The reconstruction of the Frauenkirche in Dresden

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ABSTRACT: For 200 years the characteristic appearance of the stone dome of the Frauenkirche has been dominating the silhouette of Dresden. Near the end of the Second World War it was reduced to rubble. After the political turnaround in East Germany the reconstruction project of this important building of Saxon Baroque has been tackled. The intention was and is to reconstruct the Frauenkirche according to archeological reconstruction principles. New findings of engineering science had to be applied in a sensitive manner. The essential engineering problems involved in the reconstruction of the Frauenkirche in Dresden are here presented and the relevant solution approaches shown. They are the result of extensive scientific tests, static calculations and comparisons of the most varied structural versions. The paper concludes with a brief summary about the current status of the reconstruction work.

1 HISTORY

The stone cupola has been dominating the skyline of Dresden for two hundred years, at the same time being its crowning element (Figure 1). The masterpiece of Saxon Baroque had withstood the bombing attacks on the city on February 13th and 14th 1945. But the ensuing blaze sweeping the centre of the city also spread to the interior of the church, gutting it completely. Then, on the morning of February 15th, the church collapsed in a giant cloud of dust (Figure 2).

The Frauenkirche in Dresden was built in the years from 1726 to 1743 by the Master Carpenter of the Dresden Town Council, George Bähr. It was constructed with Saxon sandstone. Even the cupola consisted completely of stone and did not have any special roofing or sealing layer. The sandstone cover had to fulfil that function.

The dimensions of the ground plan were 43 x 43 m (Figure 3). The main cornice had a height of 26 m, the thrust collar of the cupola was located at a height of 65 m and the tip of the cross on the lantern was 93 m high. The main cellar was laid out in the shape of a Greek cross. Above the cellar rose a central, round church hall, its outline being formed by eight slim stone columns (Figure 4). Above the columns there was an arch of a cylindrical vault, which carried the flat inclined interior cupola and the double-walled exterior cupola with a diameter of 26 m. The slim interior columns were an architectural design element.

Figure 1 : The Frauenkirche before its destruction in February 1945
(photo: SLUB, Deutsche Fotothek)

Figure 2 : View onto the heap of ruins after the destruction of the church
(photo: SLUB, Deutsche Fotothek)

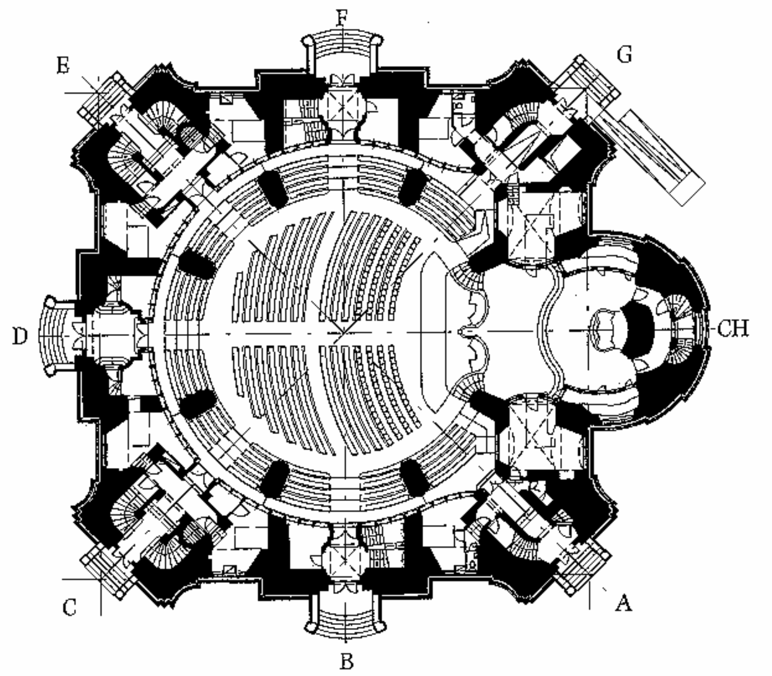

Figure 3 : Ground plan of the church

Figure 4 : View into the interior of the church before destruction
(photo: SLUB, Deutsche Fotothek)

The master builder George Bähr had intended to support the high loads of the stone cupola not only by the columns, but also by the surrounding masonry via the V-shaped walls starting from the slim interior columns (see Figure 3). According to the scientific knowledge of his time and his background as a craftsman, George Bähr was unable to substantiate his structural concept with calculations. The birth of architectural statics did not happen until late in the 18th century. Due to settling of the building site and compression of the masonry and the columns the estimated load distribution to the outside was disturbed. It was not realized to the extent that Bähr had hoped for. This led to a very high load on the interior columns. The result was that soon after construction of the cupola the masonry, the cupola and particularly the columns started to develop cracks.

In the twenties of this century the condition of the building was causing great concern, so that it was decided to carry out comprehensive refurbishment measures. In the first stage, the interior columns were extended with steel bands. Later, in the thirties, the foundations were reinforced and three reinforced concrete anchors were added to the interior walls of the main cupola shell.

