International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 5 (May 2025), PP 168-176

Holistic Risk Protection of Cultural Heritage Buildings against Natural Hazards

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Abstract: *Cultural heritage assets consist part of the history and the identity of civilizations. The prevalent method of construction up to the early 20th century for cultural heritage (CH) buildings was unreinforced masonry (URM) structures.These structures are particularly exposed to seismic and climate change risk, because they were conceived according to empirical rules, considering only gravitational loads. The devastating impacts of natural hazards due to climate change and seismic events of the last century, especially in the Mediterranean region with earthquake prone countries, proved that physical threatens are directly and closely related with the vulnerability of the building exposure appraising major social and economic losses. UNESCO, within the Organization of Protection of the World Cultural and Natural Heritage recognized many European towns as World Heritage Sites, encouraging the protection of cultural heritage around the world. Additionally, the EU Internal Security Strategy aims at increasing Europe's resilience to crises and disasters.The mitigation of structural vulnerability and the adequate management of the provoking risk aim to maintain and strengthen the CH buildings resilience with safety, economic, social and historical benefits. The old town of Xanthi in Greece has been selected as case study, an area constituted of traditional cultural heritage buildings with vernacular architecture recognizing the threat of three types of physical hazards: earthquake, flood and wildfire risk.*

Date of Submission: 10-05-2025 Date of acceptance: 20-05-2025

I. Introduction

Natural hazards are a threat multiplier for cultural heritage sites, and have the potential to substantially affect the safety, the lifespan and the functionality of European cultural heritage (CH) buildings and subsequently have impacts on the normality and the quality of life. Physical catastrophes to cultural heritage assets appraise major social, economic and historical losses. The preservation and valorization of historical buildings for mitigating the structural vulnerability performance and strengthening the risk protection and resilience of CH buildings is urgent.

Scientists and stakeholders tackle the problem of natural hazards – impact on historical traditional buildings. Their main strategic scope is to deliver a holistic risk analysis approach, integrating existing knowledge, providing innovative techniques and instructions for assessing the structural vulnerability performance, mitigating and managing the natural induced risk and strengthening in sequence the risk protection and resilience of European CH buildings to future hazards. The appropriate steps in order to fulfil this purposeare the use of: a) validated methods/ tools to assess natural hazards impacts, vulnerabilities, and risks and to prioritize management actions; b) set of indicators to assess the performance of adaptation options and to facilitate decision making process; c) a decision support framework for CH adaptation and resilience. In the current paper, the old town of Xanthi in Greece has been selected as case study, an area constituted of traditional cultural heritage buildings with vernacular architecture recognizing for the holistic risk protection against the threat of three types of physical hazards: earthquake, flood and wildfire risk.The suggested study focuses on a common building typology which represents a wide statistical sample of the building inventory, the existing traditional Unreinforced Masonry buildings (URM). The old town of Xanthi is well known as an area of special and historic Interest, with many characterized as listed buildings, by the Ministry of Culture or/and the Ministry of Eastern Macedonia and Thrace in North Greece, with different grade of preservation (Fig. 1).

Figure 1: Cultural Heritage URM buildings with vernacular architecture located in Xanthi (N. Greece).

