Innovative applications for civil structures of the Municipality of Finiq using topology optimization and additive manufacturing

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Abstract- *The Municipality of Finiq is located in the South of Albania, inside the Vlora's County and it is just 9 kilometers from the City of Saranda. The village of Finiq is particularly important because of the presence of The Archaeological Park at the top of the hill, which has received this status in 2005. Inside the Municipality there are a lot of attractive sites, such as The Blue Eye, the main lake of the Municipality, the Monastery of St. Nikolla, located in Mesopotam, etc., making the Municipality dominated by nature (e.g. long lots of fields, hills, rivers, and lakes) and monuments that represent the cultural heritage of the municipality. Within this context some villages arise, which are characterized mostly by infrastructures and civil structures in reinforced concrete, this is strictly due to the fact that these buildings were built in the last decades, instead of what can be observed outside the Municipality, e.g. Gjirokaster. The structures of the Municipality's villages are mostly under construction, some are unfinished, abandoned, or damaged. Despite the trend of reinforced concrete building construction does not tend to decrease, the world of civil engineering is trying to find new solutions, that are also environmentally compatible and sustainable. This necessity is motivated by the fact that the industry of concrete is the most energy-intensive industry in the world. In particular, two main aspects that the research is investigating to address these issues are the use of new manufacturing technologies, e.g. 3D printing, combined also with new computational methodologies, such as topology optimization, and the development of innovative materials, e.g. architected metamaterials.*

The aim of this paper is to suggest innovative approaches and methodologies in the fields of structural mechanics for civil structures. The proposed approach wants to be applied not only to buildings under construction but also to the existing ones, which could be restored or completed in some specific structural and non-structural parts. In particular, we propose new topology optimization strategies that allow us to obtain an efficient material layout with maximized performance under predefined constraints. This design method is not only used to optimize the structural behavior of the structures but also for the optimization of specific features of the structures, e.g. thermal and acoustic optimization. The interest in this computational method has grown due to the development of innovative techniques of manufacturing, i.e. additive manufacturing. In particular, there are different types of manufacturing that could be used for construction, which differ with respect to the material adopted, e.g. steel, concrete, or stone-like materials. The proposed method will be supported by several examples to understand the potentiality of the approach considering the role of additive manufacturing. Indeed, the development of new manufacturing methods has reduced the distance between the theoretical and practical representation of the optimized layout.

In conclusion, the proposed approach allows to obtain novel 3D printable structures characterized by a more efficient use of material, contributing to the realization of the concept of circular economy within the construction industry.

Keywords:
Computational design method, topology optimization, additive manufacturing.

Introduction - Finiq is a settlement located in the South of Albania in Vlora's County. The village became a municipality in 2015 when the local government reform the area by merging the former villages of Aliko, Dhivër, Livadhja, Mesopotam, and Finiq itself. The municipality looks particularly attractive due to The Archaeological Park located at the top of the hill, which received its status in 2005. Other attractions include The Blue Eye, the main lake of the municipality, and the Monastery of St. Nikolla, located in Mesopotam. The municipality is dominated by nature, with long stretches of fields, hills, rivers, and lakes, as well as monuments that represent the cultural heritage of the area. Within this context, some villages have emerged, and various civil engineering projects have been initiated to increase the attractiveness of the municipality. The main projects of interest include the rehabilitation of roads [1], such as Pilake-Kullirice, Dermisht-Dhivër-Cerkovicë, and the main boulevard of Finiq. In addition, a feasibility study has been conducted for the rehabilitation of hydraulic systems [2], including irrigation, drainage, and dams. Finally, the use of solar energy for energy efficiency [3], specifically through the SOLIS Project, is being explored. Regarding the construction sector, it is observed that most infrastructures and civil structures are characterized by reinforced concrete. Some of them are currently under construction, while others remain unfinished, abandoned, or damaged. Despite the trend of reinforced concrete building construction does not seem to decrease, the field of civil engineering is making numerous efforts to find innovative strategies for manufacturing civil structures, both structural and non-structural components. So, the needs to move to new solutions are due to the high levels of energy consumption and greenhouse gas emissions generated by the construction industry worldwide. One promising solution to address the environmental issues related to the construction industry is additive manufacturing (AM) [4]. This technology has been widely applied in various fields, such as medicine, aerospace, and automotive, while the civil construction sector presents an ongoing challenge for the application of Large-Scale Additive Manufacturing (LSAM). Initially, LSAM was primarily used for non-structural, artistic, and design purposes. In recent years, nevertheless, it has increasingly been employed to produce structural components in the construction industry [5]. In particular, the use of AM technology enables designers to create new shapes and structures that were previously unattainable. This technology has significant potential in civil engineering and it promises to drive innovation in the industry for years to come. To efficiently exploit the potential of AM technology in civil engineering applications, it is most important to consider its high degree of flexibility, customization, and design freedom. This contribution will exploit a computation tool that allows control of the high-freedom design offered by AM, which is topology optimization [6]. This design method is presented through some simplified cases extrapolated from the rural areas of the Municipality of Finiq. The paper is structured as follows: Section 2 presents the state-of-the-art proposed method and current applications, Section 3 illustrates the objective and methodology proposed in this work, and in Section 4 the numerical results are presented. Finally, conclusions and perspectives are provided in Section 5.

