Vulnerability assessment of cultural heritage structures

Mahdi Kioumarsi Kioumarsi[1], Vagelis Plevris Plevris[2], Amirhosein Shabani Shabani[1]

[1] Oslo Metropolitan University
[2] Qatar University

INFORMATION

Keywords:
Vulnerability Assessment
Cultural heritage
Digital twin
Finite element.

DOI: 10.23967/eccomas.2022.294

Published: 25/11/2022

The 8th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2022
5 – 9 June 2022, Oslo, Norway

VULNERABILITY ASSESSMENT OF CULTURAL HERITAGE STRUCTURES

MAHDI KIOUMARSI[1], VAGELIS PLEVRIS[2] AND AMIRHOSEIN SHABANI[3]

[1] Department of Civil Engineering and Energy Technology, OsloMet–Oslo Metropolitan University
Pilestredet 35, Oslo 0166, Norway
e-mail: mahdik@oslomet.no

[2] Department of Civil and Architectural Engineering, Qatar University
P.O. Box: 2713, Doha, Qatar
e-mail: vplevris@qu.edu.qa

[3] Department of Civil Engineering and Energy Technology, OsloMet–Oslo Metropolitan University
Pilestredet 35, Oslo 0166, Norway
e-mail: amirhose@oslomet.no

Key words: Vulnerability Assessment, Cultural heritage, Digital twin, Finite element.

Abstract. Cultural heritage (CH) assets are the legacy of a society that are inherited from the past generations and can give us lessons for contemporary construction. Not only the formally recognized CH assets but also the non-CH structures and infrastructure, and the interconnection between them are crucial to be considered in a vulnerability assessment tool for the sustainable reconstruction of historic areas. Since most CH assets were not designed based on robust design codes to resist natural hazards such as earthquakes, vulnerability assessment and preservation are pivotal tasks for the authorities. For this aim, Hyperion, an H2020 project (Grant agreement No 821054), was formed in order to take advantage of existing tools and services together with novel technologies to deliver an integrated vulnerability assessment platform for improving the resiliency of historic areas. Geometric documentation is the first and most important step toward the generation of digital twins of CH assets that can be facilitated using 3D laser scanners or drone imaging. Afterward, the finite element method is an accurate approach for developing the simulation-based digital twins of cultural heritage assets. For calibration of the models, the result of the operational modal analysis from the ambient vibration testing using accelerometers can be utilized. Structural analysis for the prediction of the structural behavior or near real-time analysis can be carried out on the calibrated models. However, the full finite element analysis needs a lot of computational effort, and to tackle this limitation, equivalent frame methods can be utilized.

1 INTRODUCTION

Natural hazards are severe and extreme weather and climate events that can cause catastrophic environmental consequences [1]. Such hazards can originate in different sources and systems, such as atmospheric, hydrologic, oceanographic, volcanologic, seismic, etc. They can include storms, tsunamis, floods, avalanches, landslides, earthquakes, and volcano eruptions, among others. In the area of quantitative risk assessment for natural hazards purposes, vulnerability is defined as the distribution of losses (human loss, economic loss, etc) conditioned by the intensity of the natural hazard, where vulnerability is expressed either as the probability of exceeding a given amount of loss, or as a deterministic loss index. The negative consequences of natural hazards can be expressed as the result of both the frequency and intensity of the hazard and the vulnerability of the exposed society or element at risk [2]. Vulnerability assessment is an essential step in reducing these consequences [3]. The assessment of vulnerability requires an ability to both identify and understand the susceptibility of the elements at risk. Different methods have to be used and be appropriately integrated in vulnerability assessment for exploring vulnerability from different angles or for developing the needed holistic picture [4].

Historical monuments are invaluable as they represent a relevant part of the history and culture of a country as well as humanity. Cultural heritage (CH) assets represent the legacy of a society as they are inherited from the past generations and need to be maintained and preserved for future generations. Since most CH assets around the world were not designed based on robust design codes to resist natural hazards, the vulnerability assessment and preservation of them are pivotal tasks for the authorities [5]. Valagussa et al. [6] proposed a multi-criteria risk analysis to identify and rank the most critical UNESCO World Heritage Sites in Europe, in the framework of the JPI-CH PROTHEGO project. They considered three natural geo-hazards, namely landslide, seismic shaking, and volcanic activity, for which hazard maps were available. The methodology is based on a quantitative and reproducible heuristic assessment of risk through the development of a new Risk Index, combining the level of hazard with a potential damage vector. On the other hand, Agapiou et al. [7] assessed the risk of natural and anthropogenic hazards for cultural heritage in Cyprus by integrating multi-temporal GIS and earth observation analysis. The aim was to develop an accurate methodology for risk assessment against natural and anthropogenic hazards using a homogeneous clustering of the monuments based on a variety of parameters taking into consideration characteristics of their immediate environment.

Gallina et al. [8] presented a review of existing multi-risk assessment concepts and tools, providing the basis for the development of a multi-risk methodology from a climate change perspective. Their results showed that multi-risk approaches do not usually consider the effects of climate change and mostly rely on the analysis of static vulnerability without taking into account time-dependent vulnerabilities and changes among exposed elements. Julià and Ferreira [9] attempted to pave the way toward the establishment of future multi-hazard vulnerability and risk assessment methodologies for Historic Urban Areas by offering a comprehensive review of some of the most relevant methodologies proposed in this research area. Their work focused on seismic, flood, and fire assessment methodologies, with particular emphasis on multi-hazard approaches.

