and displacement distributions.

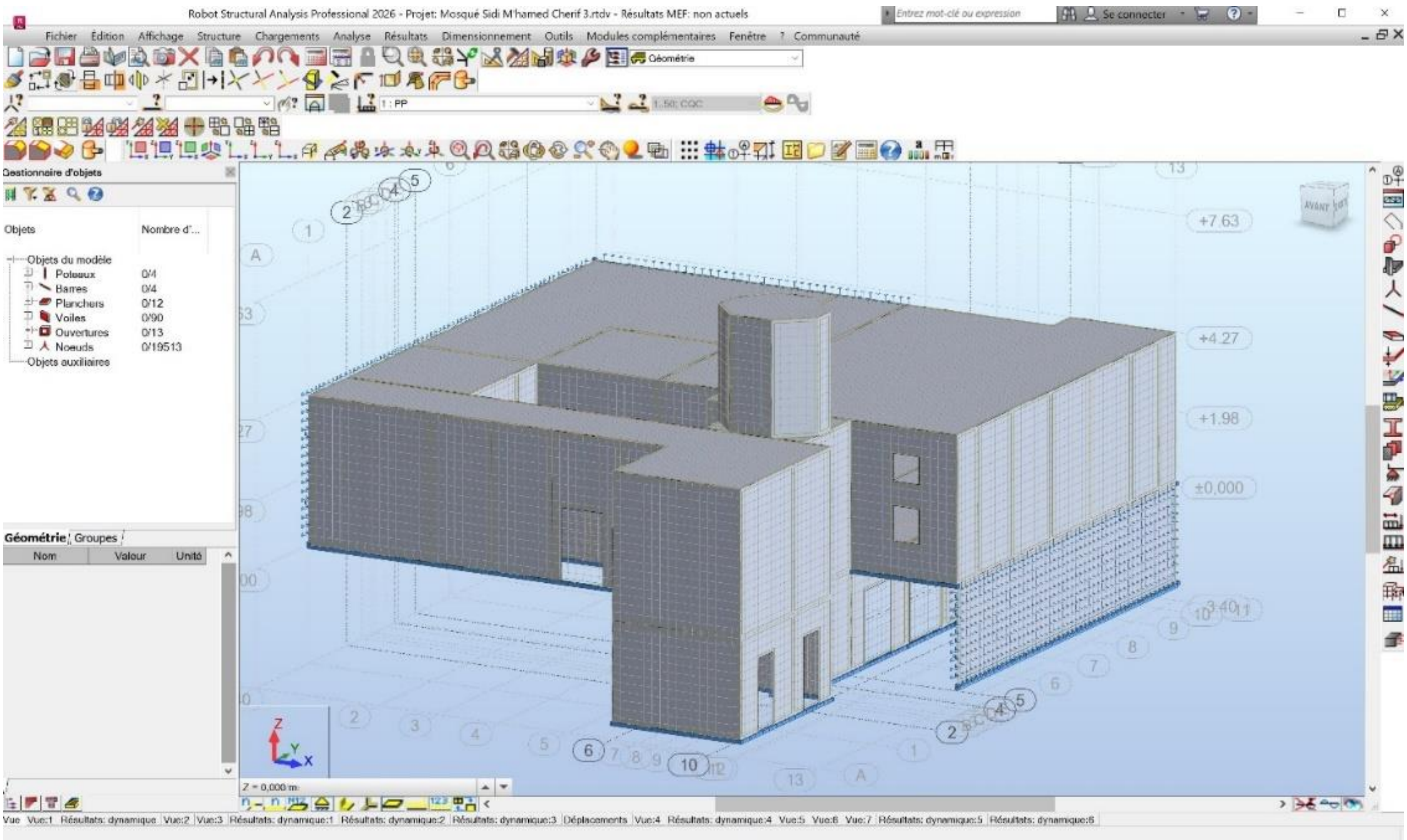


Fig. 17. The numerical model of the mosque, source: the authors, 2025

In addition to mesh convergence verification, the numerical model's reliability was further assessed through qualitative validation by comparing predicted stress concentration zones with the damage patterns observed during the on-site survey. A good agreement was found, particularly at the base of the minaret and at geometric transition zones where cracking was reported.

4.2.4. Applied loads

Following completion of the structural model, a global stability verification was performed to confirm the system's overall static behaviour. The structure was then subjected to the different load cases prescribed by the relevant regulations: permanent loads (G), imposed loads (Q), and seismic action (E), the latter being introduced via a response spectrum generated with the Spectra application.

Permanent Loads (G): These represent the self-weight of the structure and all fixed actions that remain constant over time, including the mass of the masonry, floors, finishes, and integrated architectural elements. In Robot Structural Analysis, these loads were applied as uniform surface loads (in kN/m²) acting in the downward direction (−Z), calculated as:

$$G = \gamma V \quad (1)$$

where γ is the unit weight of the material (kN/m³) and V is the volume of the considered element (m³).