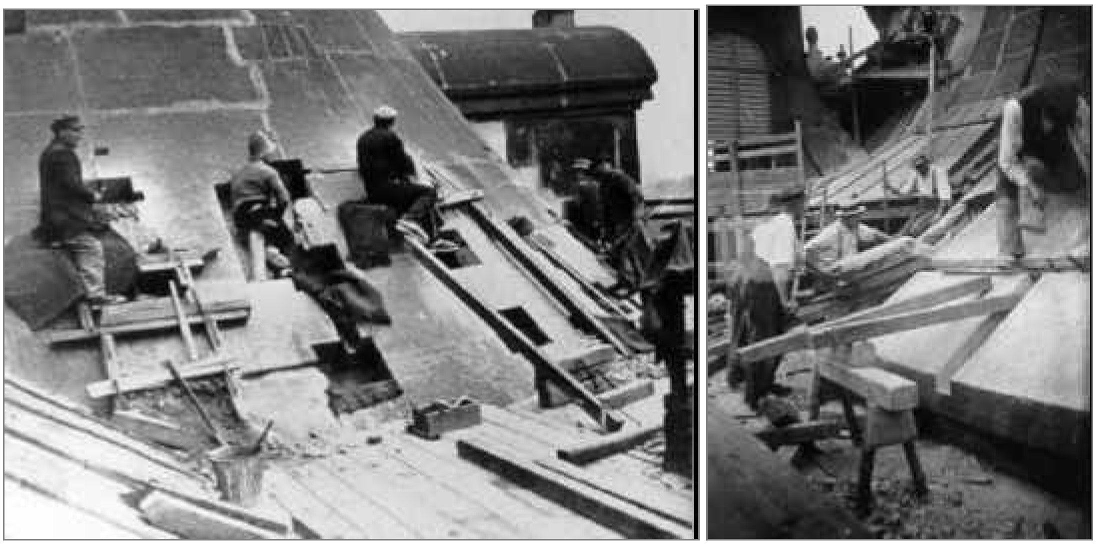

Figure 5 : Photo taken during restoration period at 20th century
(left: stone roof of the choir; right: stone roof between main cornice and cupola)

2 THE COLLAPSE

On 13 February 1945, a few weeks before the end of the Second World War, the Frauenkirche in Dresden caught fire following British and American air attacks. The fire reached the interior through the glass windows, which had burst; the wooden interior finishings then provided ample fuel for the flames. On the morning of 15 February the church with its stone dome collapsed upon itself.

By the time the fire reached its climax, the uneven spread of heat had caused additional tensions and irregular expansions to develop in the sandstone masonry. Vibrations from the detonation of high-explosive bombs that had landed in the immediate vicinity had caused old cracks in the building to re-open and new cracks to form.

The heated, already partially deformed steel girders for the galleries were still on their supports, but they exerted considerable force on the surrounding masonry and caused initial localized damage and permanent deformation. The inherent stresses arising from the irregular heating of the masonry and the tensions caused by hindrances to expansion were added to the original load stresses; the overall stresses thus increased until they reached the failure limit for the masonry. The building's safety reserves were used up. Only a slight impulse was needed to set off a chain reaction. However this impulse was not provided, as has previously been supposed, by the weakening of the cross section of an interior pier through spalling as a result of the fire. The remaining cross sections that have been found on the lower parts of the interior piers, in the area most heavily affected thermally, were still greater than the standard cross sections at the height of the gallery. Rather, the steel girders for the galleries probably must be considered the triggering factor for the collapse. These formed a ring in four tiers around the church nave; however the ring was open to the chancel, so that counteracting forces were not present. It can be assumed that the substantial expansions of the steel girders of this ring decreased again as cooling set in, causing the girders to fall because their supports were no longer in place. This undoubtedly caused exertion of lateral forces on one or more of the interior piers, which could no longer absorb them. One of the two southeastern interior piers failed.

With the lapse of this single support, the load of the dome was deposited onto the remaining piers. The extreme stress that was already on them was increased even more. The dome began to tilt slightly to the southeast, but was still held for the moment by the interior piers of the north side. This force caused them to lean outward. Around the bases of the piers the stones were literally crushed and pulverized. Now without stable support, the dome began to sink into the church interior. Already as it began to go downwards - still held together by Bähr’s wrought iron anchor rings and the reinforced concrete tie beams installed in 1938/39 - the dome pushed the mighty facade walls of the north and south sides outward.

