The structural tree: new experimentation with reinforced stone

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ABSTRACT

Starting from the reinterpretation of the natural forms that recurs in the consolidated shapes of historical buildings, the research proposes the umbrella vault as isolated self-supporting cover. The research outcome, defined with the term "structural tree", can be considered as an extreme experimentation of the cooperation possibilities between natural stone and steel reinforcement.

The idea arises from the observation of fan vaults in which appears an isolated support: its static behaviour works, of course, because of the presence of an opposite structural portion.

In this case, on the contrary, there are no lateral supports but it arises as a self-referential element, while the task of restoring the structural balance is left to the upper reinforcement that allows a free composition of the "tree" without static constraints. The study is based on a formal research that combines the possibility to create serial and repeatable compositions with the achievement of an ideal static equilibrium configuration of the stone structure that considers the collaboration between the voussoirs and the upper reinforcement.

The steel structure is not assumed as a pre-tensioned reinforcement, like in the other prototypes, but as a passive reinforcement to recreate the compression condition of the arch, usually generated by the opposing forces belonging to the two symmetrical halves.

INTRODUCTION

The revival of forms derived from nature in architecture and the subsequent association of natural structures, complex geometries and architectural forms, can be easily found in many examples, from historic structure to contemporary applications, in which the use of mathematical algorithms define the geometric principle that gives shape to the constructed form.

In this regard should be considered the work "Fractals: Form, Chance and Dimensions" by Benoit Mandelbrot, in which there are some clear connections between the field of fractal geometry and architecture, recognizing the affinity of the various architectural styles with the two opposing aspects of Euclidean geometry and fractal geometry. [1]

The tree looks like a recurring element of influence of natural form in architecture, probably for the close relationship between the forces development and its shape that creates a functional combination between support and roof.

In general this type of structure is shaped to respond to a compression behavior or to act like an inverted stressed system that collect the loads up to a single anchor point.

The tree structures can be divided into two types: those with a hierarchical organization, in which each part is geometrically similar to the whole (that can be assimilated to fractals in which the self-similarity is a distinctive property) and those in which the total weight is distributed to the main support through a single point (the umbrella structures, also defined as a sub system of the branched constructions).

Although this type of structures presents a close relationship between the load path and its conformation, the structural behavior cannot be compared with the "tree" organism as it exists in nature because the bending stresses, that in the first are systematically avoided, are a constant feature of the second. [2]

Background

The formal antecedents of this type can be found in many historical examples as isolated supports taking part of a vaulted structure, in particular during the Gothic and late Gothic period in which fan vaults and umbrella vaults have been a great spread.

In the **Jeronimos Monastery** in Lisbon, the pillars that divide the nave are joined to the barrel vault through asymmetric umbrellas with bearing radial ribs closed with thin stone slabs.

The serial organization of the supports is associated with the classical static configuration of stone vaulted structures: the umbrella is not conceivable as an isolated element but it must be part of an “arch” structure, in which the portion of the arc that originates from the support must oppose in the same way to a second identical and symmetrical portion, bringing back the system to an equilibrium configuration.

The particular configuration of the support represents an expressive intent that does not depart, anyway, from the traditional static configuration of the stone vaults.

The same happens in all the similar examples that we can find. In the **Chapter House of Wells Cathedral** the central umbrella can work thanks to the presence of the eight fans that surround it, creating a whole structure where the various parts find their balance through the equilibrium with the opposite stresses.

In the **Church of the Jacobins in Toulouse**, on the other hand, the idea of the iterable module finds its best example: there is a clear demarcation of the square spans and the repetition of the umbrella is carried out for the entire length of the nave.

But the character of isolated support can be found again only through the introduction of other materials. The Nervi’s applications of reinforced concrete resume the idea of the juxtaposition of modules simply joined together: the 16 elements that come in succession in the **Labour Palace in Turin** (1961) have a slight gap that makes even clearer the pursued concept of iteration and seriality.

The result depends, of course, from the different character of the material used. Each of the pillars presents a variable section that passes from the cruciform to the circular profile, from the base to the top, while the umbrella is composed of a halo of steel beams with variable section.

The formal expressions that exploit the potential of the steel have a great number of possible variations, so the tree element is materialized in many applications with different levels of complexity.

