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# The *Grossmarkthalle* (wholesale market hall) in Frankfurt/Main
## An early reinforced concrete shell structure.

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## Abstract

The *Grossmarkthalle* in Frankfurt/Main is an example for the implementation of the developments current at the time in terms of material technology and also the development of building methods for reinforced concrete shell structures.

The research on spatially curved structures made of reinforced concrete, was inter alia initiated by Walther Bauersfeld. In collaboration with the engineers of the company *Dyckerhoff & Widmann* it was possible to develop a new manufacturing method for thin walled domes made of reinforced concrete. The basis for these shells was a steel grid as a geodesic dome. This development was facilitated by the then newly available option to apply concrete on any surfaces using airpressure (air placed concrete). This knowledge on material and manufacturing processes provided the basis for the construction of the *Grossmarkthalle*. In parallel the theoretical analysis which focused on simply two dimensional curved surfaces was further developed.

The utilization of the building has changed, so the status quo of the *Grossmarkthalle* was analysed. Following that a respective concept for refurbishment was developed.

**Keywords**: concrete shell, monument, refurbishment, maintenance

# 1. Introduction

The idea of constructing a large wholesale market hall in Frankfurt dates back to the Wilhelminian era. After a first attempt which was interrupted by the outbreak of the First World War, the design and construction of the *Grossmarkthalle* began in 1926 according to plans of Professor Martin Elsaesser. The city of Frankfurt aimed at improving the supply of fresh fruits and vegetables for the citizens of Frankfurt as well as expanding the area of influence of the city in terms of food supply at a regional scale, which explains the size and appearance of the market hall. The *Grossmarkthalle* was inaugurated in 1928 and the wholesale market stayed there until 2004.

The *Grossmarkthalle* today comprises of the following elements:

- the east wing building (former refrigerating storage building; L/W/H: approx. 60/18/29.75 [m]),
- the market hall (L/W/H: approx. 225/55/23.5 [m]),
- the west wing building (former office building; L/W/H: approx. 60/18/29.75 [m]).

The overall building ensemble originally also included two annexe buildings (East and West), the so called Importhalle (for southern fruit imports) and an extensive transportation infrastructure between the buildings. Those structures were removed in the meantime and do not exist anymore.

The Großmarkthalle is a listed building, which will be converted by the European Central Bank (ECB) as part of its new headquarters. In this context the structure of the *Großmarkthalle* was investigated and a concept of refurbishment was developed, respecting the requirements of the historic preservation authority of the state Hessen.

Figure 1: North façade

# 2. The *Grossmarkthalle*

The *Grossmarkthalle* encompassses approximately 235 000 m³. The market hall itself is divided into three sections with five reinforced concrete half-cylindrical shells each. The shells are built according to the "Zeiss-Dywidag" system, as roof shells with edge beams (constructed as box girdres) and endplates. The box-girders are supported by inclined columns, the latter are fixed into individual foundations, as described in Kleinlogel [5], [6] and in Dischinger and Finsterwalder [3], [4].

