The furnace hall in Peitz – analyzing a 200-year old curved plank roof

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ABSTRACT: Enormous roof deformation caused a structural analysis and assessment of the curved plank roof of the Smelter Museum's furnace hall in Peitz. An extensive analysis starting with the anamnesis – the collection and evaluation of the data concerning the history of the structure and its damage - followed by an accurate assessment of the behaviour of today's structure provided the basis for the cautious strengthening concept and the preservation of the roof.

Curved plank roof structures date back to the 16th century French architect Philibert de l´Orme. His idea based on the task to roof over large buildings without any intermediate bearing by using thin and short planks only. The roof rafters were made of two or three layers of timber planks, which were nailed together in a semicircular form. They could easily be assembled on the building ground. After setting them upright they were stiffened by horizontal struts. Following an order of King Henri II, who was enthusiastic about this idea, de l´ Orme published his disquisition about curved plank roofs "Nouvelles inventions pour bien et à petits fraiz" in 1561. Although de l´ Orme announced that spans of up to 400m (!) could be realised, curved plank roof structures were rarely built during the 17th and 18th centuries. Almost fallen into oblivion, the construction method was taken up at the end of the 18th century by the architects Jacques-Guillaume Legrand and Jacques Molino. In 1783 their design of a 39 m spanning curved plank structure for roofing the Halle au blé in Paris became a world-wide attraction for the building masters.

It was especially David Gilly, Geheimer Ober-Baurath (royal Prussian privy chief building officer) under Friedrich Wilhelm II and III, who introduced this building method in Germany. With reference to de l´Orme he published a detailed handbook about the construction of curved plank roofs in 1797 [Gilly]. In contrast to de l´ Orme, who used semicircular rafters, Gilly propagated a pointed arch shape following the inverted chain model, the ideal shape of an arch. Convinced of the stability of this roof shape he totally neglected aspects of stiffening or bracing. In the following decades hundreds of these curved plank roofs were erected all over Germany. Today only some of them still exist. The propagated aspects of high load bearing capacity by using a minimum of timber often led to underdesigning of rafters and stiffening elements. The unfavourable roof shapes and the difficulty of fixing the roofing tiles on the curved rafters properly, as well as the demand for extraordinary working skills of the craftsmen, which were needed to assemble the roofs, were the main reasons for the deficiencies and the decline of these structures.

Today only 33 curved plank roofs still exist in the state of Brandenburg. The roof of the furnace hall in Peitz is one of the largest curved plank roofs of that time.

1 THE SMELTER OF PEITZ

Peitz, an ancient Prussian fortress, is situated in the Lausitz, about 100 km south-east of Berlin. The region was rich in near-surface iron ore. In 1554 the smelter was founded on royal order and primarily for military purposes. Until the end of the 19th century it produced cast iron goods like munitions, machine parts and everyday crockery. From 1898 to 1973 the buildings were used by the fishery industry. In 1973 the Smelter Museum opened. The main attraction is the furnace hall of the museum with its blast furnace, two cupola furnaces and the historical blower. The all buildings of the former Smelter: the smelter office, residential houses, the product store, the moulding shop and the furnace hall are classified as historical monuments. In 1809 the building permission for a new furnace hall was granted by King Friedrich August of Saxony in 1809. Carl Gottlob Voigtmann, the site supervisor, suggested the curved plank roof structure. Grown up on the smelter side and later on becoming the director of the smelter he was the person who was dedicated to it his whole life. In 1813, a short time before the Prussian took over the region, he even refused an order of Saxony's administration, which commanded the demolition of the smelter.

The 15m spanning and 30m extending furnace hall has a false hip roof. The building was erected in half-timber framework, later on the walls were partly converted into massive masonry works. The massive blast furnace on the southern part of the building towers 7 metre above the 13m high ridge of the roof. The roof rafters follow the shape of a pointed arch made up of three radiuses. In comparison with other curved plank roofs of that time,stiffening aspects were reasoned well by Voigtmann. The arches are cross-braced by splitting the rafters in upper and lower chord. The whole roof is longitudinally stiffened by using Philibert de l´ Orme's horizontal struts. The curved rafters consist of 2 layers, each of the planks 5cm x 28cm strong and about 1.7m long, nailed together in broken joints. Today, after 200 years of existence, the roof is critically deformed.