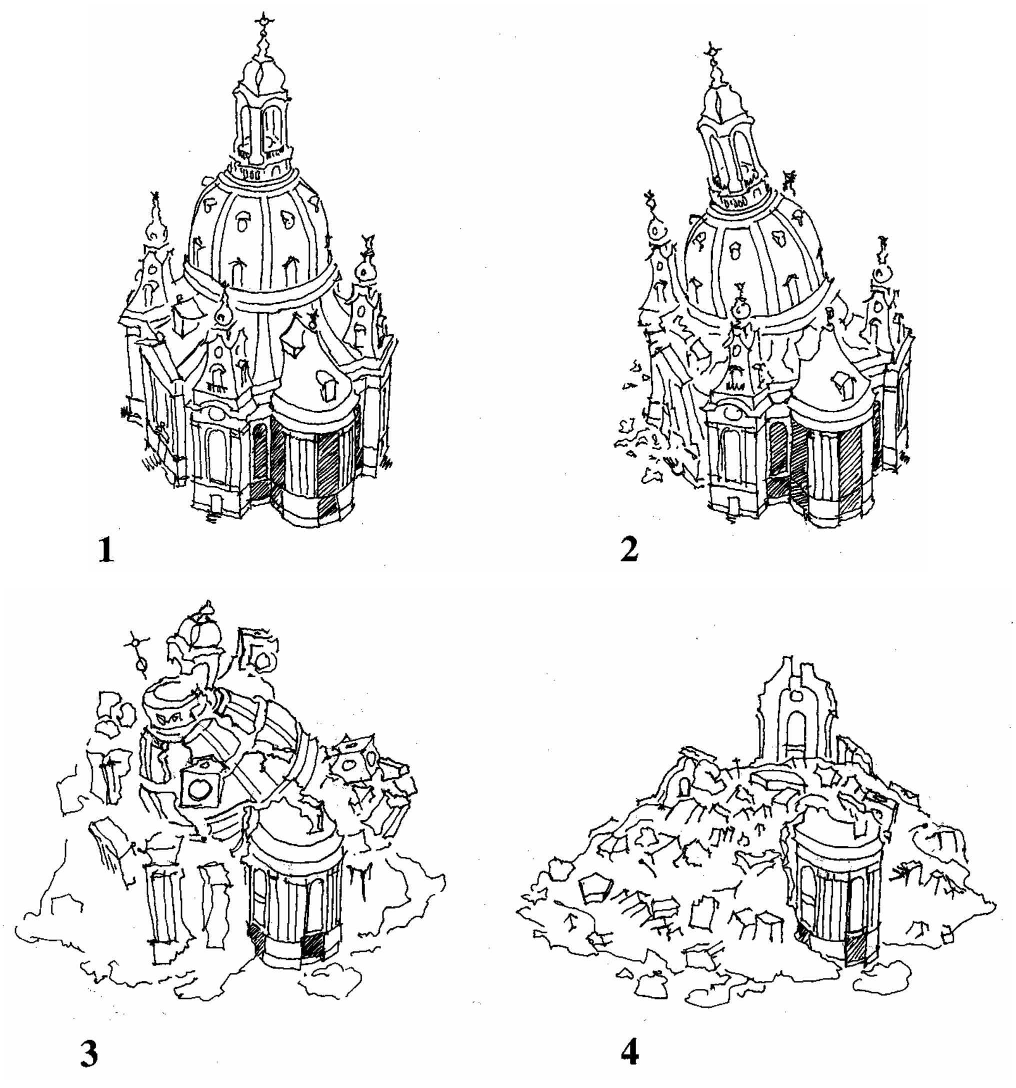

Figure 6 : The collapse of the Frauenkirche on 15th of February 1945 (sketch: D. Rosenkranz)

The exterior masonry of the chancel, which was to the east outside the line of the dome, kept standing. Falling stones damaged the side of the stone altar facing the church interior, but the altar itself did not collapse. Projecting sculptural elements of the altar broke off. Large components of the interior piers broke through the vaults of the crypt. The dome destroyed the interior walls with their vaults and arches. Through the pressure wave of the sinking dome and the immense impulse it created the west and east exterior walls above the ground floor were pulled apart at the window axes and abruptly pushed away. They collapsed upon themselves.

As the dome hit the floor the basket-arched vaults of the main crypt were totally destroyed except for small shoulders to the west and east. The vaults of the two northern burial chambers were also penetrated. The two southern burial chambers remained intact. After losing their inner supports, the roofs of the staircase towers fell onto the mountain of rubble, forming its highest points and marking the end of the collapse.

3 THE IDEA OF THE ARCHAEOLOGICAL RECONSTRUCTION

Due to the refurbishment of the twenties and thirties, complete dimensioned construction drawings were available (Prinz, 1992). In the rubble itself, facade stones, ornaments and lining ashlars could be recognized as being reusable. Even entire large sections seemed to have survived the crash entirely. A part of the northeast corner tower and the choir were jutting out of the mass of rubble. Thus, the preconditions for a reconstruction according to the rules of the preservation of historic buildings in its original shape and construction style were fulfilled (Nadler, 1992). The first attempts failed due to a lack of funds in the years after the war and in the former GDR. Only after the political turnaround and the German reunification it became feasible to put the ideas of reconstruction into action. Planning for the clean-up of the site and rough static calculations were started. These were intended to prove the feasibility of an archaeological reconstruction from an engineering point of view.

The term of archaeological reconstruction, in the understanding of art historians and the professionals participating in the reconstruction of the Frauenkirche, means the reconstruction:

- according to the plans of its builder George Bähr,
- taking into consideration the master builder’s principles,
- using reusable original materials as well as
- still standing parts of the ruin and the foundation masonry, and also
- with careful additions according to today’s engineering standards.

4 THE ARCHAEOLOGICAL RUBBLE CLEARANCE

With the “Call from Dresden” the decision was made in 1991 to reconstruct the church in its original state using whatever stones were still there from the original building and the valuable series of drawings as reference, and combining original material with modern know-how to enhance the load bearing performance of the historical construction. In January of 1993 they began the rubble clearance subject to the basic principles and modi operandi employed in constructional archaeology. The first task required sorting and categorizing the entire archive material available. The necessary planning not only involved questions of content but also issues of building regulations as the construction site, Neumarkt, is an area of great interest for the city of Dresden.

The following focal points of the archaeological mode of working formed the basis for preparing the rubble clearance:

- Collection of all the information about the findings with regard to their location as well as to the piece itself and documentation of all the information received
- Processing of the information received of the pieces and of the place where the pieces were found, clear orientation and designation of the places
- Evaluation of the individual pieces found regarding whether they are worth recording or not
- Recording of the surrounding of the pieces that have been found

- Clear and unequivocal labelling of pieces found and recording of all information pertaining to the finding
- Description, illustration and graphic representation of the piece found
- Decision on storage or filing
- Documentation of all the work stages
- Preparing drawings for mapping the place in horizontal projection and in sectional drawing depending on the work's progress
- Identification of the pieces found on the basis of all knowledge gained and available up to that point of time
- Archaeological evaluation of all the information gained and available up to that point with a view to the reconstruction of the original condition as a continuous process
- Preparation for the reutilization of parts, pieces or structures to be reconstructed

The function and aim of clearing the rubble at the Frauenkirche was to obtain information on the following focal points:

- original geometry and dimensions
- original construction
- technological problems involved in erecting the building
- materials used and utilization for building component groups
- architectonic details
- interior decoration (stucco, painting, organ, plastering, lining and finishing)
- effectiveness and advisability of restoration measures
- degree of destruction

The aim was to secure the original material as much as possible using archaeological considerations as selection criteria for the reconstruction work.

Peculiar to this task is that it is to be completed within a predetermined period of time as it is not an end in itself but rather a basis for the real task of rebuilding.

The heap of ruins has a total volume of 21.200 m³ and covers an area of 3.220 m². The volume was calculated from the surveying data with the help of PC software. For recovery purposes a rough estimate of

- 10,000 pieces of interest found
- 200,000 basic pieces

was a basis for calculation. The pieces found have a weight of 0,020 to approx. 950 kN.

For the preparation phase it was important that the manual and mechanical processes of the recovery were carried out as independent as possible of the archaeological stocktaking. The evaluation of information can be carried out either parallel to or after the stages of acquiring the information and storing the data. This time delay is possible by using electronic photogrammetry to record as much information as possible about each individual piece of interest found. The extent, depth and precision of the evaluation procedure can be decided as desired at any time.