State of art

The computational method suggested in this contribution finds its origin in the seminal work of Culmann [7]. Since this initial work, the design method has been used as a teaching tool and conceptual structural design to assist the understanding of structural mechanics fundamentals. However, the method remained constrained to theory mostly of the first proposed works, some interesting applications emerged using standard manufacturing techniques. An example is the Akugatawa West Side office [8]. The building frame was made of reinforced concrete and its shape was designed by means of topology optimization. An impulse to transit to applications was determined by the development of new manufacturing techniques, such as additive manufacturing in 1986 [9]. It gradually encouraged the community to investigate applications of topology optimization in different sectors. In particular, only recently in civil construction with additive manufacturing have been produced some optimal layouts. The most famous example in structural topology optimization is the MX3D Bridge [10], which crosses one historic canal, namely Oudezijds Achterburgwal, in the center of Amsterdam. Another notable example in structural engineering is the design of a post-tensioned concrete girder [11] by topology optimization. Recently, a growing interest has been posed in the development and design of architected materials, which have been also applied to multiscale problems to achieve enhanced materials features. These materials consist of cellular architectures with customized geometry and properties. So, various fields, such as biomedical and aerospace applications, have been involved in manufacturing hierarchical structures based on different kinds of microstructures to achieve enhanced structural and functional performances. Therefore, inspired by the potential of the multiscale formulation, this work proposes a methodology to design hierarchical structures for civil engineering applications.

Objectives and Methodology

The proposed design method aims to efficiently optimize structural and non-structural components of buildings or entire civil structures. This methodology facilitates the integration into the surrounding landscape of the civil structures with minimal environmental, aesthetic, and architectural impact. In particular, topology optimization serves as a powerful tool offering high design freedom within a prescribed formulation and constraints for the structural scheme. The modularity of the topology optimization algorithm provides flexibility to address various challenges, ranging from structural problems to multiphysics problems. However, this freedom comes with a post-processing and interpretation procedure to carefully understand the optimization output. So, the output of the optimization must be transferred to a computer-aided design environment and subsequently verified with standards for civil structures. Additionally, the post-processed frame must align with architectural criteria, such as values of views, facades, or integration of green areas [12]. In the specific case proposed in this work, the method aims to efficiently refurbish the facades of an existing building frame and propose an alternative design for an existing bridge. The methodology, integrated with modern additive manufacturing techniques [13], enables a reduction in material usage while achieving equivalent properties compared to traditional solid structures. The advantages extend beyond material reduction. Indeed, it is not detrimental to the structural performances. In addition, the optimized design contributes to enhance the architectural and aesthetic quality of standard concrete structures. This approach has been proposed to integrate engineering and architecture in order to address one of the region's main challenges – the preservation of unique rural diversity, historical heritage, and the surrounding environment [14].

