Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-46872-5

Maria Birnbaum – Construction history, conservation history

R. Barthel, H. Maus & C. Kayser
Barthel & Maus – Beratende Ingenieure, Munich, Germany

ABSTRACT: The baroque pilgrimage church is both in aspects of form and structure one of the most interesting German buildings of its time. Centre of the building is a Pantheon-style rotunda with a large brick dome. The free-spanning original roof structure above the church is well-preserved. Subsequently, construction and size of roof and dome led to grave structural problems. A first comprehensive conservation campaign in 1794–96 identified the deficiencies. Still, this and subsequent campaigns failed to establish efficient solutions.

1 HISTORY AND DESCRIPTION

1.1 *The origins*

The pilgrimage church "Maria Birnbaum" – Our Lady of the Pear-Tree –, situated between Augsburg und Munich, was erected 1661–68. Being one of the most unorthodox buildings of its epoch, its forms and constructions predate the complex spatial experiments of the famous South German Rococo. (fig. 1)

When, after the Thirty-Years War, a pilgrimage developed in the open countryside to an old pear tree with a small wooden statue of the Virgin Mary, the local commander of the Teutonic Order, Johann Philip von Kaltenthal, decided to build a church around the sacred spot. Von Kaltenthal, the driving force behind the building project, was a retired commander of the Papal Guard in Rome. As Construction supervisor, he chose the expert master-builder Konstantin Pader. Although Pader himself was a well-known architect, he had to implement Kaltenthal's ideas and suggestions for "Maria Birnbaum":

Being an erudite dilettante, the commander of the Teutonic Order found the main inspiration sources for his project in contemporary architectural treatises as well as in the monuments of Antiquity and Counter-Reformation in Rome (for detailed information about history and planning: Schütz, 1974). The unusual, even fantastic traits of the design are the results of a dilettante's architectural ambitions.

1.2 *Composition*

The main building is divided into three parts (fig. 2). Centre of the church is a large, domed rotunda, modelled after the example of the church of "Maria Rotonda" in Rome – the Pantheon. Following the main idea of the roman building, the apex of the dome is opened with a large Opaion. Since the Bavarian weather does not permit an unsheltered Opaion open to the sky, the builders chose to cover the opening with a large wooden tower, for its decoration with large statues of the twelve disciples called "Apostelturm". Thus, the tower's interior is, through the Opaion, open to the main rotunda.

Figure 1. View of the pilgrimage church from the north side.

Also differing from the design of the model, the walls of Maria Birnbaum are pierced by a number of windows. Above the window bays, the dome of the rotunda is intersected with a number of lunettes.

East of the rotunda lies the triapsidal choir (east part). As its counterpart, the elliptical west part was built around the venerated centre of the pilgrimage: A large niche in the western wall was arranged for the tree, though, sadly, it withered with the progress of the construction works. Both the east part and west part open with large triumphal arches to the main rotunda.

