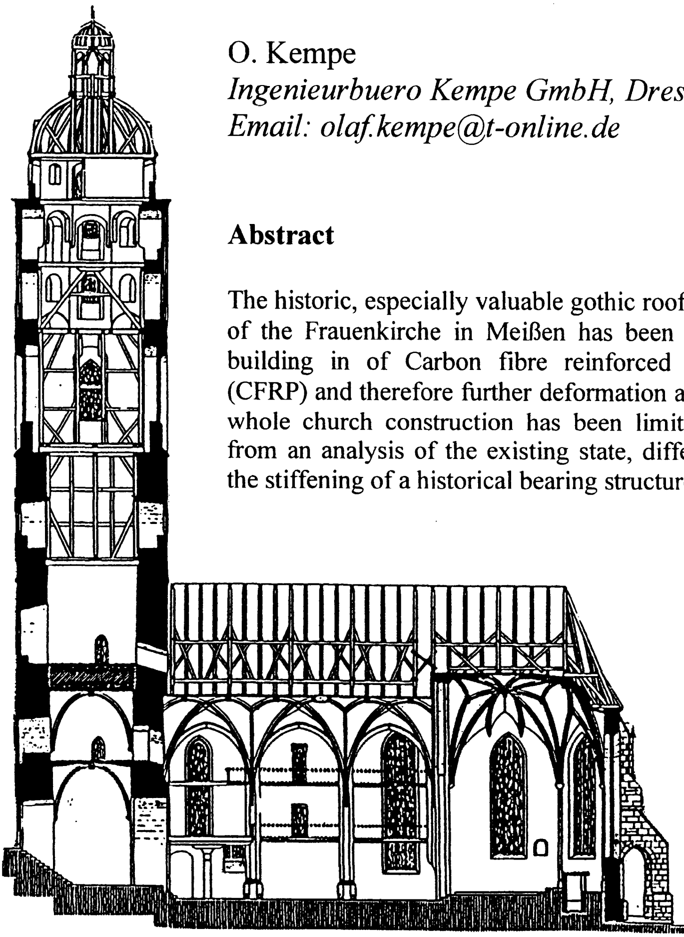
The stabilization of the gothic roof bearing structure of the Frauenkirche in Meißen with CFRP-tension



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Abstract

The historic, especially valuable gothic roof bearing structure of the Frauenkirche in Meißen has been stabilized by the building in of Carbon fibre reinforced plastics – loops (CFRP) and therefore further deformation and damage to the whole church construction has been limited. Commencing from an analysis of the existing state, different versions for the stiffening of a historical bearing structure were simulated.

Figure 1: Longitudinal section of the gothic church with baroque tower curia [1]

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1 The Frauenkirche of the City of Meißen

The Frauenkirche in the market square has been dominating the city centre of the more than 1000 years old town Meißen. Therefore the reconstruction of this church has become of great importance during the complex town redevelopment.

The Frauenkirche in its present form was built as a town church in the early 15th century. It was first mentioned in 1205. The roof truss was added to the churches aisle in about 1447 according to dendrochronological examinations. The church in its form and construction is a typical example of gothic style architecture within Saxony.