At the end of the archaeological stocktaking and evaluation sheets for the pieces of interest found showing

- the key data
- photos printed on printer
- the drawing of the piece found as well as
- the mapping of pieces found in form of drawings of façade and interior

were available. The results are used as a basis for the architect who plans the rebuilding and, depending on the usability of the pieces found, either includes them in the building being reconstructed or uses them as models. For many stones it wont be possible to find an unequivocal allocation. These are used with due consideration of their suitability for particular building sections.

The electronic pictures and key data including inventory management is handled with a database saved on CD-ROM. Due to the abundance of data acquired, regular saving is very important.

Figure 7 : The building site during the archaeological rubble clearance

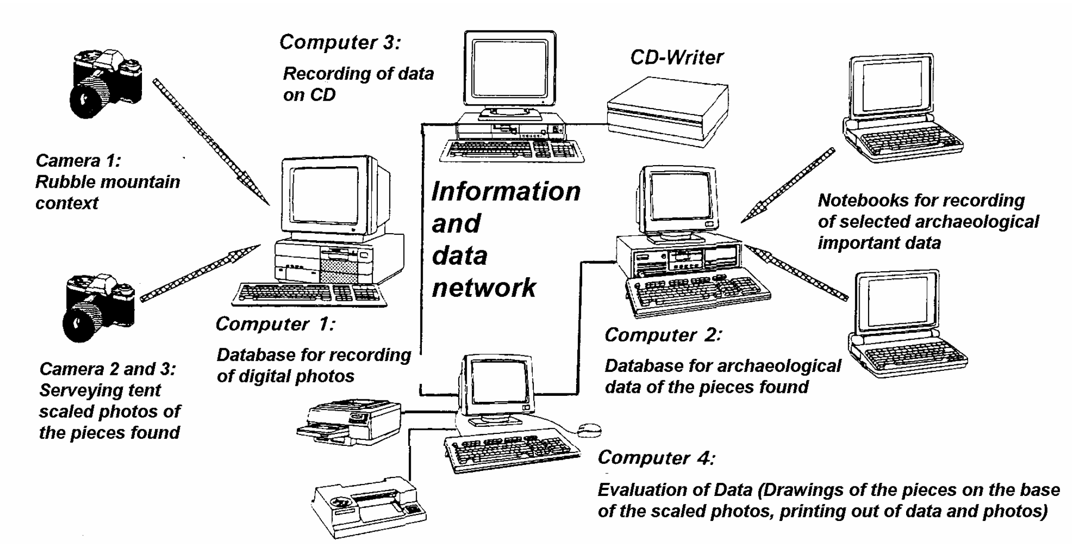

Figure 8 :The algorithm of recording of information during the recovery process (flowcharts: IVD/AVI Dresden)

5 THE ENGINEERING TASK

The formation of cracks known from the history of the building, which had kept generations of master builders busy considering solutions, were reason enough for the engineers charged with the reconstruction project to study the load bearing capacity of the building in detail. The weaknesses found in the course of these studies were the reason for the implementation of cautious improvements in the reconstruction without disregarding the basic archaeological principles. Essential engineering problems to be solved in the course of planning the reconstruction were and still are:

- the assessment of soil conditions on the building site,
- the interaction of building and soil,
- the load bearing capacity and quality of the foundation masonry,
- the load bearing capacity of masonry consisting of Saxon sandstone according to German standards and today’s scientific knowledge,
- connection of new masonry not yet subjected to loads to the existing masonry of the ruin parts already subjected to loads,
- the remaining load bearing capacity of the existing masonry,
- the improvement of the load distribution flow compared to the original building,
- the load bearing behaviour as well as mastery of the sandstone cupola design, and
- the concept of weather protection of the cupola using sandstone.

The following outlines some of the engineering problems encountered in the reconstruction of the church as a sandstone structure as well as the courses adopted for their solution.

6 THE LOAD DISTRIBUTION

During the erection of the building George Bähr recognized the problems of shear and the driving forces of the cupola. With this in mind he had conceived the building. He arranged the corner towers in such a way that they provided opposing forces to the shear of the cupola and the vault. He intended to achieve the distribution of the high vertical loads from the stone cupola to the adjacent masonry by the arrangement of two V-shaped masonry plates starting from each of the interior columns.

George Bähr was able to suspect or feel the flow of load distribution, but he was unable to make a quantification. The slim interior columns had to absorb considerable forces close to the limit of their load bearing capacities. The loads were even compounded by the fact that the cupola has a slightly eccentric arrangement towards the inside.

In order to prevent overloading the foundations and the interior columns, a correction of the load distribution documented for the original building is necessary for the reconstruction (Wenzel, et. al 1996). Therefore, the building authority, the State Office for the Preservation of Historic Buildings and Monuments in Saxony and the Engineering Partnership Frauenkirche Dresden finally decided after extensive studies and evaluation of possible alternatives on an additional anchor at the level of the main cornice.

On the one hand, it provides an additional anchor and, on the other hand, permits the introduction of forces for the improvement of the load distribution. A diagonal strut is formed in the wall plates connecting the drum of the cupola and the exterior masonry. This contributes to a reduction of the vertical load from the cupola and thus also of the bending moment in the columns. This solution represents an unobtrusive and inconspicuous addition while maintaining the original building structure and with the use of typical building materials mortar, stone and iron. Essentially, the objective of this addition is to bring the security level of the entire building up to current standards while maintaining the original building structure.