Arrighi et al. [10] attempted to codify a multi-risk workflow for seismic and flood hazards, for site-scale applications in historical cities, within a coherent multi-exposure and multi-vulnerability framework. The methodology includes a multi-risk correlation and joint probability analysis to identify the role of urban development in re-shaping risk components in historical contexts. According to the authors, the proposed multi-risk workflow can be applied to other historical cities and further extended to other natural hazards. Lately, data-driven approaches have become popular in the area of disaster risk management [11]. In this research direction, Wirtz et al. [12] highlighted the need for reliable data for high-quality natural disaster analyses. Their work outlines the criteria and definitions relating to how global and multi-peril databases are operated and the efforts being made to ensure consistent and internationally recognized standards of data management for such purposes.

Hyperion, a Horizon 2020 project [13] with partners from Norway, Greece, Italy and Spain (EU Grant agreement No 821054), was formed to take advantage of existing methods together with novel technologies to develop an integrated vulnerability assessment platform for historic areas. Through the Hyperion project, structural/geotechnical analyses were performed on the selected CH pilots to assess their vulnerability to natural hazards. This paper, by reviewing all research activities done along the Hyperion project, presents the two approaches developed to assess heritage structures, namely (i) simplified modeling and analyzing of heritage buildings, and (ii) detailed modeling and analyzing of buildings and structures. The paper is organized as follows: Section 1 is the introduction which includes also a bibliometric analysis on the broader topic. Section 2 presents a simplified methodology for modeling and analyzing masonry heritage buildings. Section 3 includes the procedures and challenges in the detailed modeling of CH pilot sites in the Hyperion project, while Sections 4 presents the conclusions of the work.

1.1 Bibliometric analysis

A look at the most recent scientific literature on the topic of vulnerability assessment of cultural heritage structures can reveal the importance of the field for the scientific community lately. To perform a quantitative investigation on this, we searched the Scopus database (www.scopus.com) with the keywords “vulnerability”, “assessment”, “digital twin”, “finite element”, “cultural heritage” and “structures”, for documents published after the year 2000. In particular the specific search query was “*TITLE-ABS-KEY (("vulnerability" OR "assessment" OR "digital twin" OR "finite element") AND "cultural heritage" AND "structure") AND PUBYEAR >2000*”. The query, made on May 31, 2022, returned 908 document results in total. Figure 1 shows the number of these published documents, per year, for the years from 2001 to 2021 (21 years). The year 2022 was excluded from the plot as it is still a year in progress (with 38 papers published so far). By excluding the year 2022, the total number of documents becomes 870. The growth in the production of scientific papers in the field is visible, showing that the topic of vulnerability assessment of cultural heritage structures has increasing importance and it is gaining popularity among the scientific community members during the last two decades.

