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Advanced procedure for documenting and assessment of Cultural Heritage: from Laser Scanning to Finite Element.

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Abstract. This paper discusses an approach for identification of historic buildings that combines Terrestrial Laser Scanning (TLS) survey, Deviation Analysis (DA) and Finite Element (FE) numerical modelling. The methodology is presented through the application to an illustrative case study: an early medieval period brick minaret located in Aksaray (Turkey). Precise direction of inclination, leaning angle, local deviations from circular building shape, deflections from vertical planes, local curvatures and related maps were obtained with high accuracy by DA, based on detailed point cloud 3D mesh model. In addition, differently from traditional approaches in FE analysis, a method for direct transfer of high accuracy TLS based 3D model to FE structural analysis is introduced. The FE model is subsequently employed to interpret and verify structural health of the historic building.

Keywords: *Terrestrial Laser Scanning (TLS); Deviation Analysis (DA); Cultural Heritage (CH); Finite Element (FE) modelling; Structural analysis; Health assessment.*

1. Introduction

The process of preservation of architectural heritage introduces different issues concerning documentation, conservation, restoration and reusing activities: it needs specific analyses based on accurate broad-spectrum surveys (especially when structural aspects are concerned). In general, the structural analysis of a monumental building requires the development of an interconnected series of operations aimed at obtaining a satisfactory knowledge of the construction where in-situ investigations are performed together with advanced numerical analyses [1], [2]. The structural assessment of architectural heritage is consequently composed of several steps that can be summarized as follows: i) geometric and topographic surveys with the identification of main constructive steps (through the analysis of historical documents) and damage survey including its evolution over time; ii) assessment of the actual damage through essays and surveys defining the variables that characterize the structural behaviour of the structure; iii) measurement and interpretation of existing stresses in some significant areas of the structure by means of static tests and identification of the monument dynamic behaviour; iv) development of numerical models (with gradually increasing complexity) able to reproduce the experimental evidence; v) numerical simulation of the structural response with respect to several load conditions (e.g. horizontal movements induced by earthquakes, etc.) that could affect the monumental building. This research consists of an iterative approach aimed at obtaining an adequate level of knowledge

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where the typology and the extension of the experimental survey must be combined with the results of numerical models of the building that are iteratively updated [1].
The accuracy of measured data directly affects decision-making and analysis process [2], [3]. Nevertheless, in documentation of cultural heritage, the needs to preserve the integrity of the historic construction make difficult to develop an extensive experimental investigation and/or to apply traditional techniques. However, local authorities and agencies devoted to Cultural Heritage (CH) preservation need complete and updated databases on territorial scale in order to plan interventions and to prevent possible damages to CH. For these reasons, there is a great interest in expeditious and non-destructive methods [4]. In this respect, Terrestrial Laser Scanning (TLS) technology allowing high accuracy measurements can be used as a versatile and powerful tool for rapid no-contact survey. TLS is a remote sensing technique offering accurate geometric characterization of the historic building, providing key information for structural and historical purposes [5] and preserving the integrity of historical constructions.
Finite Element (FE) analysis has become in last decades a predominant tool, and it is used in a majority of analysis and simulation applications. One of the key challenges in applying FE analysis to realistic model is the process of converting the acquired geometric data into a suitable format for FE analysis software. Concerning FE analysis, automated 3D mesh model generation is an old problem but great advances have been made over last years and most commercial tools have automated the process for large classes of geometries. However, it can be observed that laser scanning technologies have not been effectively used in structural engineering research fields, and only few recent researches discusses such integrated approach [6], [7]. Mesh models used in FE analysis are generally created in a CAD software and they cannot be strictly considered as "reality based" 3D models since they come from a manual user-performed remodelling approach. The adopted industry-wide solutions are to help for simplifying complex shaped models, with removing some geometric non-structural features. However, in general, accurate and detailed models allow the study of the relationship between the shape, size and state of conservation of buildings and available technical and historical information for architectural and engineering studies.
This paper discusses these issues presenting an approach for identification of historic buildings that combines Terrestrial Laser Scanning (TLS) survey, Deviation Analysis (DA) and Finite Element (FE) numerical modelling. The approach is aimed to straightforward connect architectural survey and FE modelling, and the discussion is developed by an elucidating a case study; a minaret located in the city of Aksaray (Turkey) [8] [9] (Figure 1). The case study is particularly significant since the structure has lost its vertical configuration in past time and the assessment of its actual structural behaviour asks for an exhaustive evaluation of its current geometrical configuration.

