Re-designing demolished Cultural Heritage
A study of a thin shell design for earthquake-destroyed churches in Finiq municipality

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DOI: 10.37199/o41009128

Abstract- *This scientific study involves the methods for the design of thin shells on top of cultural heritage buildings that have already collapsed in the municipality of Finiq.*
The studied object is an orthodox church in Finiq municipality, in Leshnica e Sipërme village. Its roof has already collapsed because of an earthquake and the degradation of the material. However, the dominant part of the structure, such as walls and columns, is still standing, even though need reinforcement. The maximum span of the roof is long enough to justify the use of a thin shell structure. This study tries to find an elegant solution to this problem, which combines structural beauty with the efficiency of the design and building process, defined as important aspects of a good structural design. The methods proposed for the reconstruction of the existing part of the church are the restoration methods used for monuments in Albania. The propositions take into consideration the state of degradation of each structural element. The primary goal for the reconstruction of the reinforcing elements is that they will not affect the primary function of the building and to restore and keep the cultural heritage values of the object. The pre-design of the roof is made using non-linear analyses. The shape of the new roof and its thickness are chosen to use the Hanging Model Analysis, the Sanders-Koiter equations, the Membrane Theory and a buckling analysis using the software Karamba. The designing of rigid joints, which connect the roof with the other part of the structure, is made so that the entire structure could work and behave as one, while it is loaded during its lifespan. The shell is designed as a pre-fabricated one using UHPC material and divided into panels with rigid joints between them.
The analysis and validation of the design of the structure is made with the Load Capacity Analysis in the Ultimate Limit State of it using the software Karamba.
The paper concludes by highlighting the importance of recovering the already degraded cultural heritage structures and the role that technology can play in ensuring the integration of the old part of the structure with the new one.

Keywords:
Thin shell, restoration, structural analysis.

Introduction

This study is concentrated in the pre-design of new roof on the ruins of Shën Thanasi church. Shën Thanasi church is in Leshnica e Poshtme, Finiq, with geographic coordinates 39° 50'36 " in north, 20° 16'01" in east. The church is a building of XVIII century (1711) and had been declared a monument of culture since15.01.1963. It's a basilica type, with a cupola in center with a ground surface of 100 m2 and a maximalheight of 8.6 m. It has three parts: the nave, the narthex and the sanctuary. The nave is a basilica typewith a cupola, has 3 spans of length 8.8 x 6.0 m. Two lines of columns separate the nave in three longaisles, from which the middle aisle is clearly higher and longer than the others. The columns are connected with each-other and with the perimeter walls with arches from both directions. On the western side, the nave