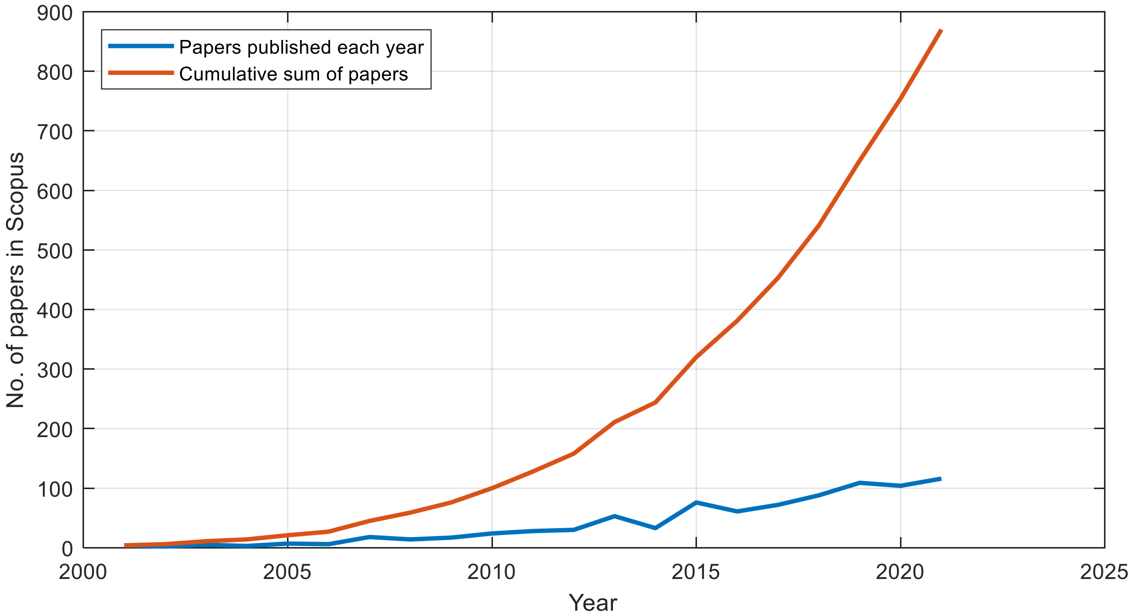


Figure 1: Papers in Scopus database, per year, for the query made

In addition, we performed a co-occurrence analysis of the top keywords of the documents, including author keywords and index keywords. For this, we use a database based on the previous Scopus query, while also taking the year 2022 into account (i.e., 908 documents in total). Within this result, we identified the top keywords of the published papers. The network visualization of the co-occurrence of the top-50 keywords are presented in Figure 2, generated using the VOSviewer software [14], with 4 clusters presented with different colors, and minimum strength equal to 15. Similar keywords were merged together manually, using a custom-made thesaurus file, to avoid duplicates due to spelling differences (for example "damage assessments" becomes "damage assessment", "3d modelling" becomes "3d modeling", etc.). In this map, the links between keywords express the frequency of co-occurrence of the keywords in the documents, while the size of each bubble (keyword) expresses the number of occurrences of a specific keyword. As expected, the keyword "cultural heritage" appears in the center of the network as the strongest keyword (with 434 occurrences), followed by "historic preservation" (217), "masonry" (194), "earthquake" (132), and "finite element method" (121). A clear cluster related to surveying, photogrammetry and laser scanning is the yellow one, on the right of the figure. On the left, one can identify the green cluster which is related to earthquakes, seismic vulnerability and retrofitting. The blue cluster on the top is related to numerical analysis methods and structural health monitoring, while the red cluster on the bottom has mostly to do with heritage conservation, restoration and non-destructive testing.

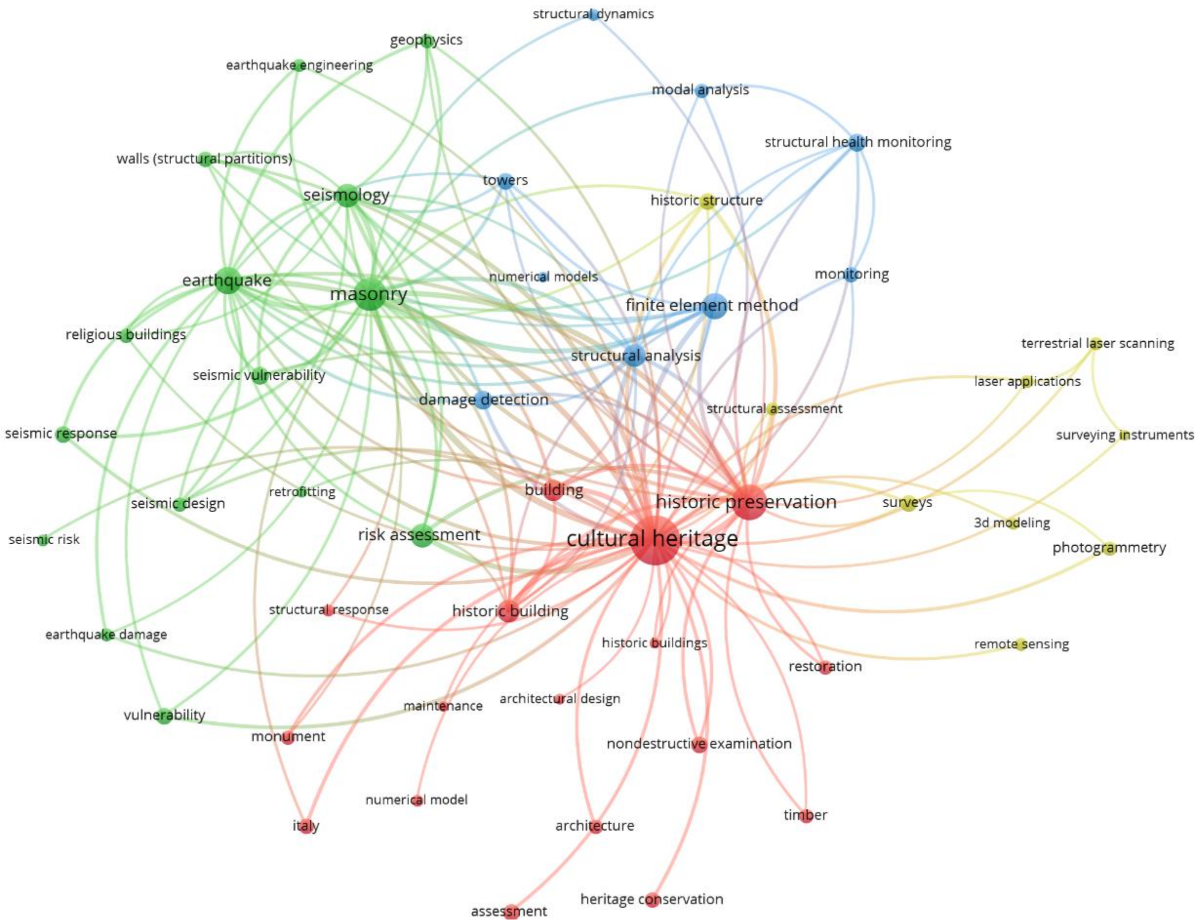


Figure 2: Bibliometric map of the co-occurrence of the top-50 keywords

Figure 3 presents the bibliometric map related to the co-authorship of the top countries in the field, based on the same database and search query from Scopus. Setting the minimum documents for a country equal to 5, the largest set of connected countries is found to be 36. From them, we select the top 30 countries. The map is presented with the minimum connection strength set equal to zero. In this map, the links between countries represent the frequency of co-authorship between the countries, while the size of each bubble (country) expresses the number of publications in the field by a specific country. In terms of the number of documents published in the field, the most active country is clearly Italy with 376 documents and 5438 citations, followed by the UK (44 and 1021), Spain (74 and 900), the US (53 and 747), Portugal (57 and 852) and Greece (40 and 571). Italy leads this map as the central country, which comes as no surprise, as it is a country with a very rich inventory of cultural heritage structures and historical buildings, while it is also an earthquake-prone area which has suffered many catastrophic earthquakes in the past and as a result researchers are particularly interested in the topic of vulnerability assessment of these structures [15].

