

Investigations into the structural design of the sandstone surface layer for the dome reconstruction of the Dresden Frauenkirche

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Abstract

Numerous theoretical as well as experimental investigations are inevitable to guarantee the durability of the stone surface of the sandstone dome of the Frauenkirche (Church of Our Lady). This paper describes a first series of experimental tests of various joint designs with the appropriate joint materials being used. The investigation concentrates on a two-stone solid that is subjected to freeze-thaw-cycling stresses. This report informs about specimen geometry, weathering programmes, applied measurement devices and techniques, forms of joint failure and the test evaluation. Finally an overview of further investigations is given.

1 Introduction

The history of the Frauenkirche shows that problems arose with the dome surface layer and in particular with the joint design already at an early stage. Only a few years after the building had been completed first repair work at the dome transition part became necessary. Photographs give clear evidence of the failures in the sandstone surface owing to the extensive joint repair work which has been carried out. This gave sufficient cause to start first investigations into the reasons of the dome surface layer defects. Therefore the dome stones which could be saved during the archaeological rubble clearance have been investigated in detail.

2 Analysis of selected dome stones saved during the archaeological rubble clearance

The investigation of selected dome stones was accompanied by the interpretation of data given in the huge photographic documentation of the two repair periods¹ in the first half of our century, it utilises the excerpt written by D. Rosenkranz² as well as the data base of single parts discovered which was compiled during the archaeological rubble clearance³.

The photographic documentation of the repair periods² provided numerous interesting details about the surface layer and the pediment at the dome transition part, respectively as well as about the repair work and the damages. The task was then to collect data and to make valid generalisations. For this reason the following criteria were of primary importance during the analysis of the parts discovered:

- historical joint construction / finding of possible joint profiles,
- detection of joint thickness and identification of possibly used joint materials,
- description of the degree to which the joint sides were roughed down and deductions about the placement time from an analysis of the joint mortar or the surface conditions of the sandstone surface layer, respectively.

The following results are some of those produced by the findings analysis⁴:

- Rebated (step) joint profiles were applied at the dome transition part only.
- Joint offsets in individual parts of the main dome exterior shell or the tambour are clear results of the later installation of crossings. The inhomogeneous condition of the joint flank and mortar residues proved the latter statement to be true.
- Vertical and horizontal joints are roughed down. This is true both for old and new stones. The joint surfaces frequently show a finer roughing down in the front part (about 10 cm). This obviously was to support a better placement of the joint mortar.
- The back sides of the facing blocks show knapping roughness sometimes, most of them were roughed down by hand only to a very small extent. As a result a good bond between mortar and the natural stone was achieved.
- It is rather probable that the wooden wedges or billets that were frequently found in the mortar residues which stuck to the joint flank served as spacers (realisation of necessary joint thickness) or for the ashlar positioning.
- Sandstones that were laid perpendicularly to their natural bedding are strongly damaged to a certain extent owing to weathering (flaking off).
- In a large number of findings forged clamps were discovered which were to joint adjacent stones. The surfaces of these clamps that were strongly attacked by corrosion caused further damage (e.g. clear spalling) to the sandstone. As a consequence non-corroding copper clamps were applied during repair work carried out in this century.

3 Joint damages and their causes

For the two hundred years the Frauenkirche has been existing there has always been repair work. Cracking occurred again and again the causes of which have always been discussed and interpreted in the most different ways by the experts. On closer consideration of the damages of the dome face as well as the dome transition part we must state that they are mainly caused by static and structural shortcomings than by material and technological inadequacies.

The static and structural concept formulated by the Engineering Consultants⁵, which is based on the latest findings of science and technology and the use of state-of-the-art computer equipment and which plans a careful enhancement of only some particular parts of the supporting structure by the means and methods we can make use of today, starts from the assumption that the causes for damaging cracking due to static and structural inadequacies are ruled out.

From the material point of view the causes can be attributed to the natural weathering of the sandstone on the one hand, in particular the weathering of joints and surfaces. On the other hand there are the negative effects of bursting due to the above mentioned forged corroding clamps. Last but not least the kind and quality of the joint mortar produce their effect.

The most essential stone and mortar properties that are relevant to damages comprise not only strength and frost resistance but mainly hygric parameters such as porosity and pore structure, water absorption and degree of water saturation. Sandstone is a porous product of nature and historical mortar was characterized by a high degree of porosity too. As a result these parameters together with the gentle slope of the exterior shell, the action of accumulating water and a thus possible long-term soakage set the preconditions of increased frost attack and an accelerated weathering process (above all in the dome transition part and in the parts of weak slope above the small dome windows). Another quantity of influence that should not be underestimated is the geometry of the sandstone plates. As a result of thermal stress considerable expansions can occur that are to be taken up by the joints. The reactive forces often exceeded the permissible strength of the joint mortar and brought about the cracking described above.

The experimental and theoretical investigations that are necessary to explain the failure phenomena are being carried in two main directions. In terms of material the interaction between stone and joint is being optimized with attention being paid to the thermo-hygric processes. This optimization is carried through within a research project⁶ at Karlsruhe University, Department of Materials Technology under the direction of Prof. Dr.-Ing. H.S. Müller. The structural design of the surface layer and the joint as well as the practical fabrication and the tests are planned to be realized at Dresden University of Technology.