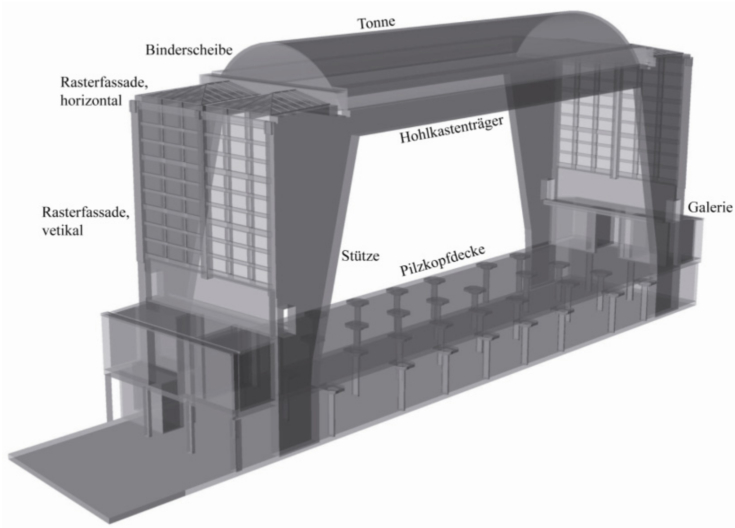


Figure 2: Segment of the *Grossmarkthalle*

The envisaged geometry of the shells is based on a circle segment with a radius of 7.50 m. The shells' thickness ranges from 7 cm to 10 cm. The reinforcement bars are set in five different layers with respective dimensions of 12-8-12-8-12 mm. Their disposition follows a rhomboid shape based on the main stress trajectories. For the concrete, a high quality Portland cement (*Dyckerhoff-Doppel*) is used in proportions 1 to 4. The edge beams of the shells are designed as box girders with dimensions of 0.8 m width and 1.9 to 2.0 m height. The side of the box-section are 10.0 cm thick whereas the bottom of the box-section is 22.5 cm thick. The top of the box-girder is slightly inclined for drainage purposes. The columns of the *Grossmarkthalle* are 0.80 m wide and 1.90 m thick. The connection between the box-girders and the columns is articulated. The articulation is designed to transmit only horizontal and vertical bearing forces.

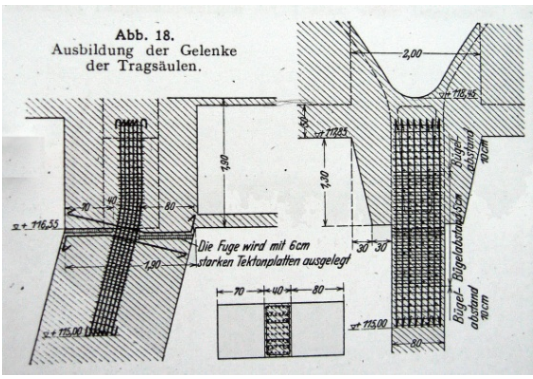


Figure 3: Concrete Hinge

The façade of the *Grossamrkthalle* is supported on half frames and spans between the primary columns. The facade frames comprise three different sections in a regular pattern.

The floor above the basement is executed as a reinforced concrete plate supported by individual columns. Each column has a polygonal section and is locally reinforced at the connection point with the floors. The columns are supported on individual foundations. The perimeter walls are built with bricks.

# 3. State of the Art 1926

Three major lines of evolution converge into the design of the *Großmarkthalle*.

- The investigation of the composite behavior of reinforced concrete,
- The progress made in prefabrication techniques and
- The increasingly theoretical calculation methods

All three developments influenced one another and established in 1926 a state of the art, which regard to spatially curved concrete structures, which enabled the construction of the *Grossmarkthalle*.

Since the second half of the $19^{th}$ century, bridges, industrial- and commercial-buildings were built as reinforced concrete structures. The use of reinforced concrete structures then gradually expanded to residential-, administrational- and academic-buildings, shown by Gideon ([4], pp. 220) and Müller-Wulckow [5]. An attempt to present its effectiveness and adaptability was the *Monier-Broschüre* by Wayss [14], which was therafter completed and updated in professional journals and publications of the different concrete unions. Even in 1929, the reinforced concrete construction was still an early stage of development.

The debate about reinforced concrete can be divided into three major themes:

- Characteristic data and behaviour of the material,
- Fabrication and manufacturing as well as
- Applicability.

The structural performance of specific building elements formed the basis for the applicability of reinforced concrete, see Mörsch [9]. With time, more and more traditional building elements – from columns and beams to plates, frames and trusses - were constructed in reinforced concrete. The increasing knowledge of two-dimensional planar load transmission possibilities logically led to the creation of shell constructions. Material specific research and development began to form an independent field of construction science, e. g. the research of Bach [1].

Reinforced concrete constructions permitted to reduce thickness of sections in comparison to traditional masonry vault and arch constructions (see Mörsch [10], pp. 217 - 240). The tolerance for the formwork (shuttering) had to be dramatically diminished in order to meet the planned thrust line, as even the smallest deviations lead to considerable unplanned bending moments in the shell. The formwork was usually made of wood which required a lot of operating expenses, which was often subject to shape imperfections and which lead to dangerous stress states while stripping the formwork.

