Automation in Construction 92 (2018) 199–213

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Stability analysis of leaning historic masonry structures

Antonio Maria D'Altri[a,*], Gabriele Milani[b], Stefano de Miranda[a], Giovanni Castellazzi[a], Vasilis Sarhosis[c]

[a] Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM), University of Bologna, Viale del Risorgimento 2, Bologna 40136, Italy
[b] Department of Architecture, Built Environment and Construction Engineering (A.B.C.), Politecnico di Milano, Piazza Leonardo da Vinci 32, Milan 20133, Italy
[c] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

ARTICLE INFO

Keywords:
Leaning tower
Limit analysis
Point cloud
Mesh generation
Masonry
Actual geometry

ABSTRACT

This paper introduces an automatic, powerful and easy to use procedure for undertaking stability analyses of leaning historic masonry structures, based on an upper bound finite element limit analysis (FELA) approach. The procedure proposed here consists of a comprehensive workflow which involves the automatic point cloud manipulation, the 3D mesh generation of the actual geometry for structural purposes (e.g. FE mesh), and a two-step FELA that reduces drastically optimization variables assuming only active few elements inside a restricted processing zone. To generalize the Heyman's intuition to complex real geometries, the use of a 3D upper bound FELA with a recursive kernel of variables reduction becomes necessary for a precise evaluation of the limit inclination that makes the structure collapse under gravity loads. This outcome permits to estimate the structural health condition of a historic structure by comparing the critical inclination angle against the actual one. To demonstrate the effectiveness of the automated procedure, the southwest leaning tower of the Caerphilly castle (Wales, UK) is investigated and failure mechanisms with collapse inclination angles are evaluated through FELA. The proposed procedure presents a high degree of automation at each operational level and, hence, could be effectively used to assess the stability of historic structures at a national scale and provide useful information to asset owners to classify the structural health condition of leaning historic masonry structures in their care.

1. Introduction

Leaning historic masonry structures are fascinating to observe. Perhaps the most famous examples include the Pisa [1,2] and the Ghirlandina towers [3]. The reason why historic masonry structures lean is a complex area of study and have stimulated the interest of the scientific community for over a century [4–7]. Due to their narrow foundations, tall and slender historic masonry structures such as towers, whose height is much greater than their width, are generally more prone to lean. Two major reasons why masonry towers tilt are: (a) lack of foundation strength; and (b) lack of foundation stiffness aggravated by progressive soil creep phenomena [4]. Several advanced soil-structure interaction models have been developed to study these phenomena [3]. However, such models require the setting of a numerous amount of mechanical parameters; most of them correlated with in-depth in-situ soil tests. Furthermore, they do not allow for a rapid check on the structural condition of the structure.

Heyman [8] was probably the first to study analytically the safety of leaning towers by assuming masonry as a rigid material unable to withstand tensile stresses. Such simplification allowed deriving a quite simple differential equation describing the crack curve delimiting the failure mechanism and providing very useful hints on the limit inclination angle associated with the collapse of the structure. However, the hypothesis of rectangular full or thin-walled sections and the absence of any irregularity along the height represent a remarkable limitation of the approach, since in practice it is not realistic. Vertical walls of towers vary considerably in thickness and they often present irregular openings [1]. Furthermore, historic towers, or other height-prevalent historic structures (e.g. walls in churches, curtain-defensive walls etc.), frequently stand in a ruined condition, and have been subjected to unforeseen load events (e.g. bombing, successive demolitions, sabotages, raids etc.) over the centuries [9]. Often, such structures suffered alternations and today, only a few portions of the original structure remain standing. Consequently, the geometry of these structures is generally extremely complex and irregular (see for instance [6]). Their complex geometries suggest to consider advanced methods of analysis where the actual 3D geometry of the structure is accounted for in the calculations [10].

One of the first challenging tasks that appears when dealing with the numerical modelling of this kind of structures lasts in acquiring their 3D

* Corresponding author.
E-mail address: antoniomaria.daltri2@unibo.it (A.M. D'Altri).

https://doi.org/10.1016/j.autcon.2018.04.003
Received 29 November 2017; Received in revised form 8 April 2018; Accepted 9 April 2018

geometric features. The use of automated surveying techniques, such as terrestrial laser scanning [11] and close-range photogrammetry [12] which produce dense point clouds, appears particularly suitable for obtaining the geometry of historic structures [13–15]. From such studies, it is evident that the use of terrestrial laser scanning and close-range photogrammetry surveying techniques could result in accurate representation of the geometry of a structure in a relatively reduced cost [16–19]. Documentation for supporting restoration works as well as monitoring of historic structures are common motivations for the use of these surveying techniques on structures of architectural heritage [20–23].

Nevertheless, the exploitability of laser scanning and photogrammetric surveys outputs, i.e. point clouds, for structural analysis of historic building is still challenging. A significant contribution to this field is proposed in [24], where an attempt to accurately capture the geometry of a structure by automatic reconstruction is presented. Moreover, in [25], a point-based voxelization method for automatic transformation of point cloud data into solid models for computational modelling was proposed. The approach involves the construction of a triangular irregular network (TIN) mesh by means of a voxel grid bounding the cloud region. However, such approach is limited to building façades and it does not capture the entire geometrical domain of the structure.