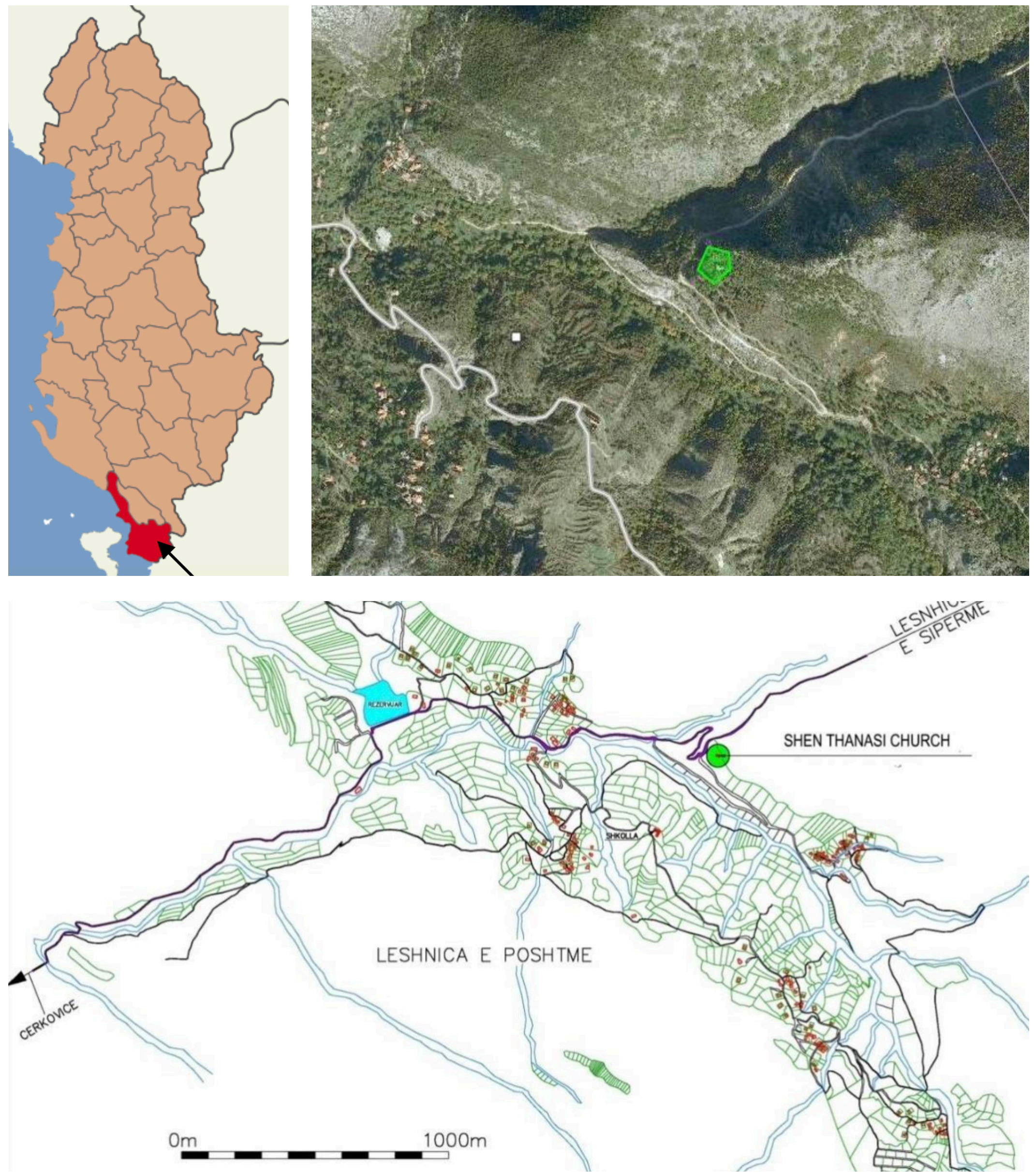

Fig1 / The site location plan of the church, taken from "Institute of monuments of culture, Tirana" source /

is connected with the narthex, which in the initial project has been open with 3 aisles in the opened part of it. Later, three of the entries were filled with masonry in order to strengthen the wall. Its structure is highly damaged during an earthquake of 4th degree Mercalli on 12.05.2014 with an epicenter in Ioannina, Greece. The perimeter walls of the church, along with arches, have cracks. The Portico Wall has a shift from the church wall, the cracks and the deformations have grown in vertical plan and there is a risk of collapse. The main cupola, along with a part of the wall in the southern part, has collapsed. All the columns beneath it have been collapsed too; one column is totally destroyed and the three others are critically damaged.

What are the possibilities of designing a new roof on top of an existing collapsed structure?

The first step for the pre-designing of the roof is to choose its material. It was mentioned since the begging of this thesis that the material being used will be concrete, but not the type of the concrete. Choosing the material affects directly in the shape of the structure, hence affects directly in the efficiency and in the beauty of the design. It should also be taken in consideration that the lifespan of the building will be at least 100 years, since it is a monument of culture.

Efficiency of the design includes two important aspects of the design: The durability and the cost of the material.

Also, the choice of shape will be optimizing its resistance against expected loads.

