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Design in Stone: Perspectives of Formal and Technological Innovation of Domes

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ABSTRACT

This study focuses the structural and aesthetic potentiality of the Apulian apsidal vaults, regarding to the innovation of the design paradigm of the dome in stone.

Apulian apsidal vaults are spherical or pseudo-spherical vaults, minor of an half-dome. They have the retraction of the keystone and a specific masonry texture. Thanks to these features, they are stable and constructively autonomous (despite the lack of the other portion of the dome).

The study gets to:

- Redesign of an apsidal spherical vaults case of study in Basilica of St. Nicholas in Bari.
- Design of innovative stereotomic domes in stone, composed of two or more hemispheres auto-stable and equipped with two or more keystones.

The paradigms developed are innovative compared to traditional ones, because:

- They apply stone stereotomy and three-dimensional infographic modeling to design methodology, opening the door to the realization of the single ashlars with CNC machines.
- They extend the use of the apsidal vaults to the domes, improving their mechanical performance and increasing the several forms that the project can gets.

KEYWORDS: stone, dome, apse, vault, stereotomy, technology, innovation, design

1 INTRODUCTION

This study derives from a research on design and construction of stone bearing elements in Apulian religious architecture, carried out by the author in Department ICAR (Science of Civil Engineering and Architecture) of Polytechnic of Bari.

Here is presented the final outcome of the research, which consists in the convergence between the Apulian architectural tradition and the new CAD-CAM technology, in the developing of new paradigms for contemporary design in freestone.

The methodological approach comes from the research on stone stereotomy conducted in the School of Architecture of Bari by Claudio D'Amato.

The method consists in coding into paradigms the elements of the stone architecture.

2 PARADIGMS AND DESIGN IN STONE

The constructive system in stone has strong expressive potential and identity characters in Apulia and in Mediterranean area.

Today, the stone of the great Apulian cathedrals has lost its role of bearing structure.

The constructive systems, in wood, iron and concrete, completely replace the traditional constructive system in stone.

The new constructive systems are composed of simple and finished elements, such as the pillar and the beam. On the other hand, the constructive system in stone is composed of complex architectural elements, such as the wall, the arc, the vault. They are composed themselves by a high number of components (the ashlars).

The construction for ashlars involves the need to anticipate size, morphology and organization of the ashlars since the design phase. The characteristics of the ashlars and the way they are organized determine both the structural performance that the aesthetic form of stone architecture.

This leads to greater complexity in the design process both with respect to achievement of aesthetic form that compared to the statical check of the structure.

To facilitate the control of these aspects, in the tradition of Mediterranean, the stone architecture design was tied to the use of constructive paradigms.

The constructive paradigm in stone is an abstract entity with morphological characters and a law for the organization of the ashlars. Within its constitutive law, the paradigm has invariant parameters and ranges of variance. These factors are familiar to the designer. The designer gets the design solution of the particular case, respecting the invariants and calibrating the parameters of the variance within the paradigm's law.

The paradigms are composed of elements and structures of lower grade, but they can also be composed in systems of higher grade, up to the complexity of the entire architectural building.

Also the stone stereotomy, since the treatises of the sixteenth century, assumes the paradigm as ordering principle (for examples, the "trompe" of Philibert Delorme and the "oblique passages" of Frezier).

Most recent updates of stereotomy use the paradigm too, such as “Foglia” and “Flexi Arch” by Giuseppe Fallacara.

After defining the constructive paradigm of an architectural element, it is now possible to check numerically the single ashlars and the overall morphology of the element. The control process takes place in the design stage through the 3D infographic modeling (CAD) and in the production of the ashlars through CAM-CNC process.

3 APSIDAL STONE VAULT PARADIGM IN APULIA

Apulia has a wide diffusion of the apses. They appear in most of the buildings for worship, both in small churches and in the cathedrals, since the early Christian Age.

Figure 1: Apsidal vaults in Basilica of St. Nicholas in Bari. The case of study is on the right

The Apulian apses belong to the architectural wall system. They determine the extroflexion of the wall to the outside. From the inside they conclude the aisles, creating usable spaces beyond the presbytery.

Each apse is composed of a wall with curvilinear developement and by a vault. The vault can be set directly on the top of the curved wall and connects the extroflexion of the curved wall to the vertical plane from which the apse comes out.