Figure 1. Photos of Minaret: (a) General view; (b); Steel cables and clamped part of minaret.

2. Methodology

Data accuracy and measurement workflow employed as methodology within the case study are shown in Figure 2. As first step, topographic survey was carried out in a local coordinate system. Afterwards, five scans were performed just around the minaret. Because of the security measurements, accessing to the inside of the minaret was not allowed. Interior of minaret was modelled based on previously available manual survey drawings, and integrated with point cloud based mesh model. Then post-processing procedure was followed and a mesh model of minaret was created. This model was subsequently converted in a watertight mesh model to be imported into the FE software employed to perform structural analyses. Some deviation analyses were carried out using point cloud based mesh model. In this analysis, the geometrical property of minaret, the inclination direction and some deviations were determined. The presented methodology is intended to provide benchmark guidance for subsequent applications with point cloud data for deviation and structural analysis.

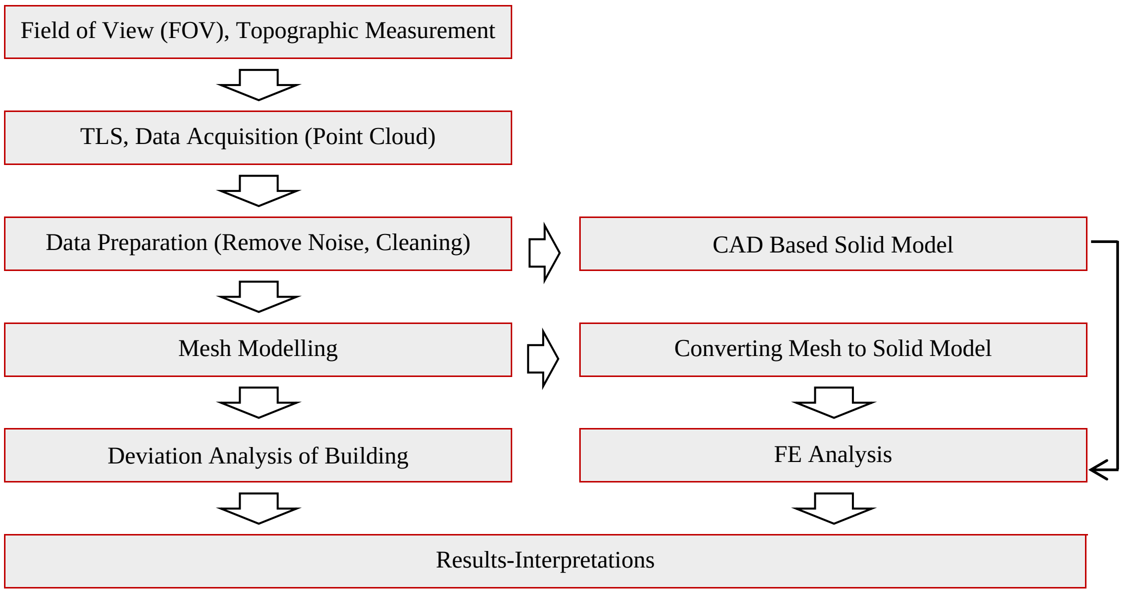


Figure 2. Methodology.

3. Minaret case study

Eğri (Leaning) Minaret is an important CH of Seljuk Empire in Aksaray (Turkey). Because of its red bricks used as construction elements, it is also referred to as Reddish Minaret. The construction period of minaret is estimated between 1221 and 1236 A.D. This minaret is an early example of Turkish buildings in Anatolia which were constructed with exactly the same Iranian and middle Asia region architectural style, construction techniques, materials and decorations as well. The Minaret has a cylindrical main trunk, with a squared shape stone basement. The distinguishing features of Eğri Minaret are the zigzag ornaments (Figure 1), some relief inscriptions on the trunk and blue and green tiles on the top of building. The height of the minaret is about 30.6 m. An internal spiral brick staircase with 92 steps leads to the balcony.

