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From point cloud data to structural modelling: the case study of the Tusk at Spynie Palace, Scotland

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Abstract

The development of digital technologies has already supported the production of accurate representations of structures, with applications in conservation, monitoring and Building Information Modelling projects. The exploitability of their outputs remains particularly challenging with respect to applications for structural analysis of historic structures. This paper investigates the use and potential of 3D laser scanning output for structural engineering applications and suggests a semi-automatic, user-friendly approach to building 3D finite element models utilizing point cloud data. Compatible computational techniques offered by commercial software are investigated, with findings applied to the case study of the 6m-high freestanding masonry tusk of Spynie Palace, Scotland. The structural response of the tusk is studied under critical load combinations that lead to stress patterns confirming the location of vulnerable areas with visible signs of deterioration on the real structure. Further research is identified with a view towards adapting the methodology to suit the needs of structural typologies and the nature of structural problems commonly encountered in properties in the care of Historic Environment Scotland.

Keywords: point cloud data; historic structures; masonry; finite element modelling; structural response

1. Introduction

The conservation and restoration of cultural heritage encompasses a range of engineering challenges that attract increasing attention by researchers and offer opportunities for novel research and industry collaborations. Numerical modelling of historic masonry structures can improve structural monitoring strategies, inform design and lead to more targeted interventions. The complex geometrical, typological and material characteristics of such structures, in

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conjunction with their large numbers around the world, make this approach of effective assessment of structural response a luxury afforded only for a very limited number of highly significant historic structures.

The development of digital technologies, including structure from motion and terrestrial laser scanning, has been identified as a game-changer and already helped produce accurate representations of structures with applications in conservation, monitoring and Building Information Modelling (BIM) projects (Valero et al., 2019, Brumana et al., 2020, Murphy et al., 2009). Utilizing the outputs of laser scanning and photogrammetric surveys, i.e. point clouds, for accurate structural assessment of historic structures remains a challenge, as most approaches for retrieving geometries from 'Light Detection And Ranging' (LIDAR) data [both airborne and terrestrial] and photogrammetry focus on rebuilding models for viewing (Martínez et al., 2012).

A range of approaches exist in the literature with reference to the reduction of 3D point clouds of complex structures into 3D Finite Element (FE) models (D'altri et al., 2018). Hinks et al. (2013) suggested a point-based voxelization method for automatically transforming point cloud data into building information models for modelling and simulation. The process entails using a voxel grid to create a triangular irregular network (TIN) mesh surrounding the cloud region. However, such technique is limited to the structure's outer area and does not capture its complete geometrical domain. Brumana et al. (2020) present a procedure to rebuild the entire geometry of a building from laser scanning data improving the output for fine geometrical details and addressing BIM interoperability issues for importing the very dense and detailed BIM models into FE software (Oreni et al., 2014).

Creating a waterproof mesh by filling empty surfaces (e.g. roof surfaces) and reducing the entire model to a more streamlined and compact form is attempted by Castellazzi et al. (2015) in their semi-automatic procedure Cloud2FEM. This procedure defines a constructive method of transforming 3D point clouds of complex structures into 3D finite element models and treats the point cloud as a stack of point sections, aiming at creating a refined discretised geometry with outputs appropriate for structural analysis that can be directly imported into FE software.

This paper reports on initial findings of a project undertaken at Edinburgh Napier University with the aim to investigate the use and potential of 3D laser scanning data owned by Historic Environment Scotland (HES), for structural engineering applications. HES is Scotland's lead public body established to investigate, care for and promote the country's historic environment that is an essential part of its cultural background and economy. Scotland is often referred to as 'a nation of stone', typified by its historic masonry buildings and castles that form one of the richest legacies of traditional and historic structures in the United Kingdom (UK). Some of these are internationally iconic structures of historical and cultural heritage. The effects of ageing though, together with environmental conditions and past natural hazards have caused significant degradation, urging for action (Hyslop et al., 2006). Since 2017, the Scottish Government has worked with HES to develop a long-term Infrastructure Investment Plan for restoring, enhancing and conserving the built heritage, support the tourism industry and continue to provide a world-class experience for visitors. As part of this, within the £11 million Engine Shed project, Scotland's first national centre for historic environment conservation skills was created, hosting the Digital Documentation Team with the mission to digitally document every place and object in their care (Wilson, 2020).