A proposal for pre-designing an UHPC concrete thin shell. Case study: Shën Thanasi church, Leshnicë, Finiq

Choice of the material

Based on those criteria, two different

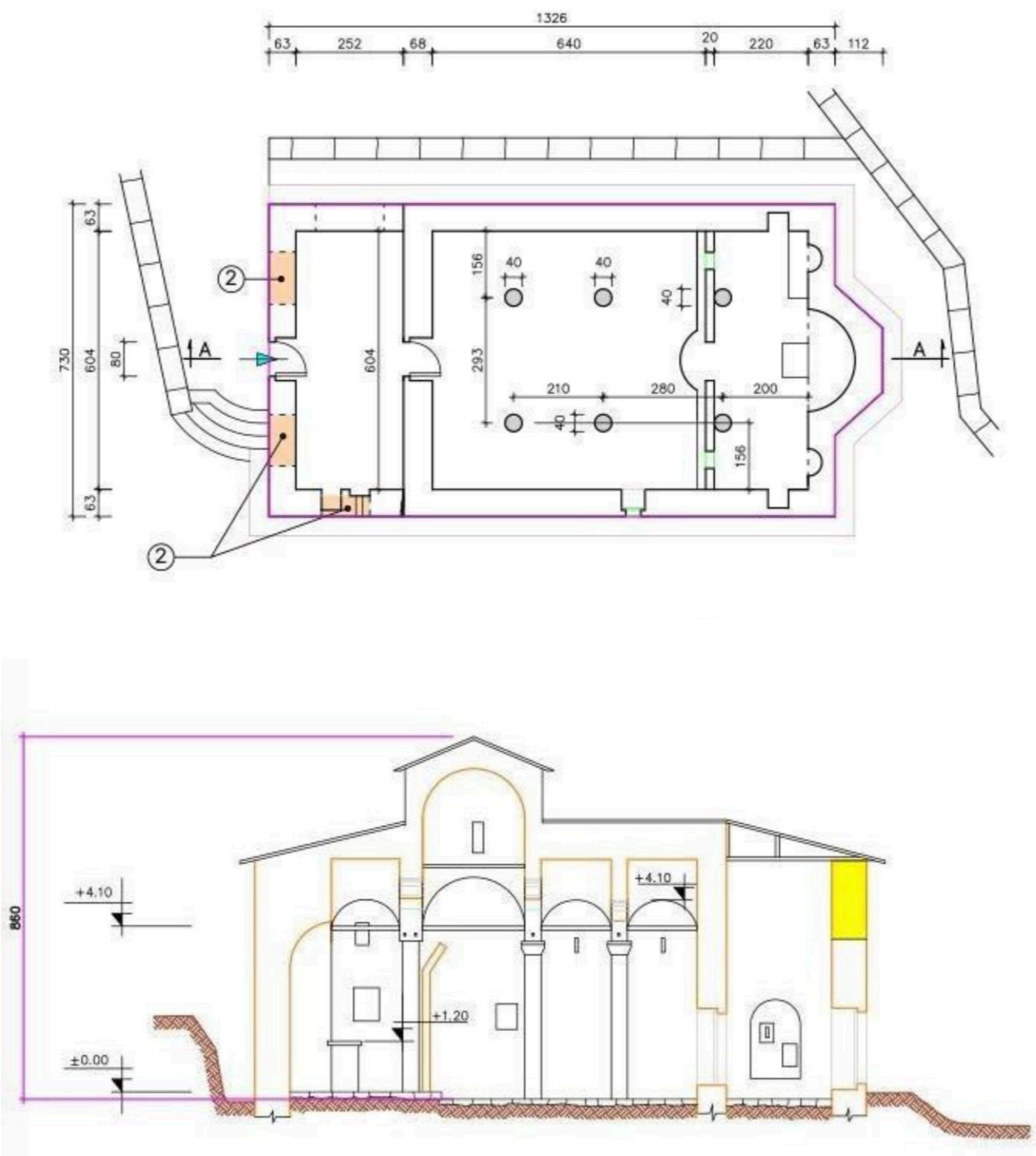

Fig2 / The plan and the section of the church, taken from "Institute of Monument of Culture, Tirana"
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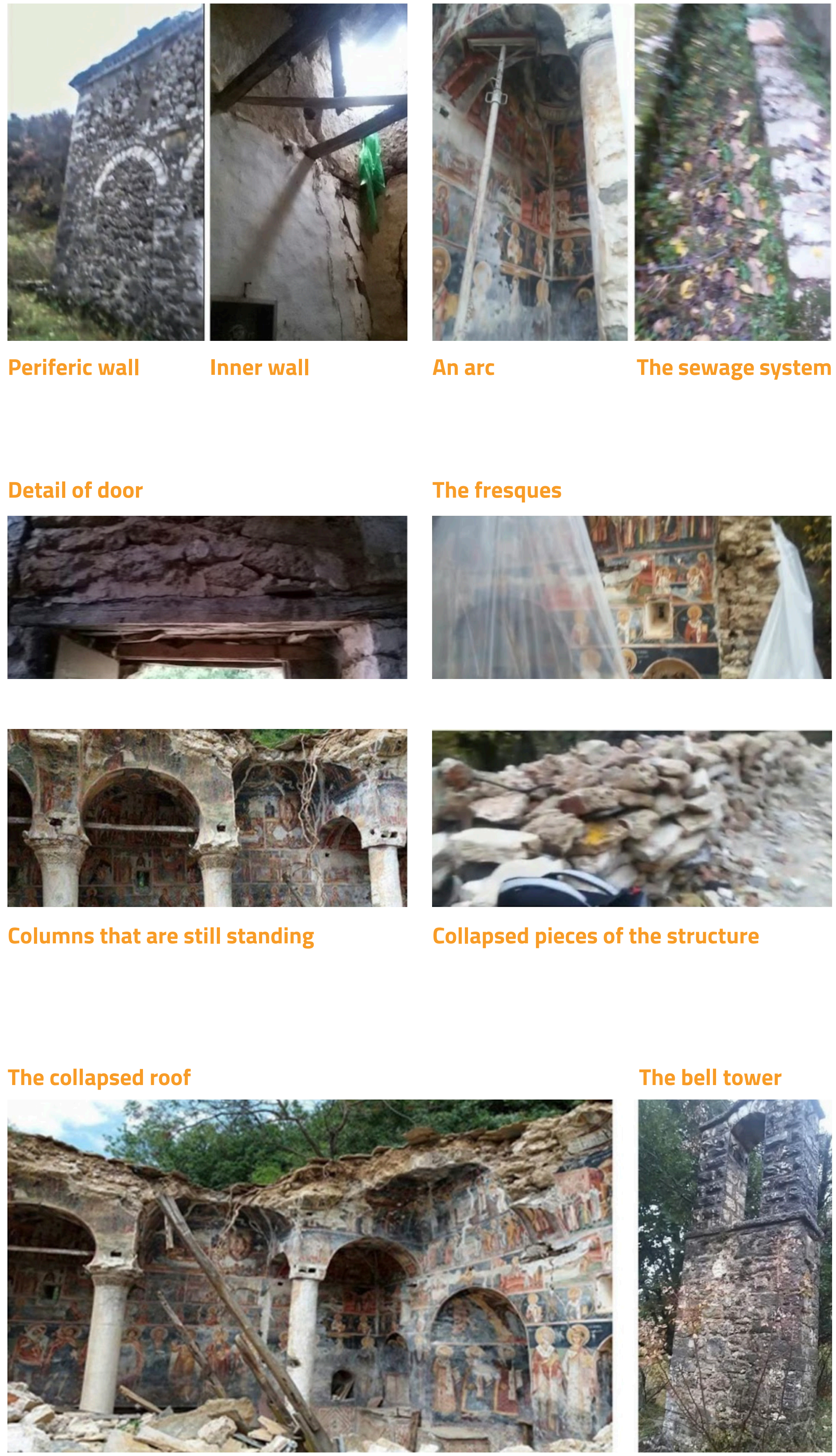

Fig3 / The view of the church after the collapse
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types of concrete are studied:
- Concrete (C30/37)
- Ultra High Performance Concrete (UHPC)

Durability
- Concrete (C30/37)

This type refers to a typical class of concrete with certain physical and mechanical characteristics accepted by European standards, which are mentioned in the Tab1.
- Ultra High Performance Concrete (UHPC)

UHPC refers to fiber reinforced materials with a cement matrix and a characteristic strength between the values 150 to 250 MPa. The addition of fibers is to achieve a good performance of ductility and better resistance in tension. This kind of material is made only in laboratory conditions, hence constructive elements designed with it can only be pre-fabricated ones. Compared with the characteristics of a typical concrete C30/37, it has an outstanding resistance against all kinds of corrosion, better homogeneity, better ductility and better performance against shrinkage, creep and thermal expansion, hence better durability.