Also other engineers made proposals for the solution of the problem concerning the reduction of high actions in some regions of the building. Among them were *Günter Zumpe*, *Curt Siegel* and *Fritz Leonhardt.* On condition that the system is statically indeterminated the load flow can be corrected in different ways:

- Change of the geometry of the load bearing structure (*Zumpe*)
- Change of stiffnesses (*Leonhardt*)
- Utilization of correcting forces (*Wenzel*-Engineering Partnership Frauenkirche)

- Use of stronger materials (*Siegel)*
- Integration of additional structural elements (*Wenzel*)

Zumpe analysed the documents from the building time and the building master and interpreted them with the modern knowledge of an engineer of today. He concluded that the master builder would distribute the loads from the heavy cupola in the region of the curved stone roof between the exterior walls and the drum of the cupola (Zumpe, et. al 1999). But Bähr could not have the engineering judgment of the load flow in a shell or solid structure. He was a craftsmen (carpenter master) and worked for a long time as architect on the basis of experience. At that time of the first half of the 18^{th} century it was not usual to calculate a building. Only at the end of that century the term "civil engineer" was born and French civil officers started with the application of mechanical knowledge for the construction practice. That's why the Frauenkirche is an artifact of that time of development of construction practice and why it should be rebuilt in the original manner with careful additions due to another understanding of building safety.

The Foundation Frauenkirche Dresden decided very early to follow the proposal of *Wenzel* and install an additional polygonal ring in the height of the main cornice and to apply additional forces with the help of these anchor ring. So it is also possible to reduce the danger of cracking especially in the supporting arches bearing the cupola.

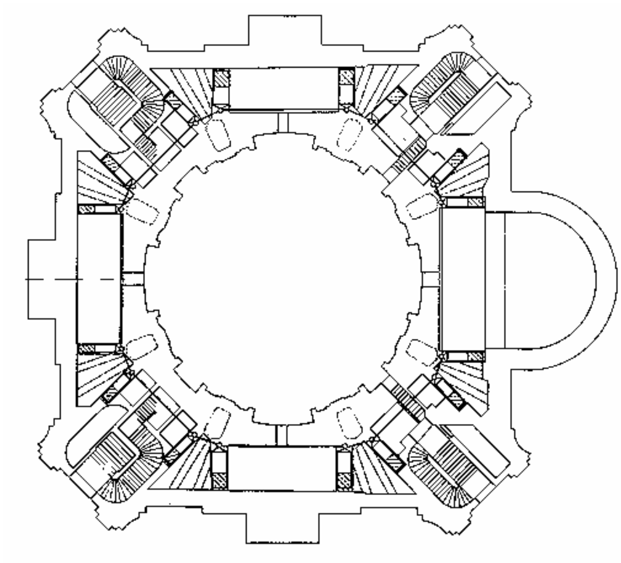

Figure 9 : Assembly of the additional anchor ring in the height of the main cornice (cross section)

7 THE LOAD BEARING BEHAVIOUR OF SANDSTONE MASONRY

The valid standard DIN 1053 (DIN 1053 T1, 1990 and DIN 1053 T2, 1984) used in Germany at the beginning of the 90^{th} was very generous in its specifications of natural stone masonry with regard to the classification of sandstone. In the final analysis, it is only suitable for limited masonry strengths, which were insufficient for the high stresses building components in the reconstruction of the Frauenkirche in Dresden in spite of changes in the load distribution. At the same time it became clear, that more detailed studies on the load bearing behaviour of masonry made from Saxon sandstone had to be carried out. So it was necessary to realize a test program for Sandstone, mortar and masonry.

The situation with the current masonry code (DIN 1053-1, 1996) relating to natural stone masonry is now the some like at the beginning of the 90^{th}, but now its allowed to use a stronger masonry on the basis of testing (DIN 1053-2, 1996).

In evaluation of the tests and additional numerical simulations was worked out a guideline for design, calculation and execution of masonry foreseen for rebuilding of the Frauenkirche (see

Jäger, et. al 1996a, Jäger et. all 1999). According to the load flow were defined 4 requirement classes for masonry. The classes differ in the strength of sandstone, the kind of mortar and the accuracy of the units.

The masonry of the Frauenkirche in Dresden must be classified in the stonework of the exterior walls and in such of the interior walls. The facade is made from large cut stones and the masonry backup is made from smaller, so-called ”Grundstücke” (basic pieces). Both shells are closely interconnected. The interior masonry consists only of one shell of one class of stonework.

The first approximate calculation already indicated that the stresses calculated under working loads required the use of differentiated masonry qualities. These included:

- regular composite masonry from differently processed sandstone with various joint gaps and mortars under compressive stress,
- ashlar stone work with sawed stones and very narrow joints to achieve a high load bearing capacity under compressive stress,
- composite and cut stone masonry with various joint gaps under shear/compressive stress, and
- creep of masonry consisting of Saxon sandstone.

The experimental investigations were accompanied or supplemented by further analyses of the old and new stone material as well as the historic mortar. On the basis of the latter analyses, the mortars to be used under current conditions have been conceived on a lime basis. The tests with regard to masonry were carried out jointly with the chair for Planning of Load Bearing Structures of the faculty of Architecture and the Otto-Mohr-Laboratory of the faculty for Civil Engineering of the Dresden University of Technology.

Essential findings in the test series on the load bearing behavior of Saxon sandstone masonry under compressive forces were:

- The failure of masonry can occur in sandstone due to transverse tension failure, as well.
- The strength of the stone, the size of the stone, the joint gap and the mortar quality are important influencing parameters on the strength of masonry.
- Resistance of the masonry to fracture of up to 82 % of the stone strength used can be achieved with a joint gap of < 5 mm.
- Marked effects of plasticity as with other building materials (concrete, steel) do not occur in masonry consisting of Saxon sandstone. The failure due to fracture can be classified as brittle.

As a result of the evaluation of compression tests, formulae were created for the determination of resistance to fracture of masonry and factors for its reduction for the determination of building component resistance (*Berndt* 1994 and 1996). In doing so, more differentiated influences than otherwise usual in masonry construction were considered within the scope of the method of limit states. The advantage is, that the masonry can be better evaluated and situations occurring in the construction of the building can be assessed more realistically. For a general application a simplification of the formula system would be necessary.

The shear-compression tests (see Fig. 10) formed the prerequisite for concrete evaluation approaches for this type of load. These were again developed by *Berndt* (1996) according to the ultimate limit state method with consideration of partial safety factors and were taken into consideration in planning work for the reconstruction.