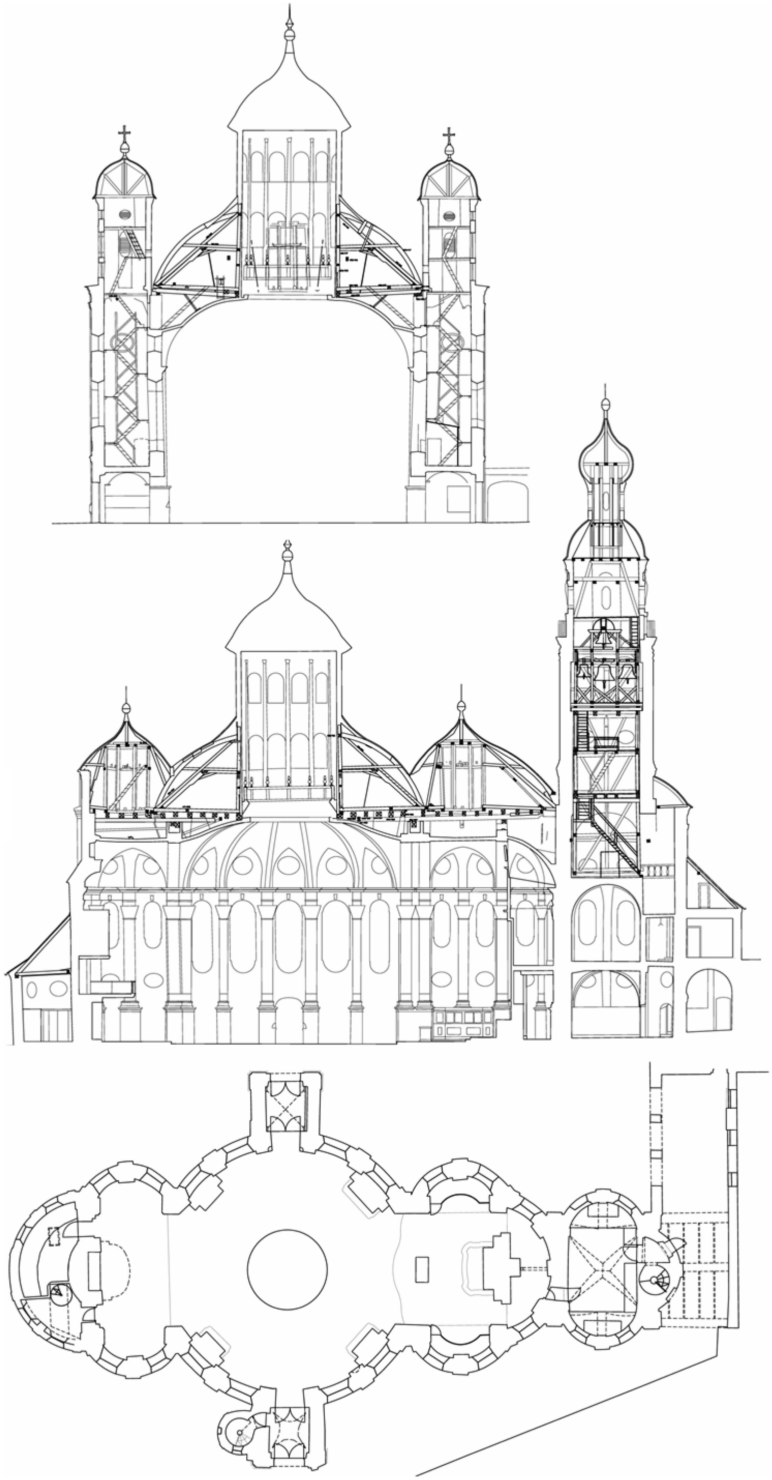

Figure 2. Ground plan and sections: top: Section through the rotunda and the Apostelturm, view in eastern direction, middle: longitudinal section, view in northern direction, bottom: ground plan with west part, rotunda, east part and bell-tower.

Walls and the large vaults are built with bricks, the whole church is covered with plaster; the interior offers the typical rich stucco.

Already during the construction period, the plans were modified and amended. After having brought up the outer walls, builders and client were concerned about the stability of the walls under the main domes' load. The outer walls of the rotunda were planned as high and slender, with no additional abutments to take up the dome's horizontal thrust. To avoid structural damage, two square towers were added as "buttresses" on the north and south of the rotunda.

1.3 *The construction of the roof over the rotunda*

The main roof over the dome was finished in 1663. Master carpenter and, presumably, designer of the roof was Gabriel Schwarz from Augsburg (Eberl 1897). Following to the building's design, the roof is divided into three parts. Above the central rotunda, the main part forms a domed roofline pierced by the high cylinder of the "Aposteltürm".

The carpenters designed the roof structure as 15 m free spanning above the apex of the dome. The wooden structure of the Aposteltürm is fully integrated in and supported by the roof construction. Due to the open, freely visible interior of the tower, it was impossible for aesthetic reasons to have any roof beam crossing the tower's middle part. Thus, the tower forms a large six-meter-diameter wooden cylinder free of any supporting elements in the middle. With its plaster and stucco, beams and shingles, statues and balustrades, it has a dead load of about 290 kN. Dead load as well as wind load have to be supported and transferred to the outer walls by the roof structure.