Today the minaret leans towards North-West direction. For safety reasons, in 1973 the minaret was strapped down from the upper part and was tightened to the ground with steel cables. In recent years, some additional investigations have been carried out to determine possible reasons for the movement and the inclination of the minaret. Eğri Minaret was employed as representative case study to test a methodology where the actual geometric anomalies and the structural state of the minaret are assessed and evaluated in a diagnostic perspective with point cloud based 3D models and data.

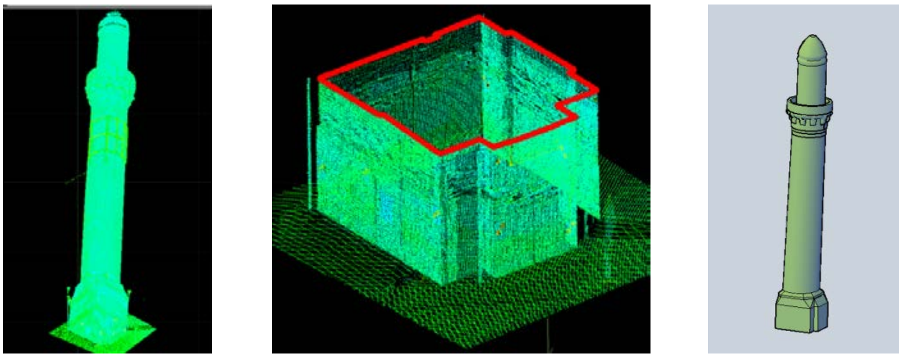
4. Architectural survey

TLS acquires high resolution data sampling of the observed object surface with an accuracy of few millimetres. It allows the acquisition of high-resolution point cloud data in relatively short time and gives the possibility of reducing the in-situ survey time, and the cost on human employment [10]. The need for detailed survey of complex historic structures highlights that traditional surveying techniques are usually cumbersome and time consuming when applied to historic constructions. The experiences of last decades proved that traditional survey techniques are not able to provide the required accuracy,

to limit the in-situ survey time and to reach the level of detail needed for the digitalization of cultural heritage. Today, the necessity of providing data for digital databases has become more essential, compared to the past. With the help of the fast development and improvement of the information and communications technologies (ICT), to ensure data for digital databases has become more easy and strong, but also demanding. Data acquisition with TLS provides detailed 3D models capable to describe complex architecture for different purposes, such as: photorealistic representations, historical documentation, FE analysis aimed at checking the safety of the structures or risk assessment analyses aimed to verify the effects resulting from progressive damages or from the onset of new damages [11]. TLS based point cloud 3D models allow many type of geometrical check and comparison (horizontal or vertical deviations, rotations and inclinations of walls, relative or absolute displacements, etc.). TLS can also provide precise geometrical survey in order to know the buildings in details with all deformations and anomalies (crack movements, surface deformations, material, etc. [12]).
In this study the FARO Focus^{3D} S-120 terrestrial laser scanner was employed and high resolution and quality settings were adopted in order to obtain good quality data. The acquired data set was approximately 7 million points. After simplification, 3 million points were used for triangulated surface model of minaret.