For this reason selected joint profiles were subjected to a defined freeze-thaw-cycling stress in combination with different built-in positions and joint materials in a first test series carried out in a joint project of the Institute of Structural Design and Timber Construction at Dresden University of Technology and the Material Test Institution for the Building Industry in the Free State of Saxony

(MPA Dresden). At this point we would like to express our warm thanks to all staff members who contributed to the successful work on these tests.

4 Short description of a test on the behaviour of joints under freeze-thaw-cycling stress

4.1 Purpose and objective of the test

The objective of the test that will be described in the following was to determine the expansions due to temperature changes in nearly waterlogged composite sandstone units, to investigate different joint profiles and built-in positions as well as to test the joint mortar that was developed particularly for the above-grade masonry in a modified form.

4.2 Test programme

4.2.1 Specimens

Two sandstones grouted up with a joint in panel or course position were chosen as specimens. The joint mortar mentioned above together with silicon to a certain degree were chosen as joint material. The joint profiles used besides the straight joint were to fulfil the following functions:

- extension of the flow distance of penetrating moisture and
- improved toothing of adjacent stones.

In accordance with this the behaviour of a rebated or a groove joint, respectively under freeze-thaw-cycling stress was to be tested as well. The exterior geometry of the two-stone unit was about 10 cm x 21 cm for the face and 10 cm for the depth with a joint of 1 cm being arranged in the centre (cf. Fig. 1). The test layout used Posta sandstone from the stone pit in Wehlen near Pirna.

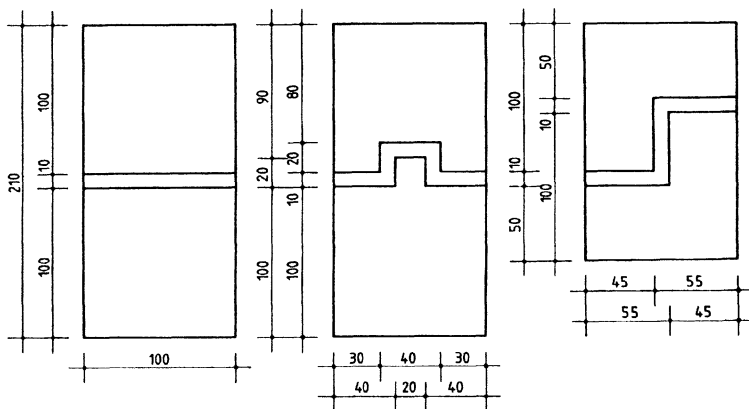


Figure 1: Side view specimen with different joint profiles

As for the façade a certain dead load is effective on the horizontal joint. It results from the own weight of the sandstone plates. This condition was to be simulated by a fastening. The fastening was brought about by two tension members that were arranged in longitudinal direction of the composite unit and were made of Invar steel that has a very low coefficient of expansion at atmospheric temperatures. As a result the major portion of temperature expansions is moved from the stone into the joint. The tension members were connected with two U-sections that are placed at the face sides and which are additionally fitted with a lock nut to avoid slipping.

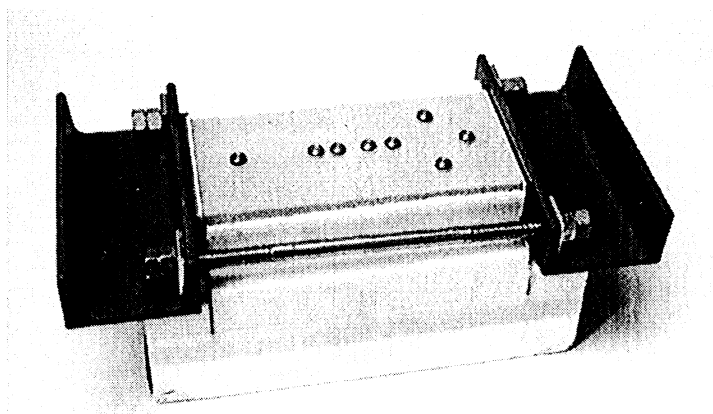


Figure 2: Fastened specimen before freeze-thaw-cycling

In addition to the specimens already fastened the same number of non-fastened two-stone samples were subjected to freezing to find out what the maximum of expansions due to temperature changes and moisture stress will be.

Moreover, the specimen was cased in Styrofoam and the joints were caulked so that only the face was wetted with water during the short raining period planned within the freeze-thaw cycles, which was similar to the actual conditions at the dome. Another reason for the casing was to keep the specimen temperature constant during the expansion measurement to avoid a distortion of the measured results.

4.2.2 Test programme

4.2.2.1 Number of specimens and freeze-thaw cycles With respect to the joint profile 16 specimens were subjected to defined freeze-thaw cycles. The number of specimens results from the following:

two specimens each coursing, mortar joint, fastened and unfastened;
 coursing, silicon joint, fastened and unfastened;

and the specimens of the panel construction analogously.