Imposed Loads (Q): Variable actions associated with the use or maintenance of accessible areas. For the minaret, these were limited to maintenance loads at the roof level, calculated according to:

$$Q = q_k A \quad (2)$$

where q_k = characteristic imposed load (kN/m²) and A = relevant surface area (m²).

Load Combinations: To assess the global structural response under various solicitations, two principal combinations were considered:

Static Case: 1.35G + 1.5Q

Seismic Case: G + ψ_2Q + E

These combinations enable the evaluation of the structure's behaviour under both service and seismic conditions, in accordance with the Algerian Seismic Regulations (RPA 2024).

The Kasbah of Algiers lies within a high-seismicity zone (Zone IV), corresponding to northern Algeria. The local soil is classified as type S1 (rock), characterised by high bearing capacity and rapid seismic wave propagation [3].

Located at the heart of the protected sector of the Kasbah, the mosque is classified as a Category II building. This classification entails the application of an importance factor $\gamma_I = 1.3$ and a behavior factor $q = 1.5$, in accordance with the provisions of RPA 2024 for unreinforced masonry structures [53]

All these parameters were employed to generate the elastic response spectrum (Fig. 18), subsequently integrated into Autodesk Robot Structural Analysis for the modal analysis.

Furthermore, a sensitivity analysis was conducted by varying key modelling parameters, including the masonry's elastic modulus and boundary conditions. The results indicated that moderate variations in these parameters led to only limited changes in modal frequencies and displacement patterns, thereby confirming the robustness of the numerical model and the stability of the obtained results.

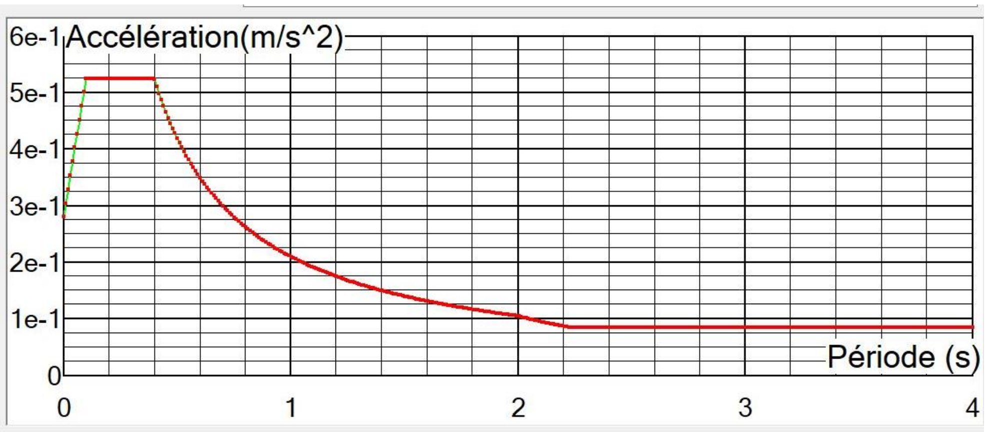


Fig. 18. Elastic Response Spectrum according to RPA 2024, source: the authors, 2025

4.3. Types of analyses performed

The assessment of structural stability under both static and seismic conditions requires the implementation of three complementary analyses that together provide a comprehensive understanding of the building's global behaviour.

4.3.1. Linear static analysis

The initial stage of the numerical investigation focused on determining the distribution of internal forces – namely, axial loads, bending moments, shear stresses, and support reactions – within the masonry walls. This step aimed to verify the structure's stability under permanent and imposed loads, ensuring that the numerical model behaved consistently before being subjected to dynamic excitation.

The analysis was performed using the three-dimensional model of the mosque to evaluate nodal displacements at several characteristic points. The results indicate very limited displacement values, ranging from 0.001 to 0.005cm, confirming the high stiffness of the overall structure and the absence of significant deformations in the walls. These outcomes validate the accuracy of the model parameters – mesh density, material properties, and boundary conditions – and confirm the linear elastic behaviour of the structure under gravitational loading.

4.3.2. Modal analysis

The modal analysis aimed to identify the structure's natural frequencies, mode shapes, participation factors, and effective modal masses corresponding to each vibration mode and direction [54]. These parameters are essential for characterising the dynamic response of the minaret and evaluating its susceptibility to seismic excitation. An initial computation of the first ten modes provided a preliminary understanding of the vibration behaviour. However, to achieve a more representative dynamic response – accounting for at least 80% of the total mass participation – the analysis was extended to fifty vibration modes. This refinement ensured an adequate description of the structure's dynamic characteristics and its overall interaction with the supporting mosque body.