Figure 10 : Shear-compression test with high compression

The essential results of the creep tests were that the stone, due to its preload in the mountains, does not experience any creep deformation and that creep is essentially limited to mortar. It may be considered as being completed after a time period of six months to one year. Creep factors for the calculations were determined from the tests.

The results of the tests and analyses that were carried out have been summarized in a masonry guideline for the reconstruction of the Frauenkirche in Dresden (see *Wenzel*, et. al 1996). This summary also contains specifications for craftsmanship and building materials as well as inspection notes.

In order to realize the stresses existing in the masonry with economically justifiable expenditures, various masonry requirement classes have been defined according to the flow of forces. They are intended to guarantee a uniform safety level throughout the building. The strength of the masonry of different requirement classifications was controlled by the selection of stone material, the quality of the mortar and the joints. A differentiation must be made here between existing masonry and masonry to be built new. The existing masonry was assessed with regard to its strength on the basis of detailed analyses. Four different strength classification will be used for newly built masonry (see Fig. 11). The joint gaps will vary around an average of 1.5 to 0.6 cm.

AK 1	AK 2	AK 3	AK 4
$\beta_{D,St}$ = 43,1 MN/m²	$\beta_{D,St}$ = 43,1 MN/m²	$\beta_{D,St}$ = 43,1 MN/m²	$\beta_{D,St}$ = 56,0 MN/m²
MG II (Mö 5)	MG II (Mö 5)	MG II (Mö 5)	MG III (DF 4)
$\bar{t}$ = 6 mm (VM) = 15 mm (HM)	$\bar{t}$ = 6 mm (VM) = 15 mm (HM)	$\bar{t}$ = 10 mm	$\bar{t}$ = 6 mm
$\beta_{D,Mw}{}^{R}$ = 8,0 MN/m² (VM) = 3,2 MN/m² (HM)	$\beta_{D,Mw}{}^{R}$ = 8,0 MN/m² (VM) = 3,9 MN/m² (HM)	$\beta_{D,Mw}{}^{R}$ = 5,1 MN/m²	$\beta_{D,Mw}{}^{R}$ = 9,7 MN/m²

VM … facing masonry
HM … backing masonry
$\beta_{D,St}$ … compressive strength of units
$\beta_{D,Mw}{}^{R}$ … compressive strength of masonry, design value
$\bar{t}$ … mean value of the joint gap
AK … requirement class
MG … mortar group according to German masonry code (DIN 1053-1: 1996-11)

Figure 11 : Classification of sandstone masonry according to the masonry guideline for the rebuilding of the Frauenkirche

Lime mortar with hydraulic additives will be used for normal masonry. A special mortar has been created for masonry with narrow joint gaps and high stress loads. 'Trass meal', which has been proven suitable for natural stone masonry, has been chosen as a special additive to the mortar.

In order to achieve and document the parameters on which the static calculations are based in the actual building, a quality assurance system has been implemented. It starts in the quarry and in the manufacturing plant of the mortar and ends with the acceptance of the masonry sections on the construction site. The quality assurance system requires certain expenditures, but permits, on the other hand, a timely remedy in case of possible irregularities. Now it is possible to conclude that the decision to introduce these quality assurance system was right. Sandstone is a natural material and changes its parameters during the long time of breaking stones in different quarries. The system was necessary to guarantee the needed level of strength. The rebuilding of the church is in this case also an example of the consequent utilization of the semi probabilistic method of design with partial safety factors in the ultimate limit state.
In order to find approaches close to reality for the modelling of the building, extensive preliminary studies have been conducted in accordance with the possibilities of the utilized program packages. The behaviour of the masonry is determined by its components mortar and stone. Stone behaves nearly elastic, while mortal behaves ideally elastic, ideally plastic. However, separate modelling of both materials for building components and supporting framework is neither possible nor sensible, it is only justifiable for micro modelling. These were used in particular for the recreation of test results and the calibration of the mechanical models. Generally, the analysis of supporting structure is carried out with the aid of so-called 'smudged models'.

The essential analyses of the total load bearing performance were carried out by more precise calculation with consideration of material laws close to reality. In case of the program package ANSYS, the approach of DRUCKER-PRAGER proved to be the most suitable of the implemented material laws (Bergander, et. al 1996). It has the disadvantage that, in the end, the possibility of the transmission of tensile stresses is still assumed even under cracked conditions, which is not the case after the formation of cracks. The inaccuracies occurring due to this may not be satisfactory mechanically, but is negligible in a building practice point of view. In this way the office of the author succeeded, with justifiable expenditures and under utilization of standard software, to carry out masonry calculations close to reality.

8 THE CUPOLA

The cupola of the Frauenkirche was a double-shell construction, which had consisted of an outer shell of 1.3 to 1.5 m thickness and an inner shell of 0.25 m thickness. Both shells were interconnected by transverse masonry pieces (see Fig. 12). The outer shell had no additional roofing skin. Weather protection was provided a sandstone top layer of approx. 0.25 m thickness, which was connected to the lining masonry throughout. Wrought-iron ring anchors were located between the top layer and the lining masonry. The cupola had relatively large window openings permitting the light to penetrate. The cupola was topped by a lantern with a height of approx. 18 m (refer to Fig. 12). It is intended to reconstruct the cupola of sandstone according to the archaeological principles.