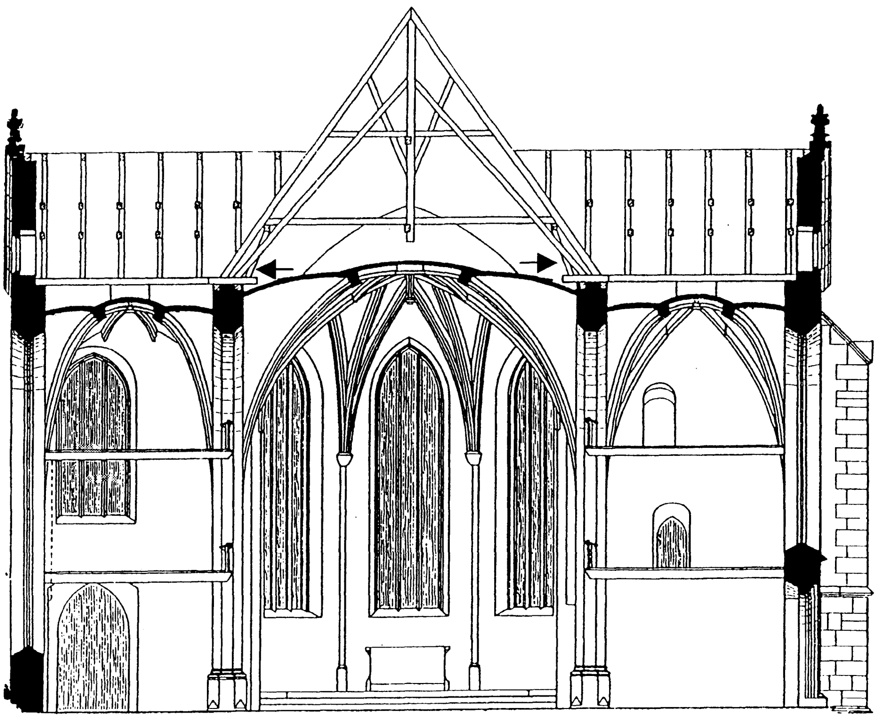

Figure 2: Cross-section with principal rafter A5 [1]

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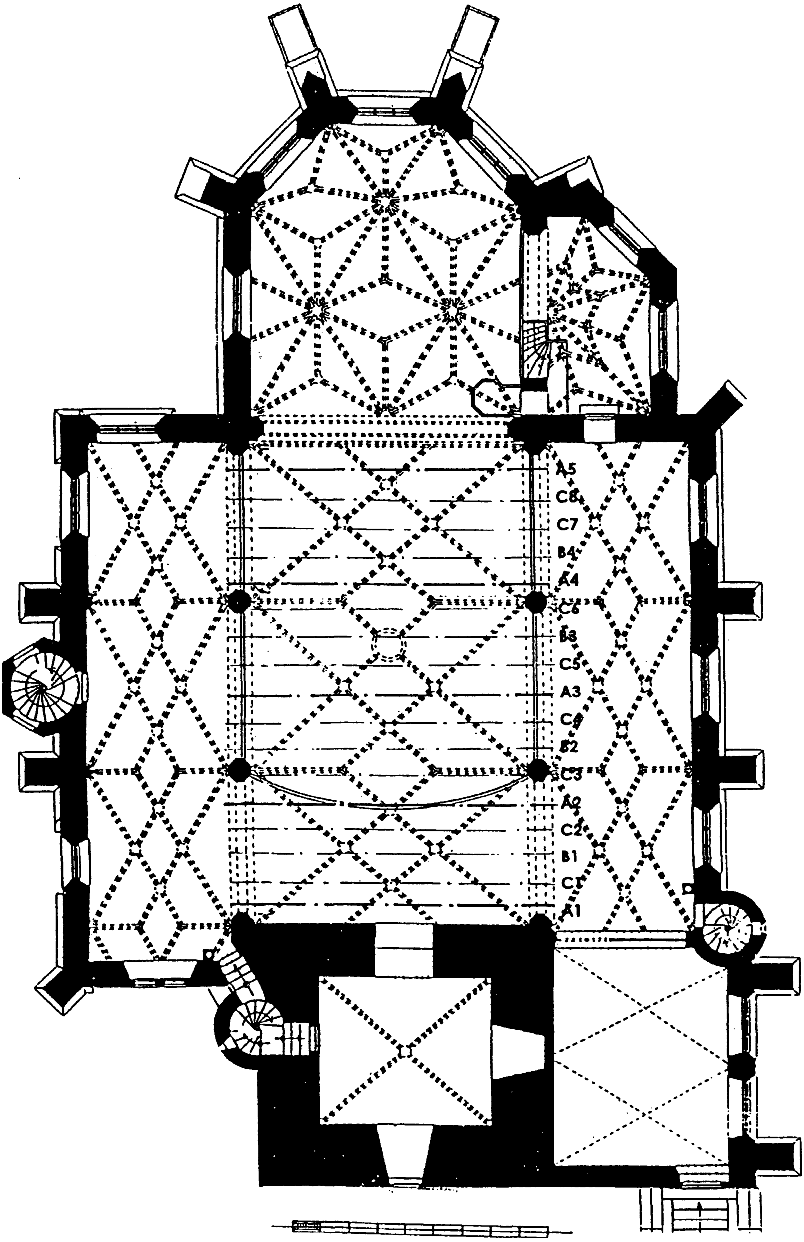

Figure 3: Ground-plan with principal rafters A1-A5 [1]

2 The importance of the roof structure of the Frauenkirche

Due to the importance of the gothic roof structure, as one of the last of its special kind in the east of Germany, the reconstruction was not a routine repair.