4.3.3. Spectral (seismic) analysis

The seismic response was evaluated through a spectral analysis based on an elastic response spectrum defined according to the RPA 2024 provisions. This method simulates the dynamic behaviour of the mosque and its minaret under earthquake loading representative of northern Algeria's seismic context. The equivalent seismic forces derived from the spectrum were combined with static loads to determine the maximum stress and displacement fields throughout the structure. This integrated approach allows a precise estimation of the building's seismic performance while remaining fully consistent with current engineering standards and national regulations.

4.3.4. Stress evaluation according to the Von Mises criterion

To interpret the combined effects of multiple load actions, the Von Mises equivalent stress was used as a global indicator of stress concentration within the masonry structure. Although originally developed for ductile isotropic materials, the Von Mises stress is frequently adopted in finite element analyses of masonry structures to visualise the distribution of combined stress states under complex loading conditions. The equivalent stress is expressed as:

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} \tag{3}$$

This formulation helps identify the most critically stressed regions of the structure, particularly around openings, geometric discontinuities, and support zones, where stress concentrations are amplified under seismic excitation. However, since masonry exhibits brittle and anisotropic behaviour with limited tensile capacity, the Von Mises criterion should be interpreted primarily as a qualitative stress indicator rather than a direct failure criterion for masonry collapse assessment.

5. Results and discussion

5.1. Modal analysis results

Modal analysis yields fundamental frequencies ranging from 2.45 to 7.94 Hz (periods 0.13–0.41 s), reflecting the globally stiff behaviour characteristic of massive masonry structures. However, the cumulative translational mass participation remains critically low - 8.83 % in UX and 6.63 % in UY over the first 50 modes (Fig. 19) - far below the 90 % threshold stipulated by Eurocode and RPA 2024. This result is attributed to the highly dispersed modal energy induced by the irregular geometry and heterogeneous mass distribution of the structure, a phenomenon documented in comparable masonry tower studies [39]. Consequently, a significantly larger number of modes would be required to capture the seismic response through modal superposition fully.

The fundamental mode (Mode 1, f = 2.45 Hz; T = 0.41 s, UX participation: 1.84 %) is governed by overall lateral bending of the minaret along its height, consistent with a fixed-base cantilever-like behaviour and maximum displacements at the top (Fig. 20). Mode 2 (f = 3.09 Hz; T = 0.32 s) corresponds to lateral vibration in the orthogonal direction. Mode 3 (f = 3.43 Hz; T = 0.29 s) reveals a coupled dynamic response involving the minaret and the adjacent prayer hall (Fig. 21). The latter is structurally connected to a neighbouring building through barrel vaults. This configuration generates spatial stiffness discontinuities and complex load transfer mechanisms at the minaret–prayer hall interface, which constitute critical vulnerability zones under seismic lateral loading.

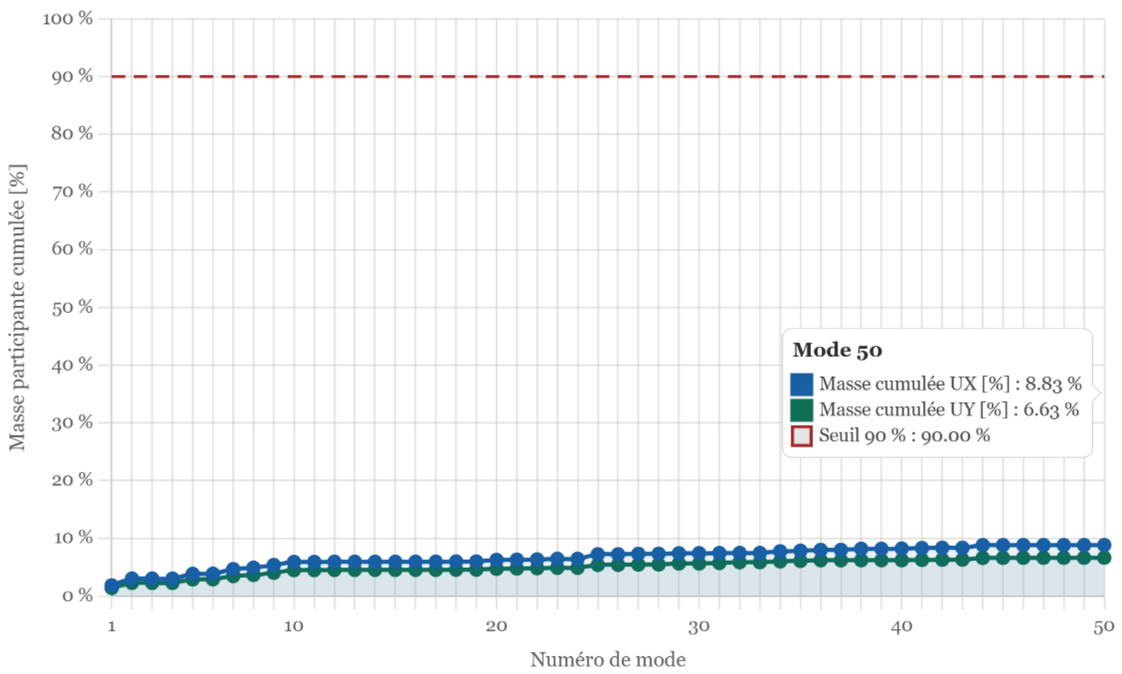


Fig. 19. Cumulative participating masses UX and UY as a function of the mode number – First 50 eigenmodes – regulatory threshold of 90% (EC8 / RPA99)