3.1 Aesthetic and formal considerations

The geometry of the apse and of its components varies depending on the building. However, the Apulian half-domical vaults are spherical for the most part.

Moreover, they are usually set to a circular segment minor than the semicircle. From a formal and aesthetic point of view, the reduction of the impost segment allows you to limit the depth of the apse, to integrate the apse into the wall the better you can.

These types of vaults are a portion of dome smaller than half dome. So the keystone cannot be aligned with the geometrical center of the sphere and have to move back. This makes it impossible to build the Apulian hald-domical vault with the same constructive system normally used for the construction of the whole domes or half-domes.

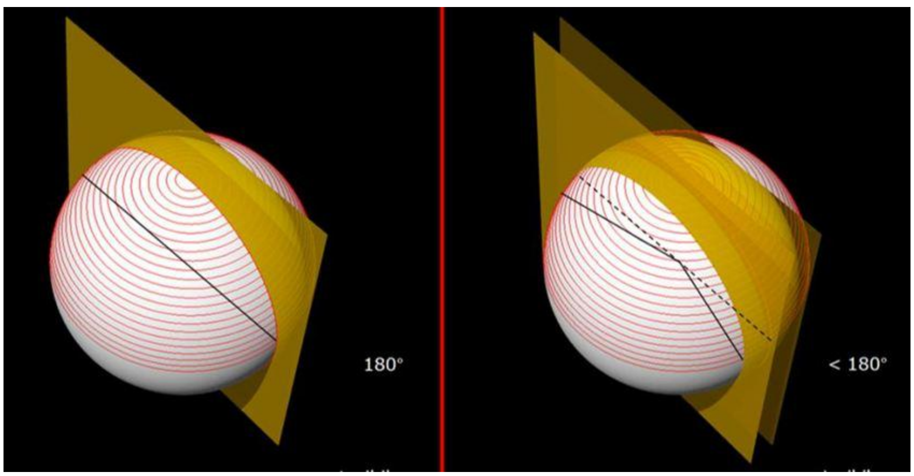

Figure 2: Constructive problem in apsidal spherical vaults minor than half-dome

Then, the constructive solution adopted by Apulian *magister* to build the half-domical vaults increase the grades of freedom of the project, with respect to the dome and the half-dome.

In fact, this solution allows the connection between a circular segment of impost and the intrados of frontal arch, which are both belonging to the same spherical surface, without limits to the vault depth.

The basic parameters of the half-domical vaults design are the radius of the intrados sphere and the distance between the sphere's center and the chord subtended to the circular segment of the impost.

3.2 Geometrical and constructive considerations

The basic problem of spherical vault minor than half-dome is the placement of the keystone off-axis with respect to the geometrical center of the intrados sphere.

The most common solution in Apulia provide the rows are inclined towards the bottom of the vault. The rows have variable height: maximum at the frontal arch and minimum at the bottom. In this way you can have enough space at the top of the vault to place the key stone. Paolo Perfido (2008) notes the advantages of the rows inclination: reduction of the use the centering and reduction of vault thrusts on the plane of the frontal arch (where there is no resistance, because of the lack of the other dome's portion).

To meet these needs, the ashlars of the Apulian vault are all different by each other, repeatable only once for symmetry.

3.3 New geometrical and constructive hypothesis

The research explains the geometric model and the construction technique employed by Apulian magister to cutting the ashlars and put them in work.

The developement of the inclined rows can be attributed to the conic sections of the sphere subtended at the intrados.

They are easily obtainable in the building-yard using two rods.

The first rod is pivoted to the geometric center of the sphere of the intrados and has length equal to the radius of the sphere. The second rod is pivoted along the horizontal axis or the vertical axis of the vault, off-axis respect to the geometric center of the sphere. The first rod rotates freely in space. The free end defines the locus of points belonging to the spherical surface of the intrados. The second rod rotates with a constant angle. The inclination of the rod defines a conical surface. When the two rods meet, they materialize in the building-yard the locus of the intersection between the sphere and the cone.

The geometric model can now be checked numerically in a simple manner through and the infographic 3D modeling.