The task was conceptional, reconstructing the roof truss with regards to current preservation orders. From a detailed analysis of the existing entire structure, a diagnosis was found. This was the basis for a therapy with minimal reconstruction measures [2].

In particular the historic roof bearing structure in its originality is a technical monument and should be preserved in its appearance. Therefore new stiffening had to be clearly identifiable as additional reconstruction measures. On the other hand they had to be in harmony with there surroundings but also reversibly, without destroying its aesthetics.

To meet this challenge, which was also demanded by the Saxon Commission on Historic Monuments, extensive version examinations were developed in regard to the material, the shape and the technique of possible stiffening.

3 Damages and analysis

The following substantial damages were discovered in the roof truss of the Frauenkirche Meißen and resulting damages were found out the supporting masonry:

a) Destroyed connections between the lower collar beam and the rafters and braces,

b) Strong deformation of the framework in general, in particular, within the area between the lower collar beam and the base point,

c) Damages caused by the infestation of insects and fungus, mainly in the bottom areas of the braces, truss posts, stubs of ceiling beams and wall plates,

d) Constructive damages to the longitudinal framework within the choir area and damages caused by erroneous repairs in the past

e) Cracks in the masonry between the load-bearing longitudinal walls and the connected transept vault over the nave (see Figure 3).

4 Diagnosis and existing construction

From the analysis and static-calculated tests the following results derived:

a) The gothic vault reaches into the roof truss with a strong camber in such a way, that the connecting anchorage beams (tension beams) are missing in the collar roof (see Figure 2-8). Therefore the lowest collar beams received tensile forces which they could not transfer to the rafters via their connections. At these points the treenail connections were overloaded by 250 %.

b) The maximum permissible stress of the rafters and braces was exceeded by 15 %.

c) The maximum horizontal displacement towards the outside caused by stress amounted to 6.1 cm at the rafter base.

The calculations as well as the existing deformation state give evidence, that the roof truss was in motion and that the wooden timber fastener opened. The masonry of the nave received serious shearing forces from the roof. This fact is underlined by the filled in cracks of the transept vault of the nave, which are gaping again and which have a total width of up to 4 cm (!).

Therefore it can be concluded, that the repair and reconstruction of the truss in its old form alone would not be sufficient enough to guarantee its entire stability and to prevent the masonry from other damages in the future.

5 Therapy and preplanning

To strengthen or even better to relieve the load on the collar connections and to reduce the horizontal forces and displacements of the base points and the tensions inside the rafters and braces additional measures for the strengthening of the construction had to be taken.

A three-dimensional model of the roof bearing structure with all details and deformations deriving from the analysis was established in the FEM-program ANSYS in order to weigh up alternative preliminary considerations and versions for the stiffening. Eight important load combinations where applied; temperature stress, wind stress, snow load (stress) and dead load according to DIN were used.

