*RE*habilitation of European *V*aulted Masonry Structures for *ARC*hitectural *H*eritage Preservation (REVARCH)

Field of Study : Architecture, Arts and Culture, Structural Rehabilitation

Mandatory training needed to apply for this research topic : Engineering or Architectural Engineering or Architecture Master Degree

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ABSTRACT

Masonry arches, vaults and domes are among the oldest structural elements, used for centuries to construct both monumental sacred, civic and defensive buildings and “minor structures”, including common urban buildings and traditional rural houses. For centuries, arches and vaults have been the most common solutions for building floors and coverings. In addition to their structural elegance and technical complexity, these systems often feature precious finishings, particularly in more prestigious buildings, enhancing both their artistic and architectural significance. Masonry arches have also been widely employed in bridge construction, from the Roman era up to the 20th century, characterizing still today a significant portion of Europe's in-service road and railway bridges.
The development of vault structures has resulted in many distinct construction typologies now part of Europe's architectural and structural heritage. These historical systems deserve deep investigation, preservation, and upgrading. The need to retrofit masonry structures is particularly urgent, as highlighted by recent European programs aimed at renovating building stock to improve energy efficiency and reduce structural vulnerabilities, especially to natural disasters like earthquakes.
Given these considerations, this project aims to widen knowledge of the typical vault systems used across different European countries, focusing on both their artistic-architectural and structural aspects. The assessment of some significant case studies will allow to investigate the structural deficiencies leading to the proposal of innovative retrofitting technique able to mitigate the vulnerabilities. Complete guidelines will be developed to report a complete summary of the research investigation and provide practical procedure for structure rehabilitation and preservation.

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Research aims and methodology

As highlighted in the abstract, masonry vault systems are an integral part of Europe's architectural and structural heritage, requiring thorough investigation, preservation, and, where necessary, retrofitting. Understanding these structures involves analysing construction techniques and materials, which vary depending on the period and regional specificities of construction methodologies, as well as on theenhancement and the circulation of technical knowledge, on the skills and the ambitions of architects and contractors, on the different required functional needs. As thrusting structures, their construction has always been in the past, in absence of scientific assessments, a challenge and a matter of deep concern for architects and builders, which proceeded empirically, experimenting different technical choices according to the specific case and site. This process must be approached through historic research, exploring, cataloguing and digitising archival as well as iconographic sources, primarily drawings and sketches, and printed sources, such as architectural treaties and handbooks and the historical scientific literature on the arch behaviour, combined with on-site investigation and diagnosis on the material documents. All of which are essential as a starting point to fully understand the vaulted systems evolution over time, the role of geometric shapes, structural details and of material properties.

Mansory vaulted structures, in particular, present different construction techniques and typologies that vary from country to country due to factors such as material availability and production, construction era, and social, economic and cultural influences. The first objective of this project is to explore these factors in order to identify common features and differences in the construction techniques used across different European Unita regions, especially focusing on the Modern age up to the 19th century and selecting, through time and space, a significant number of vaulted structures and systems with analogue configuration to deepen and compare. Collaboration between researchers from various universities and disciplines, particularly crossing history of art and architecture and civil engineering, is vital for this, providing an opportunity to exchange technical knowledge and develop comprehensive guidelines that – through relevant study-cases selected within the monumental architectural heritage as well as within "minor" traditional or functional buildings – outlines the key characteristics and distinct features of arched, vaulted or domed typical systems.

This first step of the research is crucial for the project's second phase, which focuses on analysing the primary structural vulnerabilities of these systems to define effective assessment methods, retrofitting strategies and monitor structural degradation over time. Arches and vaults are frequently susceptible to various vulnerabilities, both static and dynamic. In addition to material deficiencies, these weaknesses often stem from the fact that historical buildings were typically not designed according to formal guidelines, as is the case today, but rather based on empirical rules derived from practical experience. As a result, many structures, including buildings and bridges, require strengthening to meet the modern structural codes for serviceability and ultimate limit conditions.

Furthermore, according to Europe's earthquake hazard map, several Southern European countries—such as Italy, Portugal, Spain, Greece, and Slovenia—are at high risk of significant seismic activity. Masonry structures, particularly those containing arches and vaults, often present considerable seismic vulnerabilities that must be mitigated through appropriate retrofitting interventions. When these structures have already been subjected to seismic actions, it is essential to implement solutions that allow repairing and restoring their structural and architectural integrity, being conservative and respectful of the unique structural and architectural features.

In light of these considerations, the project also aims to promote the development of static and seismic retrofitting techniques that can be easily applied to vaulted structures across different countries. The proposed retrofitting methodologies will have to meet some basic principles of structural green and sustainable rehabilitation, including material compatibility and reversibility of the retrofitting interventions, without neglecting the adoption of advanced high-performance materials. As a result, the technical guidelines developed in the first phase will be expanded to include specific retrofitting strategies suitable for the various arch and vault systems analysed in the project. These techniques will be presented along with simplified analytical calculations useful for preliminary design. Additionally, the guidelines will feature a section on classifying typical damage

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patterns observed in existing vaulted structures, supporting the assessment of structural deficiencies and the selection of appropriate retrofitting techniques.

