ONGOING STUDIES ON EPHESUS ANCIENT THEATRE WITHIN THE SCOPE OF SAFEGUARDING CULTURAL HERITAGE THROUGH TECHNICAL AND ORGANIZATIONAL RESOURCES MANAGEMENT (STORM) PROJECT

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ABSTRACT

Safeguarding Cultural Heritage through Technical and Organizational Resources Management (STORM) is a collaborative project which is funded by the Horizon 2020, the European Union (EU) framework programme for research and innovation. The main objective of this project to provide critical decision making tools to all European Cultural Heritage stakeholders charged to face climate change and natural hazards. The project improves existing processes related to three identified areas: Prevention, Intervention and Policies, planning and processes. An important result of STORM will be a cooperation platform for collaboratively collecting and enhancing knowledge, processes and methodologies on sustainable and effective safeguarding and management of account environmental and anthropogenic risks, and of using Complex Events processing. Results will be tested in relevant case studies in five different countries: Italy, Greece, UK, Portugal and Turkey.

This study mainly focuses on Ephesus Ancient Theatre which is one of the case sites in STORM project and presents the current status and the ongoing studies to the theatre within the scope of STORM project. In the first year period, three dimensional (3D) laser scanning technology and computational models of Ephesus Ancient Theatre has been developed from high definition laser scanning (HDS) data, namely the Point Cloud (PC) data. Then, a seismic toolset which consists of a 3D seismic sensor (GEOSIG force balance accelerometer), 24 bit A/D converter, a modem, a GPS for synchronizing and a dedicated GSM line for online transfer of the acquired data, has been located at the ground and top level of the theatre and the seismological data has been collected by using the seismic toolset. In the second step, a 3D computational model using the finite element method has been created from the PC data and structural analyses were conducted to investigate the theatre vulnerability by using collected seismic data from the site.

Keywords: STORM Project, Ephesus Ancient Theatre, Historical Structures, Point Cloud, Ambient Vibration Test, Finite Element Analysis

1. INTRODUCTION
Cultural heritage has been a guide, pulling millions of people every year to archeological sites, churches, fortress, monuments and museums etc. For this reason, protection of European Cultural Heritage is of the top priority for policy makers, the institutions in charge of protecting those, tourists, and educators at local and national levels as well. Europe's cultural heritage is being lost at an alarming rate, not only due to natural decay and human impacts but frequently also as a result of environmental changes, climatic conditions or natural hazards. This non-renewable resource, in all its diverse physical forms, needs safeguarding for future generations. Cultural heritage, an important component of individual and collective identity, also fuels tourism in Europe, a significant economic sector on which many communities depend. Heritage has effects in other economic sectors in line with the EU policy statement towards an integrated approach to Cultural Heritage realization of the value of the EU heritage (UNESCO, 2013). However, the increased frequency and intensity of extreme weather events together with risks associated to natural hazards present an added challenge for the sustainable management and conservation of cultural heritage in Europe, calling for improved adaptation and mitigation strategies in this vulnerable sector.

In the last four decades, many studies and research have carried out works on preventive strategies aimed at protecting the EU cultural buildings and sites (English Heritage, 1998; EMERIC I, 2006; PROHYTEC, 2008; PERPETUATE, 2012). Although different in their nature and specific objectives, all these projects had prevention and public policies at their core and where (unstructured) support is given by existing disaster procedures. But none of them has focused on the following step: What to do next? To put such valuable information in a practical and useful set of tools for heritage safeguarding and taking it to the next level is where the STORM project differs from all others. It will create a new innovative set of processes and tools, useful for heritage sites, organizations, governments and citizens across Europe.

