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An integrated Terrestrial Laser Scanner (TLS), Deviation Analysis (DA) and Finite Element (FE) approach for health assessment of historical structures. A minaret case study

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ABSTRACT

This paper presents a multi-disciplinary approach for identification of historic buildings structural health with combination of Terrestrial Laser Scanning (TLS) survey, Deviation Analysis (DA) and Finite Element (FE) numerical modelling. The proposed methodology was discussed through the application to an illustrative case study: an early medieval period brick minaret (Eğri Minaret) located in Aksaray (central Turkey). After standing upright for several centuries, the minaret has developed tilt, and today the structure is supported with steel cables. 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. Differently from traditional approaches in FE analysis, the paper discusses a method for direct transfer of high accuracy TLS based 3D model to FE structural analysis software, subsequently employed to interpret and verify structural health of the historic building. Through the discussion of the results, it can be considered that the integration of these different techniques (being the whole process non-destructive, effective and expeditious for surface analysis) is a promising methodology for health assessment and analysis of historic constructions.

1. Introduction

Preservation of architectural heritage in modern society is a societal challenge [1]. This process introduces different problems concerning documentation, conservation, restoration and reusing activities. Besides, 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 [2,3]. 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 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 [2,4].

The accuracy of measured data directly affects decision-making and analysis process [5,6]. 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

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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 [7]. 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 [8] and preserving the integrity of historical constructions.

Finite Element (FE) analysis has become a predominant tool in engineering, 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 [9]. 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 [10,11]. 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. Here rely the differences between architectural and structural survey in interpretation of "authentic" geometry. Architecture and structure disciplines work on the same object with complementary refinement of the employed 3D models. 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 presents a multidisciplinary approach for structural analysis of historic buildings aimed to connect straightforward architectural survey and FE modelling through the discussion of an elucidating a case study. The considered case study is a minaret located in the city of Aksaray (Turkey) whose structural behaviour under wind and earthquake loads was recently investigated by Ural et al. [12]. 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.

In the following, the acquisition of the geometry and the deviation analysis from vertical planes based on TLS data are discussed after a description of the adopted methodology and of the minaret. Afterwards, a 3D model based on point cloud data is used in FE analysis software to build a numerical model of the structure. Then, this model is comparatively employed to evaluate the effect of the current tilt of the minaret in its seismic behaviour.

2. Methodology

Data accuracy and measurement workflow employed as methodology within the case study are shown in Fig. 1. 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

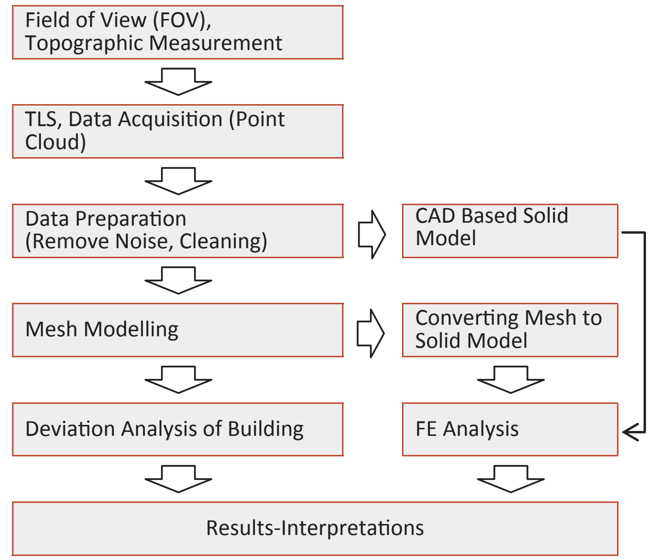

Fig. 1. Methodology of experimental study.

deviations were determined. The presented methodology is intended to provide benchmark guidance for subsequent applications with point cloud data for deviation and structural analysis.

3. Description of minaret

Eğri *(Leaning)* Minaret is a very important cultural heritage of Seljuk Empire in Aksaray (Turkey) (Fig. 2). Because of its red bricks used as construction elements, it is also referred to as Reddish Minaret (*Kızıl Minare*). The construction period of minaret is estimated between 1221 and 1236 CE within reigned period of I Alâeddin Keykubat. 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, some relief inscriptions on the trunk and blue and green tiles on the top of building [13]. Eğri Minaret demonstrates the presence of craftsmanship with brick muqarnas on the projection of minaret balcony: even if they are mainly decorative elements, they also improve load-bearing capacity of minaret ([14–16]). The height of the minaret is about 30.6 m. An internal spiral brick staircase with 92 steps leads to the balcony (Fig. 3).

The minaret today leans towards North-West direction due to unknown reasons. There is a still conflict between different scholars about the minaret inclination reasons ([12,17–20]). Bayrak et al. [17], f.i., believe that the tilt is an original feature of the construction and it represents the genius of the architect. According to hypothesis, the architect designed the minaret in order to protect it from possible inclination towards the river direction because of unstable ground. Some scholars, on the contrary, claim that the inclination is due to ground water and soil structure [12]. Similar problems in historical minarets are discussed in [21–24].

For safety reasons, in 1973, the minaret was strapped down from the upper part and was tightened to the ground with steel cables on the opposite direction of its inclination. In recent years, some additional investigations have been carried out to determine possible reasons for the movement and the inclination of the minaret. After periodical measurements of the minaret (and analysis of soil features and ground water level) scholars obtained that the minaret did not moved during the monitoring process [17].

In the present research, Eğri Minaret was employed as representative case study to test a methodology where the actual