Cost of material

Depending on the cost of material, a study which connects the referent prices of both materials with a/t ratio of possible shapes is made. For the calculations of thicknesses are used equations of Sanders-Koiter with the assumption that the load that shells will carry is a point-load on the maximal height of the shells, perpendicular with their surfaces. The referent prices are taken 445 €/m3 for UHPC according to "INNOVAcrete.com", which is the main website of the company closes to the studied object. For C30/37is taken a referent price (Cost = 90 €/m3), according to the previous experiences. The possible shapes that are taken into consideration are spherical cap, ellipsoid cap and cylinder segment.

The cost of the structure will be lower if concrete C30/37 will be used. However, since UHPC is a more durable material, the structure made with it will last longer and the cost of the maintenance will be lower too. Hence, UHPC is chosen as the material of the shell and its price will be taken into consideration when choosing a/t ratio and the surface shape, as it is shown in the diagrams above.

Choice of the shape and the height

Based on the material

As it is mention earlier in this chapter, choosing the material affects directly in the shape of the shell. That happens because the shape must be in a way that it will use the material benefits and make use of its characteristics properly. UHPC has an excellent resistance in compression and the resistance in tension is almost 10% of it. For this reason, shapes that work in tension while are loaded by their dead loads will be avoided. Those types of shapes include tortricids and catenoids.

A structure that works in compression will always be accompanied by the effect of buckling. Hence, the structure will fail from a stress way smaller than the maximum stress of the load capacity. For this reason, a structure that works in compression can never be a minimal surface. Hence, all the minimal surfaces, like Enneper's surface and helicoids, will be avoided.

Since the cost of UHPC is way higher than of a simple concrete, when the shape of the shell is a spherical cap, this type will be avoided as well.

Type of concrete	Standard strength		Design Strength		Elastic modulus	Density	Poisson ratio	Shrinkage factor	Creeo Coef,	Thermal expansion Coef.
	MPa	MPa	MPa	MPa	MPa	kN/m³		µm/m		µm/m/°C
C30/37	30	2	20	1.33	33000	25	0.2	>100	<1	10
UHPC	180	10	150	8	58000	25	0.2	<10	0.3	11.8

Tab1 / Physical and mechanical characteristics of C30/37 and UHPC Heat-Treated Ductal BS1000
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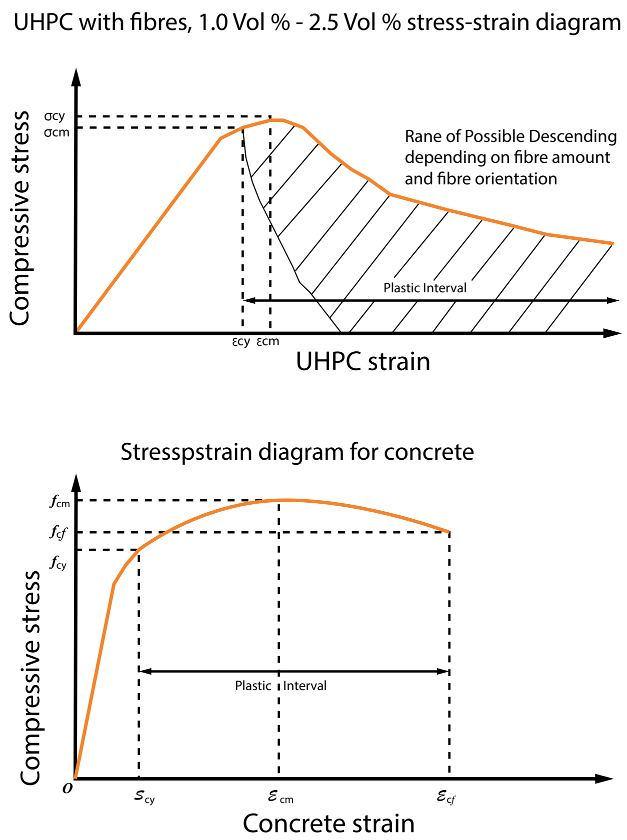