Together with the considerable span of 15 m, the design and implementation of a fitting wooden structure was a highly difficult challenge for the carpenters without any precursor: The structure combines several systems. Its roots lie in the established system of the rafter roof with collar beams and trusses. In purely technical terms, the structure forms a rotation-symmetric three-dimensional hanging truss (fig. 4): The tower's cylinder forms in its upper part a pressure ring and at its base a tension ring. The pressure ring is situated at the joint of roof skin and tower. Twelve radial struts – the rafters – take up the vertical loads and transfer them to the outer walls. The horizontals forces are tied back to the outer walls by tie-beams linked to the tension ring. The lower part of the tower is suspended on the pressure ring, the upper part above the roof skin stands on the ring. Fixed between both rings, the tower is supported against horizontal forces.

The roof is divided into the following parts (fig. 3):

The massive Ground Beams (A) span parallel over the eaves. During the construction, they provided a stable ground level for the erection of the roof's upper parts. The beams have a length of up to 15 m and

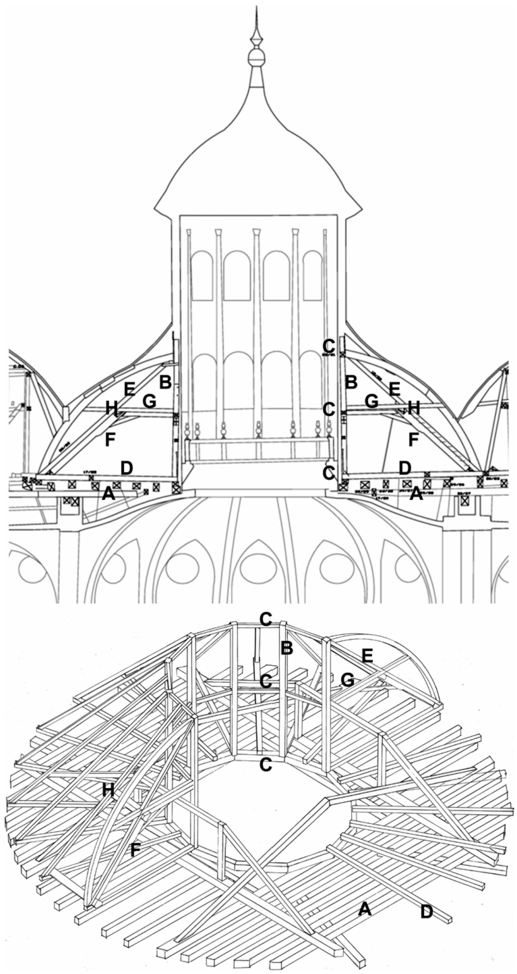

Figure 3. Top: longitudinal section through roof structure and tower, bottom: isometric view of the main roof. A: ground beams, B: tower posts, C: wooden rings, D: tie beams, E: rafters, F: truss post, G: collar beam, H: intermediate purlin.

profiles of up to 35/30 cm. Around the Opaion, the ground beams are interrupted by trimmers.

The wooden structure of the Aposteltürm consists of twelve vertical posts (B) and curved horizontal wooden rings (C). The main roof construction above the ground level consists of radial twelve trusses with 24 additional rafter units in between. The units form a full circle, the smaller roofs above the western and eastern part of the church were added after the completion of the main structure.

The main trusses are basically designed as variations on the traditional type rafter units. They are adapted to the local requirements by being vertically bisected and radially aligned around the shank of the central tower. Accordingly, every unit consist of the