The **Atocha station** (Moneo, 1984-92) can be considered a direct consequence of the Nervi’s conception previously mentioned: once again the pillars are made of concrete but the square module is divided into 4 triangles in which the beams are arranged parallel one to another. [3]

In the **Oriente Station in Lisbon** (Calatrava, 1998) the steel is, unlike the examples already cited, the only structural component: the branched supports bear four inclined squares made of parallel bars, forming a light roof.
The ramification of structure is carried to the extreme in the **Stuttgart Airport** (Gerkan, Marh & Partners, 1990), in which each support presents a triple subdivision in 48 branches to connect it with the flat roof; in this point their diameter reaches only 16 cm [4]. As a direct derivation, in the project **"the Tote"** in Mumbai (Serie Architects - 2009) the ramification fit to the roof inclination and the two sides join one to another in the central part.

In the **Expo Roof of Hanover** (Thomas Herzog - 2000) the mutual cooperation of wood and steel in an umbrella structure presents another conception: the four wood shells, made of crossed beams, define double curvature surfaces and connect to the supporting tower through a steel connection.

Here the idea of the umbrella changes and introduces the bending and deformation of surfaces, brought to the limit in the Shigeru Ban's projects, as in the **Nine Bridges Country Club** (Korea **–** 2010) or in the requalification project of the **Powerhouse Museum** (Ultimo, Sydney, Australia - 2012).

Previous experimentations

The structural tree arises transferring to stone the idea of isolated support through the reinterpretation of natural forms; the research subject is to find conformations and methods through which stone masses can find their equilibrium configuration without the typical mutual contrast of the vaulted systems.

The various aspects of the prototype proposed are, of course, a consequence of previous experiments designed with the aim to combine the morphological research with the optimization of the structural behavior.

In the **Alexandros Obelisque** (Fallacara, 2006), presented at the Biennale of Venice, two devices, that will be proposed and modified in several ways, appear for the first time: the pre-stressed steel reinforcement and the research about joints.

The steel reinforcement could compensate, in terms of overall resistance, the weaknesses of the stone; the joints were designed imitating the knee anatomy**,** with the aim to allow the movement of the blocks without risking to damage the stone. Neoprene was used in the joints like cartilage, imitating the same spatial configurations between the contact surfaces of blocks.

Subsequently, the structural arrangement of the pre-tensioned reinforcement will be re-applied in the construction of the **Oblique Obelisque** (Fallacara, 2010), in which its function is even more important in order to contrast the horizontal thrust of the structure, due to the oblique conformation.

In this case carbon bars are applied to the structure, in order to connect the vertex of the obelisk with a point of the triangular base positioned about 2/3 from the cathetus. Each ashlar is then fixed using a dedicated product that prevents the seeping of epoxy resin into the axial bore of the ashlars or into the contact surface between blocks. The carbon bars were bonded into the obelisk foundations using a direct injection of epoxy resin executed from the top.

Fundamental can be considered the contribution of the prototype **Foglia** (Fallacara, 2009), constituted by a suspended portion of arch in order to create balconies or canopies**.**

Here is improved the concept of the incomplete arch behaviour that needs to be balanced through external forces in order to find the static equilibrium: here that forces are supplied introducing a 'leash' on the extrados that blocks the keystone in the semi-arch, guaranteeing the


compression of the ashlars. Paradoxically, in this way, the more traction applied, the more the load bearing system is static.


The prototype

The tree structure is designed as an isolated and iterable structure formed by a central trunk from which start 8 arms. Each of the stone branches is defined by a lowered curve and shows a decreasing height up to the outermost point of the structure.

The possibility to create an independent element is given by the presence of a passive reinforcement that, starting from the center of the trunk, connects and compresses all the blocks of the 8 branches and ties the extremity, giving rise to a contrast force that recreates the elements compression.