II. Analysis Methods for Unreinforced Masonry Heritage Buildings – State of the Art

Historic Cultural Heritage buildings of the 19th and 20th Century are a significant part of the built environment of European cities and require special attention due to their intrinsic historical and cultural value. Load-bearing masonry buildings (URM) of this class are a living part of history, identity and civilization and as such, they are protected by international treaties and organizations. Over the several decades of their lifetime, most of those buildings have suffered from structural damages of different severity level, especially those of earthquake prone countries of the Mediterranean basin with high seismicity (Pantazopoulou, 2013). In many cases, they remain operational and in good condition (Fig. 1). An increasing interest for their rehabilitation has recently emerged from entities, agencies and authorities which, have the legal right and duty to preserve, maintain, manage and restore CH inventory with target to contribute to public safety and urban systems resilience. Hence, there is a strong need for research with focus on improving risk protection and mitigation strategies associated to CH sector. The main difficulties encountered during assessment are the complications owing to the mixed type of structural system used in the past (combination of timber or iron floors and roof, massive load bearing walls) and the spatial mass distribution in the vertical elements, as compared to conventional buildings with lumped masses. Contrary to contemporary structures, where the horizontal structural elements provide adequate diaphragm action to horizontal displacement, in URM buildings lack of continuity at the perimeter connection between the rather compliant timber floors with the load bearing walls limit the engagement of diaphragm action, which would be essential in order to secure uniform storey translations during seismic response, thereby minimizing damage (Pardalopoulos et al., 2016).URM constructions typically present several structural fragilities and are therefore at significant risk if subjected to even moderate risk induced activity. Evaluation of potential damage under future natural threatens is therefore essential in the mitigation of risk, even for regions with moderate to low hazard. Since the risk hazard is unavoidable, efforts should be placed on the vulnerability assessment and on the subsequent upgrading of the structural performance by the implementation of strengthening strategies. A traditional unreinforced masonry (TURM) building type comprising timber-laced construction (TL), was the preferred structural system in several cities of Northern Greece up to about 60 years ago when it was displaced by reinforced concrete. With regards to the old-town of Xanthi the TURM-TL buildings comprise a vital portion of its historical fabric (Fig.2). Primary construction materials are stone and timber, often tied in strategic locations with iron clamps and ties to improve member connectivity. The structural system combines a stiff load-bearing timber-laced stone-masonry wall system for the lower floor, with the upper floor made of an infilled timber frame. The load bearing structure comprises stone masonry foundation with connecting mortar; in some cases, to improve the redundancy of the foundation particularly in compliant soils, a supporting substrate layer made of treated timber is provided under the foundation. Load bearing walls in the first floor including the major interior divisions are made of stone masonry with lime-type connecting mortar and carefully tied timber-laces. Secondary interior dividing walls were made of light timber-woven gages coated with a lime-based mortar, usually reinforced with straw or animal hair. In construction of a traditional house these three structural forms were used selectively, combined in an overall structural system and expanded in space following well-defined rules depending on their weight, load-carrying capacity, and stiffness so as to optimize distribution of mass, stiffness and deformation compliance. Energy dissipation through internal friction is a characteristic mechanism for all three structural forms described (laced masonry, infilled timber frames and timber-woven walls), extending over a large range of deformation capacity prior to failure. This type of behavior to seismic loads is enhanced by the partial diaphragm action of the floor system, to a degree that depends on the robustness of its structure and the manner of its connection or attachment to the load bearing walls. In many of these buildings the roof timber truss is elastic and does not contribute by diaphragm action to the structure (Karantoni et al., 2013).

Figure 2. Typical samples of traditional houses in the historical center of the old town of Xanthi.

In the context of URM structures, the term "Analysis" is used to refer to two complementary attributes of the procedures used in assessment of the building response: - (A): Methods of discretization and assembly of the structural model used in order to represent the actual building in the framework of a calculation algorithm. - (B): Methods used to satisfy the governing equations and subsequently solving for the internal stress state generated in the structure in response to applied external disturbance (Pantazopoulou, 2013).

Different approaches for the determination of risk exist in the literature (Fig.3). Vulnerability can be discriminated in physical, economic, social and environmental. The targeted mitigation of vulnerability and risk contributes to the reduction or even more the elimination of losses provoked by natural hazards. Additionally, ambiguities encountered during URM buildings structural assessment such as the complications due to the mixed type of structural system (combination of timber or iron floors and roof, massive load bearing walls) and the spatial mass distribution in the vertical elements, as compared to conventional buildings with lumped masses. Additionally, ambiguities encountered during URM buildings structural assessment such as the complications due to the mixed type of structural system (combination of timber or iron floors and roof, massive load bearing walls) and the spatial mass distribution in the vertical elements, as compared to conventional buildings with lumped masses.