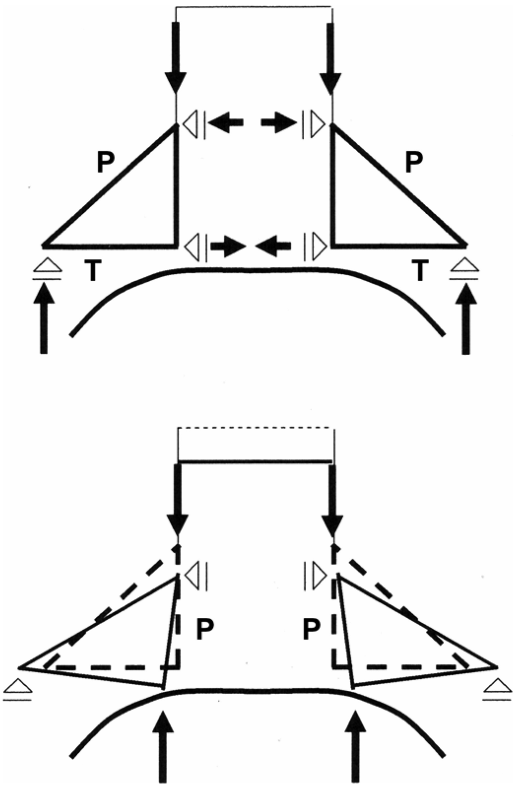

Figure 4. Top: intended structural system of the roof with pressure and tension rings, the rafters serve as strutting; bottom: structural system after deformation, the tower has lowered on the dome (P: Pressure, T: Tension).

following elements: tie beam (D), rafter (E), bisected roof truss (F) with truss post and truss beam, collar beam (G), intermediate purlin (H) and struts.

The collar and truss beams abut against the tower's posts; the end-points on the tower are connected with one of the horizontal wooden rings. The tie-beams are connected to the tension ring at the tower's foot. The rafters prop up against the tower in an inclination of 45°. Bent wood-strips on the rafters' backside form the roof's curved outline. The intermediate purlin, as part of the truss, is uncommonly strong, it is executed as a closed polygon encircling the main roof. Generally, the joints of the timberwork follow the local tradition, though at some crucial points, they are adapted to the construction's specialities: The connection between the rafters and the posts is carved with a shoulder; the parts of the pressure ring connect to the posts at the same level with mortice and tenon. Accordingly, the rafters serve as strutting for the wooden tower; the lower parts of the posts serve as hanging members. They are connected to the tie beams with mortice and tenon; the tie beams are fixed with a trenched joint to the tension ring. The tension ring is formed by a series of bent beams, which are linked by a wrought iron ferrule on the outside. Though a stringent implementation of the basic design would have afforded it, there is no vertical suspension between the tower posts and the tie beams.

2 THE FIRST CONSERVATION CAMPAIGN 1794–1796

2.1 *The structural analysis of 1793*

After 130 years with only minor restoration works, roof structure and masonry of "Maria Birnbaum" were in dire need of repair. After some heavy storms, the deformations of the roofs and cracks in the outer walls and the dome led to a general discussion of the building's future. A detailed experts' analysis should clarify the causes of the damage as well as appropriate actions. The expertise was carried out by the master-mason Johann Singer and the master-carpenter Mathias Hafner.

The expertise and the documentation are preserved: it offers a fascinating glimpse into early conservation concepts and technical aspects of building conservation. The two craftsmen drew up detailed plans of the church with an accurate survey of the masonry cracks. On the basis of the survey, the causes of the structural damage and a possible course of action for the conservation were explained.

The drawings show that the ground beams as well as the tension ring and the tie beams had lowered on the apex of the dome around the Opaion. (fig. 4)

The original, intended locations of the beams as well as the deformation figure are drawn. The mortice and tenon joint between the posts and the tie beams is open, between both members is a gap: this indicates that the tower cylinder itself did not lower; the rafter-strutting was obviously still intact. Due to the lack of a vertical suspension between the tower posts and the pressure ring, theses parts of the structure could lower independently.

For the master-builders, it was evident that the apex of the brick-dome could not support any additional loads. In the accompanying text, they explain that in the case of heavy wind, the tower becomes unstable and moves. As result of the open joints at the tower's basis, the shank has no horizontal fixation at its foot ring. Under wind-load, the tower can contort around its support at the upper pressure ring. The percussions caused by the movements induce cracks and local deformations on the dome shell.

Additionally, the experts observed a visible inclination of the outer walls. This effect results mainly from the influence of the large dome. As effect of the deformations, the perimeter of the eaves widened.