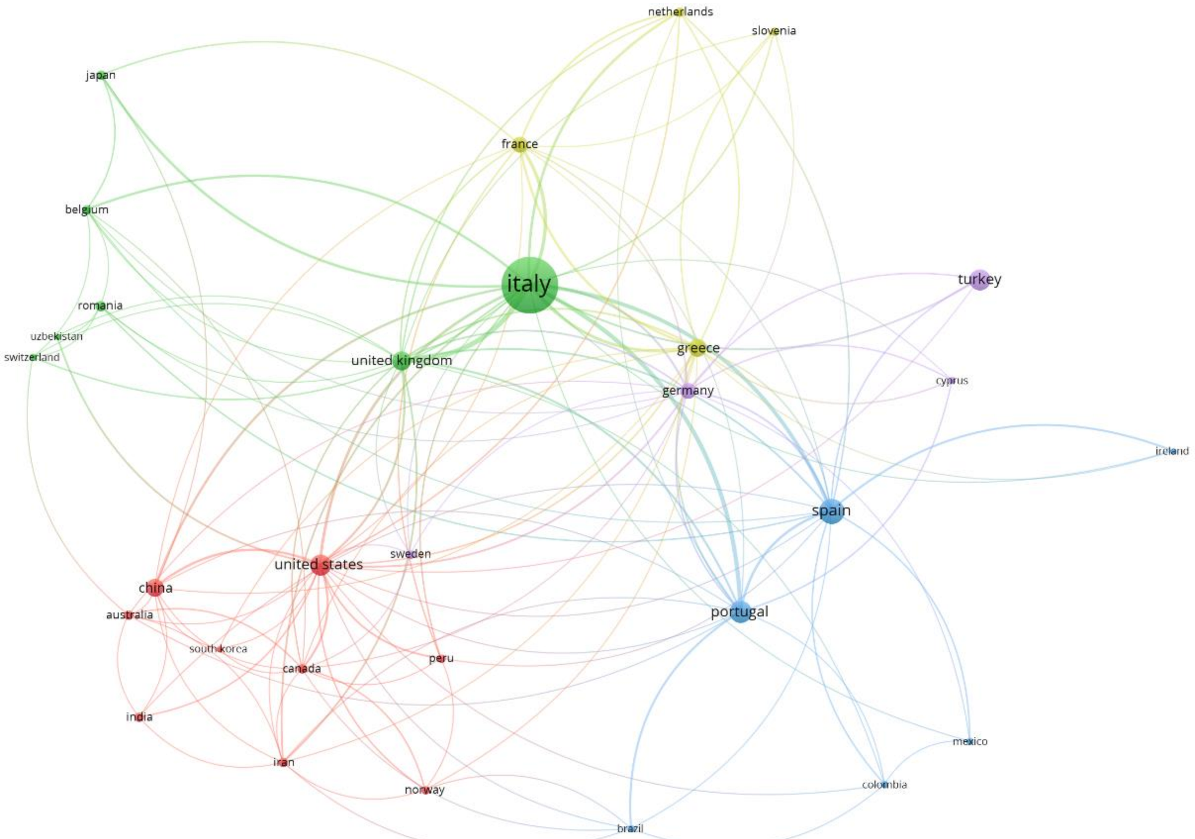


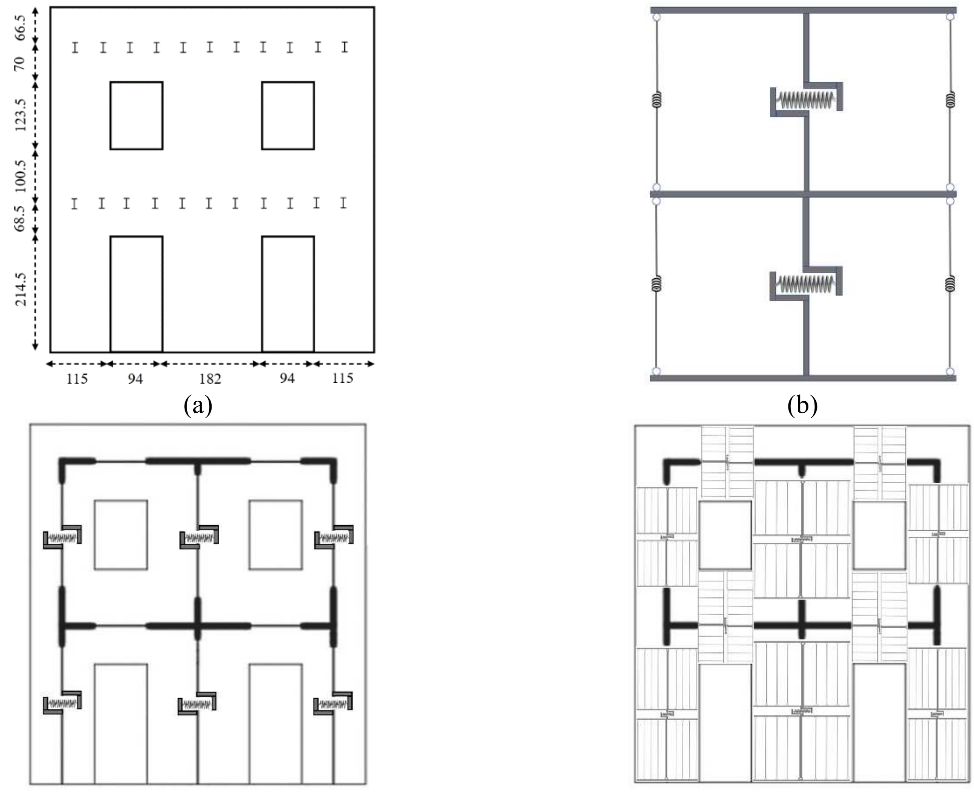
Figure 3: Bibliometric map of the co-authorship of the top-30 countries