The proposed method is a combination of the Finite Element Method (FEM), which is a typical analysis used in engineering, and an optimization algorithm that allows us to find the optimal distribution of holes and links, i.e. optimal layout, of a given domain. In recent decades, several methodologies and formulations have been developed to pursue an optimum structural layout, which varies according to the problem statement. The aim of topology optimization is to find the most efficient layout β of a physical system $\Omega \subseteq R^d$, where d is the dimension of the problem, whose behavior is described by the solution u_Ω and supported by Γ_D and loaded by Γ_N as shown in Fig1.

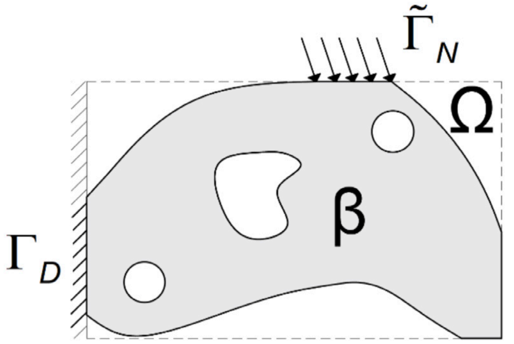


Fig1 / One-material problem setup: design domain, boundary conditions, and optimal layout
source / the author

The most common formulation [15] adopted in topology optimization is the compliance-based with volume constraint as described in (1).

Here, the objective function is the minimization of the compliance $C=\mathbf{F}^T\mathbf{U}$, which means the maximization of the stiffness, while the constraints are represented by volume, which is the sum of elements'

$$\min_{\mathbf{z}\in[\underline{\rho},\bar{\rho}]^N} C \text{ subject to}$$
$$\sum_{l=1}^{N} \rho_l \leq \bar{V}$$

densities, and it has to satisfy a desired volume fraction v. The compliance is given by the displacement vector $\mathbf{U}$ and the force vector $\mathbf{F}$, which is independent of the design variable. The displacements are given by the solution of the equilibrium equation $\mathbf{K}=\mathbf{UF}$. The formulation (1) can be written in discrete form [16] as:

where $\mathbf{V}=(\Omega_l)$ is the vector of element volume and $m_V(\mathbf{y})$ is the vector of element volume fractions, where $\mathbf{y}=\mathbf{Pz}$ collects the design variable $\mathbf{z}$ by the filtering weight-matrix $\mathbf{P}$. The formulation (2), which is valid for one material inside the domain Ω, can be extended for multiple materials, that means different mechanical properties (e.g. Young modulus E and Poisson's coefficient υ) and different material matrix D, which provides the stresses produced by an elastic strain state. The multi-material problem setup is illustrated in Fig2.

$$\min_{\mathbf{z}\in[\underline{\rho},\bar{\rho}]^N} C=\mathbf{F}^T\mathbf{U} \text{ subject to}$$
$$g=\frac{\mathbf{V}m_V(\mathbf{y})}{\mathbf{V}^T\mathbf{1}}-\bar{v}\leq 0$$

The formulation (2) can be extended for multi-material problem [17] in a discrete form as:

where N is the number of discrete elements, m is the number of candidate materials and g_j, $j=1,\ldots,K$, is the function that represents the volume for each constraint. The volume constraint g_j restricts the selection of each material m in the sets $\boldsymbol{\varepsilon}_j$ and G_j. These contain, respectively, the element and material indices related to constraint j.

The multi-material formulation (3) allows, through the theory of homogenization [18], to implement microstructures, which are incorporated in the topology algorithm though the elasticity matrix D. This approach is commonly known as homogenization-based multi- scale topology optimization [19] and it finds origin in the seminal work of Bendsøe & Kikuchi [20]. This method has been revived due the development of new technologies, such as AM, enabling the design of hierarchical structures with functionally graded properties. The one-material (2) and multi-material formulation (3) have been applied to optimize two simplified domains inspired by real context extrapolated by the Municipality of Finiq: called in this contribution as Wall (Fig3) and Bridge (Fig4). The Wall domain has been defined as an intervention in a part of the facade of an existing building in the main boulevard of Finiq, while the Bridge domain has been supposed as a building design alternative to the existing transport infrastructure that links the municipality of Saranda to Finiq.

$$\min_{\mathbf{z}\in[\underline{\rho},\bar{\rho}]^{Nxm}} C=\mathbf{F}^T\mathbf{U} \text{ subject to}$$
$$g_j=\frac{\sum_{i\in G_j}\sum_{l\in\varepsilon_j} V_l m_V(\mathbf{y})}{\sum_{l\in\varepsilon_j} V_l}-\bar{v}_j\leq 0, j=1,\ldots,K$$

Results

The formulations (2) and (3) have been applied to optimize a wall and a bridge domain as illustrated in Tab1.