Walther Bauersfeld proposed a different approach for the realisation of reinforced concrete shells, described in Kurze [8]. The design of the planetarium for optical works in Jena in 1922/1923 was based on a projected spherical surface. The shell had to be supported by the existing roof due to a shortage of space and thus had to be quite light. In collaboration with the engineers Mergler and Franz Dischinger from *Dyckerhoff & Widmann*, they accomplished to design a shell built in 1923 triangulated with a set of unique custom-built steel bars. The reinforcement is fixed to the steel bars to take up the forces in the shell. A climbing nine square meter wooden formwork is mounted on the inner side of the shell and shifted further after every concreting step. The concreting was conducted from the outside by means of sprayed concrete. Due to the high costs of the manufacturing of steel bars, the principle was developed further into a systematic formwork technique ([15], [16]), which was also used for the roof of the *Grossmarkthalle*. This formwork technique permitted to remain accurate to shape and the mathematical form-finding as well as to avoid hazardous mechanical states during the stripping of the falsework (see Kleinlogel [5], p. 12).

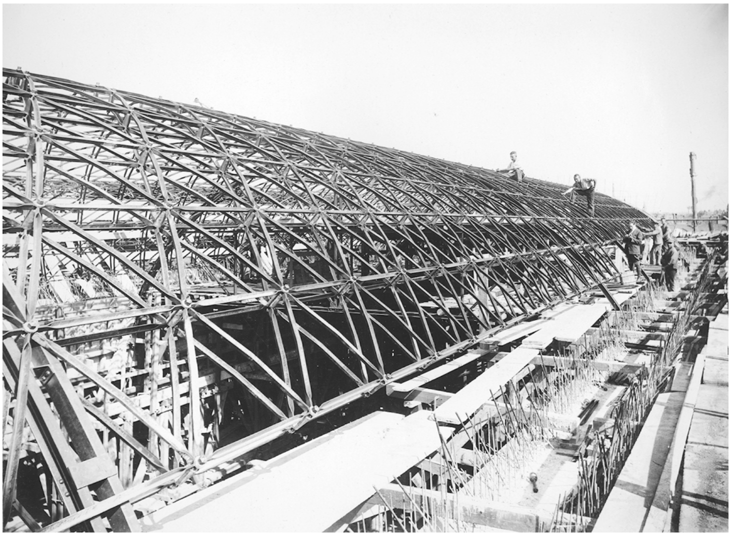

Figure 4: Formwork

The concreting was conducted based on the spread mortar technique (“Torkretverfahren”), which was introduced in Germany by Carl Weber. This technique emerged in the US in 1909 and was patented [17] in the German Empire in 1919. Pneumatic driven pipes spray the wet or dry cement mixture on the intended surface.


Figure 5: Concreting

The applicability and practical use of these new construction methods were described by various building associations, who also developed the relevant codes (compare [13]). The structural safety concept of the *Grossmarkthalle* was based on a predictable and sufficient margin between the actual working load combined with the ultimate load and load capacity of the structure. The exhaustive experiments conducted by Wayss & Freytag formed the basis to develop new calculation methods which focused both on the structural behaviour and on the cost-effectiveness of the material applicability. The calculations of the reinforced concrete section investigated the internal stresses equilibrating the external loads and established the necessary reinforcement to take up the tensile forces. The difficulty was to assert the inner stress states of the structure. In addition to the calculative approach of the market hall, a large scale experiment was also conducted. In parallel to the construction of the main hall, an experimental shell in a scale of 1 to 3 was constructed and gradually loaded between the 11$^{th}$ of April and the 4$^{th}$ of Mai 1927. The main goal was to obtain information on the stability of the cylindrical shell, clarified by Kleinlogel [5] (p. 15). He reports in [6] (pp. 25) the results of these tests. Corresponding to the testloads the deformation was measured with the measuring point in the centre line of the model.The experiment proofed that the structure apossessed sufficient material behaviour and sufficient load resistance.