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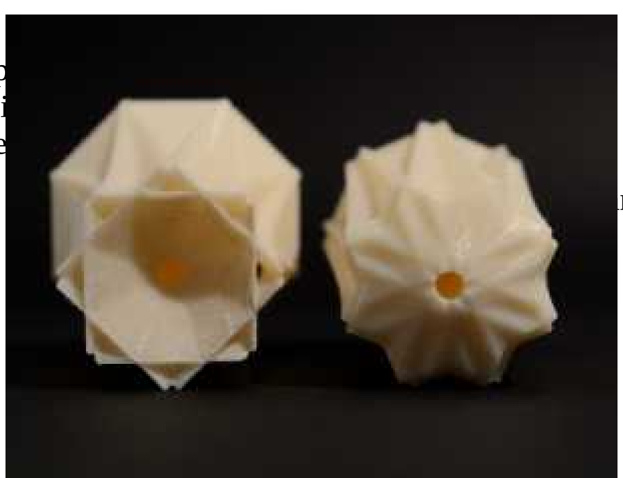


The overlapping elements of the stem have been designed according to a star-shaped interlocking joint that made them integral, very important especially for the last part that acts as a coupling for all arms.

In order to experimentally verify the structural behaviour has been used a maquette made of plastic material (ABS), created by computer numerical control machine, that replies the voussoirs shapes with the contribution of the upper reinforcement.

This construction on a small scale has allowed checking the strong points and weaknesses inherent to the considered system, constituting a first step substantially coincident with the outcome of the structural analysis.

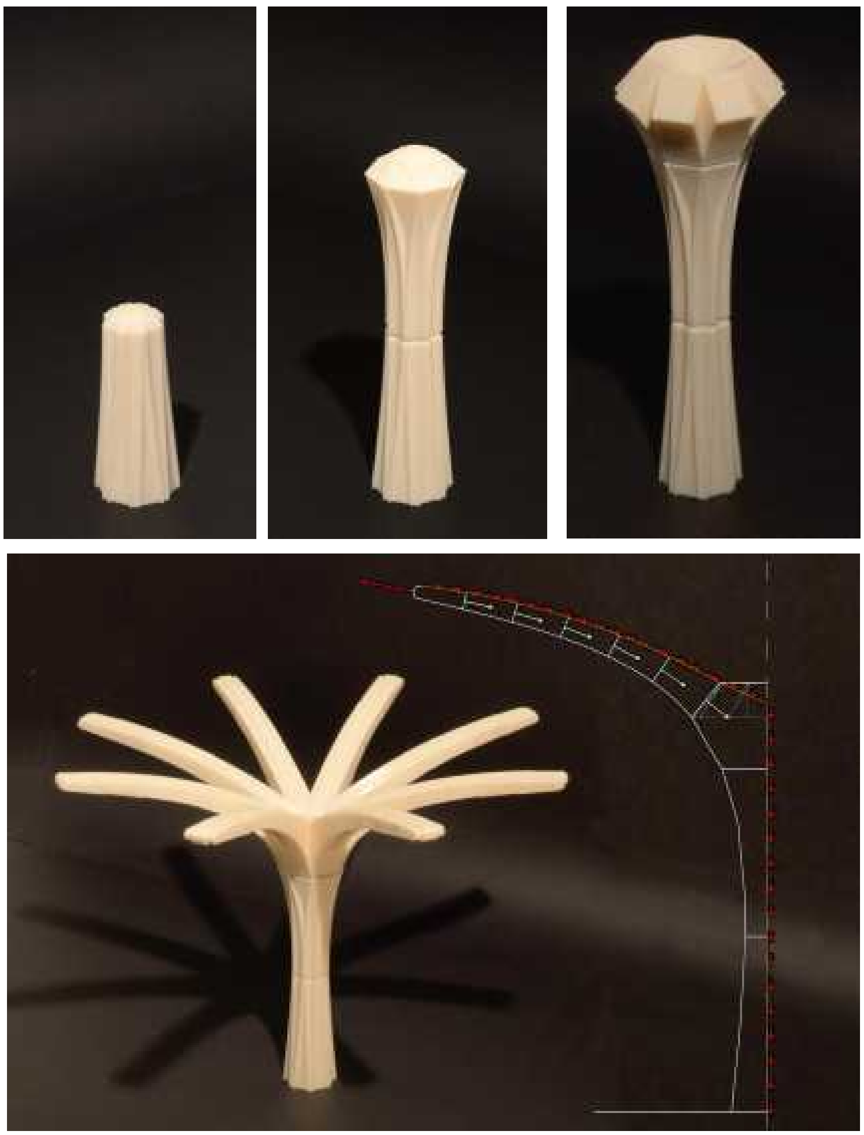
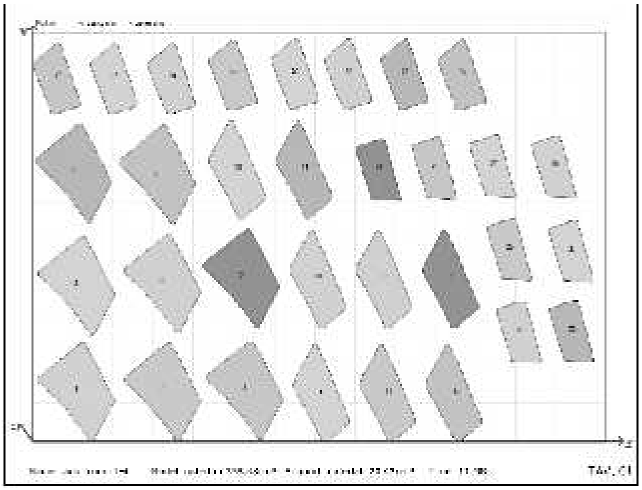
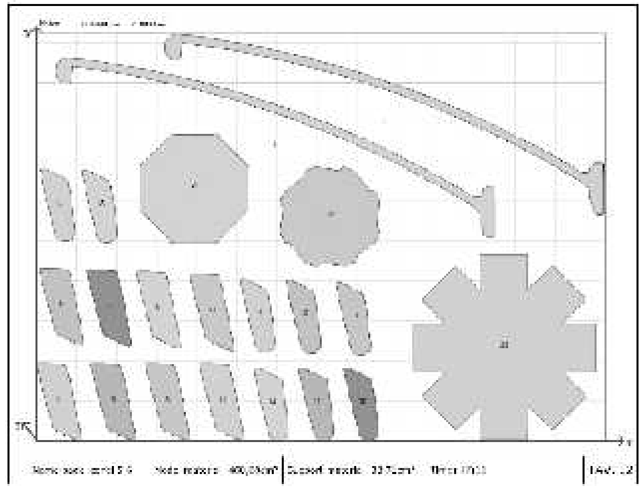