The research undertaken clarifies the applicability of 'point cloud – to – FE model' methods for data owned by HES, shedding light on each operational level (point cloud manipulation, mesh generation, numerical analysis) with a view towards establishing requirements for the development of an easy-to-use procedure for undertaking structural analyses of complex historic masonry structures within commercial computational tools. Following a systematic review of options for mesh generation for structural purposes using 3D point cloud data and an investigation of compatible computational techniques offered by commercial software, the exploratory application of findings to a case study was focused on the structural analysis of the 6m-high free-standing tusk of Spynie Palace, at the north of Scotland. It appears as an isolated pillar and forms the only upstanding remains from a 15^{th} century load-bearing curtain walling of considerable archaeological significance. It was chosen as an example of a very irregular structure in need of intervention, to demonstrate a pilot process for creating a 3D solid mesh compatible with commercial engineering software, while using simplified material laws and boundary conditions to allow for a first-stage structural assessment.

2. Case study

2.1. The structure

Spynie Palace (Fig. 1a) is located on a low ridge of Cherty Rock immediately to the south of the Spynie depression and is the best-preserved medieval episcopal residence in Scotland (Hes, 2019), with surviving ruins dating back to the 12th century (Lewis and Pringle, 2002). The south, west, and east ranges were remodeled between the 15th and 17th centuries, including rebuilding the South-East and North-West towers and constructing a new banqueting hall block along with the north range. Spynie remained the bishop's palace until the end of the 17th century and then was abandoned falling swiftly into disrepair when the ironwork and timber were removed, and the walls were plundered for stone. In 1920 the palace was scheduled as an Ancient Monument and was given into guardianship in 1973 (Hes, 2019). The monument is comprised of a number of very ruinous upstanding masonry buildings, located around a quadrangular courtyard (Thacker, 2017).

The 'tusk' is a 6m high masonry pillar that appears to the north of the south range as an isolated structure (Fig. 1b). It forms the only upstanding remains of the gallery extension to the south range built during the 15th century. The evidence suggests that this walling was an integral part of two structures, one of which held the chapel. Images from the archaeological excavations in the 1990s suggest that the top of the foundations of the tusk was exposed but with no further information with respect to their exact depth and condition. Repointing and consolidation work during 2016 reported that the tusk is slightly unstable and sways when pushed. Keeping in view the site's archaeological potential and addressing the structural stability of tusk, the digital documentation team of HES conducted a laser scan survey and gathered data in the form of a point cloud.

The masonry is generally constructed of sandstone rubble, with sandstone dressings and is fully lime-bonded in all visible upstanding sections (Thacker, 2017). These lime source materials were texturally consistent with limestone samples collected from local outcrops (Thacker, 2019). Although the structural units are presented with differing shapes, sizes and states of deterioration, their macroscopic appearance suggests their principal origin being from local quarries such as Spynie near Elgin, producing pale siliceous freestones.

Fig. 1. (a) Aerial image of Spynie palace (tusk highlighted); (b) image of the tusk from the west

2.2. From point cloud data to FE model: methodology

Processes necessary to simplify and reconstruct a 3D mesh model from point cloud data were performed (Fig. 2), taking into account the needs of this specific structure and the availability of tools and resources within the project. The point cloud initially contained 10.337.388 vertices which were then simplified to 10.000 for further processing, still corresponding to an adequately detailed geometry of the structure reflecting surface variation (Fig.3). A point set simplification algorithm (Lee and Jong, 2008) was applied by means of the open-source software Meshlab (Cignoni et al., 2008). Cleaning operations, pre and post-processing, were performed on the data set to remove overlap of captured data points and improve the accuracy of the point cloud, before creating a TIN mesh connecting triplets of nodes to create non-overlapping triangles (Huang, 1989) by application of surface reconstruction and Poisson disk sampling algorithms (Kazhdan et al., 2006, Corsini et al., 2012) using Meshlab (Fig.4). These operations create smooth, robust surfaces while representing accurately noisy data and allow scanned data to be fitted, surface gaps to be filled, and existing models to be re-meshed with uniformly distributed sample points.