STORM plans to introduce an integrated framework and a platform providing tools and services both at macro level to give a global view of the entire value chain and at specific level to promote the improvement of specific processes for protection and prevention. A novelty of STORM is to promote both views in the same framework; STORM will allow users to address each single issue within a simple process supported by the related technology. The STORM integrated framework will manage those modules to give a view that can be drilled down to give stakeholders the possibility to improve it. To support this, STORM will introduce a system to identify existing processes adding critical relationship management automation to improve the process itself. STORM aims to provide critical decision making tools to all European Cultural Heritage stakeholders affected by climate change and natural hazards. This will be a new innovative capability to improve existing processes related to three identified areas: Prevention, Intervention and Policies, planning and processes (Figure 1).

![Figure 1. Overview of the three areas in which STORM will focus on](image)

The proposal of STORM project should aim to develop eco-innovative solutions to help mitigate the effects of climate change and natural hazards on cultural heritage sites, structures and artefacts taking
into account the values they hold for people and respecting their historic and cultural integrity. Effective adaptation strategies, systems and technologies are needed for better risk management of vulnerable heritage materials and for mitigating damage to cultural heritage assets. Proposals may include case studies and address any research gaps or barriers needed to respond to this challenge, including aspects relating to innovative environmental assessment methodologies, integrated monitoring technologies and systems, improved non-invasive and non-destructive methods of surveying and diagnosis including wide area surveillance, cost-effective conservation and restoration techniques, risk management, disaster prevention and quick damage assessment when catastrophes occur. The STORM action will encompass the following test sites: the Diocletian Baths, Rome, Italy; Mellor Heritage site, Manchester, UK; Roman Ruins of Tróia, Portugal; Historical Centre of Rethymno, Crete, Greece; and Ephesus, Anatolia, Turkey; as well as one other relevant site run by an associated partner Pompei, Italy. The STORM project also counts on the support of ICCROM, an intergovernmental organization dedicated to the conservation of Cultural Heritage founded by UNESCO. The STORM methodology will address the whole ecosystem including design, prevention, implementation, intervention, as well influence policies and processes at all levels (individual, private and government). The final case of each cycle is the triggering point of new cycles of improvements and enhancements at policy and tools level. Ephesus Great Theater, as a selected pilot site will focus on, and all current situation (hazard and threats) and selected monitoring systems will be explained in this paper.

2. PERFORMANCE BASED ASSESSMENT OF HISTORICAL STRUCTURES

Performance based assessment (PBA) is a new stream line of research on heritage buildings. In general, the subject of PBA of historical structures (including mosques, churches, monuments, towers, aqua structures, etc) is both significant and challenging. Evaluation of seismic performance for existing historical structures has been mentioned in many standards (ASCE 41, 2006; EC8-3, 2005; PERPETUATE, 2012). Seismic evaluation of these structures is usually carried out by linear or nonlinear procedures. ASCE 41 (2006) is applicable to all types of buildings and structural materials (concrete, steel or masonry) for seismic rehabilitation, i.e. it is not solely intended to be used for historical structures. ASCE 41 (2006) requires each structural component be classified as primary or secondary prior to selecting component acceptance criteria, whereas for the analyses, the members are classified as either having force-controlled or deformation-controlled failure modes. The acceptance criteria are defined in terms of drift ratio corresponding to a predefined performance level. EC8-3 (2005) is mainly intended to provide seismic evaluation procedures for existing buildings and for the design of retrofitting projects from conceptual design to structural analysis. A recently completed European Research Project, PERPETUATE has developed guidelines on how to seismically assess heritage buildings based on performance-based evaluation principles. PERPETUATE (2012) has been specifically developed for seismic evaluation and retrofitting of cultural heritage buildings using the performance-based assessment methodology as proposed in both ASCE 41 (2006) and EC8-3 (2005). PERPETUATE (2012) requires a nonlinear static analysis resulting in a pushover curve (base shear vs. lateral displacement curve) on which four damage levels are defined, namely, slight damage (SD), moderate damage (MD), heavy damage (HD), and complete damage (CD). Modeling and verification requires PBA of the structure. PBA suggests pushover analysis be used until a target displacement is reached according to the selected performance level (PL). Engineering demand parameter is the lateral displacement for pushover analysis. When nonlinear dynamic analyses are used, incremental dynamic analysis curve corresponding to lateral force is plotted against the lateral displacement. Incremental dynamic analysis is carried out scaling peak ground acceleration of the selected strong earthquake ground motions records. PLs are classified into three different groups; namely, use and human life, building conservation and artistic assets conservation. The seismic performance of the heritage building is then defined from high performance level to low performance level as operational, immediate occupancy and life safety for use and human life PL; no damage, damage limitation, significant but restorable damage and near collapse for building conservation PL; near integrity, damaged but with low aesthetic impact, severely damaged but still restorable, loss prevention for artistic assets PL. A Simplified seismic hazard assessment method is illustrated in Figure 2.
3. EPHESUS GREAT THEATRE