The wall geometry has length L = 7 m, height H = 3.5 m, and a passive region to

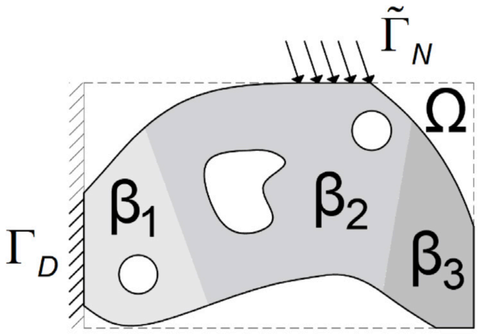


Fig2 / Multi-material problem setup: design domain, boundary conditions, and optimal layout source / the author

support the linear distributed load (q=5 KN/m) with a thickness h_p of 0.20 m. While, the bridge geometry, has length L= 80 m, height H = 10 m, and a slab h_p of 0.5 m with q = 10 KN/m. In particular, the geometry and boundary conditions, i.e. supports and loads, defined in this example are not representative of a real situation. Indeed, real applications require a more appropriate and complex formulation, which considers material behavior, and extensive analysis of loads. So, the proposed case studies have the purpose of showing the approach proposed and this innovative method applied to structures and infrastructures.

The results demonstrate that boundary conditions (loads and supports) are compliant to input setup and the distribution of material satisfies the volume constraints, i.e. volume desired as 0.3 for the wall domain and 0.1 for the bridge domain. Moreover, it is possible to observe that both cases show a coherent distribution of material to support the loads applied. In addition, in the optimization process have been implemented microstructures generated through a thermodynamic concept called spinodal decomposition [22], which allowed for the creation of functionally graded structures within the optimized domains. These architectures are generated through a spontaneous separation of a single thermodynamic phase into two phases, with one phase considered solid and the other void. The spinodal topologies are characterized by tunable anisotropy and a non-periodic structure, which enable the concept of functionally graded structures. In Tab2 are illustrated the architectures adopted in the multi-material topology optimization. In particular, these microstructures are considered of isotropic material with unitary elastic modulus and Poisson's coefficient of 0.3.

The optimized layouts obtained through topology optimization show that anisotropic microstructures are located in a consistent manner at the required state of stress in the structure. For instance, the columnar microstructure can be observed in areas where the principal stress is expected to follow the vertical direction to support the load applied, while isotropic architectures are located where there is not a preferred principal stress direction, and these allow a transition between columnar and lamellar topologies.

Conclusions

This contribution aims to outline the potential application of topology optimization in the community of Finiq. The design method allows to optimize of an assigned layout reducing the amount of material to use and providing design freedom to the structure architecture. In addition, the solution provided allows us to think of a new methodology in design and conceptualized components of buildings or structures to integrate with the low aesthetic impact of the environment surrounding. Moreover, the results show intuitively an expected design for a bridge and wall under the applied load and boundary conditions with a single and multiple material formulation. To achieve the objective of manufacturing these optimized structures ulterior structural analysis and experimental tests are needed to transit the theoretical results to real applications. In conclusion, future works will involve mathematical techniques to address real structural problems while considering the material behavior of the printer. Specifically, the research aims to focus on manufacturing structural and non-structural components for civil structures using large-scale additive manufacturing techniques. In conclusion, future works will involve the study of materials used with AM techniques, and efforts will be made to adopt more appropriate formulations that address real structural problems while considering the behavior of these materials.