2 STRUCTURAL ASSESSMENT STARTS IN HISTORY

The anamnesis, the evaluation of numerous archive materials, served as the basis for the structural assessment. Already by evaluating the historical documents, drawings and photographs the main problems of the roof could be pointed out. During a careful visual assessment of today's structural elements a better understanding of the structural behaviour of the roof was obtained. One by one the structural elements like rafters, junctions, footings, intermediate bearings and stiffening elements were analysed with special regard to their static modelling in the calculation. Damage was noted and evaluated in its effects on the structural behaviour.

Some results:

1. The enormous roof deformations have already existed for more than 50 years. The whole roof structure turned and shifted, this caused failure of connecting devices, critical support conditions and contraction because of abrasion. During the last 50 years the walls and working platforms inside the building were changed and rebuilt several times, which affected the support conditions of the rafters. The rafter footings were originally fixed in the half timber frame structure. Today they stand separately, which made them suppler.

Changing the roofing continuously raised the roofing loads during the history of the roof, which raised the danger of buckling.

2. In 1955 residents recognised that the massive blast furnace, which supports the middle part of the roof, sank. The blast furnace is founded on a pile foundation grille. In the 1980´s the foundation of the blast furnace was examined by the director of the museum. Former assumptions on furnace sinking were confirmed. The ground-water level was about 30cm beneath the upper beam ends. As a result they rotted. Open-cast mining activities in the surrounding areaside had caused the lowering of the ground-water level. In 1992 gauge marks were installed to monitor further furnace movements. From then till now the furnace sank another 2cm with a maximum of 2.2cm at the south-eastern edge of the furnace as the comparison of 1992 survey data and today's measurement demonstrates. Different sinking depths result in a south-east leaning of the furnace, which corresponds to today's roof deformation.

Two aspects could have caused the leaning:

First, the ground water level sinks from the south-eastern to the north-western edge of the furnace as today's measurement points out.

Second, by analysing ground plan drawings from the end of the 18th century it can be assumed that the prior furnace stood slightly more to the east than today's furnace. Different subsidence activities could have caused a westward leaning.

Five rafters of the northern curved plank roof are supported by the blast furnace. The sinking furnace caused deformation of this part of the roof by pulling it down.

3. In the course of the visual assessment of the roof deficiencies concerning the stiffening of the roof were discovered. Many of the original horizontal stiffening struts are missing. The horizontal strut stiffening was originally thought to keep the rafters in distance to each other, their cross sections were developed to resist compression as well as tension forces. Some struts were replaced by thinner elements which do not resist compression forces anymore. Because of cracking many joints are not able to resist tension forces anymore.

3 PROPOSALS FOR STRENGTHENING

During the last decades different engineers tried to stiffen the roof, various kinds of stiffening elements were added to the original structure. Many of the strengthening elements attached later do not work anymore; some of them never worked properly.

In 1955 the East-German engineer Preiss, well-known for his competence, already gave a sustainable concept for roof strengthening. He suggested adding a wind brace in the middle part of the northern roof, which was to be fixed on the blast furnace and reach down to the foundation. He regarded the blast furnace as a core. Following his concept, the deformed curved rafters were to be thrown back into alignment while roofing the building with double-laid tiles. Missing elements of the historical horizontal strut stiffening were to be added. The whole roof was to be attached to the furnace.

Only some of the suggested measures were carried out in the following years.

A wooden wind brace was added to the structure. It was not fixed on the blast furnace and because of conservator's objections did not reach down to the foundation. The rafters were not aligned; horizontal stiffening was not completed. Today the wind brace in the northern part of the building is not properly fixed anymore, elements of the wind brace are threatened to fall down. Altogether a well thought-out concept, which was not executed consequently enough.