3.1 Historical Background

Ephesus, once the most important trade center in the Western Anatolia, is one of the oldest settlements in Turkey. The ancient city of Ephesus is situated in Selçuk district, İzmir Province in Turkey. This unique city is also called Ephesus Ruins at the present time. It is considered as a valuable ancient city not only in Turkey but also in the world due to its natural, historical, and archaeological assets. Ephesus has been located on the historical trade roads and it has been conquered by many ancient civilizations throughout its history. Therefore, over the centuries, ancient Ephesus City has imposed many different cultural effects and architectural styles (Figure 3).

This historical city host many different structures including theatre, library, baths, walls, and houses. The ancient city is visited by 2 million visitors roughly every year. This magnificent city has been added to UNESCO’s World Heritage List in 2015 (UNESCO, 2015).

Ancient Ephesus City has a historical and cultural background for nearly 8,000 years. Therefore, there are many historical monuments inherited from different civilizations. Thus, it is very rich in terms of the cultural and historical heritages. One of these valuable historical structures is Ephesus Great Theatre which is situated in the city center.
Ephesus Great Theatre is the biggest structure in the ancient city and it was first constructed in the Hellenistic Period, in the third century BC during the reign of Lysimachos, was enlarged and formed its current style during the Roman Period. This open-air theatre was initially used for drama, but during later Roman times gladiatorial combats were also held on its stage. Historical records indicate that the theatre had a seating capacity of 20-25,000. The cavea (seats) has sixty six rows of seats, divided by two diazoma (walkway between seats) into three horizontal sections. There are three sections of seats. In the lower section, the Emperor's Box was found. The seats with backs were reserved for important people. The audience entered from the upper cavea. The stage building is three-storied and 18 meters high. The facade facing the audience was ornamented with relieves columns with niches, windows and statues. There are five doors opening to the orchestra area, the middle one of which is wider than the rest. The structure was constructed with stone blocks, marbles and backfill materials, which are composed of rubble and mortar. The integrity of the Ephesus Great theatre remains is relatively high. Theatre is the largest and best preserved ancient building in Ephesus. The serial components contain sites which demonstrate the long settlement history of the place, each making a significant contribution to the overall Outstanding Universal Value. Together the components include all elements necessary to express Outstanding Universal Value and the property is of adequate size to ensure the complete representation of the features and processes which convey the property’s significance. Archaeological works has been going on at Ephesus for more than a century largely by Austrian Archaeological Institute (UNESCO, 2015). The permanent excavation team also includes, in addition to archaeologists, an extensive cooperation of scientists from complementary disciplines. The excavations are carried out by the Austrian Archaeological Association with the involvement of national and international research facilities and on the basis of an annually renewable permit by the Department of Antiquities of the Republic of Turkey (UNESCO, 2015).

