Innovative V-Shaped Column Design for One-Way 3D Truss Systems in Preserving Archaeological Sites

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Abstract. This research represents the final phase of a comprehensive study on the structural behavior of roofing systems incorporating innovative 3D steel truss beams and structural glass panels, specifically designed to safeguard historical and archaeological sites. Recognizing the vulnerability of these cultural assets, often located in seismically active regions, the study establishes a robust design methodology to address both gravitational and seismic challenges. This approach has previously led to the development of efficient design charts, as detailed in earlier publications by the authors. Expanding on the roofing system, the study delves into the conceptualization and parametric design of the supporting structures, comprising steel variable-section truss portals and V-shaped columns. Following the optimization of the system's performance under gravitational loads, the design methodology is applied to a case study, verifying its effectiveness in seismic regions through incremental analysis.

Keywords: Steel 3D lattice beams, V-shaped columns, Archaeological sites, Cultural Heritage, Structural Optimization, Parametric Design

1 Introduction

Spatial trusses are integral elements of the broader category of spatial structures, defined by their three-dimensional behaviour (spatial behaviour) and primary reliance on axial loading (truss behaviour). Constructed from tetrahedral or hemi-octahedral modules, typically made of tubular metal, these trusses are assembled through welding or intermediate nodes. Their design offers superior torsional and flexural stiffness, particularly in out-of-plane directions, making them advantageous over planar trusses in applications requiring self-support during construction or in the absence of lateral restraints. The origins of spatial trusses trace back to the early 1900s, notably in the gliders and wing structures designed by Alexander Graham Bell. Their adoption increased significantly with the advent of reliable connection systems, peaking in the 1970s with prefabricated truss structures, and they continue to be used extensively in modern industrial and complex architectural applications.

This research investigates the integration of spatial trusses with structural glass to create innovative roofing solutions for monumental and archaeological sites. It is part of a larger project focused on the development and industrialization of advanced welded steel truss systems for lightweight floors and roofs, specifically tailored for cultural heritage preservation. The project includes extensive numerical and experimental optimization studies, as well as a capacity-based design methodology to mitigate brittle failure and ensure ductile performance under extreme loading conditions. Full-scale experimental investigations have been instrumental in capturing the intricate three-dimensional behaviour of spatial trusses, which traditional analytical models often fail to represent accurately.

This paper concentrates on the conclusive phase of the research, focusing on the conceptualization and parametric design of supporting structures. Following a brief overview of the construction system, the study details the development of a novel support framework, incorporating steel variable-section truss portals and V-shaped columns. After optimizing the structural response under gravitational loads, the methodology is applied to assess the system's suitability for seismic zones, validating its robustness and effectiveness through incremental analysis.

2 Description of the structural system

The system under investigation is a hybrid steel and glass structure featuring a roof made up of spatial trusses arranged in a one-way configuration, referred to as BB.CC. (an acronym for "Cultural Heritage"), which was previously explored in a dedicated research program [1-3]. These trusses, designed efficiently using design charts, demonstrate exceptional flexural-torsional stability.

The primary load-bearing system comprises portal frames with V-shaped columns, engineered to resist both vertical and horizontal forces. The design of these columns, illustrated in Fig. 1, is presented in detail in this paper.

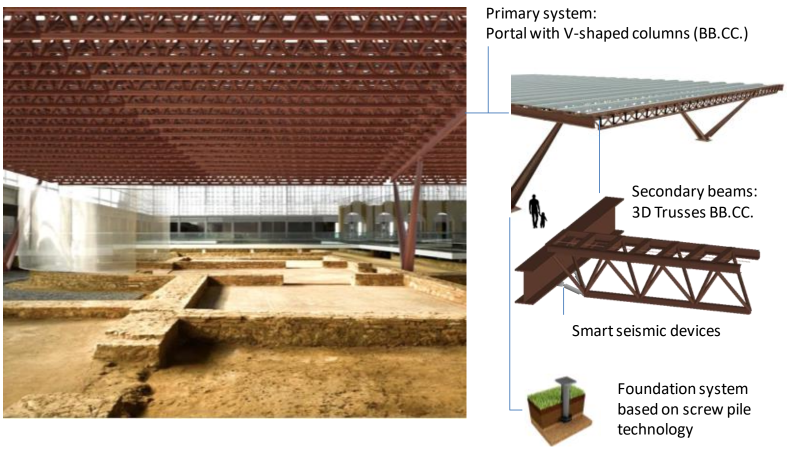


Fig. 1. Description of the structural system.