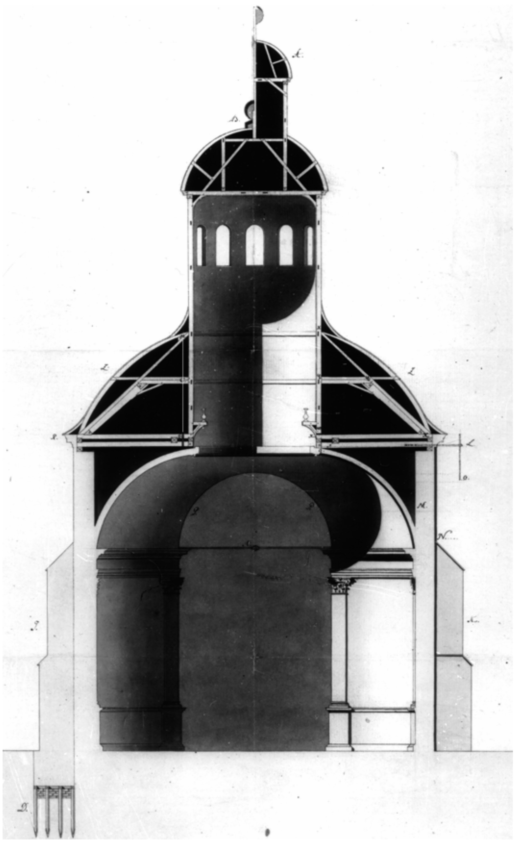

Figure 5. Diagram from the master-builders' expertise, 1793: the diagram shows possible conservation measures with additional buttresses, height reduction of the tower, tie rods in the triumphal arches und suspension rods in the roof.

Cracks opened in the windows and the vaults, the dome's apex lowered further.

As possible repairs (fig. 5), the builders proposed to reverse the deformations in the roof structure. The lower parts of the roof – the ground beams, tie beams and the tension ring – should be suspended with iron ties to the rafters and the pressure ring. A new wooden support for the iron ties should be constructed in the angle between rafters and tower. The suspension would have been tightened with screw joints.

To reduce the wind load on the tower, it was proposed to remove the high wooden lanterns on the top – "if the building is not to much defaced".

For the stabilisation of the masonry, the expertise suggests to add additional buttresses to the outer walls. The buttresses should be set up in the bays between the windows "that take up all the loads"; due to the wet and unstable subsoil, they should be executed with a pile foundation.

Both triumphal arches between the rotunda and the western and eastern part of the church were to be stabilized with wrought iron tie rods. The tie rods would have been freely visible in the church. To put tension on the rods without exerting any percussion, a screw coupling should have connected its parts.

The estimated amount of iron for the tie rods was 5.5 "Bayerische Zentner", i.e. about 310 kg. With a guessed profile of ca. $10\,cm^2$ and a density of $7.85\,kg/dm^3$ this would have added to iron ties of about 40 m length. The triumphal arches have a span of about 15 m each, so, together with all connections and further parts, this seems altogether realistic.

The costs of these ironworks would have added up to 126 f – the largest single position in the calculation. The total sum for the restoration works would have been about 1300 f.

2.2 *Implementation of the conservation works*

Due to the great urgency of the works ("...only in case of utmost need, the works can be delayed an other year..."), the conservation was executed in the following years, 1794–96.The implemented conservation design differs from the master-builders' proposals: Financial and aesthetic aspects lead to grave changes in the plans. Instead of expensive wrought-iron ties between the rafters and the basis of the tower, four massive strutted frames were positioned around the tower shank. Two major frames, spanning east-west, were used to suspend the tie beams, two minor frames, spanning north-south, support the lower part of the tower. They prevent the tower's base from moving, at least in one axis.

The addition of buttresses on the outer wall was abandoned. Probably as a result of aesthetic considerations, the wrought-iron tie rods in the triumphal arches were shifted into the zone above the vaults. Hence, they were not visible from the interior of the church. Instead of full-iron rods, only the end pieces were made of iron, the main body was executed as wooden tie beam. The planned complex screw joint was abandoned. As a substitute for the strong original design, additional tie-beams were introduced above the vaults of the eastern and western part.

Only the reduction of height and weight by removal of the wooden lantern on the main tower was executed as planned. With the abandonment of the elaborate original plans, subsequent damage on the structure was inevitable.