Figure 8-9-10-11 Assembly stages of the maquette





(rapid prototyping elaboration and manufacturing by Vito Cascione, PhD Student - Department of Civil Engineering and Architecture, Polytechnic of Bari, Italy)

The stone prototype in scale 1:1 will be built during the next July, in collaboration with the *S.N.B.R.* Society of Troyes and the *Atelier de la Pierre d'Angle* in Brignoles, with the aim to confirm the rightness of the static research. The stone cutting will be done with CAD/CAM processes in Troyes, the assembly will take place in Brignoles.

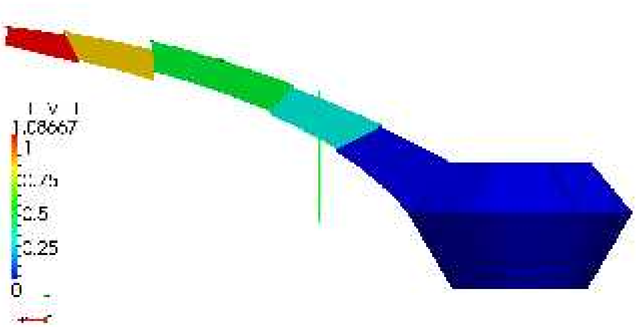
Numerical analysis methodology

Concerning this first prototype, the assessment of the stability is proposed using the LMGC90 open platform [5][6] dedicated for the modeling of large collections of 2D or 3D objects. The Non-Smooth Contact Dynamic discrete element method [8][3] is used to perform the mechanical behaviour of the "structural tree". The stone blocks are modelled as 3D rigid elements interacting by a Signorini-Coulomb friction law applies for contact points between blocks. In order to consider the tensile effect of the steel elements, an additive interaction law describing the behaviour of an elastic wire has been introduced to connect the rigid elements on their upper-part. An initial prestress and a rigidity relying on the product of the Young modulus by the steel section [illegible] etry of the structu[illegible]ng a given geometry of the tree and a stone property restricted to its density (2000kg.m^{-3}) due to the rigid modelling, the friction coefficient and the initial prestress remain the variables that could influence the mechanical behaviour.

