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Structural analysis of complex forms in the german baroque

Analiza konstrukcji złożonych form z okresu niemieckiego baroku

Keywords: Analysis, Masonry shells, German Baroque

Słowa kluczowe: analiza, powłoki konstrukcyjne, niemiecki barok

1. INTRODUCTION

The research about structural behaviour of brick and stone masonry roofs has been very intensive by the Scientific Community during the last decades. The knowing level of roofs based on canonic forms (cylinders, spheres), like barrel vaults or spherical domes, is very high. In this sense, our research is focused on the structural analysis of complex masonry roofs, in which the creation of the roof surface is not so simple and where another structural schemes appear. In this analysis, we will treat roofs of the Central European Baroque, especially some complex roofsmainly developed by two great architects who were able to built light and geometrically complex masonry roofs made from two different structural schemes.

Roofs designed by Dientzenhofer Dynasty, characterized by a design based on a structural load bearing skeleton, contrast to those designed by Balthasar Neumann, who defend a continuous roof without any kind of structural reinforcement.

2. THE WORK BY DIENTZENHOFER FAMILY

Dientzenhofer Family excels in the design of special compositions of roofs that rest on warped brick masonry arches which are used as structural skeletons. We can appreciate these warped ribs at St. Klara, in Eger (Cheb) (Fig. 1), at St. María Oboriste, in Prague (Fig. 2), or in the east of Germany [1].

Christoph Dientzenhofer was the creator of the warped rib and he uses it in the majority of his works. This rib is defined by the intersection between two cylinders with different diameters. The lack of knowing about intersections between quadric surfaces caused that Christoph Dientzenhofer had to define his roofs from the known intersections between the cylinders that we have just commented (the warped ribs) and the outline, creating compatible surfaces that rest on them.

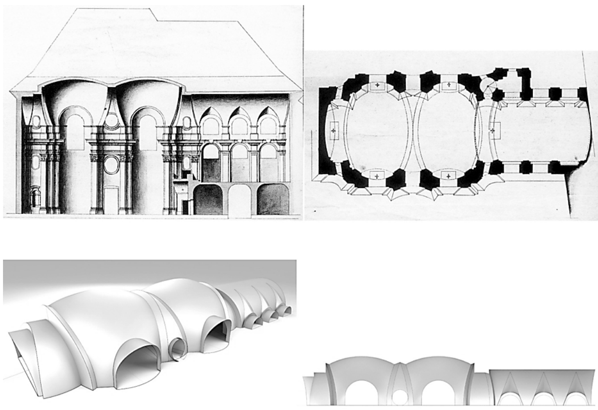

Fig. 1. St. Klara, in Eger. Christoph Dientzenhofer. Ground plan, Section and 3D-model

The first example that we are going to present is the Benedictine Monastery of Banz, the greatest building built by the Dientzenhofer Dynasty, with Johann Dientzenhofer as the main author. On the other hand, we will also present the most representative works made by Balthasar Neumann. He based the design of his brick masonry roofs on the geometrical compositions of the Dientzenhofer Family, introducing alterations in the structural scheme. Neumann developed roofs without great reinforcement ribs acting as global stabilizing elements. His designs are characterized by surfaces that are connected

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Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

among themselves like a continuous skin. His designs present some secondary ribs, but some authors have demonstrated that they are due to construction reasons rather than the necessity of a real structural reinforcement [3], as we can appreciate at the Residence, in Würzburg [4] or in his design for the roof in Neresheim. However, we will present in this document the Basilica of the Fourteen Holy Helpers (Vierzehnheiligen), as his most outstanding example.