3 Structural conception and design methodology for V-shaped columns

The structural design of new or retrofitted structures, guided by a scientific approach and well-defined performance criteria (see Fig. 2), follows a systematic three-step process: material selection (Step I), structural system selection (Step II), and initial member sizing (Step III). Each phase plays a crucial role in ensuring both the functionality and aesthetic integration of the structure within its intended environment.

The first step, namely the material selection, is fundamental to the conceptual design process. It involves choosing the most appropriate materials for both the structural system and the protective elements of the design. This decision is informed by a comprehensive evaluation of technical factors, such as structural efficiency, load-bearing capacity, and durability, alongside architectural considerations, which include the visual impact of the materials and their ability to blend harmoniously with the surrounding context.

Given the specific challenges posed by archaeological site applications, the material selection also considers environmental factors like weather exposure, as well as preservation requirements. After considering both formal and performance-related factors, weathering steel grade S355J2 was chosen as the optimal material. Its corrosion-resistant properties, durability, and ability to develop a protective patina over time make it particularly suitable for use in sensitive archaeological environments, ensuring long-term structural integrity and minimal maintenance.

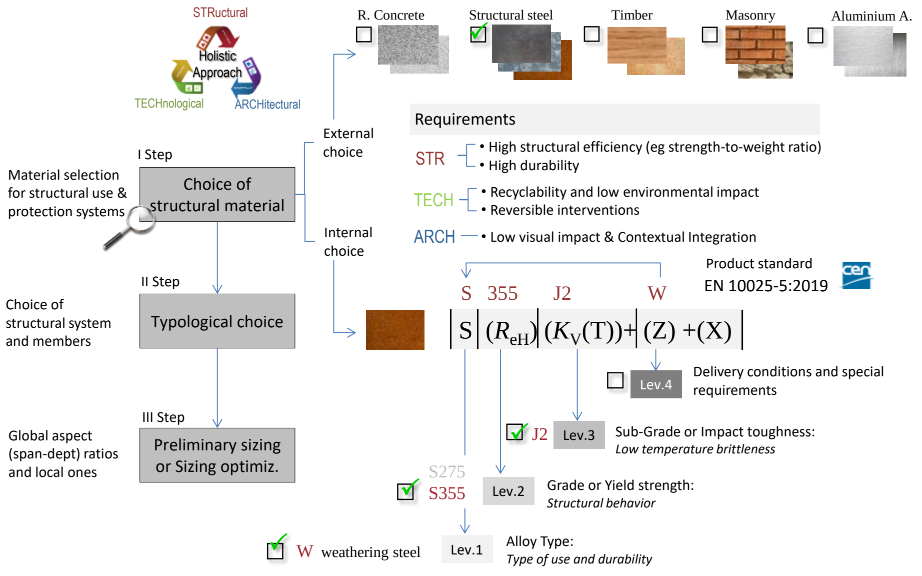
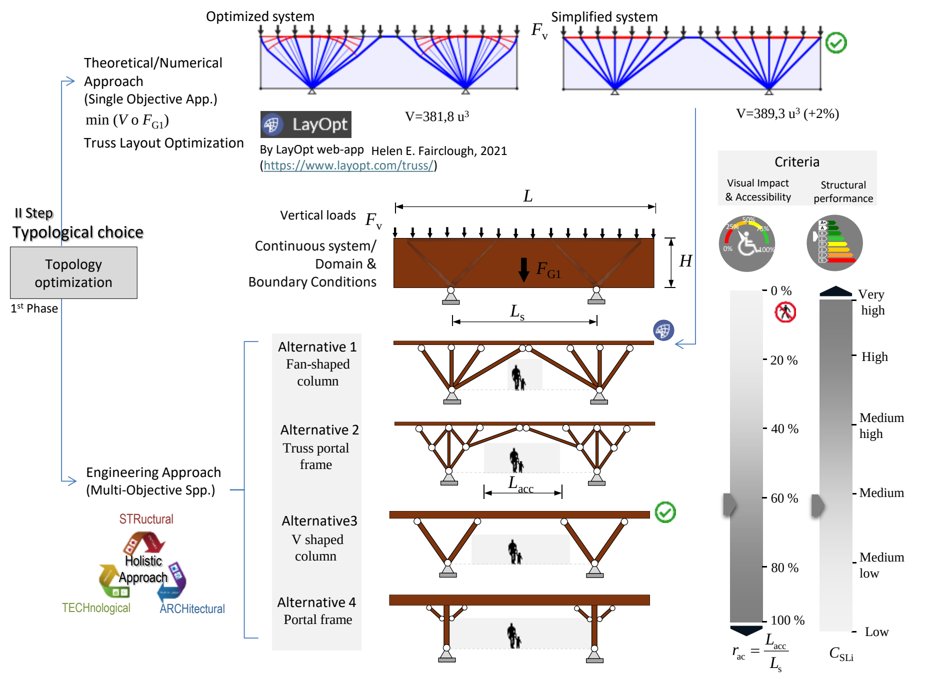