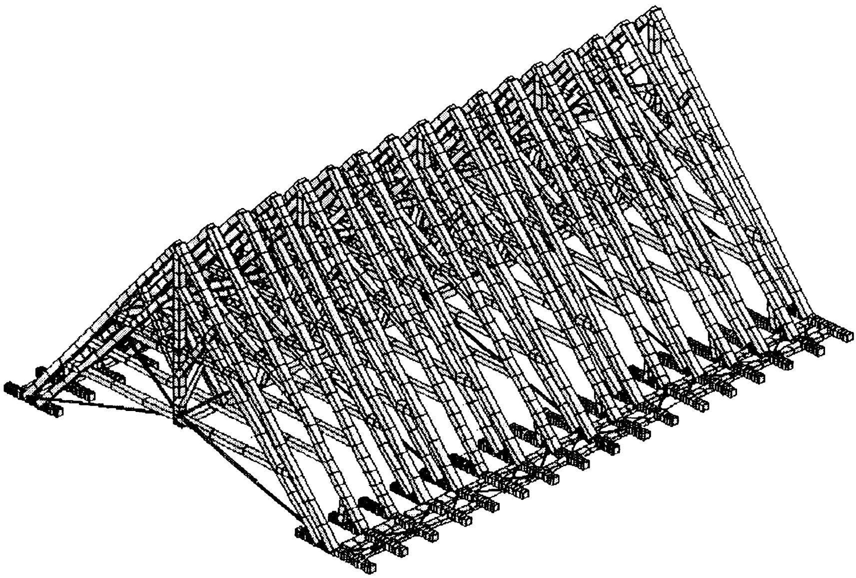

Figure 4: Isometric of FE-model with CFRP-tension and horizontal bracing

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In order to realize the idea of a remedial reconstruction that is reversible and where the truss remains its status as a architectural listed building historical design weaknesses should be kept. Additional structures that shift loads from weak points should compensate and relieve the load from the historic system.

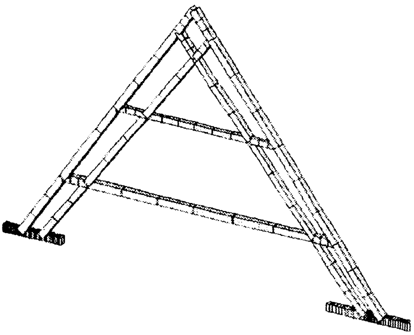

Figure 6: Principal rafter type B1

The main points of the verification process for the constructive solution of this reinforcement were based on:

a) the material to be use for the bracing and crossing of the truss;
b) the shape of a bracing and crossing;
c) the reinforcement of each brace level or just individual levels and the opportunity of directing the shearing forces of the unstrengthened levels into the neighbouring strengthened levels.

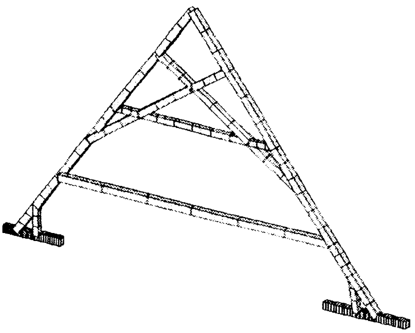

Figure 7: Principal rafter type C1

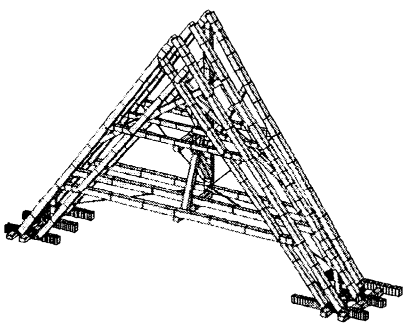

Figure 5: Principal rafters type A1-C1-B1

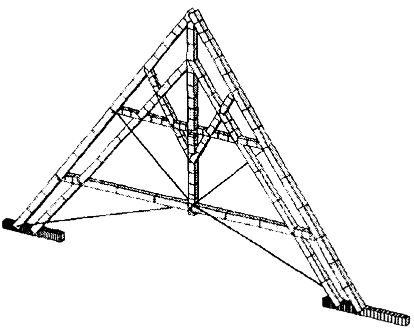

Figure 8: Principal rafter type A1 CFRP-tensioned

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to a):

A discreet form of steel, GFRP and CFRP for the strengthening, that fits into the historic construction, would be fundamentally possible. Due to the large cross-section a stiffening with timber would contradict this idea.

A steel-bracing would efficiently relive the bearing structure. However, under a temperature stress of +50°C in summer and -20°C in winter, that means 70K, a displacement of the base points of the framework of 1.2 cm would occur. GFRP-prestressing bars, in this case, had a very elastic behaviour and were not temperature neutral.