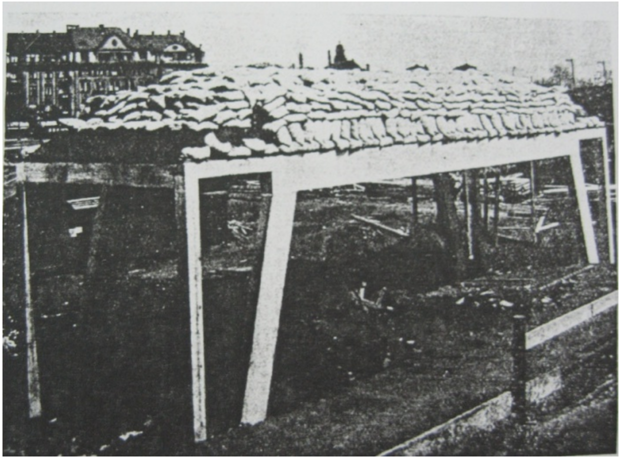

Figure 6: Experimental Shell

The building companies were responsible for teh correct dimensioning of the reinforced concrete structure. Thus, they had an economic interest in the analysis of the existing internal stresses which postulated the respective reinforcement devices as well as the construction of the structure. By virtue of his experience in Jena, Franz Dischinger also used the “Zeiss-Dywidag-System” for cylindrical shells under the condition that binding elements or transverse beams were built at a certain interval and that the bending stiffness of the curved parts was sufficiently low. This formed the basis for the membrane theory of shells for the determination of the internal stresses. Bauersfeld wrote this idea out and put it into practice for the roofing of an industrial building in Jena in 1924, compare Kurze [8] (p. 68). The second pprototype was constructed on the “GeSoLei”-fair (Gesundheitspflege, Soziale Fürsorge und Leibesübungen) in Düsseldorf in 1926. Ulrich Finsterwalder who started to work for *Dyckerhoff & Widmann* in 1923, focused on the development of the shell theory for transversally stiffened cylindrical shells (see also Kurze [8] (p. 69)).

The then innovative structural concept of the market hall created the possibility for an integrative building concept thanks to progress made in terms of material technology, pre-fabrication and calculation methods. Prioir to the start of the construction works in December 1926 the city of Frankfurt, i. e. the building department headed by Martin Elsaesser, designed a preliminary draft. The guidelines for the functional and architectural design were cominde with a technical competition between the different material crafts represented by steel-, timber- and concrete- companies. The aim was to receive a structural concept which fulfils the architectural ambitions with economic and maintenance requirements. The call for tender showed that the City of Frankfurt was well aware of the technical challenges resulting from the preliminary draft of the *Grossmarkthalle*. The competition between the different material crafts resulted in a cylindrical reinforced concrete shell. The structural concept, the construction design and the calculation were drawn up by Dyckerhoff & Widmann and the final construction was conducted in a consortium with Wayss & Freytag. Both firms had a 30 year-long experience in this technique and were actively participating in further material researches. In contrast to the well-established steel- and timber- works, only few experiences with reinforced concrete structures transferring spatially load had been made until the construction of the *Grossmarkthalle*.

Alf Plüger described in [12] a proposal for undestanding the structural behaviour of the shells. A tube, which is supported by endplates, is divided according to length. The truncated part of the tube is replaced by edge-beams. The principal behaviour of the shell is shown in figure 7 below.