5. 3D Modelling process

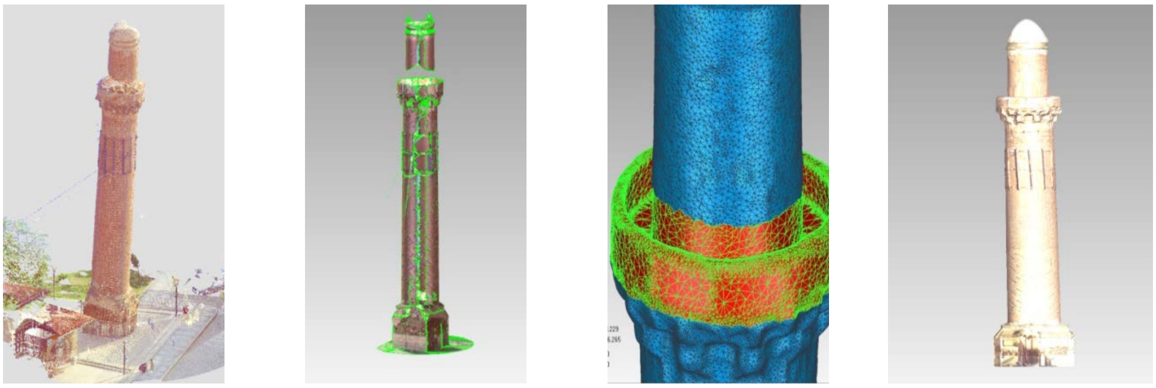
With rapidly increasing availability of laser scanner data, and the growing pressure to use it, engineers who need to work on spatial data have tried to find optimum solutions for obtaining 3D models based on point cloud data [7], [13]. However, it can be observed that still the engineer's community commonly do not use directly point cloud data as basis to build the computational models needed their FE analysis. Tognaccini [14] discussed that the development of structural models based on point cloud data can be performed substantially by three different techniques: the first one is to prepare model in CAD software, the second one is to create a mesh model and convert it to a structural model using sections. Last one is to create non-uniform rational B-splines (NURBS) surfaces with some approximations of point positions. Extending Tognaccini, classification to different techniques for data acquisition structural models can be obtained with five different methods [9]: 3D modelling procedures from a first (CAD modelling) to a last typology (creating mesh convert mesh to NURBS) are growing in complexity. Correspondingly, as long as techniques for 3D modelling getting more advanced, 3D models accuracy increases.



Point Cloud in CAD — Creating section in CAD — Creating solid model using sections.

Figure 3. CAD base solid modelling process.

CAD base models are widely used for FE analysis because both do not require having complex software and easily allow to obtaining results. This technique, the most commonly employed methodology for generating FE models, is based on regular 3D modelling in a CAD software combining primitive solid shapes with some unions, subtractions and intersections commands, without using point cloud data. A CAD model based on point cloud data requires almost the same process than a manual or topographic survey based modelling, but in this process needed distances are taken directly from point cloud data (Figure 3). At the end of these processes, a 3D model can be obtained but many characteristics of the original geometry can be lost. A positive aspect of this approach is that processing and converting watertight 3D models to numerical models for FE analysis are relatively easy for simple shape geometries.



Aligned and cleaned point cloud data | Triangulation with halls and un-scanned parts. | Process of repairements filling of halls and gaps. | After filling and repairements.

Figure 4. Mesh model process.

Although there are some commercial solutions for the transformation of laser scanning point cloud data into mesh and solid models, these tools have significant limitations that are mainly related to the management of big amount of data. These mesh models need to be further converted into suitable numerical models. The 3D model for FE analysis was created by using these techniques (Figure 4). The sections can be defined with regular steps (as contour lines) up to upper part of the building, and can be exported to CAD software to create 3D mesh / solid model. A second limitation in the models transformation process is the need of overcome spars and missing data and to limit the loss of accuracy in the conversion process, that is a challenging task.

It can be observed that while the methodology for acquiring 3D data of objects using TLS is well-established with different approaches, data analysis procedures still need to be improved. In order to obtain reliable results, high accuracy metric survey becomes more essential in order to determine the vulnerability of buildings, especially in case of ancient structures that are characterized by irregularities [15]. It is finally noteworthy to observe that since Eğri Minaret was scanned from the ground level, there were several “holes” in the point cloud 3D model especially at the top of the balcony. In this case, it is possible to develop a hybrid workflow to obtain some data at points which laser scanner beams cannot reach, such as aerial photogrammetry with UAV (Unmanned Aerial Vehicle) [16].