The third phase of the project involves the detailed evaluation of some of the techniques identified to assess their effectiveness and applicability to real scenarios. Researchers will select significant real case studies, including both monumental and secondary buildings, as well as bridges. These structures will be investigated from both architectural and structural perspectives. Where necessary, retrofitting interventions will be proposed, and their structural behaviour will be analysed to assess the obtained improvements. For this purpose, the latest analytical and numerical analysis methods will be employed, in line with Eurocodes and national code recommendations. These case studies will also serve as practical examples to assist professionals in designing the proposed retrofitting solutions.

The fourth phase is more experimental and involves laboratory testing to evaluate the performance of one or more of the retrofitting interventions proposed in the guidelines. The laboratory of structural engineering "P. Pisa" of the University of Brescia is equipped to host these activities, providing facilities for both material testing and experiments on small- or full-scale specimens. These tests will simulate the seismic or static behaviour of selected vaulted structures (e.g., a cross-vault or a masonry arch bridge) before and after retrofitting with proper strengthening technique. The results will show the actual effectiveness of the interventions and provide valuable insights to validate the analytical and numerical methods typically used for masonry structures analysis. The experimental activity represents an additional opportunity to promote the exchange of ideas and point-of-view regarding the topics of this project. Moreover, it offers an opportunity for master's students and researchers to actively participate in the project's activities and potentially engage in international study experiences.

Relevance and added-value of the proposed research in relation to the current state of knowledge

The structural behaviour of vaults, from a theoretical point of view, is a topic scientifically studied from the 18th century. Numerous and well-known studies have been produced and critically analysed even by contemporary authors. However, a purely theoretical approach often contrasts with the reality of building practice: until the 19th century, performance practice proved to be very distant from theoretical principles. This evidence demonstrates, on one hand, the relevance of the theoretical aspects, but, on the other hand, it always requires direct and in-depth knowledge of the historic buildings through appropriate researches, surveys and investigations in situ. To assess the structural vulnerability of existing vaults, engineers must understand historical construction practices and building techniques.

Providing interdisciplinary knowledge of construction methods, both theoretical and practical, this project aims to prompt innovative and more grounded research on a valuable part of the architectural heritage such as vaulted structures, guiding as well the creation of intervention guidelines for their rehabilitation, monitoring and conservation.

Furthermore, the project aims to go beyond an approach focused on the analysis of individual and most relevant cases, which predominantly characterises the current literature, aiming to settle a first network of knowledge related the construction techniques of European masonry vaults from the modern age up to the threshold of contemporaneity. This, considering and comparing some of the main structural types widespread in the territories of the Unita Alliance, highlighting their design and material conception and thus offering the bases for a more conscious action of conservation and valorisation.

On the strict historiographical side, the project also undertakes the collection, digitisation, and critical comparison of archival documents and printed sources relating to the design and construction aspects of masonry vaults, thus starting a first mapping of direct and indirect sources on the subject in the different European Unita areas.

Regarding the engineering disciplines, despite vaulted structures are widely spread over different European countries, the information provided by the scientific literature is still limited. Most of research studies focus on the analysis, either analytical or numerical, and structural assessment of existing structures but they do not investigate the possible retrofitting techniques suitable for reducing the vulnerabilities.

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Interdisciplinary nature of the research together with the alignment with the CHORAL programme and complementarity expertise of the teams

The present project is strongly consistent with the CHORAL program, which mainly focuses on the different aspects of cultural heritage. The project stresses the current need for preserving and investigating vaulted structures, which are an important part of the architectural and cultural heritage of all the territories involved in the UNITA Alliance. Conservation and restoration efforts require a thorough investigation of the architectural and structural features, which will benefit from the expertise of researchers from the different countries participating in this project. The interdisciplinary nature of the research is proved by the different expertise involved in the project, covering research areas like architecture and its history, material science, material technology and structural engineering and rehabilitation. Additionally, the complementary knowledge of the researchers is enhanced by their familiarity with the unique structural sites within their respective countries. The dissemination of the project investigations and results will be fundamental to spread the knowledge of vaulted structures and promote their preservation and restoration.

Output plan including publication and dissemination activities

The dissemination of the research activity will be carried out at different levels and channels. First of all through publications in international scientific journals, communications in international and national conferences and workshops, extending as well at a local level with the involvement of school, protection and government bodies and interested stakeholders of the investigated territories. Based on the level of the research achievements, the final thesis will be published in an indexed book.

Estimated schedule

The research, organized over a 3-year period, begins with an initial 6-month phase focused on surveying the current state of knowledge at the international level, specifically within UNITA and other European countries. In the following 6 months, potential case studies will be identified within the territories of the UNITA universities for further study, verifying and collecting the available related archival documentation. The subsequent six months will be dedicated to analysing these archival sources and outlining the design and construction history of the selected case studies. In the meantime, the inspection of the cases will be carried out to provide a survey of local historic constructive realities as well as to start the first structural assessment. The remaining 18 months will be mainly devoted to all the activities regarding the structural analysis, monitoring and testing. The candidate will submit a short report on the research advancements every three months.

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