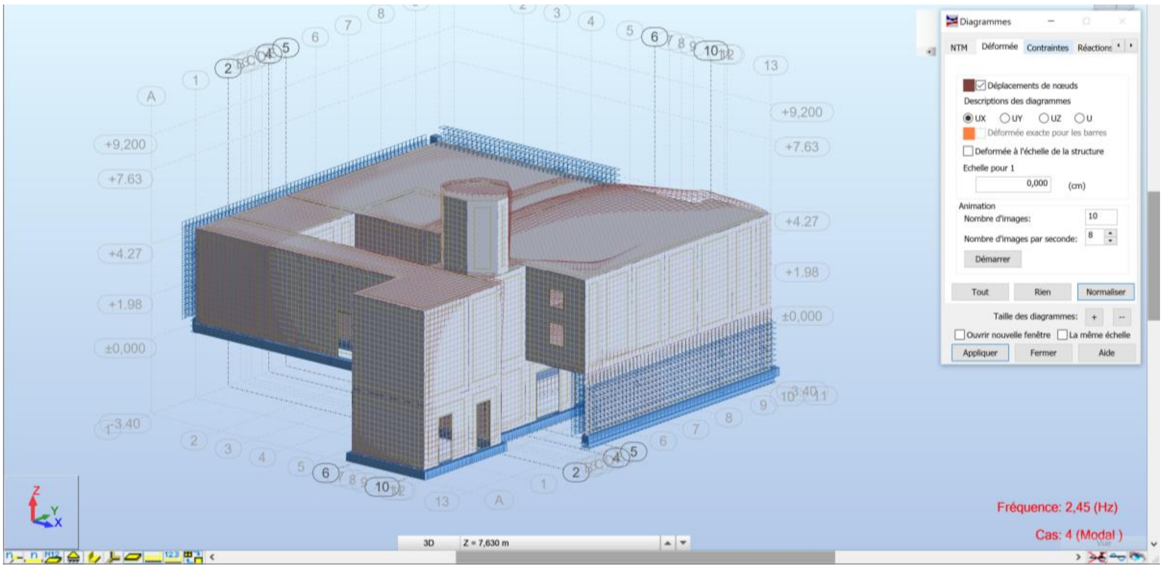


Fig. 20. The fundamental model shape (f_2 = 2.45 Hz), source: the authors, 2025

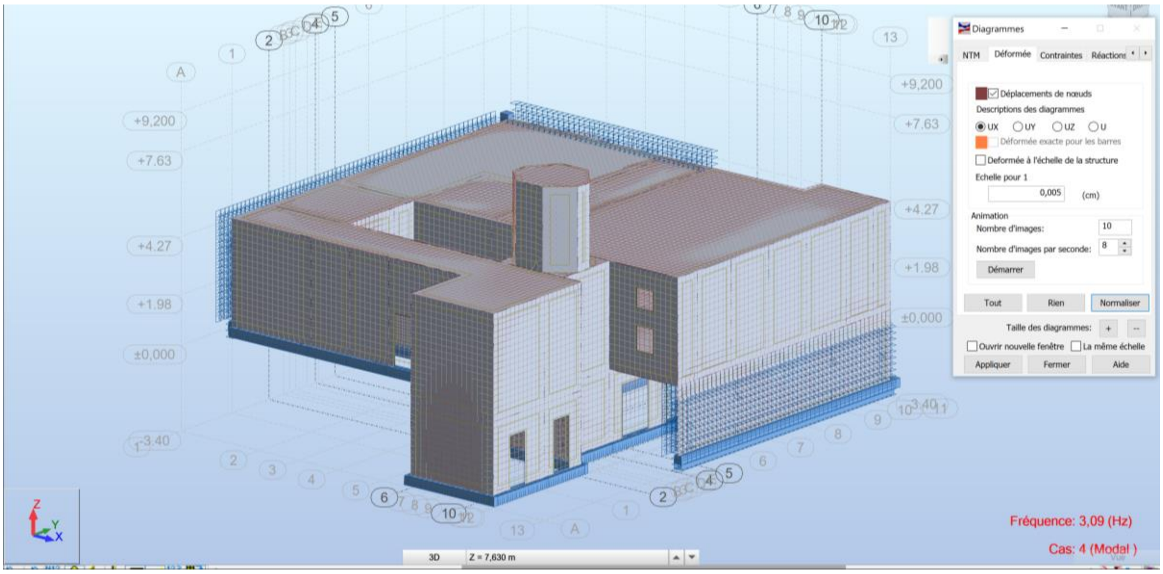


Fig. 21. Second modal shape of the mosque obtained from the finite element model (f_2 = 3.09 Hz), source: the authors, 2025