4 REDESIGN OF A TRADITIONAL APSIDAL STONE VAULT

The constructive hypothesis was tested by 3D laser scanner survey, 3D CAD analysis, and redesign of a case study: the right side apsidal vault the of the Basilica of St. Nicholas in Bari (Laboratory of Degree "Puglia Romanesque," graduate students: A. D'Amelio, F. Preziosa, G. Reale, F. Rubino, S. Scarda, M.G. Ventrella).

The survey shows that the arc is 2.14 meters in radius, the chord is 4.22 metres and the maximum depth is 1.82 meters. Then, depth is 0.32 meters less than the radius. The intrados surface is spherical, with a radius of 2.14 meters.

The redesign has followed the stereotomical principles.

The geometrical model of reference for the developement of the rows is the conical intersection of the sphere subtended at the intrados. The study highlights two different methods to get the masonry texture of the original element.

4.1 Conical Sections - cones with vertex on the horizontal segment of the impost

In the first case, the frontal arch should be decomposed into an odd number of radial segments, converging to the center of the arc

Once defined the thickness of the vault, the beds of contact between the rows are the result of the conical intersection. The cones have vertical axis. They have vertex on the horizontal axis of the circular segment of impost.

Since the circular segment impost is less than the half circumference, the vertices of the cones should fall in a segment of its horizontal axis astride the chord.

The segment where the vertices of the cones fall, can have length greater than the half distance between the chord of circle of impost and the axis passing through the center of the sphere (eg 5/8) The segment must be included for the most part between the chord and the center of the sphere (eg. 4/5) and for a small part between the chord and the bottom of the vault (eg 1/4).

The first rows, starting from the tax, are the intersection of the thickness of the vault with cones with vertex at the same point, coinciding with the beginning of the segment previously identified The other rows are obtained for subsequent conical section with cones having vertex at different points, gradually moved towards the bottom of the vault.

The cones are off-axis with respect to the sphere. Therefore, the conical intersections generate inclined rows, with decreasing height from the front arch towards the bottom of the vault.

The generatrix of the cone passes through the joints of the intrados of the respective segments of the frontal arch.

The inclination of the rows of the vault does not match the radial joints of the frontal arch. Consequently, the frontal arch must be equipped with its own thickness and the rows should be inner clamped to it.

The joints between the segments of each row are obtained by intersecting the generic row with a beam of plans for the vertical axis of the frontal arch.

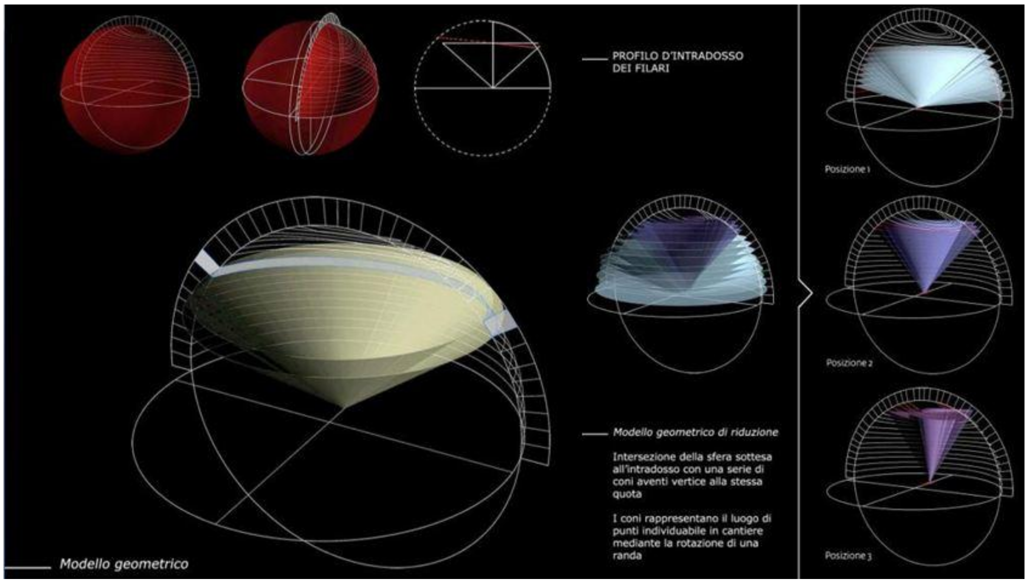

Figure 3: Redesign of the case studied with the first method

4.1 Conical Sections - cones with vertex on the vertical axe of the frontal arch

In the second case, the frontal arch should be decomposed into a number of odd wedge-shaped segments.