Dealing with actual buildings, two main difficulties arise: (i) the automatic filling of very long vacancies (roof structures for instance), and (ii) reduction of the whole model in a more simplified and compressed form. To overcome these issues, a semi-automatic procedure (called CLOUD2FEM) to transform three-dimensional point clouds of complex objects into a three-dimensional finite element model has been presented in [26]. The procedure conceives of the point cloud as a stacking of point sections and aims at solving the problems connected to the generation of finite element models of these complex structures by constructing a fine discretized geometry with a reduced amount of time and outputs ready to be used for structural analysis problems [27]. A recent application of this procedure to a full-scale medieval fortress and its subsequent seismic assessment by means of nonlinear static analysis is reported in [28].

Once the mesh is available, it can be used within several computational tools for the structural analysis of historic masonry buildings. Particularly, such approaches are usually based on: a) the finite element method (FEM) [28–35]; b) the discrete element method (DEM) [36,37]; and c) limit analysis [38,39]. Interesting comparisons of computational techniques are provided in [40–42].

Another interesting issue is to determine the maximum inclination angle that leads to the collapse of a tower due to the loss of stability under the application of gravity loads. Concerning a no-tension material with rectangular cross section, Heyman [8] was able to analytically determine the collapse inclination angle and the corresponding crack pattern shape. Unfortunately, an analytical approach for real irregular geometries is hardly applicable, and an automatic procedure is needed. To deal with such key issue is one of the two aims of the present paper.

Firstly, a simplified and rapid procedure for the automatic transformation of point clouds (surveyed on historic structures) to 3D FE meshes, passing from the concept of watertight mesh, is proposed. The accuracy of the geometry of the mesh generated appears suitable for structural purposes. Secondly, following the Heyman's work [8], the use of a two-step 3D upper bound finite element limit analysis (FELA) on the generated mesh is conducted and the critical condition (i.e. maximum inclination capacity) of a leaning historic masonry structure is evaluated.

The procedure is indeed an upper bound limit analysis with FE discretization obtained by means of tetrahedron rigid elements and rigid-perfectly plastic interfaces exhibiting frictional behaviour and very low cohesion (i.e. mimicking a quasi no-tension material with friction).

Considering that FE meshes obtained from detailed laser scanner surveys would be constituted by hundreds of thousands of elements and interfaces, the limit analysis problems derived would be characterized by millions of variables, i.e. in practice impossible to solve even with super-computers. An alternative to parallelization is proposed for the first time here, which is essentially a master-slave approach conceived with the aim of reducing drastically the total number of optimization variables. The procedure is based on the hypothesis that the tower collapses for the plasticization of few elements located in a limited processing zone, which is a-priori established in the first step. Elements with centroids inside the processing zone are assumed potentially active. The rest of the mesh is excluded from computations and it is treated as a single rigid body characterized by six degrees of freedom (i.e. three centroid velocities and three rotation rates). The solution of the linear programming problem found in the first step provides a more accurate estimation of the potential interfaces undergoing plasticization. In the second step, the processing zone is further reduced to those elements whose interfaces exhibit meaningful inelastic deformation rates plus few contiguous ones, to further drop-down the optimization variables. Conversely, the failure surface linearization on the active interfaces is refined to obtain more accurate estimates of the collapse multiplier. The master-slave kernel is then coupled with a sequential linear programming algorithm to deal with the linearization of the normalization condition equation, which results nonlinear due to the assumption of the inclination angle at failure as collapse multiplier.

The outcome obtained with the limit analysis permits to practically estimate the structural health condition of a leaning historic structure, e.g. by comparing the maximum critical inclination angle against the actual one. Since the computational approach proposed herein presents a high degree of automation at each operational level (i.e. survey, point cloud manipulation, mesh generation, numerical analysis), its usage could be addressed to the stability analysis of historic structures at a national scale. In particular, this approach could be beneficial for asset managers, which want to classify the structural condition of leaning historic assets in their care and devise action plans for their survival.

In this research, the southwest leaning ruined masonry tower of the Caerphilly castle (Wales, UK) is employed as a case study to demonstrate the effectiveness of the proposed approach. The paper is organized as follows. Section 2 briefly presents the case study. Section 3 describes the automatic procedure for the stability analysis of leaning historic structures. Section 4 reports the analyses results and their discussion. Finally, Section 5 highlights the main conclusions of this research work.

2. The leaning tower of Caerphilly castle, UK

In this section, a brief description of the case study related to the southwest leaning tower of Caerphilly castle, used to test the effectiveness of the proposed approach is reported. The case study is merely used to demonstrate the effectiveness of the proposed automatic procedure for assessing the structural stability of leaning historic masonry structures.

Caerphilly castle is a medieval fortification in Caerphilly, South Wales, UK. The castle was constructed by Gilbert de Clare in the 13th century [43] and it is the second largest in the UK. Fig. 1 shows the southwest leaning ruined tower of the Caerphilly castle. The tower has been in a ruined and leaning condition for several centuries [8,44].

The tower is approximately 17 m tall. It used to have a circular ground plant of approximately 9 m in diameter. Today, the inclination of the tower is approximately 10°. For the sake of comparison, the campanile of Pisa is 55.86 m tall and leans at an angle of 5.5°. The southwest tower is made of stone masonry with a fully irregular texture. No information is available about masonry material properties, soil stratigraphy and foundations. However, medieval fortified structures were generally characterized by particularly shallow foundations [9]. According to Renn [43], the deterioration subsequent leaning of the tower was probably the result of subsidence caused by dewatering in