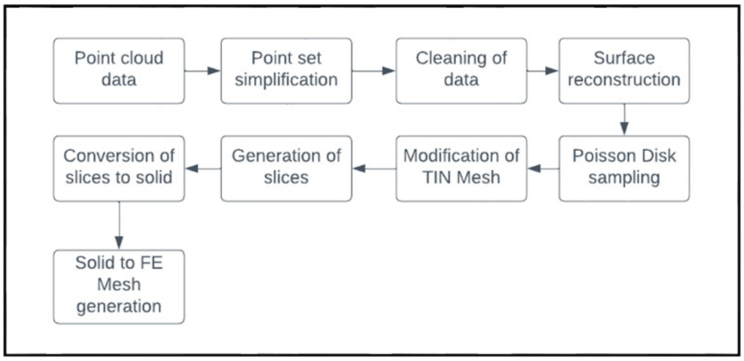

Fig. 2. The process of FE mesh generation from point cloud data

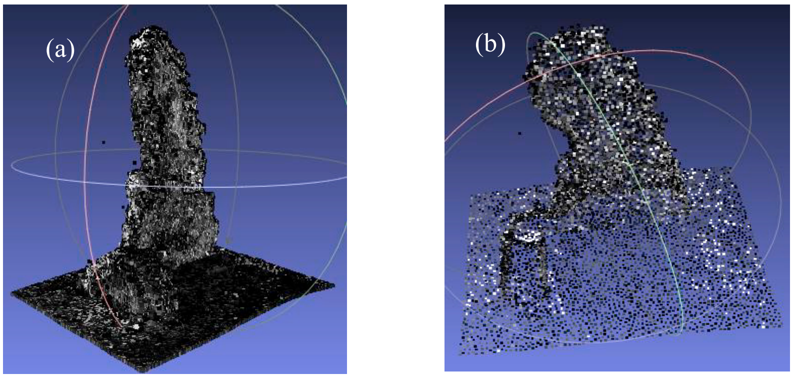

Fig. 3. Representation of the point cloud simplification (a) original: 10.337.388 vertices; (b) simplified: 10.000 vertices

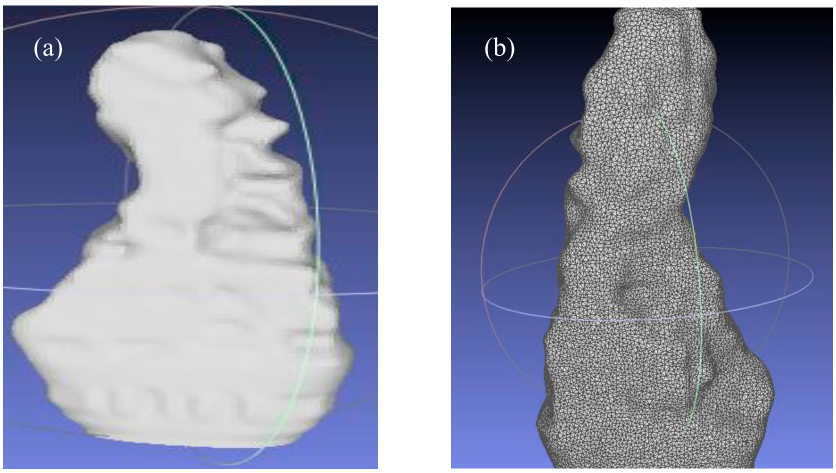

Fig. 4. (a) Application of the surface reconstruction algorithm; (b) TIN mesh generated from the Disk sampling algorithm

The TIN mesh was used as the basis for the creation of a 3D manifold surface and then a 3D solid structure using the software SolidWorks (Dassault Systèmes) that constituted input compatible with FE commercial software. The structure was divided into slices keeping in view the average dimension of the stone which were then connected, generating the solid between their boundaries and filling the in-plane space. Once the solid volume was created, it was imported into a file format compatible with commercial engineering software suitable for structural applications.