Fig3 / Wall case study: a) top view of Finiq and location of the building considered [21] b) lateral view of the specific façade of the building considered. source / the author

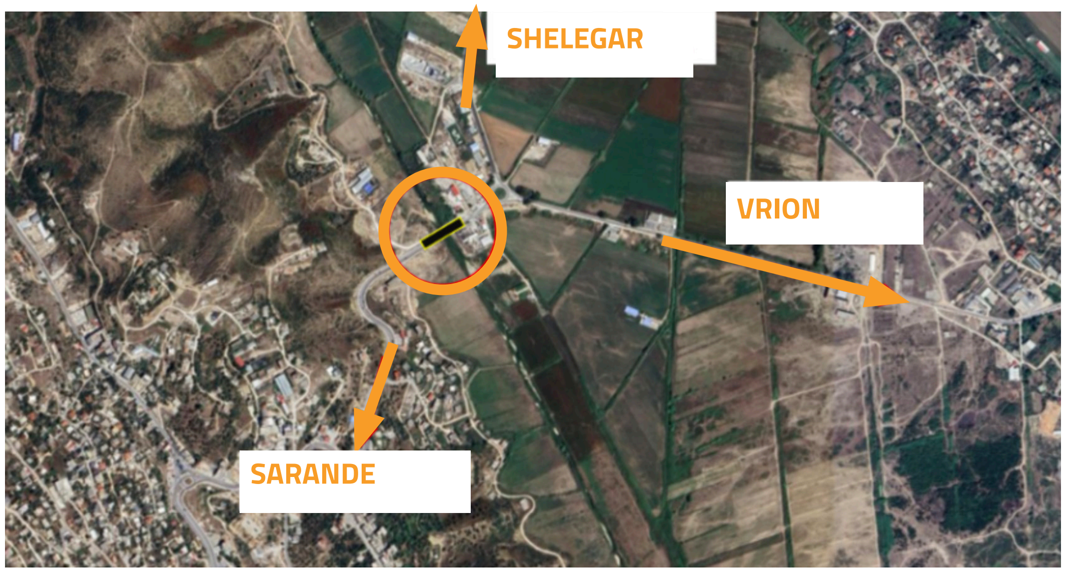
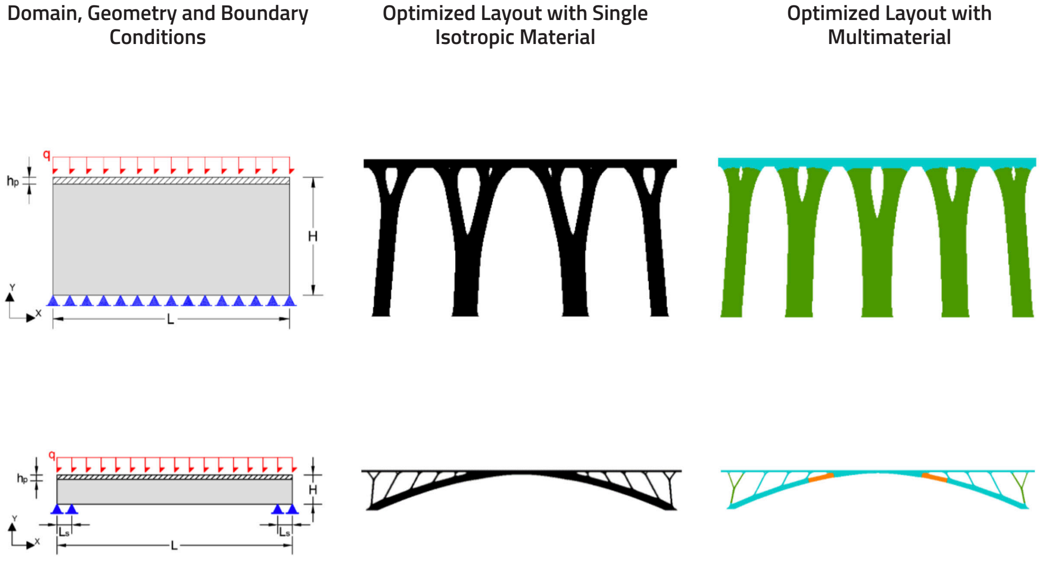