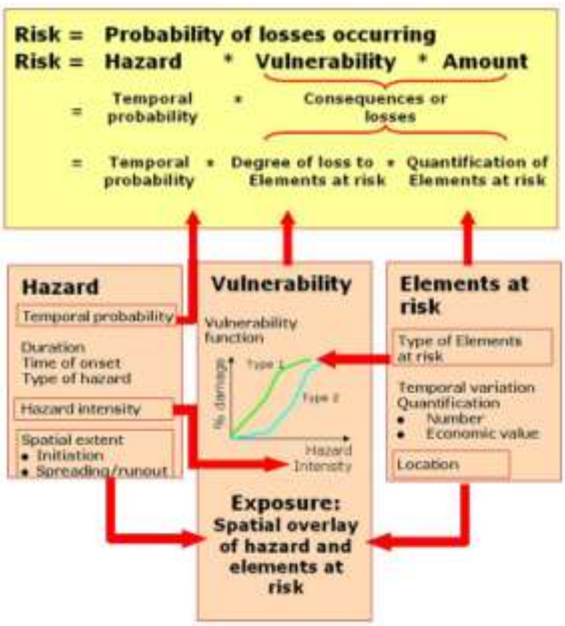

Figure 3: Basic function of risk (Van Westen et al., 2011).

2.1 Seismic Hazard

Different vulnerability and risk assessment methodologies exist depending on the quality and availability of information, characteristics of the building stock inspected, scale of assessment, methodology criteria, degree of reliability of the expected results and use by the end-user of the information produced (Fig. 4) (Vicente et al., 2011): **(i)Direct techniques** use only one step to estimate the damage caused to a structure by an earthquake, employing two types of methods; typological and mechanical: typological methods—classify buildings into classes depending on materials,construction techniques, structural features and other factors influencing building response. Vulnerability is defined as the probability of a structure to suffer a certain level of damage for a defined seismic intensity. Mechanical methods—predict the seismic effect on the structure through the use of an appropriate mechanical model of the entire building or of an individual structural element. Methods based on simplified mechanical models are more suitable for the analysis of a large number of buildings and require only a few input parameters. A commonly used method belonging to this group is the limit state method, based on limit state analysis (displacement capacity and demand). **(ii)Indirect techniques** initially involve the determination of a vulnerability index, followed by establishment of the relationships between damage and seismic intensity, supported by statistical studies of post-earthquake damage data. **(iii)Conventional techniques** are essentially heuristic, introducing a vulnerability index independently of the prediction of the level of damage. They are used to compare different constructions of the same typology in a certain region, analysing features that predominantly affect seismic resistance and calibrated by expert opinion. **(iv)Hybrid techniques** combine features of the methods described previously. Qualitative and quantitative parameters must be defined and vulnerability indexes be calculated as the weighted sum of these parameters, classifying the building according to their vulnerability. They constitute a reliable large-scale assessment and have been extensively applied in many case studies were recently implemented for the seismic vulnerability assessment of masonry structures in several historic city centers. Classes of vulnerability are associated to each parameter which reflects the relative importance of each one of them on computing the vulnerability index that characterizes the seismic behavior of a masonry building. The parameters include aspects such as: (a) connection between orthogonal walls, horizontal diaphragms and roofs; (b) the ultimate shear strength of the vertical elements; (c) type and quality of the masonry; (d) plan regularity and configuration; (e) roof typology, weight and thrust; (f) number of floors; (g) the type of foundations; (h) number and location of wall openings; (j) the previous damage state. The significance of the fundamental response shape as a diagnostic tool for seismic assessment of existing structures has been illustrated in recent studies in the field of seismic assessment. The fundamental translational shape is a compound property that conveys information about the tendency for localization of deformation demand in the structure. Therefore, the fundamental shape of a structure can be used to identify likely points of concentration of anticipated damage through the distribution of relative drift, while at the same time identifying lack of stiffness and the relative significance of possible mass or stiffness discontinuities.