6. Deviation Analysis

Deviation Analysis (DA) method allows recognition of possible anomalies that can be related to non-uniform material distribution, localized defects, basement and/or terrain instabilities and past seismic effects. Besides regular contact and contactless structural analysis, DA method can provide some data about the structural problems of the building, and it can detect the deformations which have to be considered in modelling process. Different deviation patterns can be correlated with different type of deformations and damages, and they can be used to identify possible external causes. The DA method is composed by three main steps: i) computing deviations of the model with respect to a reference object usually considering Euclidian distance, ii) visualizing deviations or creating deviations maps, and iii) analysing these maps for the description of problems [17].

6.1 Determination of inclination direction

Studies on verticality of high buildings can be carried out by cutting point cloud or mesh models and analysing the obtained sections. The trend of vertical axis can be computed by identifying the centre of each section and joining them. This method can provide data related to local leaning, tapering angle, radius of building, and local deviations from local curvatures [5]. Reconstruction of vertical axis may be refined through the extraction of more sections by a smaller interval without complicating the analysis [15]. This method was applied to the minaret, and several curves were used for determining the leaning angle which resulted -70.04° North. The vertical inclination trend was described by connecting the centre points of consecutive curves, and comparing it with a vertical line. At the end of this process, the deviation between the vertical reference and the average leaning angle was measured as 2.79° North. In a similar way, it was possible to compute the distances from the centre of every curve with respect to the vertical axis. The maximum linear deviation from the vertical axis was obtained on the top of the minaret and resulted 1.28 m (Figure 5).

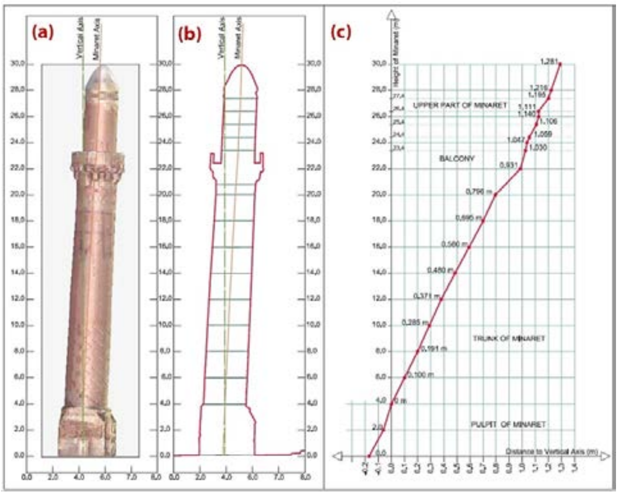


Figure 5. (a) Side elevation of minaret with central axis and inclination direction; (b) Section of minaret with central axis and inclination direction; (c): Diagram of inclination direction and distances from centre of the curves to vertical axis.

6.2 Deviation analysis with respect to orthogonal planes

Deviation analysis is not only useful for documentation of tall buildings; it can be also employed for documentation of all interiors, internal walls, celling and floors of all typology of buildings. Identifying of overhang, progressive changes of inclination, differential movements of the structures and detailing the study of structural elements are just some examples of many fundamental information that can be obtained and useful for analysing the structure behaviour [15]. This data can be obtained by some analyses based on mesh or point cloud models of structures. A DA is not just measurement of an object, it is exactly a comparison of a precise mesh model based on point cloud data with a reference plane or created 3D shapes. Thanks to this analysis some geometric differences could be defined by carrying out detailed comparisons of deflection from verticality with respect to a vertical plane orthogonal to the one (which is also vertical) containing the main inclination direction.

The reference plane was set up tangent to the minaret in the lower part of the trunk since the inclination starts from there, and this point considered reference point of the minaret (Figure 6). Deviations maps respect to this plane were obtained: the range of the mapped distances was between +1 m and -1 m. Maps of the colours from blue to red represent different distances between references plane and minaret surface. It can be observed that the deviation of the upper part of the minaret exceed the maximum value (1.281 m from vertical axes). Deviation of main trunk upper part reaches to maximum value (0.931 m). Deviation of base of minaret was observed less than 0.2 m from the vertical axis. Similar to this comparison, main trunk of minaret was compared with a best fit cylinder which was created using minaret horizontal sections (from lover and upper part of the minaret). It was observed that, because of the inclination, the maximum distance was measured on the North-East side of the main trunk (0.058 m). Some deflations can be observed as dark blue colour areas in deviation map on lower and upper part of trunk especially on South-West and South-East directions. These deviations can be observed mainly in the opposite site of bulged part of minaret (Figure 7).