Fig9 / Bridge case study: top view [21] source / the author



Tab1 / Wall and Bridge: design domain, geometry and boundary conditions, optimized layout with single isotropic material and optimized layout with multimaterial
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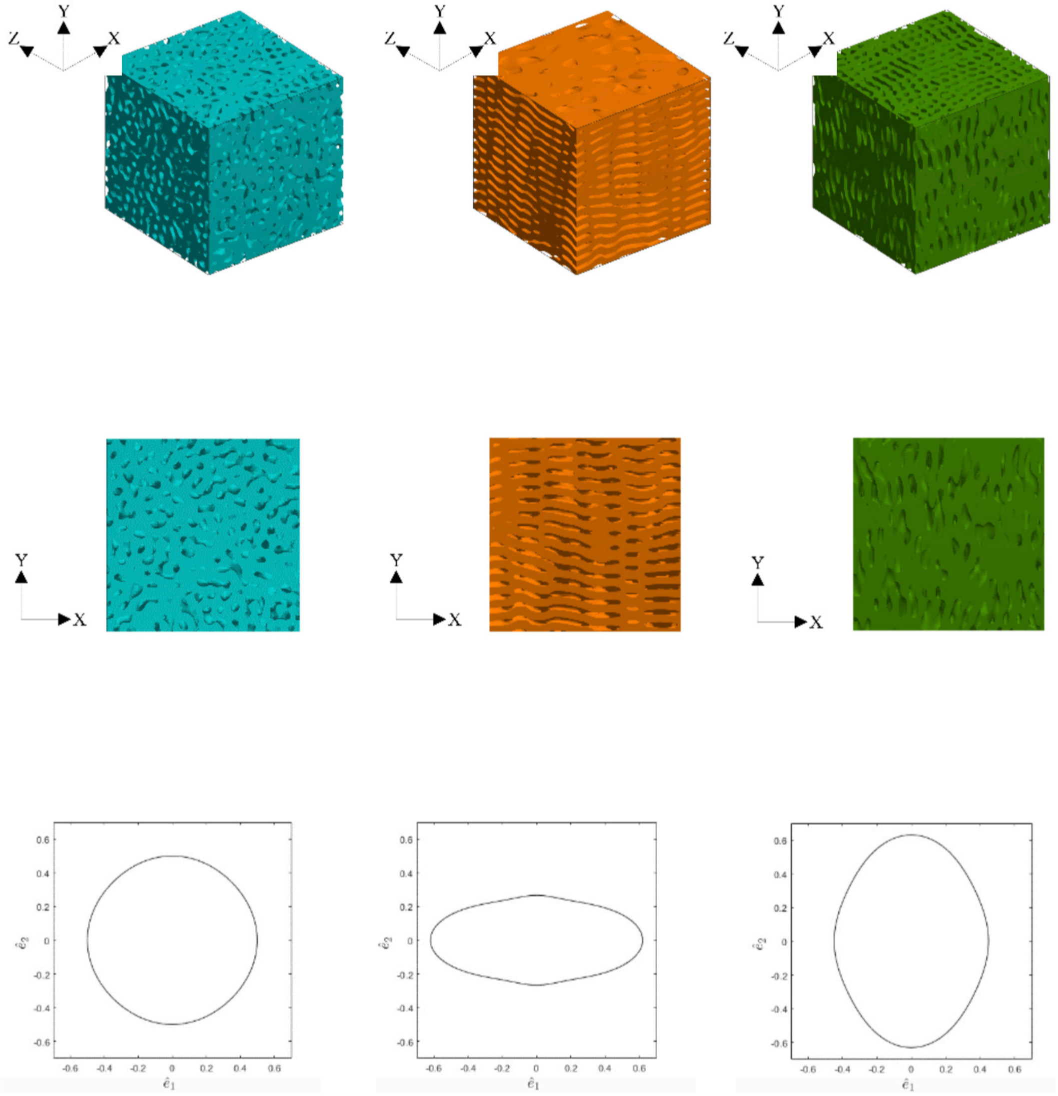

Tab2 / 3D view, 2D view (X-Y) and elastic surfaces of spinodal architectures
source / the author

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