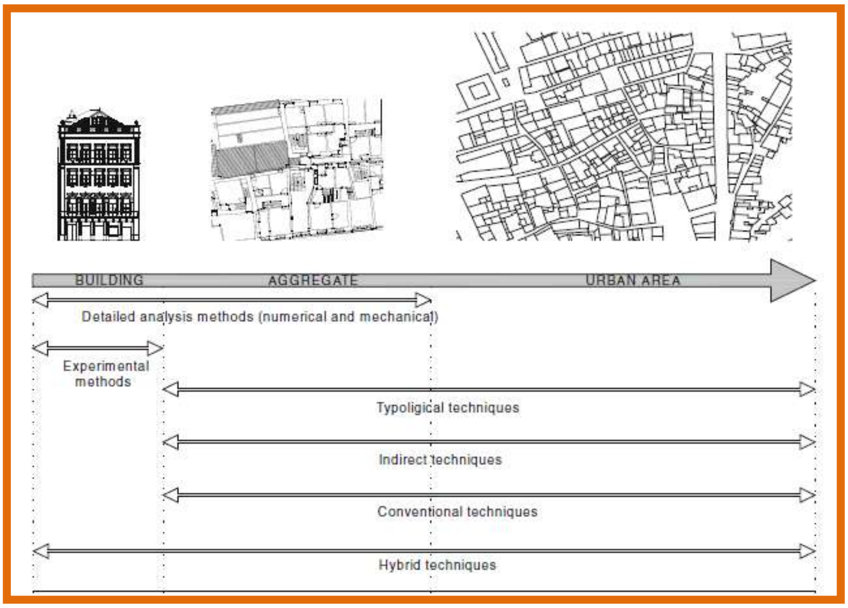

Figure 4: Vulnerability assessment levels.

2.2 Flood Hazard

General characteristics for the flood damage estimation (Fig.5) are the building use, the maintenance level, the location of doors and openings where flood water can enter and the distance to flowing waters, which may determine the damages due to erosion(van Westen et al., 2011). In order to evaluate flood damage, several parameters that characterise the severity of a flood can be used. The most important parameters influencing flood impact are (Genovese, 2006): water depth, duration of flooding, flow velocity, sediment concentration and size, wave or wind action, pollution load of flood water, rate of water rise during flood onset. The emerging damage is dependent on the type of flood event coastal, fluvial and pluvial flooding. Further, the flood duration needs to be regarded especially for the assessment of productivity losses. The velocity of flowing flood water can impact the structure and lead to severe damages, especially when the water carries debris. Transported sediment and water contamination can cause serious damage to the building materials and contents and may produce large clean - up costs. The flood depth and duration determine how much load the structure needs to bear and may lead to weakening of the structural system. The rise rate of a flood may also be considered, since a fast water level rise reduces time for warning and evacuation. Flood water performs different actions on buildings (Sterna, 2012). Analysing existing methodologies for flood vulnerability assessment of existing buildings is concluding that a majority of damage functions is existent: FLEMO, Damage Scanner, Flemish Model, HAZUS, Multi – coloured manual, Rhine Atlas, JRC model, HEC – FIA model. Damage to buildings from flooding is caused by a number of factors. There are two factors that can be considered most important: structural type and building height. The most frequently applied parameter in the flood damage assessment is the inundation depth.

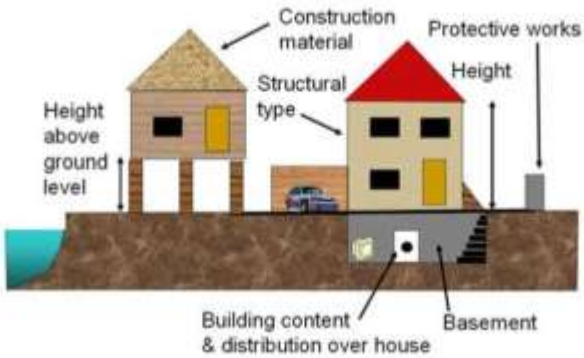

Figure 5: Flood vulnerability characteristics (van Westen et al., 2011).