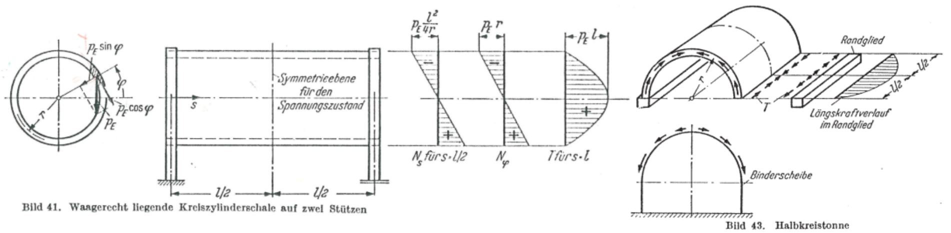


Figure 7: Loadbearing Transfer

These principles were further developed for the *Grossmarkthalle* and combined with the design by Martin Elsaesser into an ingenious prototype. Besides its dead load, Dischinger and Finsterwalder described in [2] and [3], that the load bearing structure had to transfer the loads from the roof covering, the variable wind and snow loads and thermal fluctuation damage-free and safely. The control of thermal expansion in the longitudinal and transverse direction was a key step of the process. In the longitudinal direction, the thermal expansion was given a reasonable limit through a division of the market hall structure into three main sections with respectively five half-cylindrical shells each. The façade, which was directly exposed to weather conditions, was subject to an additional partitioning. The three central fields of the facade were detached from the two edge fields of the façade. In the transverse direction, the shells were connected via a concrete articulation with the inclined columns. The wind loads were taken in by the inclined frames of the façade in combination with the horizontal parts of the gallery and the fixed columns.

# 4. Analysis of the status quo of the *Grossmarkthalle* and the development of the respective concept for refurbishment

*4.1 Concept for the analysis of the status quo of the Grossmarkthalle*

In addtion to the analysis of the original documentation still available (fragmentary available drawings of the reconstruction, documentation of the building applications for the renovations, the bill of costs of the maintenance measures as well as the transcripts of the inspections), on-site inspections proved to be mandatory in order to assess the status quo of the *Grossmarkthalle*.

On the basis of the results of these inspections a research scheme was developed. This research scheme takes into account the various construction methods and times, the various production methods of the involved construction companies, the aging of buildings in general and the minimal maintenance which was conducted throughout the years. This scheme was divided in view of methodical and temporal issues. Methodically was distinguished between objectives that allow a survey of the existing condition and the refurbishment methods of object-specific design taking into account the character of a heritage building.

The objectives include the investigation of the structural status quo, the investigation of the compressive strength, Young's modulus, the concrete density, the pattern of cracks, the level of carbonation, the concrete cover above the reinforcement, the type of the existing reinforcement and its distribution within the concrete as well as the corrosion of the existing reinforcement.

The measures for the refurbishment take into account the surface textures, the degree of moisture within the concrete, the gas permeability and the tensile strength of the surfaces. With regard to the preservation of the *Grossmarkthalle* the colour and brightness of the concrete surface are analysed and the surface textures and weathering are recorded.