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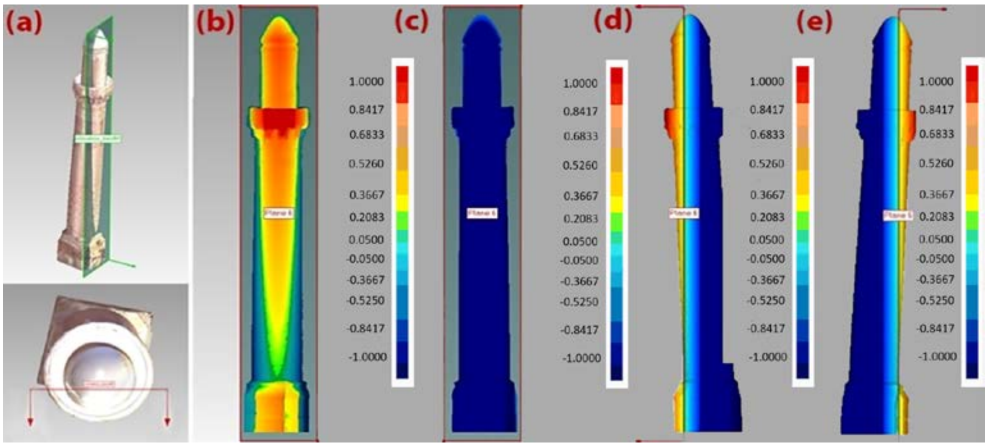


Figure 6. (a) Position of reference plain; (b) Leaning direction deviation; (c) Opposite site of leaning; (d) West site of leaning; (e) East site of leaning.

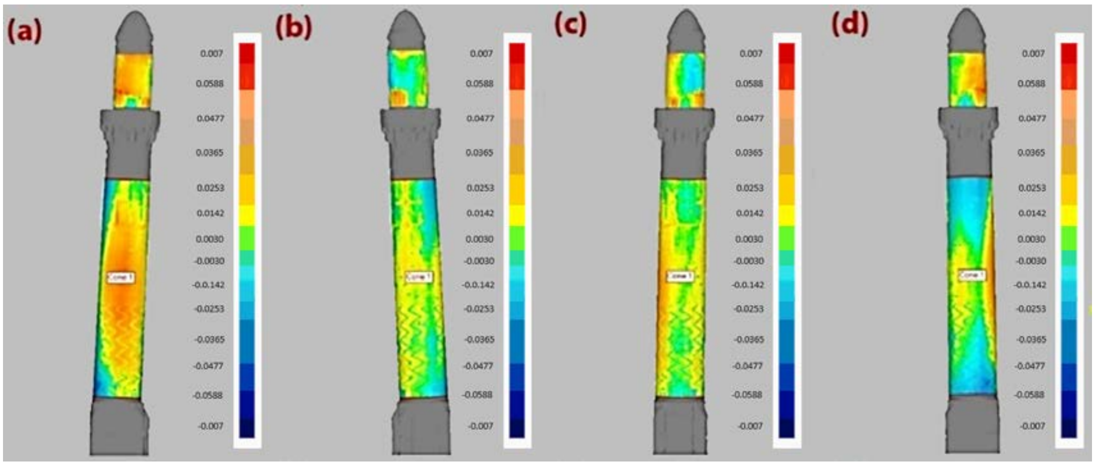


Figure 7. Surface maps of minaret trunk with best fit cone from four directions. (a) North-East (front, entrance) (b) South-West (back) (c) North-West (right) (d) South-East (Left).