Fig4 / The stress-strain diagram of concrete
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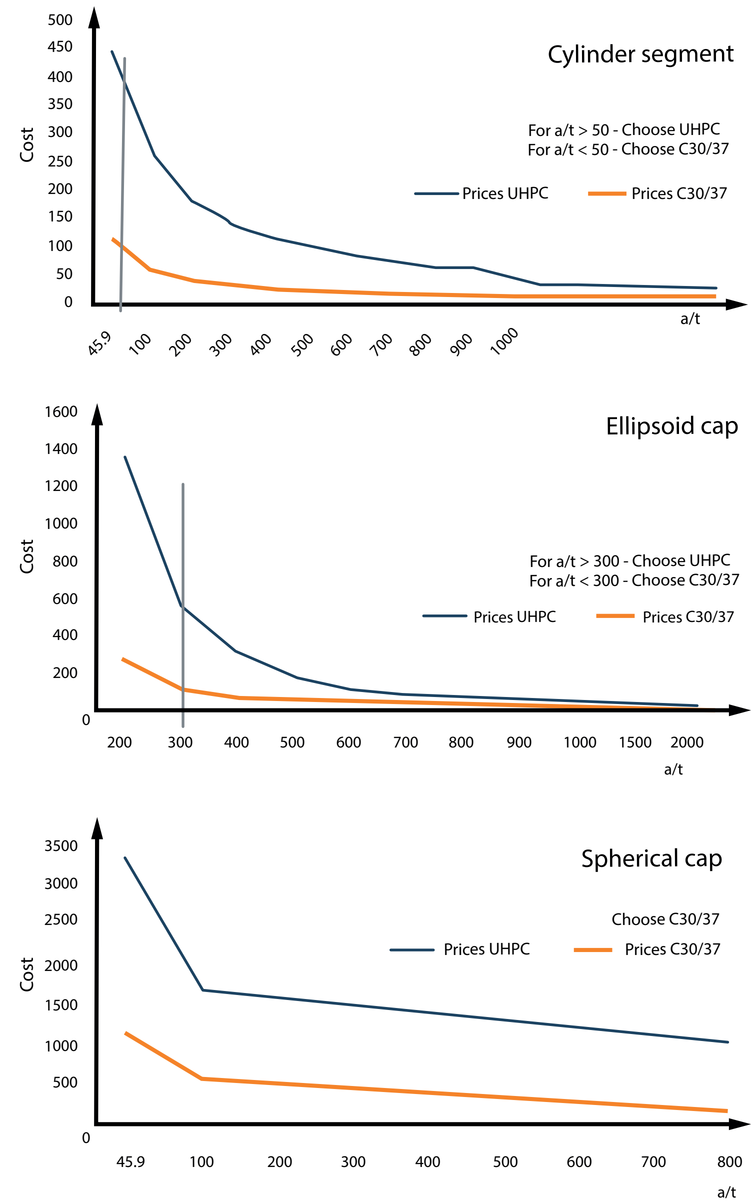