3 CONSERVATION CAMPAIGNS 1865–1938

Approximately 70 years after the first campaign, in 1865, the building was, again, in a foul state. In the meantime, the ownership had changed from the Teutonic Order to the kingdom of Bavaria. The government decided to tear down the decrepit church.

Only with the personal involvement of local farmers, the church could be rescued. The farmers organized a restoration campaign, further works continued up until 1895.

Dendrochronologic evidence shows that the works carried out in the roof structure were comparatively simple: some rotten beams had to be exchanged, the dimensions as well as the joints of the historic structure were simply copied. Presumably during the late-nineteenth-century campaign, a number of pressure props was inserted between dome and roof structure. Wooden planks on the brick shell are used to avoid point loading. The diagonal props are wedged under the roof's ground beams. It is not completely sure if the props were inserted to counteract further deformation of the roof by strutting it against the seemingly strong brick structure or if the props should prevent the dome from bursting. The immediate danger of a collapse could not be ruled out: the measures taken in the late 18th century were not fit to prevent the tower from lowering on the apex of the dome. The cracks in the main vault already surveyed in the expertise of 1794 can indeed be interpreted as signs of overloading. The position of the props indicates that they were meant to stabilize the dome at one third of its outer perimeter.

In course of the 19th-century works, another attempt was undertaken to secure the lowered beams by suspending them with tie rods. The elements run diagonal from the backside of the rafters, just above the collars, to the ground beams. On both ends, the tie rods have screw threads for bracing.

This measure opened the opportunity for an alternative load transfer in the roof structure. The loads of the central tower and of the ground beams are suspended by the tie rods to the main joint of the truss unit. Here, they can be transmitted by the intermediate purlin under the rafters. The purlin is, with a height of 30 cm, uncommonly strong, und with its butt joints it could, at least in theory, act as a surrogate pressure ring. In reality, though, the desired effect of the design did only partially work. A sufficient retraction of the deformations could not be achieved by bracing of the screw threads. Also, it is highly probable that, at the time, a great number of the roof's wooden joints were already corrupted by deformation, mould or insects.

A further restoration campaign followed in the 1930s. In course of the works, the roof coating was replaced – any structural deficiencies of the church were simply ignored.

4 STUCTURAL STRENGTHENING IN 1970–75

Around 1970 the cracks in the church's outer walls had become so massive that measures for strengthening of the masonry structure were necessary.

Figure 6. In the 1970s campaign, two concrete ring beams were implemented. The historic rendering was stripped off.

To prevent any further inclination of the walls, two massive ring beams of reinforced concrete of about 0,4 m height were inserted in the masonry structure. Both ring beams encircle the complex outline of the building. The lower ring beam runs at the height of the vault springers underneath the bull's eyes. This level is very well fit for counteracting the dome's horizontal forces but for a grave handicap: Due to the geometry of the two triumphal arches, both halves of the ring beams can not be connected at the intersections of the rotunda with the eastern and the western part of the building. The ring beam follows the richly moulded outline of the building.

The second ring beam, situated above the tow of bull's eyes, is introduced to compensate this problem. A straight connection of both ring-halves is, even at this level, not possible. Still, both halves could be connected with concrete frames above the masonry of the triumphal arches. The frames are connected to the ring beams in the vault's pendentives. Only minor repair work was executed on the wooden roof structure: in spite of grave structural deficiencies on joints and timber beams, the strengthening of the masonry structure was thought sufficient to guarantee the stability of the building.

5 DAMAGE ASSESSMENT IN 2005

5.1 *Actual condition and damage assessment*

A restoration of the interior was planned after some minor damage on plaster and stucco. In preparation to the works, the roof structure was assessed by the authors. Basis of the analysis was a detailed, true-to-deformation survey. With these large-scaled plans, every single knot of the roof structure was assessed. The extent of the damage is grave: about half (48%) of the ground beams' (A) head parts are badly decayed.

One third (32%) of the tie beams' (D) heads and about 60% of the joints of rafters (F) and upper pressure ring (C) are damaged by mould, humidity or pests. Additionally, a large number of joints of the roof trusses is deformed.