7. Numerical analysis

The three-dimensional FE model of the minaret (Figure 8) was built based on the data discussed in previous section according to the macro-modelling technique. The ANSYS software was employed, and the FE model was aimed to investigate the effect of the actual tilt of the minaret on its seismic behaviour. Both the masonry trunk and the internal stairs were modelled by 8-nodes isoparametric solid elements (Solid65). In absence of a specific experimental campaign (tests, core drilling, mineralogical surveys, GPR survey, etc.) apart from the visual inspection, the mechanical properties of the walls (mainly specific weights and modulus of elasticity of masonry) were initially estimated based on literature data. The mean elastic modulus was estimated about 1500 N/mm^2, which is close to values already utilized in other works, and the specific weight of the material was assumed equal to 18 kN/m^3. To assess the effect of the tilt on the structural behaviour of the minaret, modal analyses and pushover analyses were performed.

Pushover analyses were performed considering time invariant load distributions for the lateral forces, namely: (i) a uniform distribution (U) and (ii) a triangular distribution (T). The uniform distribution is representative of the behaviour of the building near collapse, and the triangular distribution is representative of the behaviour of the building in its original undamaged configuration. U and T distributions were applied separately according to twelve equally spaced horizontal directions (with an angular scansion of 30°). The corresponding capacity diagrams were built considering the displacement of the top level of the minaret and the base shear V_b. The analyses were performed employing a force controlled incremental Newton-Raphson algorithm that allows for the simulation of the ascending branches of the response up to the maximum base shear V_{bmax}. For the sake of brevity, in the following only the results obtained with the uniform distribution are reported and the capacity diagrams obtained with the twelve pushover analyses are reported in Figure 9a. As a consequence of the tilt of the minaret, it is possible to observe a significant variation of the maximum base shear that range between the 0.07 and the 0.18 of the total weight of the minaret depending on the assumed loading direction. In order to provide a synthetic representation of the performed pushover analyses, the results are also represented employing the three-dimensional domains called capacity baskets [18]. In such representation, each pushover curve is represented along the input direction in a three-dimensional plot where the radius of the capacity basket is equal to the base shear coefficient (or to the maximum displacement achieved among all the considered directions). Such simple representation allows an easy identification of the stronger and weaker directions of the minaret.

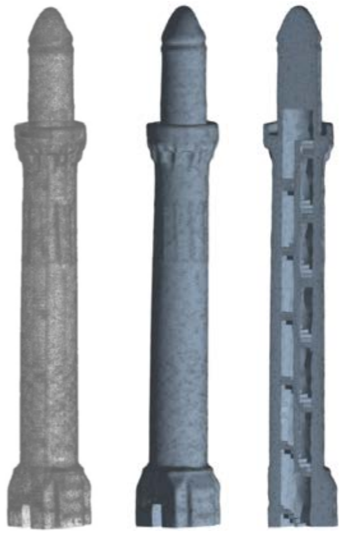
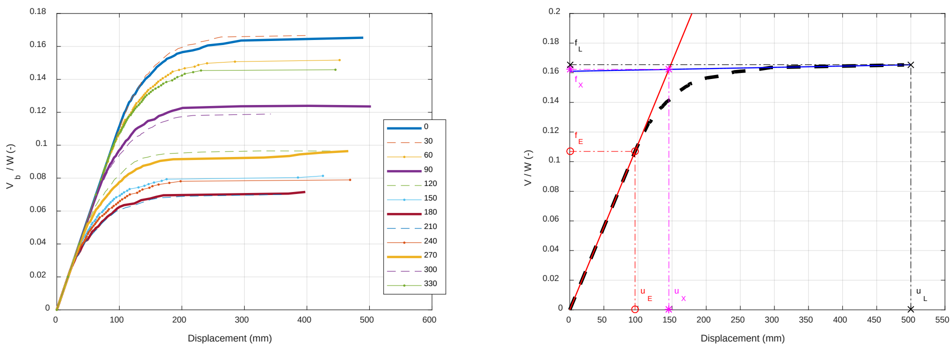