Fig. 2. Conceptual Structural Design (CSD): Steps and material selection (I Step).

Once the design requirements, constraints, and structural concept have been defined, the next step is the selection of the structural typology. This can be achieved either through the adoption of established engineering solutions or by employing a structural optimization process. The goal of the optimization process is typically to minimize cost or weight, or to maximize the overall structural performance, ensuring that the design is both cost-effective and efficient. In hybrid frame-truss systems, the optimization process is often referred to as "layout optimization," and it is typically conducted in three distinct phases:

1. *Topology optimization:* This phase focuses on determining the optimal configuration and connectivity of the structural elements, essentially finding the best overall shape of the structure. It considers the load paths and how the materials should be distributed to achieve the most efficient use of resources.
2. *Shape optimization:* This phase fine-tunes the geometry of the structure, focusing on optimizing the shape of the components to enhance structural performance. This stage refines the form to meet specific performance criteria such as minimizing deflection or maximizing stiffness.
3. *Sizing optimization:* This final phase involves determining the optimal sizing of individual structural elements (such as beams, columns, or trusses) to ensure that they are appropriately dimensioned for the loads they will carry. This stage balances the material usage with the desired structural performance, ensuring the elements are neither oversized nor undersized.

As shown in Fig. 3, the combination of theoretical analysis and engineering expertise led to the selection of a portal frame structure with V-shaped columns as the optimal typology for the primary load-bearing system.



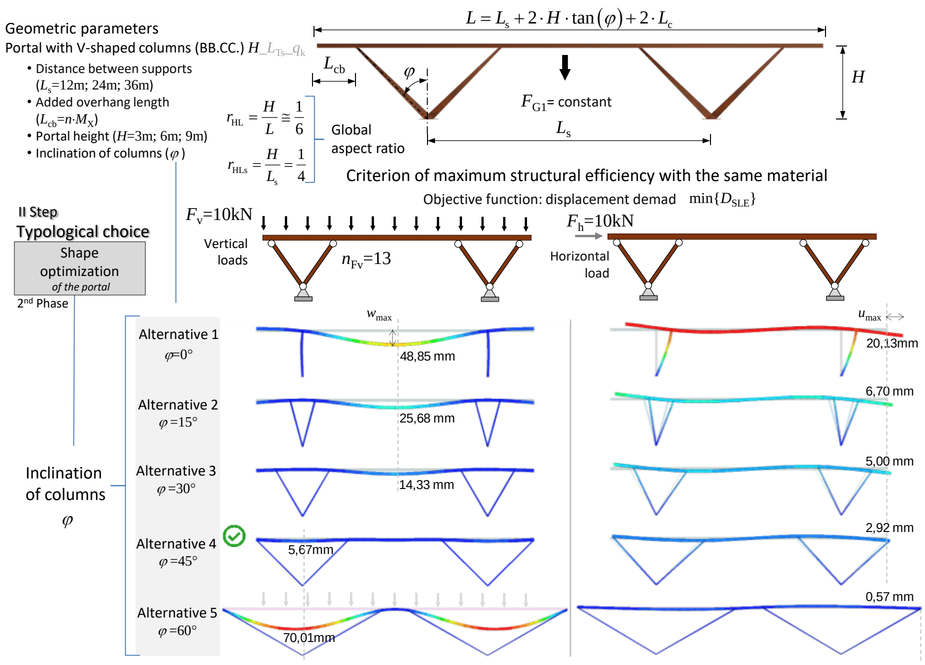


Fig. 3. Typological choice (II Step): Topology and shape optimization processes.

For the specific application of a lightweight roof, the V-shaped columns were designed with an optimal inclination of 45 degrees. This angle was selected to achieve a balance between structural efficiency and aesthetic considerations. Structurally, the 45-degree inclination optimizes load transfer, ensuring that forces are efficiently distributed to the foundation. Aesthetically, this angle provides a visually striking form that complements the overall architectural design, enhancing the space without overwhelming it. This balance is particularly important in monumental and archaeological site preservation, where both structural integrity and visual impact are crucial.