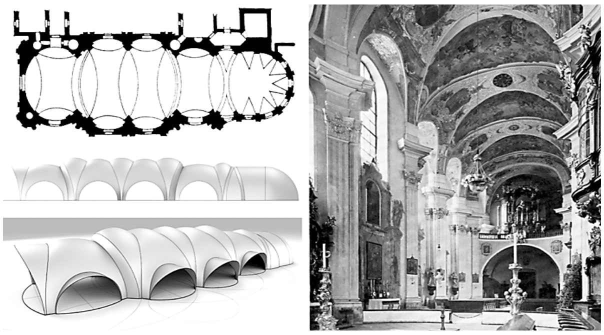

Fig. 2. St. María en Brenov. Christoph Dientzenhofer. Planta, Vista interior y modelo 3D [2]

2.1. Benedictine monastery of Banz

The church in the Benedictine monastery of Banz (Fig. 3) is organized according to Benedictine canons, that is, churches only with one nave. It counts on a sequence of three spaces that is solved through warped ribs [5]. The roof scheme consists of a sequence of longitudinal and transversal vaults that rest on powerful ribs 100 × 70 cm in section (Fig. 4). To solve the intersection, one of the vaults get the rib from its lower face and the other from its upper one, generating the typical inverted "V" solution proposed by the Dientzenhofers [6]. We can appreciate a clear commitment with the construction in its correct execution and its refined intersections.

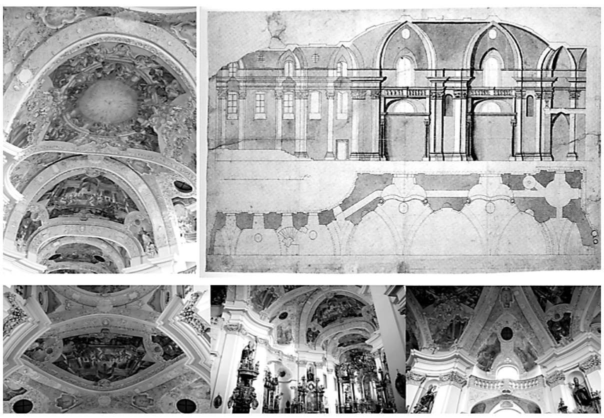

Fig. 3. Church at the Benedictine monastery of Banz. Plan by Johann Dientzenhofer. Views from the inside

It is a 55 m long, 15/20 m wide and 30 cm thick roof, made in brick masonry. The dimensions of the bricks are 14 × 28 × 5.5 cm and 1.5/2 cm lime mortar is used. There are two schemes that we can associate to the walls. On one hand, we find great-thicknesswall-pilasters at the main nave (4.3 in slenderness) and continuous walls at the final part of the nave (6 in slenderness). In this particular case, how the construction process can alternate the final deformation of the roof and thus its stress state has been studied, specially considering the effect of the load corresponding to the wooden over-roof.

The structural analysis has been made using ABAQUS 6.9-1. A mesh with solid elements has been used for the definition of the model (Fig. 5). In this case, and due to the complex form, we have choose tetrahedral elements with intermediate nodes (C3D10M). The final model has 11.5 e06 DOFs. Firstly, we have carried out an elastic linear analysis, because the building presents a good state of conservation without substantial pathologies.

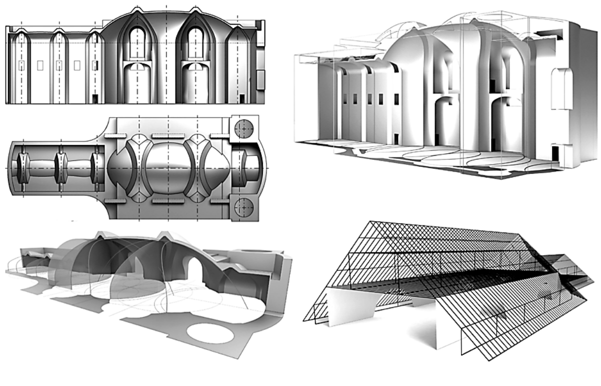

Fig. 5. Church at the Benedictine monastery of Banz. 3D model used for the structural analysis

We have considered the following mechanical properties for all the analysis that we present in this document [7]:

$$E\ (MPa) = 2000;\ \upsilon = 0.2;\ \rho\ (Kg/m^3) = 1700$$

In the case of the Benedictine monastery of Banz, the total weight of the wooden over-roof has been estimated to be 250Tn, considering the frame showed in the picture (Fig. 5).