These observations indicate that the structural system behaves as a partially integrated assembly rather than as a monolithic structure. In this context, the dynamic response of the prayer hall is influenced by the constraints imposed by the adjacent building and the supporting vault system, resulting in a non-uniform stiffness distribution. This configuration may induce differential displacements under seismic excitation, thereby amplifying local stress concentrations, particularly at the base of the minaret, where cracking and failure were observed.

Furthermore, this behaviour is reflected in the low modal mass participation ratios obtained for the initial modes, which remain below 10 % even after the first 50 modes. This is primarily attributable to the concentration of mass within the load-bearing masonry walls in the absence of rigid diaphragms, as well as to the flexible connections between structural components – characteristics inherent in traditional masonry construction [55]. The use of shell elements further distributes the modal energy across a large number of degrees of freedom, thereby necessitating a significantly higher number of modes to achieve adequate mass participation [55,56].

Consequently, the dynamic behaviour is governed not only by geometric characteristics but also by modelling assumptions and structural interactions, which collectively lead to a response dominated by local vibration modes rather than global ones.

5.2. Spectral analysis results

The spectral analysis corroborates the modal study's findings. Maximum horizontal displacements at the top of the minaret remain below 5mm, confirming the high rigidity and overall stability of the structure. These small amplitudes indicate the absence of significant differential movements between structural levels and confirm the minaret's global stiffness. Two critical stress concentration zones were identified:

- at the base of the shaft, where high bending and shear stresses occur due to fixed-base conditions; and
- at the transition between the main body and the balcony, where geometric discontinuities and stiffness variations contribute to local stress amplification.

These areas represent the most vulnerable parts of the minaret under seismic excitation, subject to stress intensification due to horizontal oscillations. The spectral analysis further confirms that the minaret's dynamic response is dominated by lateral sway modes in both the longitudinal and transverse directions, while torsional effects remain limited.

5.3. Von Mises equivalent stress distribution

The stress distribution map illustrates the equivalent Von Mises stresses generated by the combined effects of self-weight and imposed loads [57,58]. Under static conditions, maximum stress values reach approximately 0.78 MPa, with the highest concentrations ***occurring*** at the base of the external load-bearing walls, particularly along the eastern lateral façade (Fig. 22). This pattern reflects a predominantly gravity-driven behaviour, characterised by:

- Peripheral walls carrying the majority of vertical loads;
- Localised compression peaks at the soil–structure interface (shallow foundations);
- A concentrated load transfer induced by the minaret onto the adjacent bay without triggering any significant global instability.

Under seismic loading, the equivalent Von Mises stress distribution reveals significantly higher stress levels, with maximum values reaching approximately 2.37 MPa. The most critical stress concentrations are mainly located in the following regions:

- Along the base of the peripheral walls, where the highest stress levels are observed;
- At roof level, particularly along the western side, due to the interaction with taller adjacent buildings exerting lateral pressure on a comparatively less rigid façade;
- At the interface between the minaret and the main structural body of the mosque, identified as a zone of strong dynamic interaction potentially susceptible to localised cracking.

Moderate stress levels, ranging from 0.6 to 1.2 MPa, are mainly distributed along the intermediate walls, while lower stress values (below 0.4 MPa) dominate the lower portions of the structure, especially near the main façade (Fig. 23).

Although masonry is known to exhibit brittle and anisotropic behaviour, the Von Mises equivalent stress is commonly employed as a qualitative indicator of stress concentration rather than as a direct failure criterion. Nevertheless, the obtained stress distributions provide valuable insight into the most vulnerable regions of the structure under both static and seismic loading conditions.