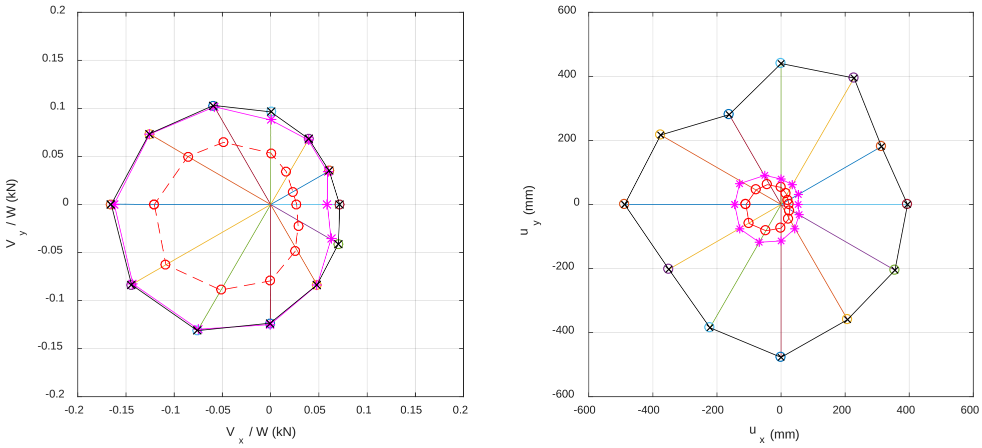
Figure 8. Views of the FE Model.

The capacity basket was built in order to synthetize three representative points of each pushover curve as illustrated in Figure 9b: i) the point correspondent to the end of the elastic branch ([u_E, f_E] denoted with a red circle); ii) the intersection between the tangents of the elastic and plastic branches of the pushover curve ([u_X, f_X] denoted with a magenta star) and iii) the point correspondent to the end of the pushover curve ([u_L, f_L] denoted with a black x-mark). These points were subsequently represented in the capacity basket reported in Figure 10. The irregularity of the minaret both in terms of strength (Figure 10a; continuous lines starting from origin represent the base shear evolution during the analyses: lines are straight lines since a load control Newton-Raphson algorithm was employed) and displacements (Figure 10b; continuous curves represent the top displacement evolution during the analyses) for the uniform force distribution is clearly readable: significant variation of both the maximum base shear and the maximum displacement characterize the pushover curves along different directions. It is possible to observe the out-of-plane deviation of the control point with respect of the pushing direction. In addition, the capacity basket immediately shows the weakest direction of the minaret that, obviously, is the one corresponding to the tilting plane, which has been characterized with a good accuracy thanks to the availability of an exhaustive and precise TLS survey. In this respect, the TLS survey results a very important tool both to generate high resolution and precise 3D models of the structure and to provide the accurate information needed for the elaboration of 3D FE models allowing the investigation of the expected structural behaviour in extreme load conditions.



(a) (b)

Figure 9. (a) Capacity curves obtained according to the twelve 30° degrees spaced horizontal directions; (b) Selected representative points of the pushover curves.



(a) (b)

Figure 10. Capacity basket: base shear (a); top displacement (b).

8. Conclusive remarks

In this paper, the health assessment of a brick minaret with both DA and FE model based on TLS was examined. TLS technologies can be considered as powerful tools for historical buildings analysis and monitoring projects. DA is a relatively fast and easy, innovative, contactless and non-destructive method for assessing building global and local deformations. With respect to the case study, DA provided the following result: i) an average deviation angle from vertical axis was measured and the leaning direction was determined; ii) partial anomalies, wall deformations and inclination maps were obtained easily and this data can support further analysis and decisions related to the structure; iii) partial sections and plans of structure were obtained directly from mesh models and they have been used for analysing anomalies of structures.

3D models of the minaret were obtained with tree different approaches and creating a mesh model and converting it to solid model, was recognized as a process fast, accurate and able to preserve the original geometry with a good accuracy. This approach resulted effective for FE modelling despite some difficulties related to transforming TLS data to mesh/solid models (and simplification of these models to computational models for FE analysis). The usefulness of the accuracy of the geometric survey by TLS has been discussed evaluating comparatively the seismic vulnerability of the tilted minaret through the pushover approach: it was observed a variation of the maximum base shear that range between the 0.07 and the 0.18 of the total weight of the minaret depending on the assumed loading direction, thus denoting the importance of the precise characterization of the minaret geometry.

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