2 SIMPLIFIED MODELING AND ANALYZING

Unreinforced masonry (URM) buildings are an inevitable structural typology in historic areas. URM is susceptible to earthquakes, and many URM buildings are located in high seismicity zones [16]. Therefore, efficient methodologies for seismic vulnerability assessment of URM buildings at a large scale are needed to improve the resiliency of historic areas. Although various simplified analytical methods have been proposed, simplified numerical methods should be utilized to decrease the uncertainties due to the development of supercomputers. The equivalent frame method is an efficient and robust method for nonlinear modeling of URM buildings. Different macroelements have been developed to simulate the URM structural components [17]. In the following section, three macroelements, including the unified model (UM) [18], composite spring model (CSM) [19], and the double modified macro vertical line element model (DM-MVLEM) are reviewed [19].

The UM is considered the most simplified method. Each URM wall in each story is modeled with a macroelement. The UM macroelement consists of two truss elements at the two ends of the wall with linear behavior and a nonlinear shear spring with a trilinear backbone in the middle. The initial in-plane stiffness of perforated URM walls can be calculated based on the equivalent height method (EHM) [20]. In CSM each pier can be modeled using a nonlinear shear spring with a specific backbone curve and ignoring the nonlinear behavior of spandrel elements [19].

DM-MVLEM is a new macroelement developed considering the axial-flexural interaction effects with a lower computational effort than the fiber elements to simulate piers and spandrels. DM-MVLEM consists of two modified MVLEM elements [19]. Although MVLEM elements are available in the Opensees framework library [21], they cannot be modeled in the horizontal direction to simulate the spandrel elements [22]. For this aim, the elements should be modeled using truss and rigid link elements. Figure 4 shows the Pavia door wall which is modeled using the UM, CSM, and DM-MVLEM methods.



(a) (b)

(c) (d)

Figure 4: (a) Geometry of the perforated two story URM wall tested at the University of Pavia (dimensions in cm), and the developed models based on (b) UM, (c) CSM, and (d) DM-MVLEM

No open-source graphical user interface (GUI) is available for simulating the nonlinear behavior of URM buildings in the versatile OpenSees software framework. In light of this, Hyperomet has been developed to bridge the gap between the nonlinear analysis of URM buildings and OpenSees users. The GUI has facilitated the modeling of URM buildings using UM and DM-MVLEM methods, and material properties calculators are also provided to reduce the possible human error. Furthermore, pushover and incremental dynamic analysis (IDA) [23] are also eased by providing a user-friendly GUI to input the parameters and derive the corresponding curves.

3 DETAILED MODELING AND ANALYZING

The CH sites need to be numerically modeled to have an accurate structural assessment by considering geometry loss and material degradations. This part presents the procedure and challenges in the detailed modeling of CH pilot sites in the Hyperion project.

3.1 Analysis of building materials and deterioration processes

One of the challenges in assessing the material properties of the heritage building is the fact that destructive tests are not permitted on CH sites. Heritage buildings and structures in the pilot cities of the Hyperion project were constructed with various materials during different periods and suffered different levels of material degradation and damage. However, stone masonry is a dominant construction material. Within the Hyperion project, different rock types were analyzed from a physical and mechanical point of view. The velocities of elastic-mechanical characteristics and structural anisotropy of stones were measured by non-destructive tests using ultrasonic waves. By studying the history of the used material, some experimental tests were also performed on a similar type of stone to examine its mechanical properties on each site. In addition to these activities, the other material properties needed for finite element (FE) simulation were extracted from the literature.

3.2 3D laser scanning and geometry losses

Geometric documentation is the foremost step toward developing digital twins of CH assets that can be done using 3D laser scanners [24]. 3D laser scanners that produce point clouds can be used to visualize the exact geometry. The scanning accuracy can be increased to improve the reliability of the 3D structural model [25, 26]. Therefore, 3D laser scanning was conducted to precisely determine the geometry and surface of the structures and also provide the point clouds of CH buildings. The generated point clouds data can be synchronized to develop digital twin modeling.