3. Numerical Investigation

Numerical modelling and analysis of masonry structures is challenging (Theodossopoulos and Sinha, 2013, Roca et al., 2010). The presence of joints as a primary source of weakness, discontinuity and nonlinearity, and uncertainties in the material and geometrical characteristics all contribute to increased difficulties. Several approaches of numerical modelling and analysis of masonry structures in the literature present a range of advantages and limitations (Asteris et al., 2015, Lourenco, 2002). With the aim to create a model balancing computational cost and accuracy with respect to the needs of this project, a macro-modelling approach was adopted with application of the finite element method and use of the Ansys Workbench engineering simulation software, in which masonry is described following a continuum homogenized model, implicitly considering the effects of mortar joints. As the structural units of the tusk were not arranged in continuous bed joints and there was limited information on material properties, consideration of a homogenous linear elastic material was chosen as a fitting option to capture this simplified composite behavior of sandstone blocks bonded with lime mortar and arranged in random patterns. Material mechanical properties were estimated based on data from visual inspection, test results (not site-specific) and recommendations from relevant literature (Borri et al., 2015, Hyslop et al., 2006), with the following values been considered: masonry uniaxial compressive strength f_m=1,55MPa, modulus of elasticity E=755MPa and shear strength τ_0=0,0028MPa.

The wall was considered as fixed at its base and combinations of self-weight, live load and wind load appropriate for the area were applied (Fig. 5a) for evaluating the tusk's structural response to a range of reasonable design loading conditions performing static analysis. Live loads were considered to account for restoring and maintaining activities while the basic wind velocity of 27,1m/sec applicable to the neighboring Elgin city was used for the calculation of wind pressures according to BS EN1991-4-1. The masonry volume was appropriately discretized, balancing computational costs with stability of the solution, generating a mesh of 4-node tetrahedra with 65.705 nodes (Fig. 5b).

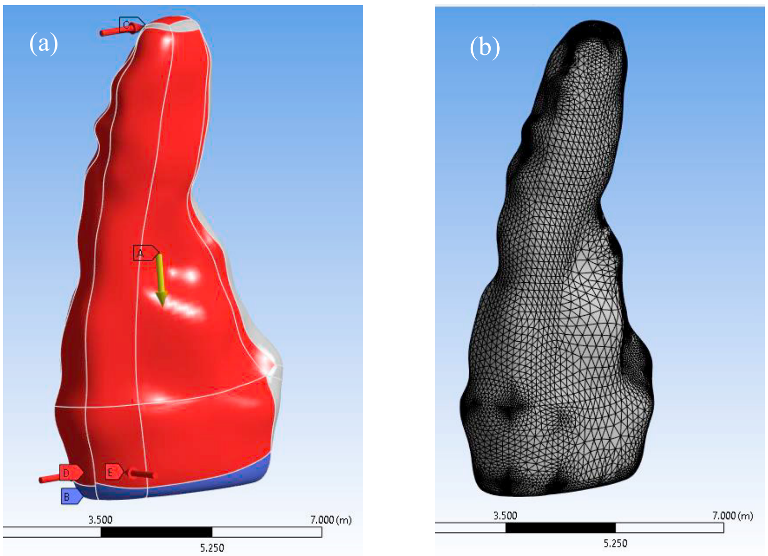

Fig. 5. (a) Application of boundary conditions on the tusk; (b) finite element mesh for structural analysis with Ansys

Given the current condition of the tusk, results were mostly interpreted by means of macroscopic examination of displacements and a ‘safety factor’ considering combinations of stresses based on a post-processing application of a Mohr-Coulomb failure criterion (Fig. 6). Results confirm on-site observations from HES that the tusk shows signs of instability and sways when loaded laterally. With the analysis assumptions considered, the stress combination for failure would be exceeded in large parts of the structure, although examining closely how this develops over the incremental application of the load combination, this does not happen before reaching about 85% of the total design load.