The beds of contact between the wedges need do not converge at a single point. They have to converge in pairs at different points along the vertical axis of the arch.

To get the points of convergence is necessary to divide the lower half-axis of the frontal arch into a number of segments equal to one half of the ashlars of the arch. This configuration allows you to easily place the key in backward position. At the same time, the joints between the ashlars do not deviate excessively from perpendicularity at the intrados (the perpendicularity at the intrados is the best condition from a mechanical point of view).

Once you have defined the thickness of the vault, the beds of contact between the rows are the result of the conical intersection. The cones have a vertical axis, vertex at the point of convergence of the ashlars and generating passing through the coupling of the ashlar on the frontal arch.

As the segment of impost is less than the semicircle, the frontal arch does not lie on the same plane as the center of the sphere subtended at the intrados. Therefore, the cones of section are off-axis relative to the sphere and generate rows inclined towards the bottom of the vault. The height of the rows is descending from the frontal arch to the bottom of the vault.

Also in this case, the joints between the segments of each row are obtained by intersecting every row with a beam of vertical planes passing through the axis of the frontal arch.

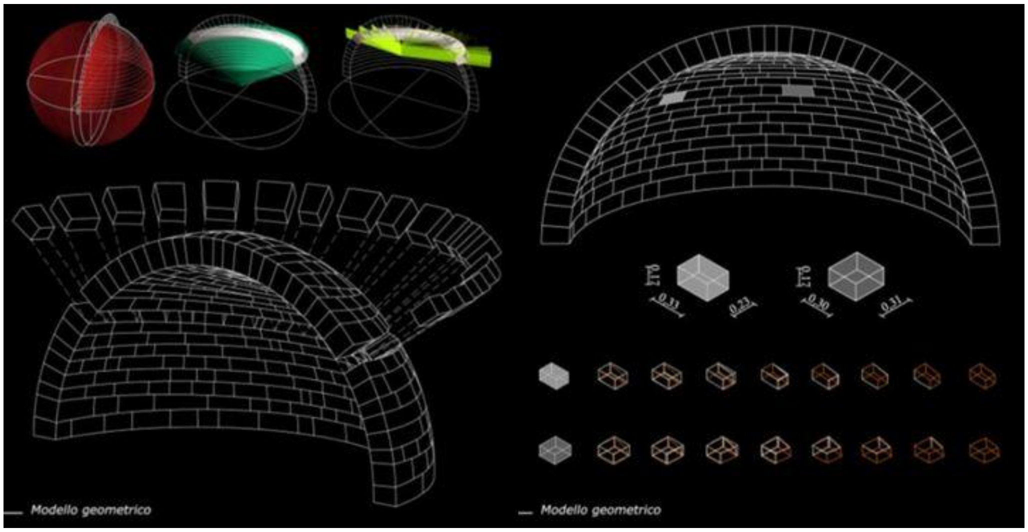

Figure 4: Redesign of the case studied with the second method

5 FROM APSIDAL STONE VAULT TO NEW PARADIGMS FOR DOMES

The research proposes two new paradigms for contemporary stone design of the domes. They come from the constructive invariant of the traditional Apulian apse's half-domical vaults. They are applied to the issues of outturned wall and of bay with dome.

5.1 Splitted Dome

The figure of the Splitted Dome can be achieved by doubling the outturned wall. Then, it derives directly from the morphology of the apse walls in Apulian building for worship. In particolar, this new paradigm is based on the juxtaposition of two outturned walls. The walls have extroflexions minor than the semicircle. The extroflexions are connected to the vertical wall with spherical half-domical vault.