3.3 Digital twin modeling

The following steps were taken into account to process the collected data from the laser scanner. The dense point clouds were first generated using an Image Based Modeling (IBM) software program. Then, to decrease the unavoidable scanner error and to produce a more precise 3D model, the scanned point clouds were registered, georeferenced, and subjected to additional processing. The final point cloud for selected CH buildings was created using the dense point clouds from the IBM software to fill in any remaining gaps in the scans. The triangulated irregular network (TIN) approach for the representation was used to turn each point object into a polygon object. More details of the digital twin modeling and 3D geometric documentation are presented in [24].

3.4 Numerical modeling and analysis

Various methodologies have been developed for 3D FE modeling of structures using the BIM model [27]. In this study a semi-automatic procedure is presented [24]. After developing the BIM model of the buildings, by using the CAD exchanger program, the industry foundation classes (IFC) format of the 3D model was converted to the standard for the exchange of product model data (STEP) in order to create the detailed 3D FEM of the structure. The details of this process are described in [28]. The shapes, surfaces, edges, potential discontinuities, etc., that had been imported were fixed using cleaning and optimization techniques.

After developing the 3D FEM geometry, the initial mechanical properties of the material need to be assigned to the model. In addition, modal analysis should be performed to investigate the dynamic characteristics of the structure. The model updating process to calibrate the actual structure's behavior is called the calibration process [29]. It should be taken into account that destructive tests are not usually permitted on CH structures; therefore, running this process is essential for CH assets to determine the actual characteristics. This structural FEM was updated using integrated accelerometer sensors' data. It should be highlighted that the calibration of the models was based on the natural frequency values and the corresponding mode shapes of the actual structure.

3.5 Case studies

The process mentioned above was conducted in the selected CH pilot cases. The selected case studies are the Slottsfjell Tower in Norway and the Roman bridge in Greece.

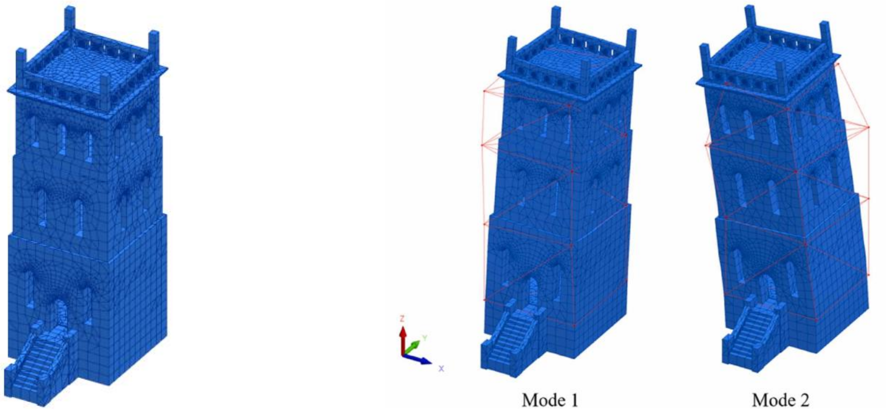
Slottsfjell Tower

In the southeast of Norway, in the city of Tønsberg, lies the Slottsfjell tower, which is located atop a hill not far from the city center, see Figure 5(a) [30]. Due to the area's association with the Viking Age, the Slottsfjell tower has a very high historical importance to both the city of Tønsberg and the county of Vestfold and Telemark in Norway. The tower was built in 1888, and the tønsbergite stone, a monzonite rock type, was used as the building material [31]. A GLS-2000 series 3D laser scanner has been used to complete a total of 20 scans of the tower's interior and exterior. The data were then synced in Recap Pro Autodesk software [32], as shown in Figure 5(b), then imported into Revit Autodesk software [33] to create the drawing, as shown in Figure 5(c).


(a) (b) (c)

Figure 5: (a) Slottsfjell Tower in Norway, (b) Point clouds synchronization in Recap Pro software, and (c) Imported point clouds to Revit for 3D drawing

The developed FE model is presented in Figure 6(a). Ambient vibration testing has been done on the tower using seven accelerometer sensors. Operational modal analysis was performed, and the results revealed the natural frequency values and mode shapes of the structure. FEMtools software package [34] was utilized to calibrate the models based on the tests results. Figure 6 presents the calibrated models based on the first and the second natural modes with modal assurance criterion (MAC) values of 64.9% and 84%, respectively.