2.3 Wildfires Hazard

The old town of Xanthi is located at the base of the mountain with the suburban forest (Fig.6). The area is surrounded by dense pine forest composing a unique beautiful nature but simultaneously acting as a continuous threat from wildfire. House losses due to wildfires are mainly influenced by fire behaviour and specific characteristics i.e. fire intensity, heat release, by house location, surroundings (defensible space, distance from forest,fuel accumulation), design and construction materials, and by fire suppression effectiveness (Papakosta et al. 2017). Usually, two damage levels are noticed: partial damage or destroy. The construction materials and design are significant parameters for the propagation and effects of fire. “Heat is affecting the strength and stiffness of all construction materials with reduction of mechanical strength. Especially steel structures can lose their loadbearing function relatively rapidly due to the high thermal conductivity of the material. Concrete and timber areless conductive, but concrete can be sensitive for spalling and timber is a combustible material and therefore the cross section will decrease. Also the effect of fire-induced deformations can be significant” (Botma, 2013). Xanthopoulos(2004)identifies factors which cause the vulnerability of a building to wildfire: fire behaviour (affected by fuels, weather and topography), location, design and construction materials of the building, flammable materials in close vicinity of the house,flammable materials inside the house, fire protection infrastructure and firefighting capacity byfirefighters and owners. The structural fire design of EN 1991-1-2 (European Union, 2002) procedure takes into account the following steps: **1.** Selection of relevant fire, scenarios, **2.** Determination of corresponding design fires, **3.** Calculation of temperature evolution within the structural members, **4.** Calculation of the firefighters and owners. The structural fire design of EN 1991-1-2 (European Union, 2002) procedure takes into account the following steps: **1.** Selection of relevant fire, scenarios, **2.** Determination of corresponding design fires, **3.** Calculation of temperature evolution within the structural members, **4.** Calculation of the mechanical behaviour of the structure exposed to fire.

Figure 6: The suburban forest of the old town in Xanthi (N. Greece).

III. Suggested Holistic Multi - Hazardrisk Analysis

It has been recognized the need of a holistic, multi-hazard and public/private cooperative approach able to tackle the problem from cultural, technical, strategical, social, and economic point of view, in order to fill the knowledge gap and to provide effective risk analysis tools. This has to be done in a sustainable way, preserving CH profitability, its social value as root of modern society and its centrality in the strategic society development, exploiting the previous work already done in the field and enabling highly collaborative workflows at local, national and EU level.

Xanthi's old town is a real treasure of the prefecture with vernacular architecture and is the most well known old town in Greece (see Fig. 7). The inhabitants and authorities of Xanthi put a strong effort into preserving its initial cultural identity and operationality under safe conditions. Characteristic types of traditional buildings are used representing the construction methods and building characteristics of the historical centres of many Mediterranean towns. The holistic risk protection of Cultural Heritage buildings would enrich the investigation of the uncertainties of impact models assessment of the CH regions regarding seismic, flooding and wildfire hazards.The holistic risk analysis methodology can be structured in three discrete axes (A, B and C): **Axe A)**The seismic vulnerability assessment of multiple CH buildings with the application of simplified analytical mechanical model,upgrading the seismic risk protection and preservation of cultural heritage sites with a proposed seismic adaptation and resilience plan, oriented to mitigation risk policies for Xanthi's old town. **Axe B)** The flood vulnerability assessment for the same traditional buildings investigated in Axe A, for different applied scenarios of flooding depth and suggestion of adaptation and resilience measures. **Axe C)** The wildfire risk assessment in the Wildland Urban Interface of the old town of Xanthi prioritizing management zones.