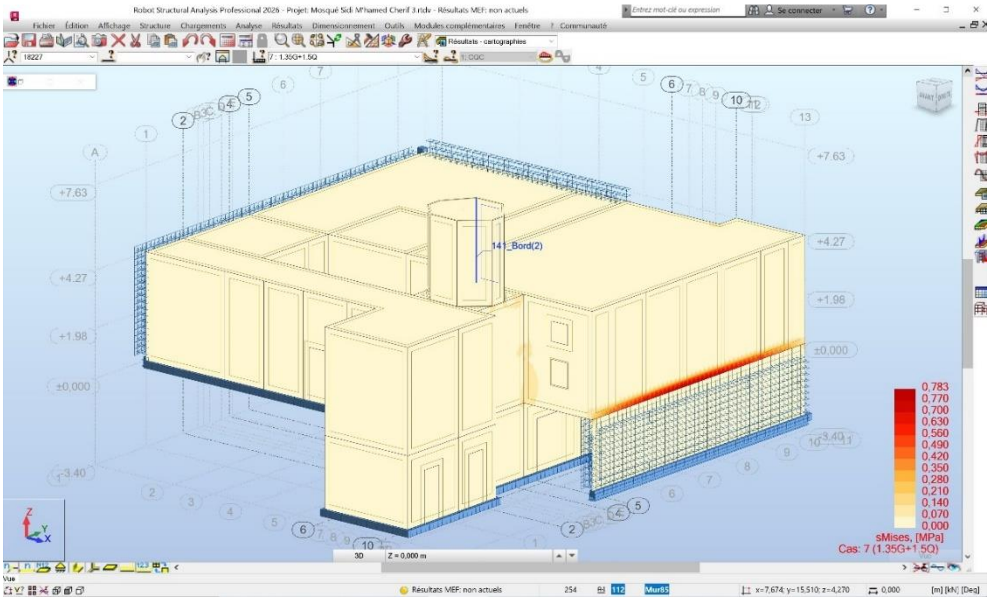


Fig. 22. Results of the stress mapping under static conditions, source: the authors, 2025

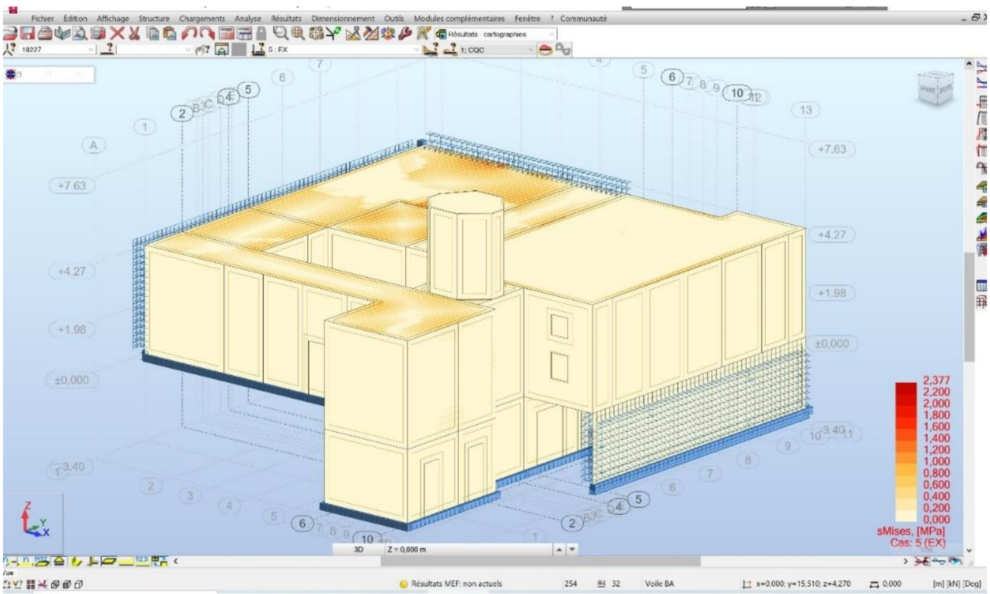


Fig. 23. Stress distribution results under seismic conditions, source: the authors, 2025

6. Discussion of results and correlation with on-site observations

The numerical analysis shows a strong correlation with the structural pathologies documented during the on-site survey. Several cracks were identified on the façades and along the shaft of the minaret, particularly at geometric transition zones between distinct load-bearing volumes. These observations are consistent with the modal analysis, which indicates a first fundamental period of 0.41s, confirming a relatively stiff global behaviour, while higher modes reveal localised dynamic effects concentrated around discontinuity areas.

These results are fully aligned with the findings of Souami (2016), who demonstrated that elevation proportions – rather than plan configuration – govern the dynamic behaviour of historic masonry structures. His study shows that tall, slender buildings tend to exhibit higher fundamental periods and larger lateral displacements, making geometric discontinuities particularly sensitive to tensile cracking [59].

In the case of the Sidi M’hammed Cherif Mosque, the FEM model confirms that the geometric transitions – especially the junction between the square base and the octagonal shaft – act as stress amplifiers under seismic loading. These vulnerabilities are further exacerbated by:

- Stiffness differences between the minaret and the prayer hall, generating stress concentrations at their connection interfaces;
- Severe cracking within the walls of the imam’s residence, resulting from the height discrepancy between the mosque (G+1) and the adjacent G+3 buildings, which may have altered the balance of vertical load transfer;
- The cumulative effects of previous earthquakes, progressive material degradation, and long-term stress accumulation are likely responsible for micro-crack propagation within the masonry fabric.