Additional to the damage of the material, the strutted frames of the 1794 restoration campaign proved to be inefficiently constructed: the frames were built without any bracing to prevent buckling. Thus, they could never act as initially intended. With buckling of the frames' post members, their stabilizing effect was defunct. The frames were not able suspend the tie-beams and to prevent the sagging of the central part of the roof.

Due to the structure's deformation, the roof's joints gape and are unable to transmit forces. The tie beams are pulled off the tension ring. This gives a clear indication that the whole load of tower and roof rests on the ground beams and trimmers; these are lowered on the brick shell. Subsequent analysis and survey made clear that the wooden cylinder of the Aposteltum rests on the apex of the dome around the Opaion.

The fringe around the Opaion is visibly deformed. The Props between dome and ground beams are under pressure, their end pieces are pressed into the wooden planks on the brick shell.

The outer walls do not show noteworthy cracks. Obviously the reinforced ring beams are effective. Therefore, the dome, not the outer walls, is immediately endangered. The brick structure has to carry the full weight of tower and roof. Additionally, the tower transmits irregular wind loads onto the dome.

For further analysis of the dome's complex geometry and its structure, a FE-model was developed (fig. 7). Parallel, a detailed survey of the cracks on the dome's upper side was made. The results of the model confirm the observations.

Calculations and observations indicate that the dome does basically act as a large barrel vault. This is due to the two large "incisions" of the triumphal arches' lunettes. The apex of the lunettes is ascending in direction of the main Opaion, the resulting geometry "bisects" the dome into two halves. Only around the Opaion, the dome does actually "work". Thus, the construction of Maria Birnbaum's main rotunda differs fundamentally from its roman model, the Pantheon.

During the surveys, the cracks in the vault were monitored by means of plaster labels. One of the first inspection of the tell-tale labels showed that movements in the brick shell had occurred.

Due to the earlier deformation of the outer walls and the lowering of the dome's apex, the brick area around the Opaion is, in geometric terms, without inclination. The bricks have a thickness of about 15 cm. With the large wooden tower resting on this fragile, deformed shell, a spontaneous yielding of the brick shell around the Opaion could occur.

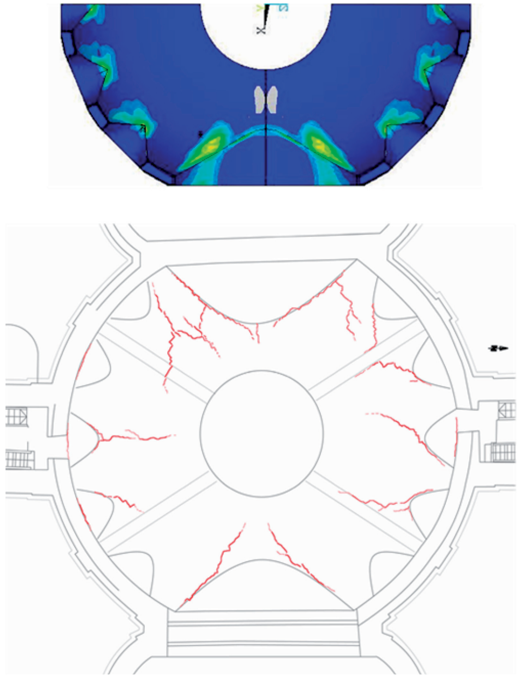

Figure 7. Below: survey of cracks in the dome's brick shell; above: FE-model of the dome under dead load.

5.2 *Emergency measures and possible conservation strategies*

The discovery of the structural deficiencies made inevitable a closure of the church for visitors. During this time, in winter 2005, a cylindrical scaffolding tower was erected under the Opaion (fig. 8). The tower supports the dome around the Opaion. The supreme level of the scaffolding was raised up under the brick shell. To preserve the precious baroque stucco, carved pieces of wood and a special kind of hardened plaster were inserted between scaffolding and dome with the help of an expert conservator.

The use of the church for the Holy Service is a bit affected by the tower but possible.

After the installation of the supporting tower, further structural and historical analysis could be carried out. The overall concept is to conserve the valuable historic roof structure in all its parts. After several centuries of ongoing deformations, it is not possible to restore the structure by repairing every open joint. The result would be the loss of most joinery details and therefore important historic information.