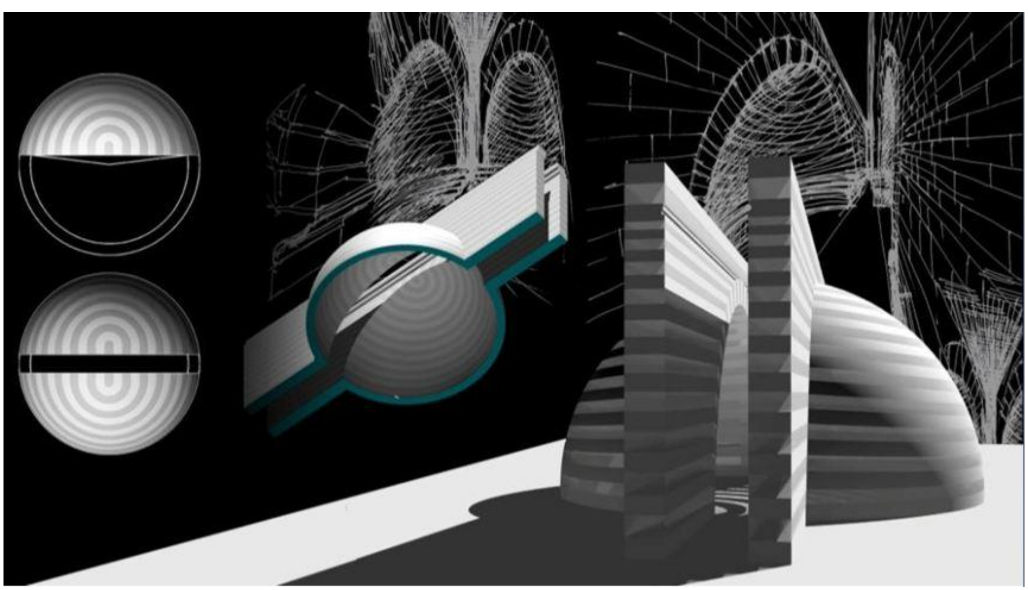

Figure 5: New paradigms for dome in stone. The Splitted Dome

The two walls are disposed specularly so that the half-domical vaults are matched. The circular segments of impost of the two vaults lie both on the same circle.So, the combination of the two half-domical vaults plays the morpheme of a dome splitted. The light passes through the rift.

This paradigm is born for an experimental project for a “via crucis” in Gargano, at Monte Pulciano Abbey. The project was carried out within the Laboratory "Puglia Romanesque" in which the writer has had the role of tutor. The Via Crucis is conceived as an obligatory path between the two juxtaposed walls. The stations are placed in the poles of the half-domical vaults. The matching vaults generate the spatial characteristics of a dome. However, they never touch. Thus, the polar tension of the station (the dome) is mediated by the longitudinal tension of the path (the light that enters the rift).

From the structural point of view, each wall provides a large support base, thanks to the outturned the shape. In addition, the masonry texture for conic sections allows the retraction of the keystones toward the bottom of each vault and the backward tilt of the rows.

Qualitatively, the overall morphology and organization of the masonry texture increasing the stability. Therefore, the structure does not require any other reinforcement structures.

In summary, this design experiment uses three aspects of the traditional paradigm of Apulian apsidal vault:

- each hemisphere is self-stable, thanks to the low thrust to the frontal arch;
- each hemisphere can be less than a half dome;
- the texture of intrados of the rows refer to the aesthetics principles of the texture of the wall, thanks to the overlapped rows (in contrast to what would happen, for example, with the “fan” texture of a trompe).

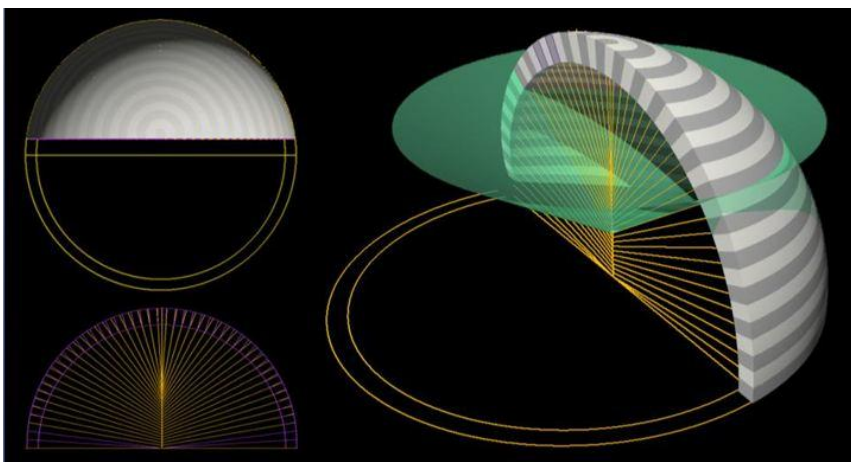

Figure 6: Geometrical model for masonry texture

5.2 Four Keystones Dome

The design paradigm of the dome with four keystones provides the polar serial repetition of a portion of spherical vault, with segment of impost minor than the semicircle. The result is a coverage of polar type.