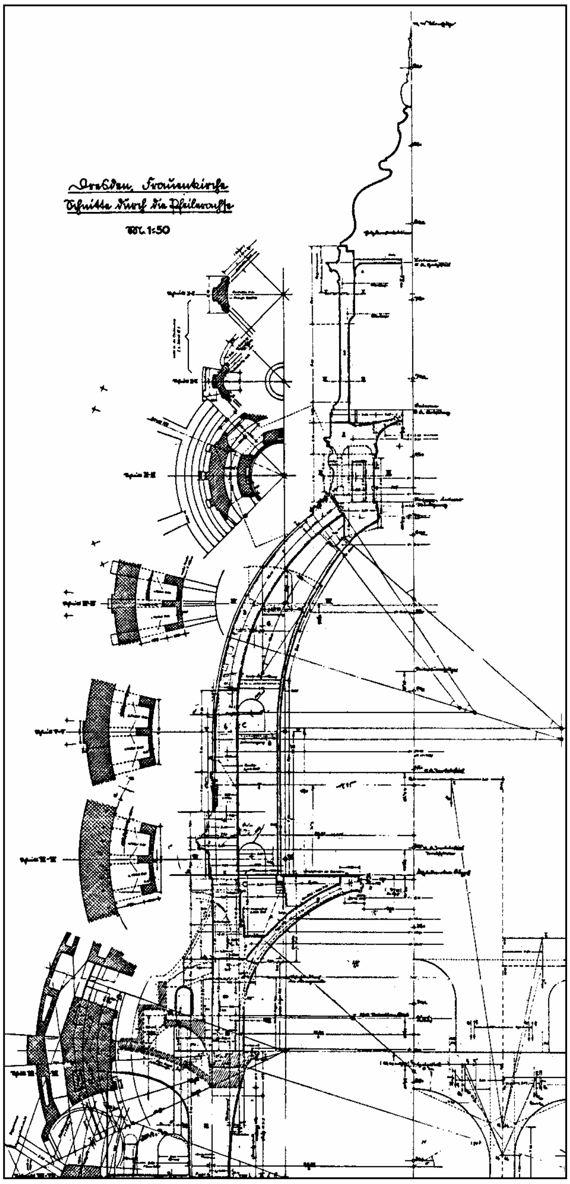

Figure 12 : Cross section through the historic stone cupola

The FEM analyses were carried out in the linear range, since it is intended to pre-stress the cupola moderately for the reconstruction (Jäger, et. al 1995). Thus, no tensile stresses will occur in meridian and tangential direction (Jäger, et. al 1996). Initially, the cupola was considered separately under observation of compatibility conditions to the supporting structure. The cupola was first calculated without pre-stresses in order to determine the necessary value of these pre-stresses. The case of a pre-stressed cupola was subsequently implemented by the introduction of pre-elongated rods at the element edges of the outer surface. The design of the pre-stressed ring anchors has been decided upon in the meantime. Six flat steel ring anchors made from high-quality fine-grained structural steel will be used. They have dimensions of 3 x 15 to 4 x 18 cm, depending on the required pre-stresses. In order to keep the friction between straining ring and masonry to a minimum, the individual sections of the straining ring are supported on teflon strips. The friction losses to be considered here are minimal. After tensioning the remaining straining channel will be injected with cement mortar, filling in the spaces between masonry and steel. In this way, a solution is created which is characterized by its high durability.

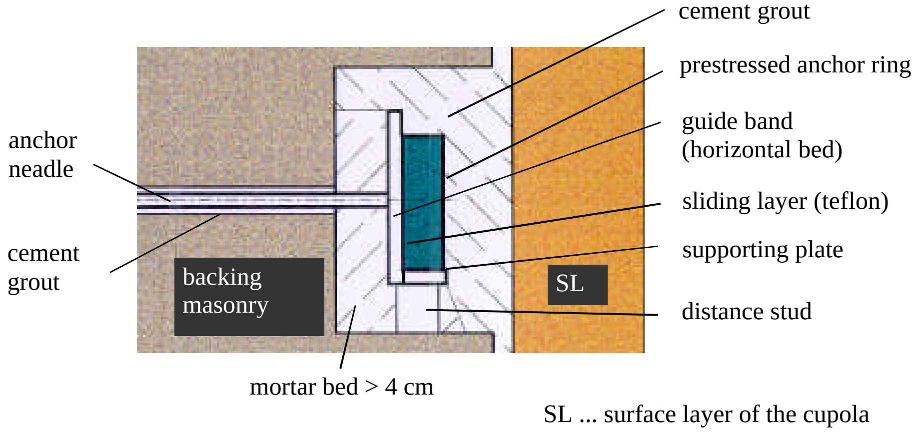

Figure 13 : Cross-section of the anchor ring of the cupola in detail (principle sketch)

The issues and problems with regards to building physics in the sandstone top layer make high demands on planning and material selection. Here, building material issues with regard to sandstone and the jointing material to be used as well as the design in view of durability must be investigated. Beside of an enormous numerical simulation work were curried out full scale tests at wall specimens of the cupola.

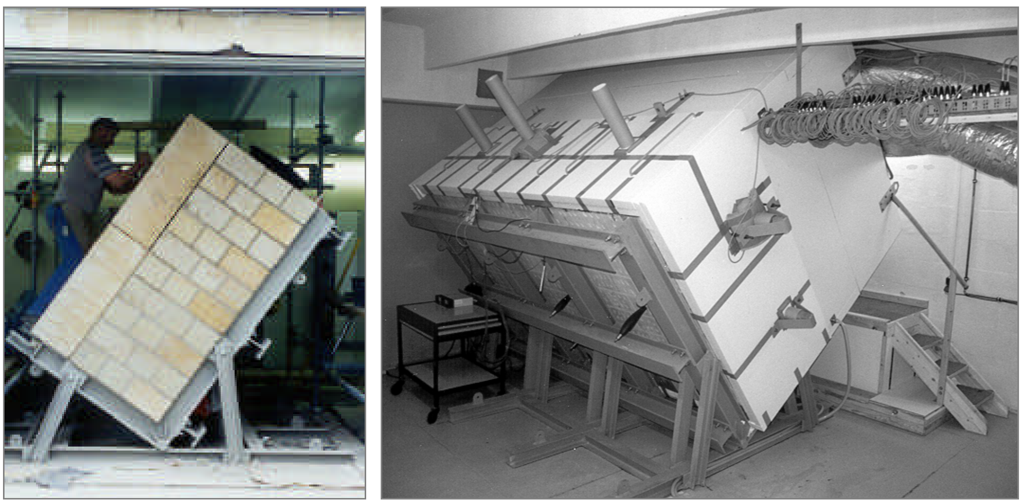

Figure 14 : Full scale test at the test laboratory of the Chair for Planning of Load Bearing Structures, Dresden University of Technology

9 THE ASSEMBLY OF THE LARGE DEBRIS PIECE GT 35

During the archaeological clearance of the heap of ruins a large number of pieces of interest have been found. Not all of them could be removed as a whole piece due to the high weight and also due to the location in the original church in zones of high actions.