In contrast to earlier conservation campaigns it was decided to implement a subsidiary, self-supporting structure.

Two types of support have been in discussion: the integration of four steel frames or the design of an

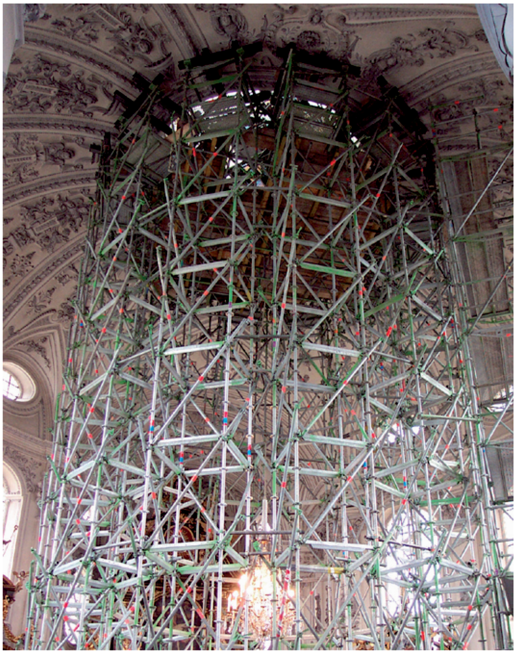

Figure 8. Supporting scaffolding tower under the dome's apex.

additional steel structure between rafters and roof skin onto which the ground beams can be suspended with tie rods. It came as a surprise that the discussion followed in the paths of the – thitherto unknown – 1794 campaign with its alternatives of strutted frames and suspension rods. Both alternatives were implemented in the roof structure as mock-ups to prove their feasibility.

Together with the local authorities and the owner – which is, again after two hundred years, the Teutonic Order –, it was finally decided to realize the alternative with suspension rods.

Relics of historic conservation campaigns are to be conserved as testimonials of a long and complex history of conservation and restoration.

6 CONCLUSION

The architectonic ideals of an erudite dilettante led in "Maria Birnbaum" to a highly innovative design and construction. The large dome as well as the complicated roof structure with the central tower open to the church's interior are without example and successor in contemporary architecture.

The realization of von Kaltenthal's visions led to a series of partially unsolved structural questions. The building was fragile and vulnerable to interferences.

Deformations and cracks made necessary a substantial conservation campaign already in the late 18th century. The 1794 expertise shows the local master-builders' thorough understanding of the structural mechanism. Roof construction as well as the problems of the large, flat brick dome were clearly realized. As an answer to the structural damages, the proposed conservation measures were appropriate. In the following discussion though, they were, for financial and aesthetic reasons, replaced by half-hearted and inefficient measures.

With the progression of damage and with the implementation of insufficient repairs began a long series of conservation and restoration campaigns. All of them tried to bring the basic mechanisms to a halt but failed. Every campaign introduced new elements to the roof structure; historic repairs were respected as part of the whole structure. The conservation campaigns mirror their times' special philosophies and fashions in conservation practice.

The 1972 campaign is, for example, typical for its time: The works' aim was not conservation of historic building constructions but the application of contemporary techniques and possibilities for structural strengthening.

In hindsight, the historic restoration campaigns were only partially effective. In spite of their shortcomings, they added to the preservation of a singular building.

Since its erection, the history of "Maria Birnbaum" is a history of conservation.

REFERENCES

Eberl, A. 1897. Maria-Birnbaum *Kurze Geschichte seiner Wallfahrt und seines Klosters sammt Statuten und Gebetbuch der daselbst kanonisch errichteten Sieben-Schmerzen-Bruderschaft.* München: Ernst Stahelsche Buchdruckerei

Hafner,M. & Singer, J. 1793. Expertise on the pilgrimage church "Maria Birnbaum". In Bayerisches Hauptstaatsarchiv, Hofm. Karton 1028, and Plansammlung 19350

Schütz, B. 1969. *Die Wallfahrtskirche Maria Birnbaum und ihre beiden Baumeister*. Phil. Diss. München, Frankfurt: Kieler Kunstgeschichtl. Studien.