The most significant displacements are located in the main vault. However, the stabilization ability of the warped ribs is clear for both, the vertical and the horizontal displacements, as is showed in (Fig. 6).

Given the scale of this example, the proposed solution count on an adequate structural behaviour without high tension values (Fig. 7). The use of great wall – pilasters essential

Fig. 4. Church at the Benedictine monastery of Banz.Brick masonry roof viewed from the extrados

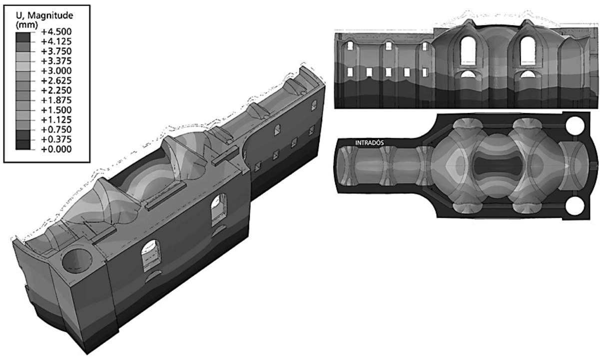

Fig. 6. Church at the Benedictine monastery of Banz. Maximum displacements

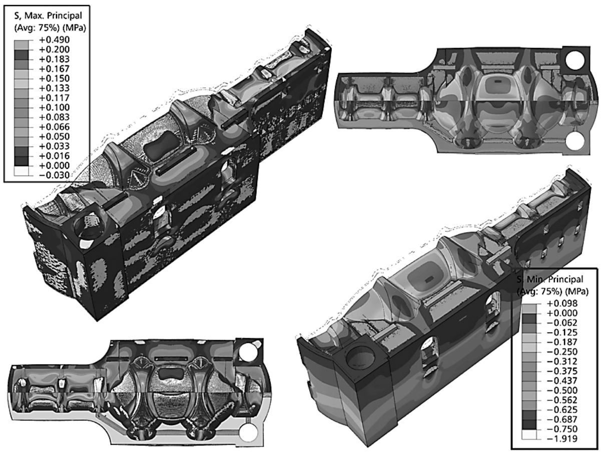

Fig. 7. Church at the Benedictine monastery of Banz. Maximum tension (SMax) and compression (SMin) stresses

for the good behaviour of the brick masonry roof, which results hard confined by the warped ribs. Due to the greater rigidity of these warped ribs, compressions flow mainly through their thickness toward the wall-pilasters.

The wooden overroof is not deciding in the stability, but contributes to the lowering of horizontal displacements (about 7%), without detriment to compressions.

The structural skeleton used works out very pertinent, because reduces tensions, confines the main vault and provides an additional and beneficial rigidity for the roof. The structural skeleton count on the elements where higher compressions are concentrated.

The tension stress states are very low, nearly null at the vaults of the main nave and a little higher at altar nave due to its lower curvature.

3. BALTHASAR NEUMANN. BASILICA OF THE FOURTEEN HOLY HELPERS (VIERZEHNHEILIGEN)

Vierzenheiligen [8] is the highest scale example (65 × 40 m in plan). It presents several features that make it especially interesting for our study: on one hand, its plan, organized from a latin crux (Fig. 8); on the other hand, its high scale, with a main vault that span more than 16m, combined to a especially complex geometry and, finally, the construction solution that was proposed.

The spatial composition consists in a series of longitudinal and transversal oval in plan vaults with a transept crown with two hemispheres (Fig. 9) [9]. The roof has no edges at the joints between longitudinal and transversal vaults. It is a continuous surface, although the intersection between two cylinders of different diameter is marked and can be seen from the inside.

The 30 cm thick roof is made using brick masonry at the base of the vaults, a sedimentary stone called Tuffstein [10] at the rest of the roof and lime mortar in both masonry (Fig. 10). The adopted solution presents no kind of structural reinforcement [3]. According to a previous analysis of the wooden overroof, its weight has been estimated at 500 Tn.