Holistic risk protection of Cultural Heritage buildings against different types of Natural Hazardscould enable the following steps taken in the future:

- Development of a comprehensive database and guidance tool for local authorities responsible for rehabilitation and renewal in urban areas;
- Integration of this database within a GIS environment for risk management of buildings at a urban scale;
- Creation of urgent plans validated by decision makers andtechnicians for urban areas, enabling the estimation and forecasting of direct and indirect consequences of their economic and physical impact based on different hazard scenarios;
- Establishment and validation of a modular approach for the creation of building vulnerability databases, as well as vulnerability assessment algorithms for other historic urban areas.

Figure 7: Vernacular architecture of CH buildings in the historical center of the old town of Xanthi.

Axe A at a territorial case study focuses on the vulnerability and risk assessment, defining strategies for strengthening the structural performance and upgrading the seismic risk resilience of CH sites. Risk analysis tool and decision support system will be established for the rehabilitation of historical city centres, validated in a large scale analysis of groups of buildings in a selected study area of the historical characterized old town of Xanthi (N. Greece). Improved version of the seismic assessment procedure for URM buildings, in proposed standardized forms, in a format that can be easily used by practitioners, especially in the case of massive structures, is a primary objective.Seismic demand may be estimated in terms of displacement demand at the building's roof, based on the principles of generalized single degree of freedom representation of complex distributed systems, consistent with the established code procedures. Displacement demand at the referencepointis then distributed through the structure following a simplified estimate of the fundamentalmode of vibration. This is calculated in each of the two principal directions of the building inplan, by applying a lateral load distribution analogous to its mass distribution. The intensityof local demand and likelihood of damage are estimated as relative drift ratios, in plan and inheight, of the masonry piers of the structure.Eurocode 8-III (2005) defines three levels for analytical assessment: KL1 (limited knowledge), KL2 (normal knowledge) and KL3 (full knowledge), depending on the availability data regarding geometry, construction, connectivity details and material properties of the structure studied. In structural components, deformation is measured by the relative displacement or by the relative drift ratio between successive points of reference (displacement difference normalized by their distance). Deformation demands are specified to determine the performance level (characterization of damage level) attained by the structure in response to the design earthquake.These values are compared with pertinent capacitiesassociated with predefined performance limits. Performance-based seismic assessment centers on the ability to identify possible damage localization, where damage is identified by the amount of deformation occurring in the various components of the structure. This procedure enables, through simple calculations, the determination of theenvelope of the developed deformations along the structural system of the examined building for a design earthquakescenario. Both demand indices and acceptance criteria are geometric variables (drift ratios that quantify the intensity of out of plane differential translation and in plane shear distortion of masonry walls oriented transversally to and along the seismic action, respectively for in plane and out of plane deformation) related through derived expressions with the fundamental response of the building.

Axe Bfocuses on the impact assessment of flooding applying different scenarios of flooding depth defining also strategies for strengthening the structural performance and upgrading the flood risk resilience of CH sites. The territorial case study will examine the same traditional buildings sample of the old town of Xanthi with case study A. Differences in the water level inside and outside the building cause lateral pressure and lead to damage of the structural elements. The capillary rise enables water to affect building components located above the flood gauge. The water flow causes dynamic pressure which fluctuates depending on how the water is flowing (turbulences, narrow profiles). In case of coastal flooding, the waves, whether breaking or not, can decrease the pressure applied to the building. Flood water can lead to buoyancy. Thus, a multi – hazard assessment will be delivered for the same building inventory and the impact of different natural hazards (earthquake and flood).