One of these large debris pieces has been the roof of the North East staircase tower with a weight of around 95 t. In 1993, after preparing and strengthening the so-called 'butterfly' has been removed from the heap. The piece was lying upside down on top of the heap of ruins. By means of a special mobile crane and with the aid of a reinforced concrete tube which was connected with the masonry by needles it was possible to lift and remove the large piece.

Figure 15 : Removal of the top of the north-east corner tower (GT 35) from the heap of ruins in 1993

On 10th August 2001 the large piece GT 35 was assembled to its original place at the top of the North-East staircase tower (see Figure 16). A steel framework was necessary to turn the large piece into its right position. This framework also helped to justify the horizontal position and to drive it to the fitted points at the supporting masonry or the tower. Both removals needed an exact preparation and were only possible within the network of all architects, engineers and skilled workmen involved.

Figure 16 : Assembly of the large debris piece (GT 35) on 10th August 2001 to its original place

10 THE STAGE OF THE RECONSTRUCTION WORK

Construction work in the region of the curved roof between the exterior walls and the drum of the cupola is currently underway (Figure 17).

The works on the building site follow strictly the planned time-schedule. For that the use of a weather protection roof that allows to work throughout the whole year is very helpful. In winter the scaffold is fully covered by tarpaulins. Only the places where units are lying are heated. In the year 2001 the reconstruction program reached following important stages:

- closing the inner cupola with the light opening of the interior
- finishing the staircase towers up to the bottom of the top (due to the limited height of the weather protection roof)
- laying the first plates of the double curved roof between the main cornice and the drum of the cupola (see Figure 17, left (stage before))

From the point of view of Building Technology the region of the curved roof is very important regarding water tightness. In the past it was one of the weakest points of the church. Owing to the porousness of the used Postaer sandstone it might happen that water penetrates unto the backside of the plate. That is why the responsible engineers decided to integrate a sprayed-on seal in the roof unto the point where the drum of the main cupola starts according to the understanding of serviceability in our time. The supporting points of the stone plates were planned in an adequate manner to the whole structure with respect to longevity. Into the spaces of the supporting ribs that have been sawed out accurately prefabricated stone dowels based on 3D drawings were integrated.

The distances between the ribs are filled with flat brickwork vaults. On the brickwork thermal insulation layer is located and the seal will then be sprayed over everything.

In 2001 the architects were starting to plan the inner finish and services according to the detailed schedule for the finish works of the interior. For matching the concepts of the preservationists it is necessary, especially in the finishing phase, to work with so-called test areas. With the aid of such completed areas of limited extensions all persons involved can get an impression and can thus either support or modify earlier decided solutions. The aim is to meet as close as possible the original conformation of the interior.

According to the timetable the construction of the cupola is scheduled to begin in 2002. The structural works will be finished in 2004. The completion of the interior furnishings of the church including the organ is planned for the year 2005. 60 years after its collapse the church will open the doors on October 2005 as a sign of reconciliation.

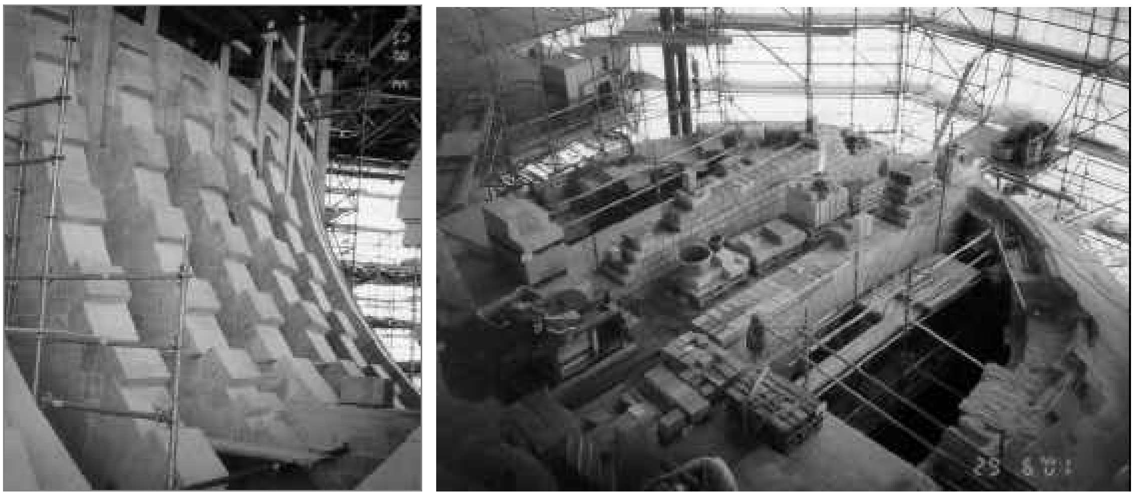

Figure 17 : View onto the building site in Summer 2001 (left: the supporting arches of the negative curved roof; right: the beginning of the choir roof)

11 CONCLUSION

The archaeological reconstruction of the Frauenkirche in Dresden represents an unique challenge to the participating architects and engineers. The building itself was a daring achievement of its master builder, who approached the limits of knowledge of the 18^{th} century. This fact is our obligation to carry out the planning and supervision of the construction according to the current status of science and technology of our century and explore new ways in the process. These have been portrayed in their essential features here and described in explanatory fashion. It is the task of the engineer to look after and control the problem areas he is working on from the theoretical assessment and design up to the technological realization. Only in this way it will be possible that the theoretical approaches will actually be transformed into reality in a masonry construction subjected to high loads of this magnitude.

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