Another expert's report was done in the 1990s. That time the engineer suggested adding a steel framework to stiffen the roof. Knowing about the blast furnace sinking, an attachment on the blast furnace should be avoided. The static calculation was done on a single, not deformed rafter. The necessary bearing capacity could just be proved. Another exemplary calculation on a single, 40cm deformed rafter showed stresses of up to 4-5 times of its bearing capacity. Based on that calculation it was demanded to throw the deformed curved plank rafters back into alignment. Again, while fitting in the steel frames an alignment of rafters was not done! Nevertheless the question is, if in the end the strict alignment of the historic curved rafters would cause cracking and the total failure of the rafters.

Examining the effectiveness of the steel framework today, its static "height" in comparison to its length seems too low to prevent further deformation. The timber and steel joints do not seem strong enough to prevent slippage. The attachment of the steel framework probably even increased the damage by forcing the rafters in unfavourable positions. Altogether the attached steel framework seems not to be an effective strengthening.

4 DEVELOPING AN EFFECTIVE STRENGTHENING CONCEPT

The 200-year old roof still exists, which, however, prove its bearing capacity. Nevertheless it was badly deformed over the time. The present and future safety of the structure can not be guaranteed. Strengthening measures are urgently needed.

The historic roof should be repaired and strengthened in a cautious way. The side walls of the furnace hall can not accept horizontal loads. In the name of a cautious intervention in the historic structure the assembling of massive, new building elements has to be avoided. Only the massive blast furnace would be able to act as a stiffening core. But the furnace is sinking. Ground improving measures need to reactivate its bearing capacity. The suggested activities follow the 1950s strengthening measures in a stricter way. Newly attached stiffening elements should be minimised. Therefore historic stiffening should be reactivated by repair and completion. It should be continuously connected to the blast furnace. The existing wind brace north of the blast furnace should be replaced by more effective stiffening. Five rafters north of the furnace should be connected by a strong but light bracing. The stiffening should consequently be fixed on top to the furnace and downwards to the base masonry.

Calculation needs to prove if the steel framework could not be totally removed from the structure.

A structural calculation checks out the feasibility of this concept.

5 STRUCTURAL CALCULATION

For the first time in the history of the roof a structural calculation considered the three-dimensional behaviour of the roof - the combined acting of rafters and stiffening elements, which gives a realistic model of the load bearing. Therefore the site measurement concentrated on the deformed roof. The survey was based on reflector-less tacheometry. The degree of accuracy of the tacheometer was +/- 5mm. The survey data was embedded in a three dimensional AutoCAD model which was transformed into the structural analysis software. The structural calculation of the three-dimensional model was the content of a diploma paper at the Brandenburg University of Technology Cottbus in spring 2003 [Lange].

The studies started on a two-dimensional model of a single rafter, on which support and junction conditions were analysed and optimised concerning their most realistic behaviour. Later on the three- dimensional model of the roof was developed. Damage of the horizontal stiffening struts was considered in the structural model. As expected, the calculation failed in 2^{nd} order theory on the three- dimensional system because of element capacity overload. A first step removed all steel frameworks from the model. Afterwards the damaged historic stiffening struts were repaired, missing elements were added. The calculation in 2^{nd} order theory failed again. After fixing the historic stiffening struts consequently on the furnace and modelling a bracing between the five rafters north of the furnace, attaching it upwards to the furnace and downwards to the base, the proof of the stability of the structure succeeded.

6 CURRENT WORK

At present precise monitoring aims to clarify questions about further blast furnace movements. Therefore the 1992 gauge marks were used again. Further on the ground water level is observed by continuous monitoring.

Some urgent repairs of damage were already done. Further measures can not go on because of a lack of money.

7 CONCLUSION

How to find a realistic model of the existing structure is always a very important question for the structural analysis of historic constructions. Historic timber structures often show damage and deformation which influence the structural behaviour. The accurate anamnesis on the history of the buildings and the precise identification of structural elements, their behaviour and damage provide a basis for a better understanding and realistic structural modelling. In very complex, deformed structures the calculation on three-dimensional, deformed structural models helps the engineer to think of more cautious and effective preservation measures.

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