The portion of vault is repeated subtended at a zenith angle of 90°. It has to be repeated four times to complete the coverage. Within each portion of 90° there are two symmetrical halves. Therefore, the minimum repeatable portion has an angle of 45°. It have to be repeated eight times to complete the coverage. The center of rotation of the polar series is the center of the circumference which the vault is setting on.

This paradigm allows obtaining a spherical dome.

The dome has pseudo-concentric rows. The rows are discontinuous on two orthogonal planes, corresponding to the four portions of vault.

The dome is equipped with four keystones. Each keystone corresponds to one of the four portions of vault and is retracted with respect to the vertical axis passing through the center of the sphere of the intrados. The retraction of the keystones determines an opening at the top of the vault. The size of the opening is equal to the distance between the chord and the center of the circular segment of impost of the vault.

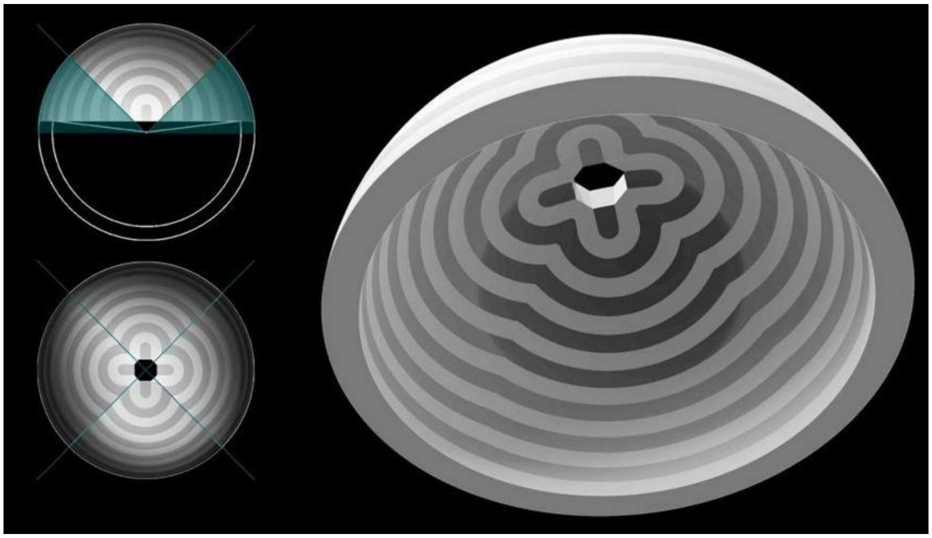

Figure 7: New paradigms for dome in stone. The Four Keystones Dome

From a structural point of view, the inclination of the rows and the retraction of the keystones facilitate to put them in work, without fixed centering.

In addition, the backward tilt of the rows leads the forces of the dome to four keys, rather than one.

6 CONCLUSION

The constructive paradigm of Apulian traditional apsidal vaults opens the door to the design of self-stable spherical half-domical vaults in freestone. They can set to any circular segment, even minor than the semicircle. This flexibility allows interesting morphological experiments of design for stone architecture, both for wall and for coverage systems.

REFERENCES

D'Amato, C., 2006. Città di Pietra - Cities of Stone (vol. III). Catalogo della mostra "Città di Pietra", sezione della 10, Mostra internazionale di Architettura della Biennale di Venezia, Marsilio, Venezia.

Fallacara, G., 2012. Stereotomy, Stone Architecture and new Research, Presses des ponts. Paris.

Perfido, P. 2008. Il sistema di racchordo negli edifici a cupola in Puglia. Il passaggio dal quadrato al cerchio, in Giovannini, G., Ginex, G. (a cura di). Spazi e culture del Mediterraneo, Ricerca PRIN 2005-2007, Edizioni Kappa, Roma, pp. 311-321.