The deformation of the walls towards the inside of the basilica is due to their self-weight, although this deformation was very probably corrected during the construction process, resulting undeformed walls which are initially stressed because of their self-weight. This is the state we have considered at the moment of the application of the load corresponding to the roof.

According to this hypothesis, and to assess the importance of the horizontal load of the roof on the walls, we next present the displacements due to the complete masonry load on the undeformed walls (Fig. 11). In the case of the Basilica of the

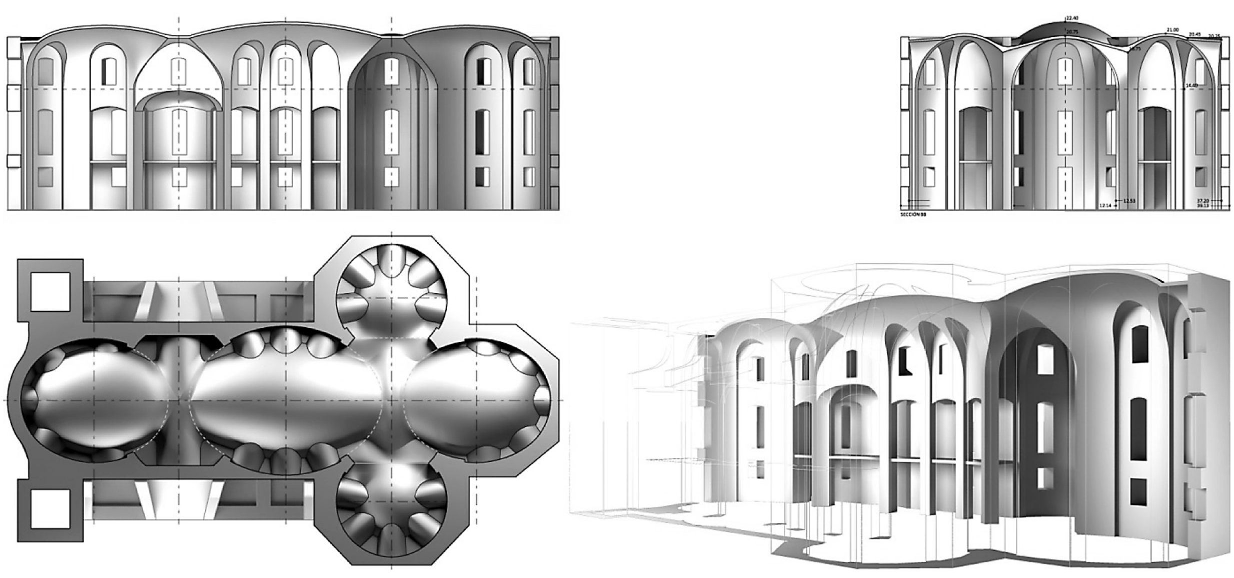

Fig. 8. Basilica of the Fourteen Holy Helpers. 3D model for the structural analysis

Fig. 9. Basilica of the Fourteen Holy Helpers. Views from the inside and detail of the warped rib as the intersection of two cylinders of different diameter [9]

Fig. 10. Basilica of the Fourteen Holy Helpers. Views from the extrados

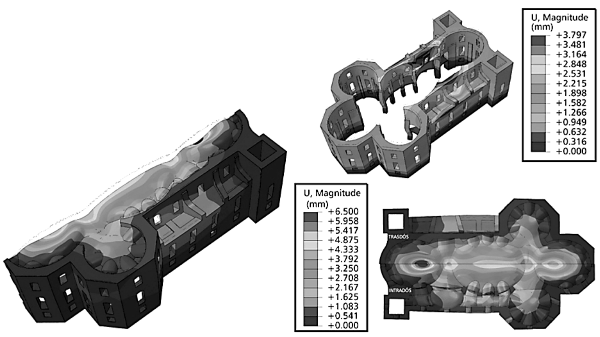

Fig. 11. Basilica of the Fourteen Holy Helpers. Maximum deformation of the walls and deformation of the roof over the undeformed walls, considering the stress state due to the self-weight