After defining the overall geometry, the columns were designed to support vertical loads while enhancing lateral stability. To optimize out-of-plane stability, welded double-T sections with extra-wide flanges were chosen, providing increased rigidity and resistance to bending. Tapered columns were selected for both practical and aesthetic reasons. This design reduces material use in the upper sections, where the loads are lower, while also creating a sleek, tapered profile that contributes to the overall elegance of the structure.

The design methodology, as illustrated in Fig. 4, integrates both pre-sizing and final sizing. This process streamlines the design, allowing for an initial sizing based on simplified criteria, followed by more refined final sizing to optimize material usage and ensure the system performs efficiently. This approach ensures that both the structural and architectural requirements are met while improving design efficiency and reducing material costs.

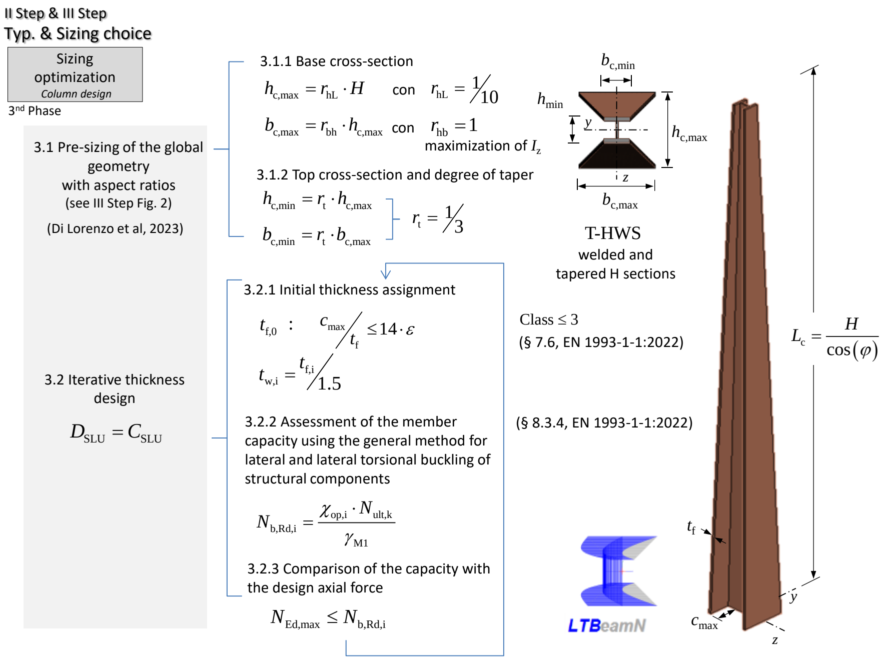


Fig. 4. Sizing optimization and design methodology for the tapered columns of the V-Shape system.

By adjusting key design parameters, three distinct families of structural systems can be generated, categorized as Low-rise, Mid-rise, and High-rise, based on the height of the frames (see Fig. 5).

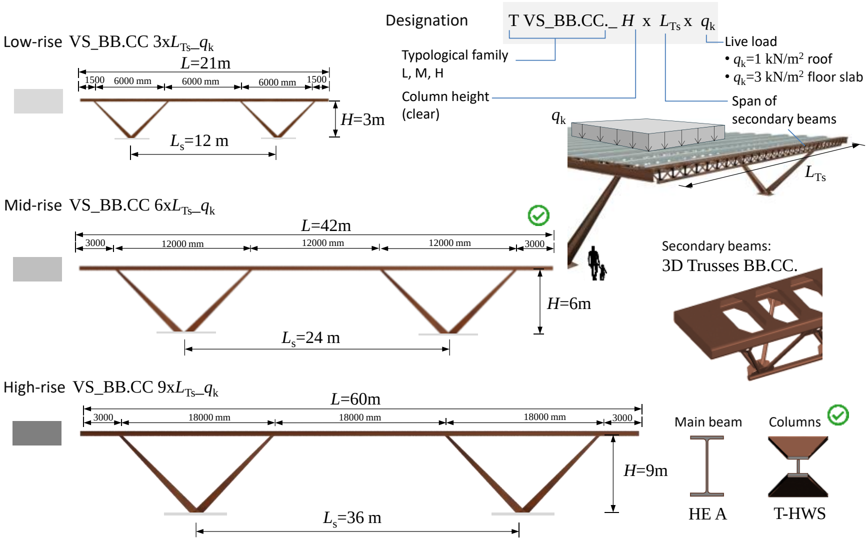


Fig. 5. Portal frame with V-shaped columns: typological families and members.