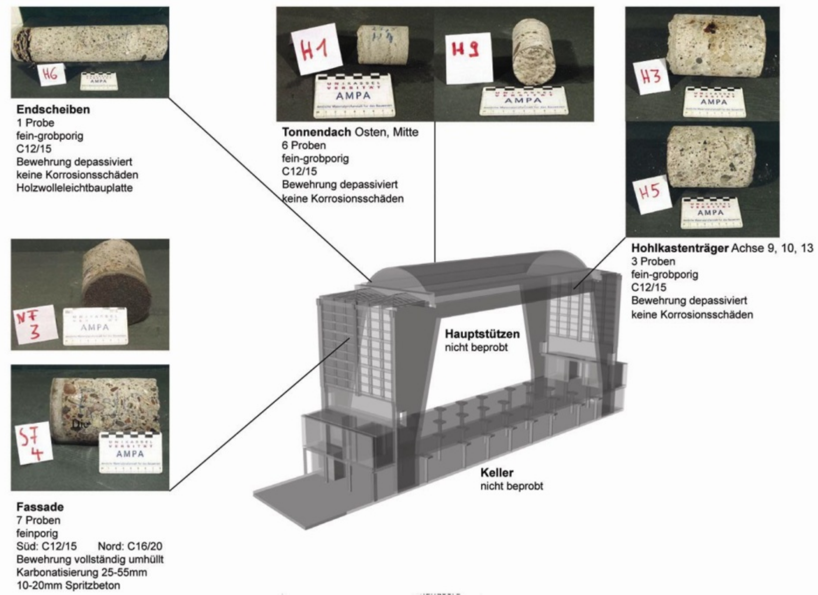


Figure 8: Results of the analysis of the status quo of the *Grossmarkthalle*

The compressive strength of the various shell elements varies with 1,8 N/mm² as teh lowest merit and 56,9 N/mm² as the highest with an average merit of 42,2 N/mm². The average value of the Young's modulus is 19406 N/mm². These results are based on 54 drilling cores. In historical design codes the requirements for the compressive strength amounts to 13 N/mm² and the requirements of the Young's modulus amounts to 14000 N/mm$^2$.

*4.2 Refurbishment of the Grossmarkthalle*

The concept for the refurbishment of the *Grossmarkthalle* can be divided into two tasks. The first task relates to the structural refurbishment, the second task deals with the restorative renovation. Since the latter is based on the former, there is only a partial independence in the choice of material and the layer sequence.

The restorative renovation of the damaged listed Grossamrkthalle is based on

- Careful handling of the existing status quo of the building,
- Selecting procedures with minimal intrusion depth, which are also tailored to the various cases of damage,
- Feasibility and reliability of repairs, few but multiple-use materials,
- Considering the scale factor (size and frequency of necessary measures),
- Preference of procedures, ideally depending only on a few parameters.

In addition, the restoration renovation gives high priority to

- The careful integration of the architectural design
- The preservation of historically important areas and surfaces
- The sampling and demonstrating the design criteria of M. Elsaesser.

The various design elements were recorded. Their structure and their characteristics were described in detail. For the renovation, the possible inclusion about deviations and damages were discussed. While assessing the actual damages design rules and codes of the construction period and current design codes were compared. This led to a system of design features related to the type of construction corresponding with a classification of damages. Based on this damage catalogue various procedures were developed and applied to sample surfaces to test their adequacy. The objectives for the renovation were optimized, in a coordinated process of the building owner, the historic preservation authorities and the relevant experts.

Figure 9 shows the results of this testing-phase. The refurbishment of the concrete, including reinforcement-protection, new different concrete layers and a finish with a dispersion-silicate paint which – corresponds to the original surface.

Figure 9: Principles of renovation, tested at one column

The refurbishment measures were classified in three different groups, depending on the status quo regarding stresses and deformation:

- Measures of low-intervention depth.
  Changing the existing construction only to a limited extent, stress and deformation changes aren't expected (e. g. removing the layers of dirt, small spatial clinker repairs and joints).
- Measures of medium-intervention depth.
  Changing the existing construction in only small areas. Occurrence only for locally different stresses and no additional design elements will need to be added. (e. g. a local break out of concrete without exposed reinforcement, medium spatial clinker repairs and joints).
- Major intervention measures.
  Altering the existing structure by adding new independent design elements. A significant change in the designed stress and deformation state is necessary for the preservation of the market hall (e. g. local break out of concrete with exposed reinforcement, strengthening and new connections).

Based on these principles and the results of analysis of the *Grossmarkthalle* the design team has established four types of measures: maintenance, conservation, completion and replacement.

In addition to the damage occurring at isolated spots which can be clearly allocated, it is possible to define different damage classes. These classes are distributed in varying concentration (density) across the building. Every type of damage corresponds to a refurbishment measure and the density of damages is related to a concentration of measure. The basic tasks are in turn assigned to material related measures. With regards to the selection of procedures the type of damage determines the type of action (measure) and the degree of damage determines the denseness of action.

# 5. Conclusion

The chosen planning process allows for a risk reduction in terms of refurbishment measures for a listed building. In particular with regard to:

- The building owner's now sound knowledge of available technology.
- The Coordination of procedures between the building owner, the design-team and the heritage authority.
- The determination of quantities of the measures required.
- The Limitation of the risk of errors during implementation on site.

The documents drawn up support site management in the supervision of the construction, enable cost controlling and presents construction companies a tool for carrying out the renovation successfully.

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