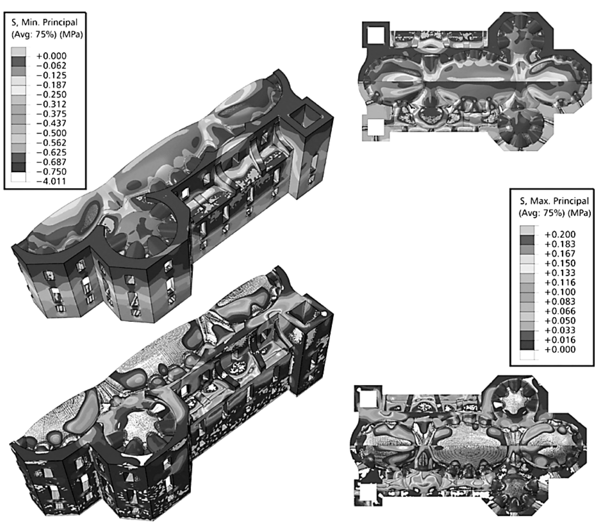

Fig. 12. Basilica of the Fourteen Holy Helpers. Principal Compression (SMin) and Tension (SMax) Stresses

Fourteen Holy Helpers, if we analyzed its complete model, we would be led to wrong conclusions, being essential the consideration of the different steps of the construction process.

As can be appreciated, we must be careful to consider deformations due to the self-weight of the walls. In this state, they present horizontal displacements which significantly modify the structural behaviour of the roof that rests on them.

We have simulated the construction process according to two steps and some substantial differences in the results obtained respect to the analysis with only one constructive step can be found. We mainly appreciate an increase of tension at the transversal vaults.

Respect to the principal compression stresses, there is also an increase respect to the one-step analysis. The stress concentration level is higher, as we can see in areas next to the symmetry plane, including the consequent decrease of this stress in the corresponding areas of the intrados. There is also an increase of compression stresses at the base of the vaults, although it is mainly located along the intersection edge between the different vaults. In any case, the obtained values are very far from the established limit one of 2 Mpa.

4. CONCLUSIONS

We can define the roofs presented in this study as light roofs, due to their small thicknesses. However, they are also shapes with features and properties that make possible defining them as elastic roofs, with a high deformation capacity and easily changeable due to external stimulations which can modify their structural behaviour in a significant manner.

We detect a certain improvement of the stress state thanks to the plastic properties that present the brick masonries used here. In this sense, stands out the thick lime joint that, thanks to its high setting times, allows some stress redistributions in the first moments after the removing of the shore, adapting in this way the shape to situations with a more homogeneous stress states and therefore avoiding local concentrations of stresses.

It is clearly evidenced the importance of making a numerical simulation having in consideration the different building stages, especially for been the masonry roof one of the last elements to be built. Therefore, it is necessary to make deformation studies to detect which of them have not got any sense in a simulation made by numeric methods.

There are other aspects that also collaborate in the good structural behaviour mentioned before. The roof organization by longitudinal vaults alternated with transversal vaults allows, in some manner, keep confined the different vaults and minimizing their deformations.

It is also clearly reflected the importance that present the tension stresses in opposition to the compression ones, not being these last ones relevant because of its magnitude.

REFERENCES

[1] Zimmer, H. (1976) *Die Dientzenhofer*. Rosenheimer.

[2] Hartmut Roidl, W. (1995) *Die Kurvierten Sakralräume Des Christoph Dientzenhofer*. Tuduv-Studien.

[3] Otto, Christian F. (1979) *Space Into Light. The Churches Of Balthasar Neumann*, Mit Press Series.

[4] R. Sedlmaier, R. Pfister. (1923)*Die Fürstibischöfliche Residenz Zu Würzburg*. München Verlegt Bei Georg Müller.

[5] Vilímková, M., Brucker, J.(1989) *Dientzenhofer*, Rosenheimer Verlagshaus.