3.2 Structural Damage

During the course of time, Ephesus Great Theatre has suffered some damage and been subject to the risk of collapse due to the natural disasters or human interventions. The skene, especially, has been substantially deformed in terms of its structural integrity and stability. The structure has only been renovated several times by using different materials. During the structure's life, construction materials have been deteriorated and have lost their qualities due to many reasons such as environmental conditions and natural disasters. Earthquake, climate change and human interventions on the historical site are among major problems of the city. Damage has observed on the structure as cracks, fractures, fissures, degradations, separation and decay of structural materials. In fact, structural damage may occur due to several factors such as the soil

Figure 3. Location of the Ancient Ephesus City
settlement, temperature variations, excessive loads, and seismic effects. The northern and southern parts of the cavea partially collapsed while the scene section totally collapsed. Various separations have been appeared between structural materials in the entrance section. Spalling and flaking have also been visible in the springing and the voussoirs of parados sections. Additional structural cracks and fractures have been observed at the facades and on top of the structure. The mortar between rubble stone units was partially eroded. The loss of this binding material caused the decrease of structural resistance of the walls (Figure 4).

4. HAZARD ASSESSMENT

Risk assessment procedure that has been envisaged in the lights of the current risk assessment standards and guidelines is comprised of following components: identification and analysis of natural hazards and climate change threats; assessing the value of heritage properties exposed to the hazards; analyzing the vulnerability of the heritage properties to the identified hazards; and identifying and analyzing the risks. Five primary natural hazards and threats have been identified for Ephesus Great Theatre based on available literature as well as climate projection and analyses that have been performed within the project. Hazards/threats with high level of significance (As Low As Reasonably Practicable (ALARP) Principle, AEMC 2015, 39) are (1) earthquake (2) wildfire and with medium level of significance (3) cold waves/ heat waves (4) landslides (5) biological infestation. Exceptional level of value of the Ephesus Great theatre has been portrayed one more time in following exposure assessment component.

5. SEISMIC DATA COLLECTION

The seismic toolset consists of a three component seismic sensor (GeoSIG force balance accelerometer), 24 bit A/D converter, a modem, a GPS for synchronizing and a dedicated GSM line for online transfer of the acquired data. The seismological data have been collected at the ground and top levels (Figure 5). A specially developed data acquisition interface software is used for the pre-processing and online monitoring of the seismic data. A snap shot of the acquired data and their location are shown in Figure 6. Since the installation of seismic stations (21th April, 2017), nearly 20 seismic events with magnitudes varying from M=3 to M=5.2, have been recorded. The earthquake response spectra of the recorded
ground motions have been calculated and used for the numerical simulation of the structural response. Initially, the numerical model of the Ephesus Theatre has been generated to predict the response of the structure to recorded ground motions. The material and geometric properties of the structure will be determined and updated considering the data provided from the geophysical measurements. The acquired seismic data will then be used as an input motion to estimate the response of the structure its vulnerable parts (side walls). In addition, the seismic data can be used to understand the damage mechanisms of the structure, early detection of structural damage and to warn the local authorities about the extent of the damage to help develop proper disaster management and planning procedures.

![Figure 5. Structural Monitoring for Ephesus Pilot Site](image)

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![Figure 6.(left) An example of the online seismic data (seismic noise) provided from the Ephesus station (right) The epicentral locations of the nearby events and recorded seismic data at Ephesus. Inlet figure shows the earthquake data recorded during the M=4.2 event in Kuşadası.](image)

6. NUMERICAL MODELS

6.1 Laser Scanning and Computational Modelling

It is important to understand the structural behavior of historical structures and evaluate their performance for the development of prevention and intervention techniques. The simplest solution for determining the structural behavior is to use computer models and numerical analyses. However, the preparation of the most convenient computational model of the structure has always been challenging. Numerical models are expected to accurately reflect the real structure in order to obtain realistic
numerical results. The accuracy of the three-dimensional (3D) models of structures is ensured by the use of high definition laser scanning (HDS) technology. This technology can provide an effective and economical solution for 3D modelling from small to large structures with different geometrical configurations and complexities. The laser scanning technology is extensively merging into many fields. The technology enables users to capture many points from the subject structure with high accuracy. In particular, the HDS technology provides both qualitative and quantitative information about a complex object which is discretized as a cloud of millions or billions of points in space. The as-found geometry of Ephesus Great Theatre was captured by means of the HDS using the laser point stations (Figure 7 and Figure 8).