A CFRP-bracing resulted in the best values of stress and deformation for all loading types. The reason for this are a neutral behaviour in terms of temperature and the high stiffness of the material. Moreover it has positive characteristics of corrosion resistance and the characteristic of having a minimal weight while having the highest stability. The necessary cross-section under use of TORAY M40J fibres for the loops accounts for only twice 5x30 mm.

to b):

Within the analyses it proved favourable to add the elements of the reinforcement, which are to be build in, to the existing joints of the trussed framework.

The problem of connecting CFRP, that is sensitive to load was solved by the loop shape of the tension elements.

to c):

Each of the brace levels shows a different degree of stiffening in its historic state, that can partially be levelled out by the two amply sized wall plates. Because of the excellent material characteristics of CFRP, in particular because of the high tensile strength, it follows that the historic concept, where only every fourth level is reinforced, can be employed. The results of the version examinations underline this. In order to transfer forces of the neighbouring levels into the reinforced levels, it will be possible with a little expense to join the two wall plates to a trussed beam of horizontal location with a high stiffness.

The described version indicates minimal displacements of the truss base point for different loads. Moreover it efficiently relieves the load on so far overloaded parts and connecting elements, and it fits appropriately into the existing roof truss. Therefore it is favourable as the most convenient solution.

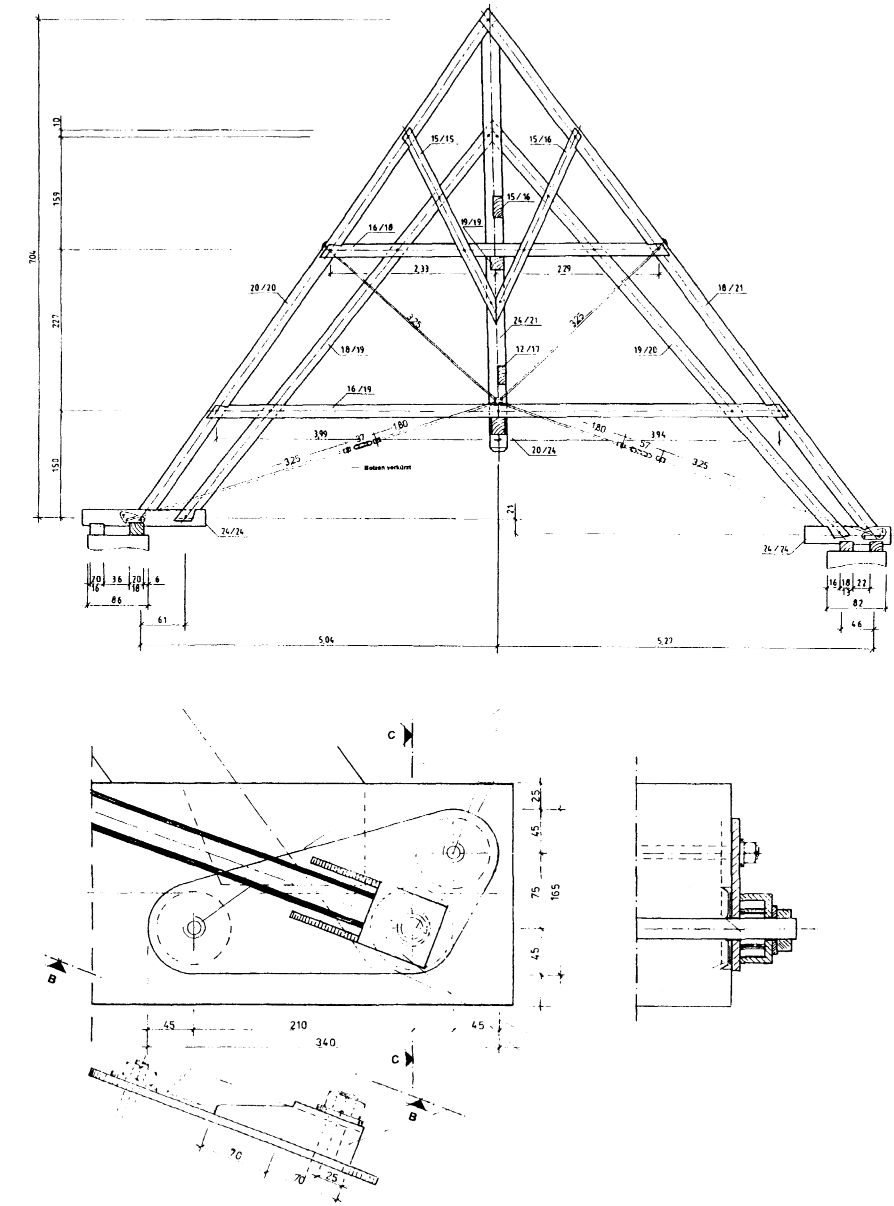

Figure 9: Realisation planning CFRP truss level A1, connecting detail of CFRP-loop