The classification of these systems is primarily influenced by the height of the structure and the span of the space trusses. The length of the space trusses (LT) is varied between 15 m, 25 m, and 35 m, and the roof's design live load (q_k) is also modified, with values set at 1 kN/m² and 3 kN/m² to represent different load conditions.

The design procedure was applied to the parametric design of the V-shaped frame columns and beams, optimizing the structural behaviour based on the specific dimensions and loading scenarios for each system. The space trusses, which act as secondary structural elements, were designed using specialized design charts developed through prior research [3]. This integrated approach allows for the creation of a structurally sound, cost-effective solution that is adaptable to a wide range of building types. The design is suitable for both low-rise and high-rise structures, meeting required performance, safety, and efficiency standards for each case.

4 Feasibility of use in seismic areas

As a final step in the study, the feasibility of using the proposed construction system in seismic zones was preliminarily assessed. Specifically, the out-of-plane behavior of the frames was analyzed, focusing on the effects of an earthquake in the transverse direction, which is the system's weaker direction.

The results of the analysis indicated that, by incorporating shock transmitters between the spatial truss beams and the crossbeam of the frames, and modifying the boundary conditions at the base of the structure, it is possible to implement this system in areas with medium to high seismic activity (Fig. 6).

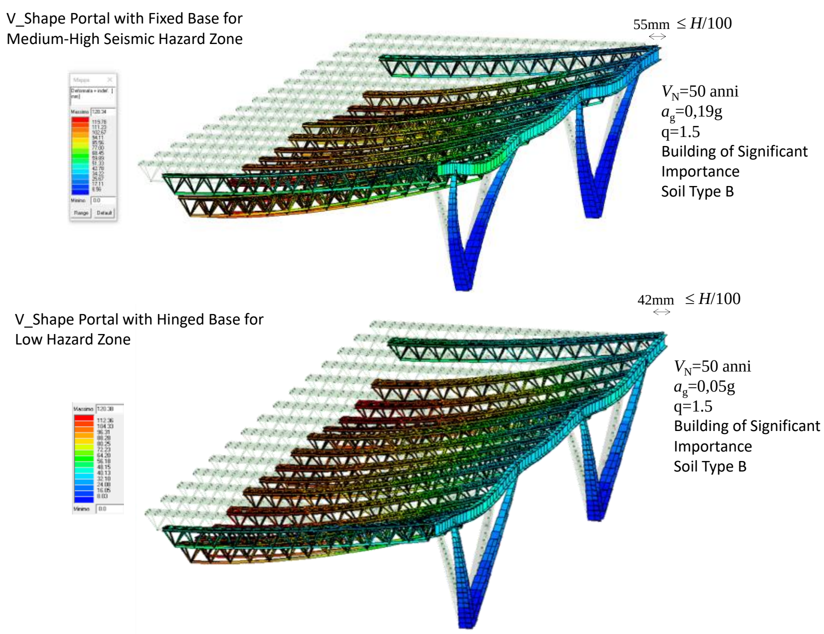


Fig. 6. Maximum lateral displacements in the transverse direction.

5 Concluding remarks

This study offers a comprehensive investigation into innovative roofing systems that incorporate 3D steel truss beams and structural glass panels, specifically designed to protect cultural heritage in regions with high seismic activity. These systems have undergone extensive analysis to ensure their suitability for such applications. A robust design methodology has been developed and validated, supported by the creation of efficient design charts, which were detailed in previous studies. This research also delves into the design and optimization of supporting structures, including steel variable-section truss portals and V-shaped columns, which contribute to the system's overall performance and stability.

A detailed case study demonstrates the effectiveness of the proposed design approach in a seismic context. Through incremental analyses, the system's structural behaviour under gravitational loads has been optimized, and its performance under seismic conditions has been thoroughly assessed. The findings confirm that the roofing system can be effectively implemented in seismic zones, ensuring the protection of cultural heritage even in areas with medium to high seismic risk.

The insights gained from this research provide valuable guidance for the engineering and design of cutting-edge roofing systems aimed at preserving cultural heritage. The proposed design methodology offers a strong foundation for future applications, addressing both structural integrity and aesthetic considerations while ensuring long-term durability in challenging seismic environments.

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