Overall, the numerical results – modal periods, cumulative mass participation, and stress fields – show a clear agreement with the observed damage pattern. The monument displays satisfactory global stability, but exhibits pronounced local weaknesses at junctions, supports, and structural interfaces. These critical zones require close monitoring and targeted strengthening measures in future restoration and seismic mitigation interventions.

7. Proposed interventions informed by numerical analysis

The Sidi M'hammed Cherif Mosque is located within the protected sector of the Kasbah of Algiers; it is therefore subject to the regulatory framework of the Permanent Safeguarding and Enhancement Plan for the Protected Sector. No intervention may be undertaken without reference to this framework, and all actions must be non-destructive, respecting the integrity of the monument, its environment, and its status as a protected heritage structure. To this end, a set of solutions and urgent measures is proposed below to preserve the building and prevent its collapse, based on comparable cases and previous studies on seismic assessment [7,60-62].

Table 1. Guidelines for a restoration project, source: the authors 2025

Priority	Zone / Issue	Proposed Intervention	Justification
Urgent	Critical cracks (stress levels > 2.0 MPa)	Lime-based grout injection	Identification by FEM of zones exceeding the critical stress threshold
	Vulnerable transition zones (minaret–roof interface, base-to-shaft connection)	Localized consolidation; hooping; anchoring	Identification by modal analysis of stress concentrations at geometric discontinuities
	Minaret envelope (humid and saline conditions)	Strengthening using the Basalt Textile Reinforced Mortar (B-TRM) system	Superior durability compared to glass fibres; compatibility with historic masonry; stress concentration zones identified at the base and transitions
	Deteriorated waterproofing and invasive vegetation	Immediate repair of waterproofing layers; removal of vegetation	Prevention of moisture penetration and further structural degradation
Medium term	Minaret–mosque interface	Stainless-steel anchors	Dynamic interaction highlighted by Mode 3 (coupled behaviour) and spatial stiffness variations
	Timber floors (absence of rigid diaphragm)	Consolidation; replacement of deteriorated thuya wood; addition of bracing	Low modal mass participation due to a lack of horizontal load redistribution
	Structural monitoring	Installation of a permanent system (crack gauges, inclinometers)	Monitoring of identified critical zones and validation of interventions
Long term	Institutional and technical capacity	Integration of BIM into restoration projects; Installation of sensors to detect structural and ground movements.	Sustainability of achievements and transition toward quantitative seismic risk management

8. Conclusions

This study addresses a major gap in the conservation practices of the Kasbah of Algiers: the absence of systematic seismic assessment in restoration projects. This omission is particularly critical in a dense historic environment exposed to significant seismic hazards and subject to progressive structural deterioration.

To respond to this challenge, we developed a comprehensive non-destructive workflow integrating Terrestrial Laser Scanning (TLS), Building Information Modelling (BIM), and Finite Element Analysis (FEA). Applied to the minaret of the Sidi M'hammed Cherif Mosque, this methodology constitutes the central contribution of the study, as it models the minaret–mosque ensemble as a unified structural system rather than treating the minaret in isolation. The results demonstrate that seismic actions are redistributed to the adjacent prayer hall walls – a phenomenon that has not been previously.

Consistent with the literature on masonry towers, seismic vulnerability is primarily governed by three factors: mass distribution, structural stiffness, and geometric proportions – including the square-to-octagon transition, height-to-width ratio, and shaft cross-section. The finite element model confirms that geometric discontinuities systematically induce stress concentrations, which correlate with the observed damage patterns.

The relatively modest height of the minaret (less than 10m) likely contributes to its reduced seismic vulnerability compared with taller structures – an aspect often underestimated in heritage evaluations. Although the model correlates well with field observations, uncertainties persist regarding material heterogeneity and modelling assumptions. Therefore, targeted and minimally invasive strengthening at critical joints is recommended to enhance structural safety while preserving authenticity.

By formalizing the TLS–BIM–FEA workflow, this study provides a transferable framework for the seismic assessment of slender masonry heritage structures in seismic regions. More importantly, it offers operational guidelines for integrating seismic risk management into the Permanent Safeguarding and Enhancement Plan of the Kasbah, bridging the gap between engineering analysis and heritage conservation practice. Future research should explore advanced dynamic analyses, improve material characterisation, and apply this methodology to a broader sample of Maghrebi minarets to support the development of regional vulnerability indices.