[6] Norberg-Schulz, C. (1985) *Weltgeschichte Der Architektur, Spätbarock Und Rokoko*. Deutche Erlags-anstalt Stuttgart.

[7] Krausz, K. (2002) *Tragverhalten gemauerter Tonnengewölbe mit Stichkappen*. Institut für Baustatik der Universitat Stuttgart. Bericht Nr. 38.

[8] Sammlung Eckert.(1987) *Aus Balthasar Neumanns Baubüro*. Mainfränkisches Museum.

[9] Hansmann, W. (1999) *Balthasar Neumann*. Dumont.

[10] Ludwig, F.*Balthasar Neumann, Dachwerke Seiner Landkirchen*, Technischen Universität Berlin.

Abstract

Shells are forms that base their behaviour in their geometry. From Antiquity, the art of building is conceived as the ability to span and grew with little pieces, like bricks and stones, until great spaces could be closed. Arches, vaults and domes work mostly because their geometrical configuration and not so much because their intrinsic strengthening.

The complexity of Baroque domes has not been studied enough until now, at least in terms of structural analysis in conjunction with geometrical concepts. This is the reason because we have carried out a research in which geometry is considered as structure. We have studied a wide series of churches of the German Baroque and we present here two of them that maybe are the most surprising: the Chapel in the Monastery of Banz, by Johann Dientzenhofer, and The Fourteen Saints Basilica, by Balthasar Neumann.

Their complex roofs, checked in situ, have been modelled using a 3D parametric design application and analysed by Finite Elements Analysis Method using ABAQUS.

The main aim of this paper is to demonstrate that the basis of the optimal behaviour is the special geometry considered for each design. These geometries allow consider only membrane stresses instead of shell stresses. Bending is really acting in border and edges and not in the general surface as occurs in concrete and steel shells. Baroque was the inventor of membranes as we actually conceive them, with examples that present such complexity that none of the great concrete builders have tried to build.

Streszczenie

Sklepienia łupinowe są formami, których zachowanie oparte jest na ich geometrii. Już od starożytności, sztuka budowania polegała na umiejętności tworzenia elementów konstrukcyjnych z niewielkich fragmentów, takich jak cegły czy kamienie, co pozwalało na zamknięcie wielkich przestrzeni. Łuki, sklepienia i kopuły funkcjonują głównie z racji swojej konfiguracji geometrycznej, a nie z powodu wewnętrznego wzmocnienia.

Złożoność barokowych kopuł nie została jak do tej pory odpowiednio przestudiowana, przynajmniej pod względem analizy konstrukcji w połączeniu z koncepcjami geometrycznymi. Z tego też powodu przeprowadziliśmy badania, w których geometria została potraktowana jako konstrukcja. Przestudiowaliśmy szereg kościołów z okresu niemieckiego baroku i prezentujemy tutaj dwa z nich, które wydają się być najbardziej interesujące: Kaplicę z klasztoru w Banz, zaprojektowaną przez Johanna Dientzenhofera, oraz Bazylikę Czternastu Świętych Wspomożycieli Balthasara Neumanna.

Ich złożone przekrycia, zbadane in situ, zostały zamodelowane z wykorzystaniem projektowania parametrycznego w 3D i przeanalizowane za pomocą metody elementów skończonych z zastosowaniem programu ABAQUS.

Celem niniejszej pracy jest zademonstrowanie, iż podstawą optymalnej pracy konstrukcji jest geometria jej poszczególnych elementów, specyficzna dla każdego projektu. Ta geometria pozwala brać pod uwagę jedynie naprężenia membranowe zamiast naprężeń powłokowych. Zginanie oddziałuje na granicach i brzegach, a nie na całej powierzchni, jak to ma miejsce w przypadku powłok betonowych i stalowych. W baroku wynaleziono membrany w naszym rozumieniu tego pojęcia, a ich przykłady mają tak złożony charakter, iż żaden z twórców wielkich budowli z betonu nie próbował nic podobnego stworzyć.