The applied methodology of **Axe C** tackles the problem of wildfire risk assessment in the wildland urban interface area (WUI) of the old town of Xanthi and the prioritization of management zones. Study of wildland fire regime in the forest area surrounding the old town of Xanthi will be performed for the definition of a number of fire weather and ignition scenarios. In addition, thematic topography and fuel maps will be created for the area of interest. Fuel mapping will be based on the appropriate reclassification of most recent existing vegetation and land cover maps which are available for the area. A fire simulator based on BEHAVE/ Rothermel's model (G-FMIS) will be used for the simulation of fire characteristics and propagation mapping based on the defined scenarios.The results will be analyzed and processed in a GIS environment together with additional thematic layers (i.e buildings) for the classification of fire risk and the definition of risk zones in the WUI environment of the old town, based on the fire behavior and characteristics due to landscape patterns (i.e topography, fuel, distribution of buildings in the WUI area). The result will be the delineation of locations and regions that are more vulnerable to wildfires in terms of direct impacts to the constructions of the WUI zone or favorable to spread the fire deeper in the resident area.

Rigorous multi hazard vulnerability assessment of existing buildings and the implementation of appropriate retrofitting solutions can help to reduce the levels of physical damage, loss of life and the economic impact of future natural events.The discrete stages of Axes A, B and C, separate or in combination, constitute a holistic approach for the immediate vulnerability and risk assessment of numerous traditional buildings providing innovative techniques and instructions for the preservation and strengthening resilience of cultural sites to natural induced risk, prioritizing the needs for rehabilitation programmes and organizing emergency plans.

IV. Beneficial Impacts of Cultural Heritage Risk Protection – Discussion and Conclusion

Natural hazards have the potential to substantially affect the lifespan, the serviceability or even destroy European CH buildings, appraising social and economic losses. The preservation in a sustainable and resilient condition of CH assets emerges urgent, as part of the history and the identity of civilizations. A holistic and rigorous vulnerability assessment of existing cultural heritage buildings and the implementation of appropriate retrofitting solutions can help to reduce the levels of physical damage, number of casualties or even the loss of lives. Furthermore, thepreservation in a sustainable and resilient condition of CH assets except of the historical and architectural benefits will give a boost to the local tourism and trade and a possible raise in the real estate rates upgrading the economic direct impacts. In addition, the provided innovative techniques and instructions for strengthening resilience of cultural sites will act positively to the safety of habitats, eliminate the cost of repairs and the loss of income due to the pause or delay of employment or the cost of injuries, which constitute social and indirect economic losses. Furthermore, multi hazard vulnerability assessment of existing buildings will prioritize the needs for rehabilitation programmes and organizing emergency plans.The target of mitigating structural vulnerability and managing effectively the provoking risk is connected with public safety, economic, social and historical benefits.

Risk protection increases societal resilience to natural hazards, starting from the protection of CH buildings that play an important role in the functioning and prosperity of societies. Risk protection has direct impact on the following EU societal values: **a.** Support public accountability & transparency, by developing priorities for the protection of CH, which could be easily communicated to the society. **b.** Strengthen community involvement in preparing for coping with natural hazards demonstrated could have devastating impact. **c.** Provide support for good governance overall, in addition to a consistent resilience framework for protecting European CH sector. **d.** The protection of CH sector is a vital and important issue that will support sustainable operationality and uninterruptible provision of services (e.g. tourism) that will maintain economic activity.

The potential of the contribution is in its ability to mobilize a critical mass of research and competence in the field of safety of cultural heritage buildings, which brings together theoretical and applied research in the natural, technical, social and economic sciences with an inclination towards practical applications. The suggested methodology sets a consolidated pathway for reinforcing resilience assessment of the national and European CH buildings, where analysis of the natural risk impacts on the structural performance is linked to measures in order to mitigate the impacts and sustain operational continuity and services. Holistic risk protection of Cultural Heritage buildings against different types of Natural Hazards has direct effects on the careers related to CH sector, namely the materials, the constructing and engineering sector, the real estate, the trade, the touristic sector, the economic and cultural sector.The knowledge generated will be provided as a public good to help public and private CH sector (Ministry of Culture/ Technical Authorities/ Civil Protection/ Municipality/ Prefecture/Technical Chamber of Greece) evaluate the risk impacts and adopt a risk analysis - decision tool and a resilience strategy eliminating the information gap of this demanding task even for specialized structural engineers.

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