Fig5 / The cost - a/t ratio diagram of different possible surface shapes of the shell
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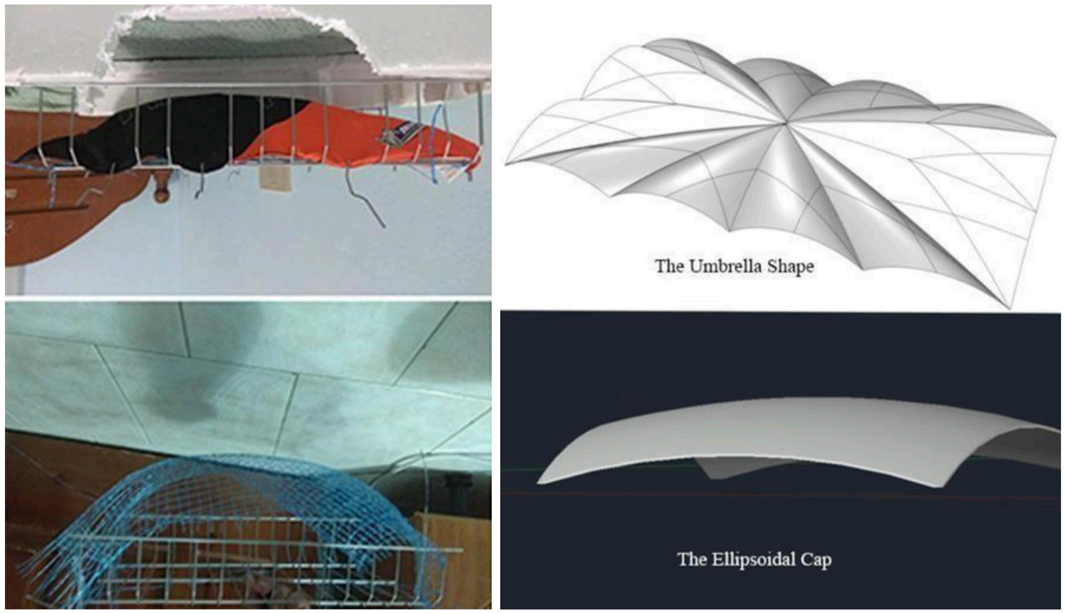

Fig6 / The chosen shapes
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Based on the spans

The spans of the shell are defined by The Perimeter Walls. They are l1=14.38 and l2=7.3 m respectively. The lengths of the spans are comparable with each-other (l1/l2≈2), so the stresses of the shell will spread in both directions X and Y of the plan of the structure. Hence, shapes that work in compression, only in one direction, when they are loaded by their dead load, will be avoided. Those types of shells include hypars and cylinders.

Design	Height (cm)
1	70
2	90
3	100

Tab2 / Design approaches based on different heights
source /

Based on height of the roof

Choosing the height affects directly the structure behavior since shells are geometrically based structures. Considering a shell with a long height, it can intuitively be said that the buckling is less likely to affect the structure comparing it with a shell with a shorter height. However, having a higher shell will require more material; hence, it will not be efficient. Having those two criteria in mind, buckling and efficiency, 3 different design approaches will undergo a linear buckling analysis before choosing the final one.

Using hanging model analysis

Two forms will be taken into consideration. The first one is an ellipsoidal cap (elpar), which pleases the conditions of an efficient and simple shape. The second one is an umbrella shape, which is less efficient than the first shape, but has more stiffness.

Results

The main objective was to create a functioning concrete roof structure and include it in a restoration of a cultural heritage building, which was expected to maintain a fine balance between aesthetical, structural and constructional efficiency.
Attempts have been made throughout the thesis to create such a shell structure by taking these factors into account.

Conclusions and Recommendations

The Umbrella Shape gives the structure a modern and complex look that gets the attention of the people, but yet, its delicacy and minimalism does not ruin the balance with the precious existing structure. The shell is elegantly combined with rest of the naves to provide a better visual representation of the frescoes and curved shapes. This is an attempt to enhance the aesthetical efficiency of the roof system, although it should be pointed out that the achievement of this aim is subjective to the reader.
Studying the structural efficiency has shown that:
Using UHPC is more efficient than using a regular concrete when designing thin shells with ratio of spans ≈ 1,5 and a/t > 300.
From 8 studied shapes, the Ellipsoidal Cap was the most efficient.

	height (m)	area (m2)	k1 (1/m)	k2 (1/m)	kg (1/m2)	km (1/m)
umbrella shape	0.7	117	0.98	0.07	0.0700	0.527
	0.9	114	1.8	0.013	0.0243	0.917
	1	113	1.59	0.004	0.0068	0.801
ellipsoidal cap	0.7	107	0.10	0.026	0.0027	0.064
	0.9	108	0.12	0.034	0.0043	0.080
	1	109	0.13	0.037	0.0053	0.088

Tab3 / Characteristics of the chosen shells with their principal curvatures
source /

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