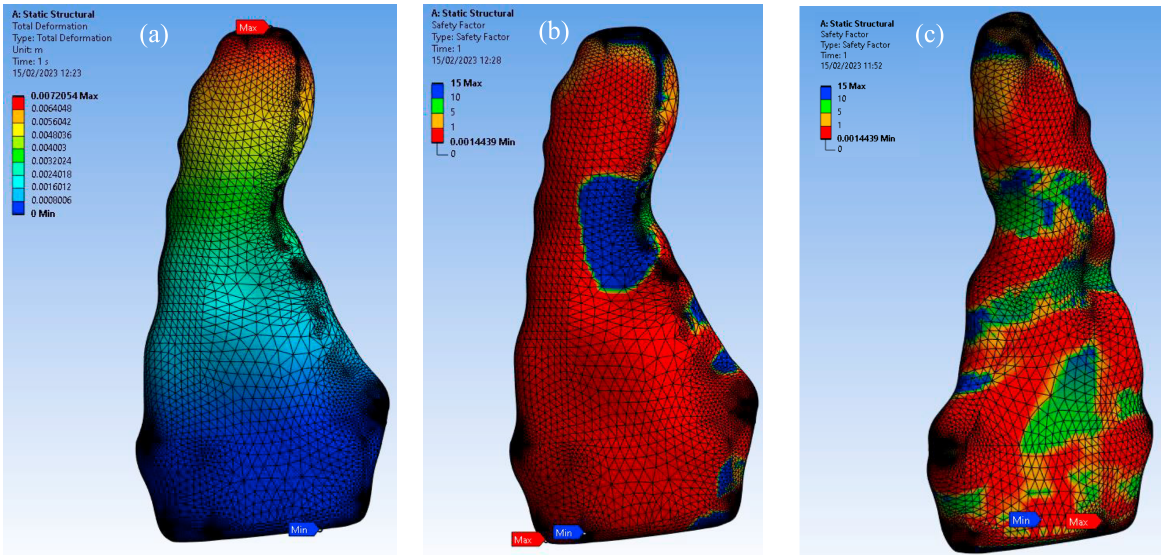

Fig. 6. Numerical results for critical load combination (a) total deformation; (b) safety factor for windward surface; (c) safety factor for leeward surface

4. Discussion

This project verified the pilot process for using existing point cloud data for structural engineering applications and confirmed compatibility of numerically observed vulnerable areas with existing failure patterns. Indeed, critical load combinations lead to stress patterns in accordance with the location of vulnerable areas with visible signs of deterioration on the real structure, exhibited mainly as diagonal cracks and splitting of joints (Fig. 7).

For this particular structure, areas of further research comprise evaluation of the potential of advanced material laws for masonry (Castellazzi et al., 2017, Jalayer et al., 2016, Addessi et al., 2014), alterations in the mesh generation choices and consideration of alternative boundary conditions including the current state of the structure’s foundations and existing defects (e.g. tilt). Based on the transferable outcome of this project, the most suitable processes for finite element mesh generation from exploiting point cloud data of historic constructions for structural purposes can be further explored and optimised with a view towards adapting them to identified needs in terms of structural typologies and nature of structural problems (Castellazzi et al., 2016, Bitelli et al., 2016).

The project was valued by all partners, for its larger-scale potential to improve structural monitoring strategies and to lead to more targeted interventions as needed. With 336 historic properties in the care of HES across Scotland, from Dun Carloway Broch to Edinburgh Castle, there is ample scope for pursuing such research that will enable structural engineers at HES to perform advanced structural analyses, that will inform the design, improve the structural monitoring and lead to more targeted interventions as needed.

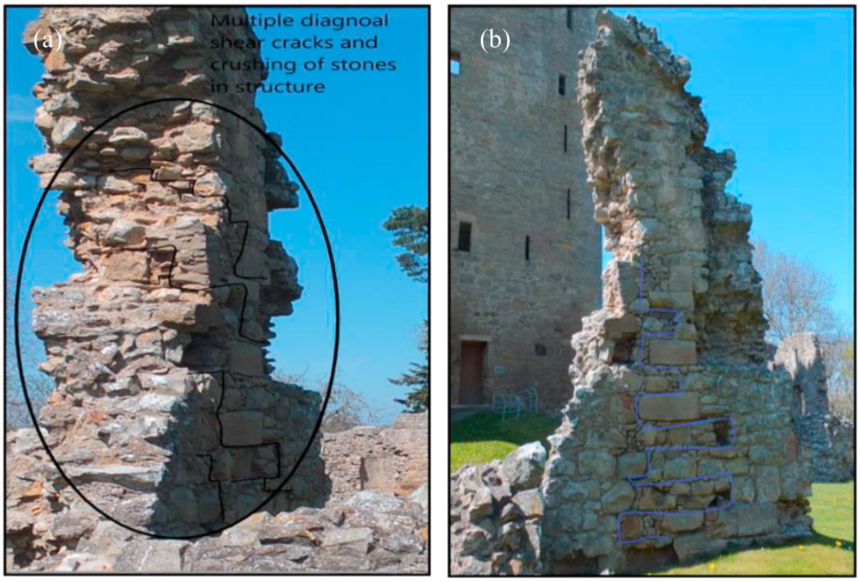

Fig. 7. Current state of the tusk with identification of vulnerable areas (a) diagonal shear cracks; (b) splitting of joints

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