![Figure 7. Point Cloud Data of Ephesus Great Theatre](image)

![Figure 8. Point Cloud Data of (a) North Side, (b) South Side of the Theatre](image)

6.2 Noise Reduction Process for Point Cloud Data

Noise can be described as the unwanted and unpleasant points on the PC data. These unwanted points can cause errors during analysis when it is too loud. For this reason, the noises must first be removed or reduced from the PC data. In this study, the noise control system was used to eliminate the unwanted and desired points. After the PC was picked up, the inaccurate points such as visitors, trees, birds and plants defined as noise were removed and a filtered PC data was generated (Figure 9).
7. FINITE ELEMENT ANALYSIS

The determination of the seismic behavior of historical structures is difficult to obtain by the use of common engineering methods. Masonry structures are composed of sub units that have different shapes and materials, which have different properties. In this case, the finite element analyses (FEA) is the most preferred method for masonry structures. Thus, the estimation of static and dynamic behavior of historical structures with finite element (FE) method has been one of the most preferred methods recently. Therefore, three-dimensional (3-D) FE models have been developed based on the structural state and the geometrical constraints of the structure. FE analyses program, ANSYS Workbench, has been used to analyze the north side of the theatre with SOLID186 elements, which has 20 nodes and three degrees of freedom per node (Figure 10).

The dynamic analysis was performed on the numerical model. In this study, a ground motions record, which is one of the strongest earthquakes in Ephesus was taken into consideration. The acceleration records of the earthquake at Ephesus Station are presented on Figure 11. The obtained results were shown in Figure 12-14.

In this study, the response of the structure to weak ground motions has been considered. In order to compare the recorded and calculated responses of the structure, a continuum model was used to represent the behavior of the overall system in weak motion. It is assumed that the structure behaves in the stick mode in low vibration amplitudes. In case of strong ground motion, the possible failure modes of the structure should be considered in such cases (strong ground motion simulations). Therefore, the structure will be modelled by discrete elements to investigate sliding and rocking behaviors of stone blocks.
Figure 10. (a) Figure Meshed model of the structure, (b) Solid Model of the North Side, (c) Simplified Numerical Model of the North Side

Figure 11. Acceleration records of the earthquake at Ephesus Station

Figure 12. Total Deformation of the Structure under the Seismic Load
8. CONCLUSIONS

The vulnerability of the masonry structures to earthquakes and seismic effects has been among the most common reasons of the collapse of masonry structures. Therefore, it is crucial to determine performance-based seismic performance of masonry structures located in active seismic zones. Therefore, the subject of performance-based assessment of historical structures has gained great attention for the last few decades.

STORM provides critical decision making tools to all European Cultural Heritage stakeholders charged to face climate change and natural hazards. The project improves existing processes related to three identified areas: Prevention, Intervention and Policies, planning and processes. STORM project plans to introduce an integrated framework and a platform providing tools and services both at macro level to give a global view of the entire value chain and at specific level to promote the improvement of specific processes for protection and prevention. STORM integrated framework will manage those modules to give a view that can be drilled down to give stakeholders the possibility to improve it. To support this, STORM will introduce a system to identify existing processes adding critical relationship management automation to improve the process itself. STORM aims to provide critical decision making tools to all European Cultural Heritage stakeholders affected by climate change and natural hazards.

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a 3D seismic sensor (GEOSIG force balance accelerometer), 24 bit A/D converter, a modem, a GPS for synchronizing and a dedicated GSM line for online transfer of the acquired data, was located at the ground and top levels of the theatre and the seismological data were collected by using the seismic toolset. In the second step, a 3D computational model using the finite element method was created from the PC data and structural analyses were conducted to investigate the theatre vulnerability by using collected seismic data from the site.

9. ACKNOWLEDGMENTS

The research carried out in this study has received funding from the European Community's Horizon 2020 Programme under grant agreement no 700191 (http://www.storm-project.eu/).

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