Figure 12-13 Model shapes from the CNC machine modeler

Results

An initial prestress of 10^{-3} m/m has been introduced into the elastic wires and a very small friction coefficient of 0.2 has initially been considered into the numerical model. This friction coefficient value has no relation with the dry friction between stone blocks, usually estimated around 0.5-0.7 but it aims at understanding the behaviour of the prototype realized in synthetic material unable to undertaken any friction. The result of the numerical modelling matches obviously well with the physical experiment. The same sliding mechanisms between joints are observed leading to a global instability of the tree structure.



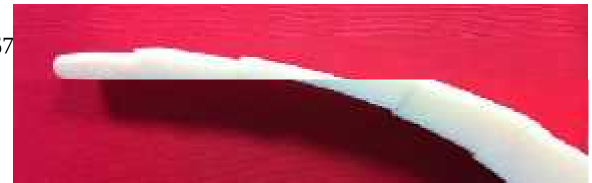


Fig.14 : Numerical modelling of one branch

Fig.15 : Physical modelling of one branch

Discussion

Further simulations have been conducted on this first prototype to consider either a greater friction coefficient or a smaller initial prestress in order to get closer to the real structure. Indeed, the dry joints would resist with a friction coefficient closed to 0.5-0.7 as previously mentioned, while the prestress could vanish by thermal dilatation of the steel elements. The variability of these parameters does not imply any important changes in the mechanical behaviour; the instability of the structure remains. Such report argues for a well-known technical requirement for stone construction, *i.e.* the joint orientation is a crucial parameter for the stability. Consequently, the branch subdivision must be redesigned properly according to the loading to assess the required stability.

Thus, a new design of the branch elements is proposed to be modelled. The joints are perpendicular to the neutral axis of the elements. A 0.5 friction coefficient and no initial prestress are considered for the calculation. Finally, this new arrangement of blocks conducts the flow of forces and the stability of the structure is achieved.

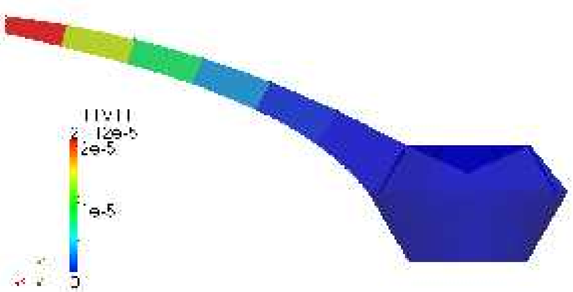


Fig.16 Stability of the new design

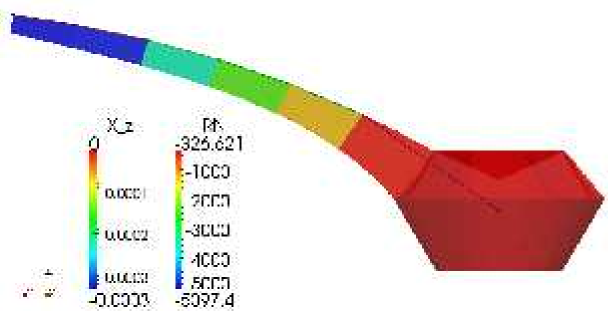


Fig.17 Maximal Z-displacement and tension into the steel elements

Design applications

The results obtained from the serial repetition of a single support may be ideal for spaces such as railway stations, markets, exhibitions halls and so on, that need large sizes combined with the effect of spatial fusion. The branches may be covered with light material, such as wood or glass, and aggregate in a free manner, depending on the required function, allowing a subsequent addition of modules without altering the overall balance of the system.

Fig.18 Design applications: railway station hypothesis
(Graphic rendering: Nicola Boccadoro)

CONCLUSION

The problem to actualize a traditional material is solved in the repetition of a shape closely related to the historical inheritance but configured with the aim to disengage from the imposed compositional limits: each tree is a self-referring structure, both in static and compositional level, and can be combined in the appropriate way in accordance to the desired result.

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