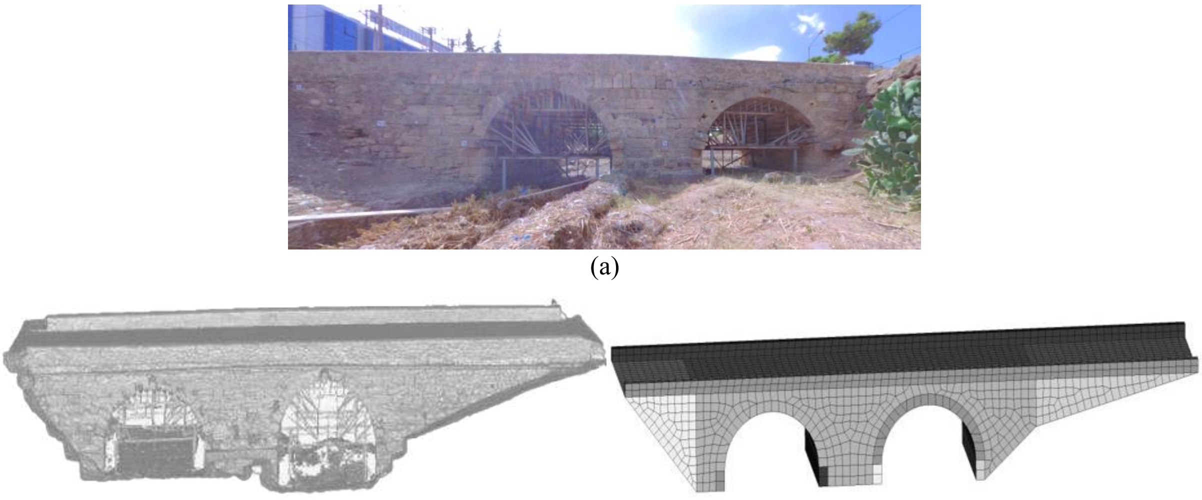


(a) (b)

Figure 6: (a) 3D finite element mesh of the tower (b) Calibrated models based on the results of the first and the second modes of vibrations

Roman Bridge

The Roman bridge, shown in Figure 7(a), was constructed on Rhodes Island in Greece, across the Rhodini stream before the Mediterranean Sea at the city’s main entrance. The arch and spandrel components of the bridge have a thickness of 0.6 m, 38.85 m long, and 8.4 m wide. The bridge is 5.2 m in height. The stone masonry bridge is dated back to the Roman era. In order to generate the 3D dense point cloud for the Roman bridge, 271 ground digital images and more than 2500 aerial drone images were taken and processed using IBM software. Additionally, 24 scans were carried out with 3D laser scanners to give the missing 3D dense point clouds generated from digital images [35]. Then the 3D models were imported to the DIANA FEA software [36]; The shapes, surfaces, and discontinuities were fixed using cleaning tolos [24]. The “sfougaria Stone” used to construct the bridge has a compressive strength of 9 MPa [37]. Additionally, reduced compressive strength of mortar is assumed by selecting a soft mortar type [38]. The backfill soil properties are based on [39]. Figures 7(b) and (c) show the developed 3D light model and FE model of the Roman bridge, respectively. The caliberation process of the bridge based on the ambient vibration testing is under development but preliminary seismic analyses were carried out.

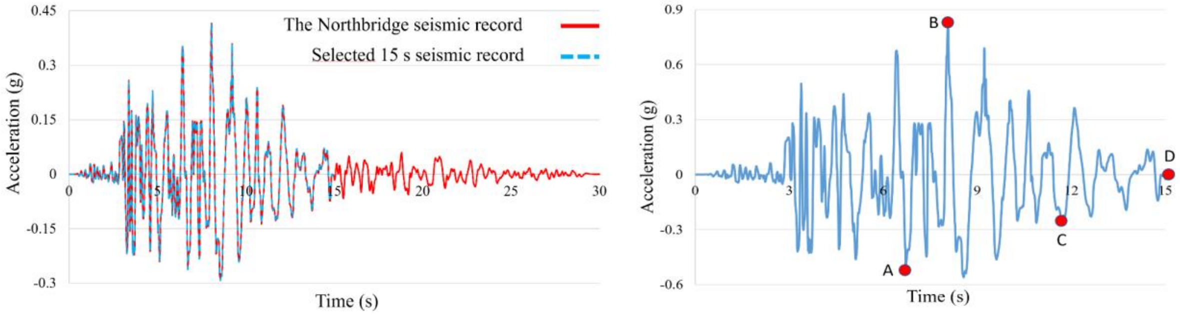

(a)

(b) (c)

Figure 7: (a) Roman bridge in Greece, (b) 3D light model, and (c) Finite element model

For modeling the bridge a contact interface element (CIE) has been utilized to simulate the connection between the backfill soil and masonry media. A very high value was considered for the normal and shear stiffness to avoid intersectition of two media [40]. Furthermore, no tension stiffness was considered for the CIE which follows the Coulomb friction model in such a way that the two media can carry shear stresses up to a certain magnitude before sliding across each other [41]. The cohesion value was considered zero and the friction angle was assumed to be 20 degrees [40].

In order to investigate the effect of the CIE, the model without CIE was also developed and nonlinear dynamic analysis was performed by applying a seismic record in the transverse direction. Note that the total number of elements of the model with CIE is 17% more than the one of the model without CIE. Rigid connection between two media was taken into account for the model without CIE.