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Annex:

Table 2. Results of the modal analysis, source: the authors 2025

Mode	Frequency [Hz]	Period [sec]	Cumulative Mass UX [%]	Cumulative Mass UY [%]	Cumulative Mass UZ [%]	Modal Mass UX [%]	Modal Mass UY [%]	Modal Mass UZ [%]	Total Mass UX [kg]	Total Mass UY [kg]	Total Mass UZ [kg]
1	2.45	0.41	1.84	1.38	0.0	1.84	1.38	0.0	1143381.34	1120785.51	0.0
2	3.09	0.32	3.01	2.27	0.0	1.17	0.88	0.0	1143381.34	1120785.51	0.0
3	3.43	0.29	3.01	2.27	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
4	4.29	0.23	3.01	2.27	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
5	4.29	0.23	3.82	2.88	0.0	0.81	0.61	0.0	1143381.34	1120785.51	0.0
6	4.32	0.23	3.85	2.90	0.0	0.03	0.02	0.0	1143381.34	1120785.51	0.0
7	4.52	0.22	4.65	3.46	0.0	0.80	0.55	0.0	1143381.34	1120785.51	0.0
8	4.60	0.22	4.89	3.65	0.0	0.24	0.19	0.0	1143381.34	1120785.51	0.0
9	4.70	0.21	5.36	4.02	0.0	0.47	0.37	0.0	1143381.34	1120785.51	0.0
10	4.83	0.21	5.90	4.49	0.0	0.54	0.47	0.0	1143381.34	1120785.51	0.0
11	4.88	0.20	5.90	4.49	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
12	5.04	0.20	5.93	4.52	0.0	0.03	0.03	0.0	1143381.34	1120785.51	0.0
13	5.16	0.19	5.93	4.52	0.0	0.01	0.00	0.0	1143381.34	1120785.51	0.0
14	5.25	0.19	5.93	4.53	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
15	5.37	0.19	5.93	4.53	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
16	5.69	0.18	5.94	4.53	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
17	5.70	0.18	5.94	4.53	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
18	5.75	0.17	5.97	4.56	0.0	0.03	0.03	0.0	1143381.34	1120785.51	0.0
19	5.91	0.17	5.97	4.57	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
20	6.25	0.16	6.25	4.71	0.0	0.28	0.14	0.0	1143381.34	1120785.51	0.0
21	6.28	0.16	6.29	4.76	0.0	0.03	0.05	0.0	1143381.34	1120785.51	0.0
22	6.31	0.16	6.33	4.81	0.0	0.04	0.05	0.0	1143381.34	1120785.51	0.0
23	6.53	0.15	6.43	4.89	0.0	0.11	0.08	0.0	1143381.34	1120785.51	0.0
24	6.54	0.15	6.43	4.89	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
25	6.54	0.15	7.22	5.39	0.0	0.78	0.50	0.0	1143381.34	1120785.51	0.0
26	6.63	0.15	7.22	5.40	0.0	0.00	0.01	0.0	1143381.34	1120785.51	0.0
27	6.72	0.15	7.30	5.45	0.0	0.08	0.05	0.0	1143381.34	1120785.51	0.0
28	6.77	0.15	7.31	5.46	0.0	0.01	0.01	0.0	1143381.34	1120785.51	0.0

29	6.82	0.15	7.40	5.64	0.0	0.09	0.18	0.0	1143381.34	1120785.51	0.0
30	6.86	0.15	7.41	5.64	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
31	6.95	0.14	7.43	5.72	0.0	0.03	0.07	0.0	1143381.34	1120785.51	0.0
32	7.05	0.14	7.45	5.85	0.0	0.02	0.13	0.0	1143381.34	1120785.51	0.0
33	7.12	0.14	7.45	5.85	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
34	7.15	0.14	7.74	6.01	0.0	0.28	0.16	0.0	1143381.34	1120785.51	0.0
35	7.16	0.14	7.83	6.09	0.0	0.10	0.08	0.0	1143381.34	1120785.51	0.0
36	7.17	0.14	7.98	6.19	0.0	0.15	0.10	0.0	1143381.34	1120785.51	0.0
37	7.21	0.14	7.98	6.19	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
38	7.35	0.14	8.17	6.20	0.0	0.18	0.01	0.0	1143381.34	1120785.51	0.0
39	7.38	0.14	8.17	6.20	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
40	7.41	0.13	8.21	6.20	0.0	0.04	0.01	0.0	1143381.34	1120785.51	0.0
41	7.42	0.13	8.30	6.25	0.0	0.09	0.05	0.0	1143381.34	1120785.51	0.0
42	7.43	0.13	8.35	6.29	0.0	0.05	0.04	0.0	1143381.34	1120785.51	0.0
43	7.43	0.13	8.35	6.30	0.0	0.00	0.01	0.0	1143381.34	1120785.51	0.0
44	7.51	0.13	8.81	6.60	0.0	0.46	0.30	0.0	1143381.34	1120785.51	0.0
45	7.61	0.13	8.81	6.60	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
46	7.77	0.13	8.82	6.62	0.0	0.01	0.02	0.0	1143381.34	1120785.51	0.0
47	7.82	0.13	8.82	6.62	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
48	7.83	0.13	8.82	6.62	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
49	7.86	0.13	8.82	6.62	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0
50	7.94	0.13	8.83	6.63	0.0	0.00	0.00	0.0	1143381.34	1120785.51	0.0