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6 Therapy / planning - realisation

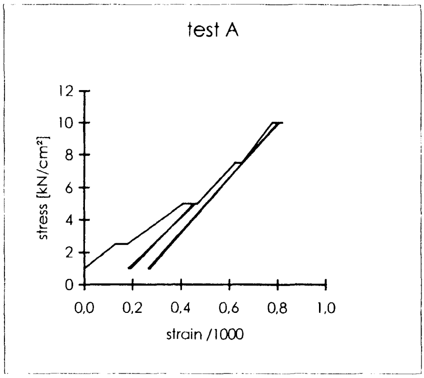
The aim of the detailed planning was to minimize the existing tensile strengths of the lower collar beams in such a way, that they can be supported by a dovetail plate with a firm (non-slipping) oak timber nail. At the same time the CFRP-bracing should be reduced in the cross-section, in order to economize material. For these reasons the CFRP-loops were partially prestressed, in order to anticipate the existing dead load of the roof structure. The induction of the prestress is done by the tightening of the turnbuckle nuts. As the CFRP-loops are linked (sometimes) at an angle within the historic timber roof truss the loops were borne with 1 mm neoprene as an intermediate layer at the drape points.

The calculated deformations, in particular the deformations at the base points are minimal and they result from the elasticity of the stressed total system. The tension reaches a maximal value of 84 % of the permissible value within a wall plate segment. The rafters, collar beams, the head runners and brace beams have a remarkably low use of capacity, that does not exceed 50 %. The prove of stability is therefore produced for all parts.

7 Experimental stability test on CFRP-parts

In order to ensure realistic examination of the CFRP-loops, that were produced by the German Institute of Air- and Universal Technic, the loops were examined separately and together with the connecting parts in 5 single tests in regard to their behaviour at the EMPA in Dübendorf [3].

The target was to determine the maximum load-bearing capacity of the single CFRP-loops and to find out the expansion characteristics of the whole arrangement. In test A the total arrangement with collar connection and bearing of 2x2 CFRP-loops were checked in neoprene stripes (70° Shore hardness) of 1 mm thickness up to a stress of 60 kN. In test D a fracture test up to 175 kN was carried out with a short loop of 1800 mm, whose lower base point had a deflection of 2° stiff and with neoprene-bearing.



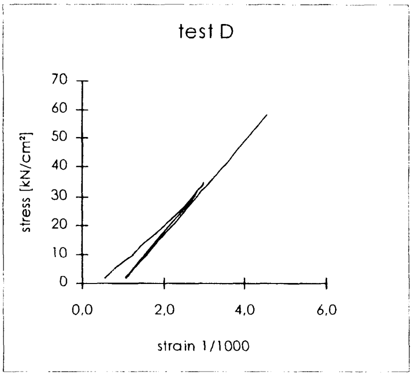


Figure 10: Stress-strain diagram of the test A and D

The breaking tension of 175 kN with inclined bearing application in neoprene for a CFRP-loop lies with a certainty of 4.4 fare over the maximal occurring value of 39 kN. The module E results in approximately 190,000 N/mm^2 from the analysis of the ingenious part results of the single tests. Therefore the material 'CFRP-loops' is suitable for use.

8 Conclusions

During the redevelopment of the gothic roof bearing structure of the Frauenkirche in Meißen the suitability of the material CFRP for the reinforcement of such timber roof structures could first be proved. Due to the specific characteristics of the material it opens up new opportunities in particular to curatorial respects, that show the employment of CFRP appears to be promising for the redevelopment of buildings in the future.

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