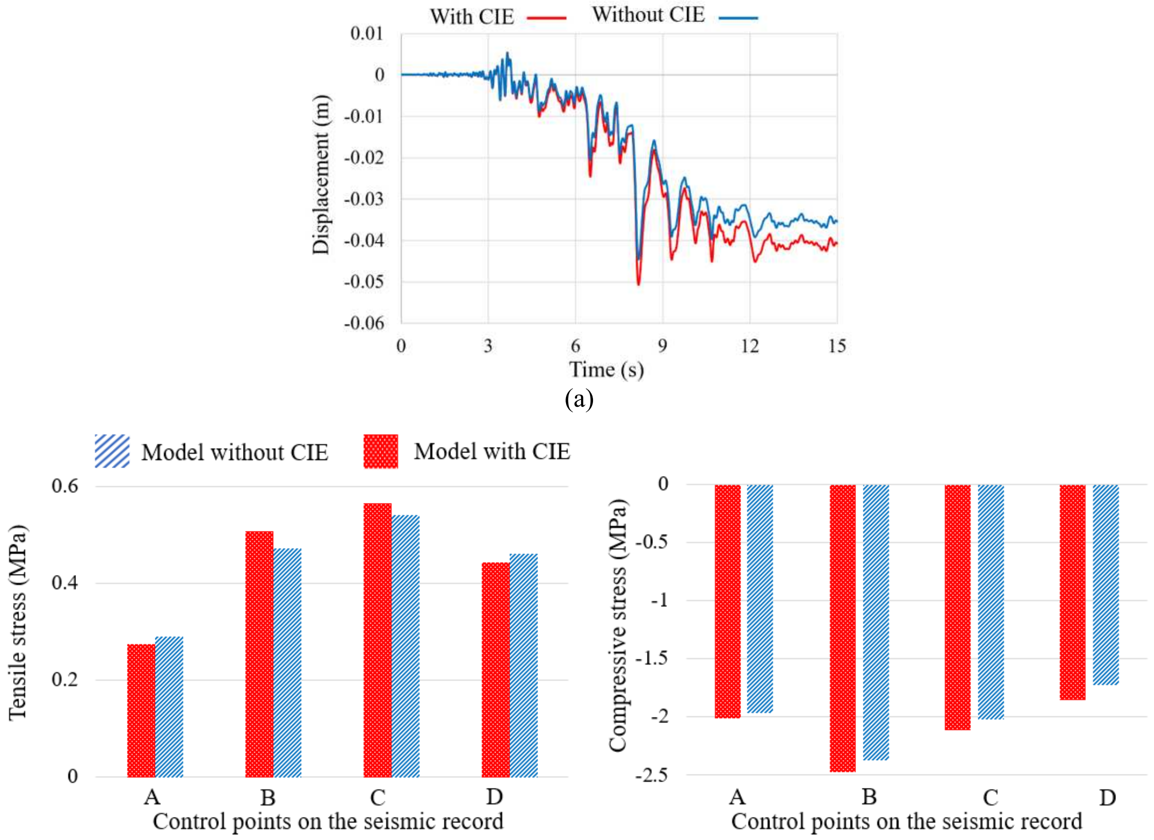


(a) (b)

Figure 8: (a) The Northbridge seismic record and (b) normalized selected 15 s acceleration time history for performing the analysis of the bridge as well as the control points

The first 15 seconds of the Northbridge seismic record (see Figure 8(a)) with an intensity of 6.7 M, a peak ground acceleration (PGA) value of 4.08 m/s^2 was selected as it is shown in the Figure, from the PEER strong ground motion database [42]. Acceleration-time history was normalized to the PGA of 0.8g where g is the gravitational acceleration and four control points with PGAs of 0.502*g*, 0.8*g*, 0.243*g*, and 0.026*g* at time 6.72 s, 8.06 s, 11.69 s, and 15 s respectively, were chosen to facilitate the comparative study on the results, as depicted in Figure 8(b).

Based on the displacement response spectrum of the crown control point in the transverse direction, plotted in Figure 9(a), considerable differences between the responses can be detected especially at the final part of the analysis. The model with CIE has larger absolute displacements, providing more conservative results, compared to the model without the CIE. Furthermore, higher values for the stress in elements of the model with CIE can be detected based on Figure 9(b) and (c). Therefore, conservative results in terms of stress and displacement values can be concluded from the model with CIE compared to the model without CIE.



(a)

(b) (c)

Figure 9: (a) Displacement response spectrum of the crown control point in the transverse direction (b) maximum tensile and (c) maximum compressive in-plane principal components of the Cauchy effective stresses

4 CONCLUSIONS

This paper presents the used methodology of the Hyperion project to take advantage of existing tools and services together with novel technologies to deliver an integrated vulnerability assessment platform for improving the resiliency of historic areas. Furthermore, the used research framework for the structural vulnerability assessment module in the Hyperion project is highlighted by presenting the application of the module in some of the case studies of the ongoing project.

Two levels of modeling have been proposed: simplified and detailed modeling. The simplified modeling can be used as an acceptable method for assessing the URM buildings. Hyperomet, a graphical software, has been developed to bridge the gap between the nonlinear analysis of URM buildings and OpenSees users. In addition to the simplified model for building, the procedure and challenges in the detailed modeling of the structures in the CH pilot sites are discussed. In the developed framework in Hyperion, the CH structures i.e., Roman Bridges and Slottsfjell Tower, were accurately modeled using 3D laser scanners, imported to the FE software, and updated using sensor data. The material properties, historical data for the structures, the effect of previous restoration processes, and the environmental/physical characteristics of the surrounding environment were considered in the developed framework.

Moreover, the results revealed the effect of modeling CIE on the nonlinear behavior of the masonry arch bridge in terms of displacement and stress values and that modeling the CIE is necessary to have results on the safe side which is close to the actual behavior of the structure.

ACKNOWLEDGMENTS

This work is a part of the HYPERION project. HYPERION has received funding from the European Union’s Framework Programme for Research and Innovation (Horizon 2020) under grant agreement No 821054. The contents of this publication are the sole responsibility of Oslo Metropolitan University (Work Package 5, Task 2) and do not necessarily reflect the opinion of the European Union.

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