For each of the combinations mentioned there are two comparative samples. Unfortunately, there are no relevant test standards for composite units so that an

appropriate test programme has been developed by analogy with related standards^{7,8,9} and technical literature^{10,11}.

The test was run in three stages with one joint profile being subjected to frost in each stage. After extensive literature investigations the number of freeze-thaw cycles was fixed at 28.

4.2.2.2 Freeze-thaw cycles

A freeze-thaw cycle comprises:

- steady cooling from + 20°C to - 20°C within three hours,
- keeping the temperature at - 20°C for three hours,
- steady warming from - 20°C to + 20°C within three hours as well as
- keeping the temperature at + 20°C for three hours.

Since the negative effects of frost splitting occur only for nearly water-saturated void space in the mortar or sandstone, the specimens were additionally wetted with water for ten seconds every five minutes at a temperature of over 0 °C.

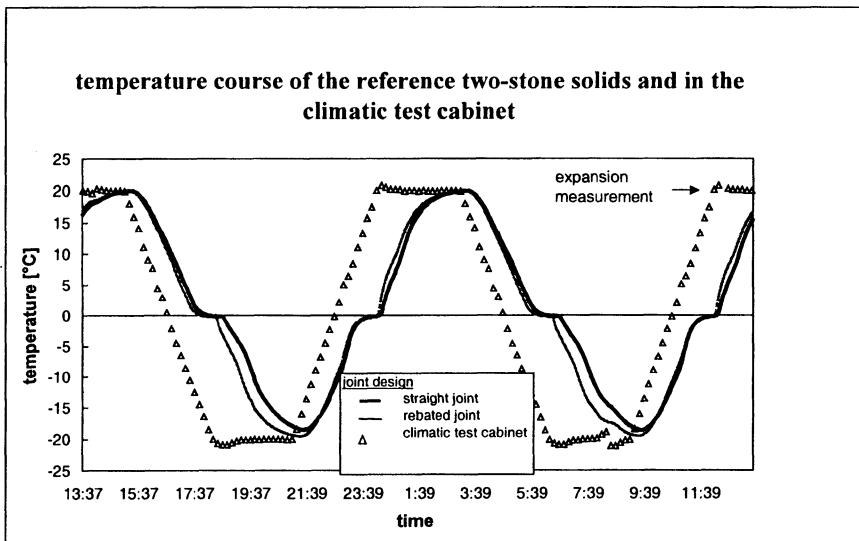


Figure 3: Temperature course in the centre of the stone and in the climatic test box

4.2.2.3 Evaluation parameters The following criteria were determined to be the main parameters for the evaluation of the frost resistance of stone-mortar-stone composite units:

- determination of water absorption in M-% before freeze-thaw-cycling test,
- determination of mass lost in M-% after freezing,
- ascertainment of expansions due to temperature and moisture stress,
- observation by inspection of the type and quantity of frost damages with indication of freeze-thaw cycling at first identification as well as at test end,

- determination of bond tensile strength between stone and mortar as ratio (before and after the freeze-thaw-cycling test, respectively as individual and mean value).

4.2.2.4 Preparation and storage of specimens First the two-stone units were grouted up with the joints near the surface (about 3 cm under the face) being carefully raked out and filled with earth-moist joint mortar only after two to three days of storage in the environmental test chamber. The joint mortar was placed in uniform layers and afterwards it was rubbed with a joint wood until a slightly shining binder tail appeared. At the same time the silicon joints were produced.

After grouting the specimen were stored for at least 90 days in the environmental test chamber at 20 °C and 65 % of relative humidity. During that time the fastening construction and the casing were built and the climatic test box was prepared. Furthermore, the following preparatory work had to be done:

- sticking of pop marks for the set expansion measurement,
- weighing of dry specimens and zero measurement with set extensometer,
- casing and fastening of the envisaged specimens,
- sealing the joints between stone and casing and labeling of specimens.

As a rule the prepared specimens (these are the two-stone units cased in Styrofoam and sealed with silicon) are subjected to the freeze-thaw-cycling stress in the water-saturated condition with the zero measurement being carried out before the test is started.

4.3 Test procedure

The tests were run in a tempered laboratory of the MPA Dresden where the fully automatic climatic test box is available that was necessary for the tests.

Unfortunately, the expansions could not be recorded continuously like in other measurement projects, model or in-situ tests by means of strain gauges or inductive displacement pick-ups since these may sometimes be susceptible to faults and not reliable under the extreme conditions of frost and moisture. This was the reason why we decided for the mechanical strain measurement. Set extensometers were applied that were put on a marked area of the specimen for a short time and which showed the respective value by means of a dial gauge. The disadvantage of this method is that the manual reading is restricted to taking extreme values only. In this special case this meant that measurements were possible at the end of the thawing and freezing periods. The temperatures within the climatic test box itself as well as in the centre of the stone were however continuously taken and recorded by means of thermosensitive elements.

During the data acquisition there was a regular visual assessment of joints and damage phenomena were recorded. A subsequent examination completed the test.

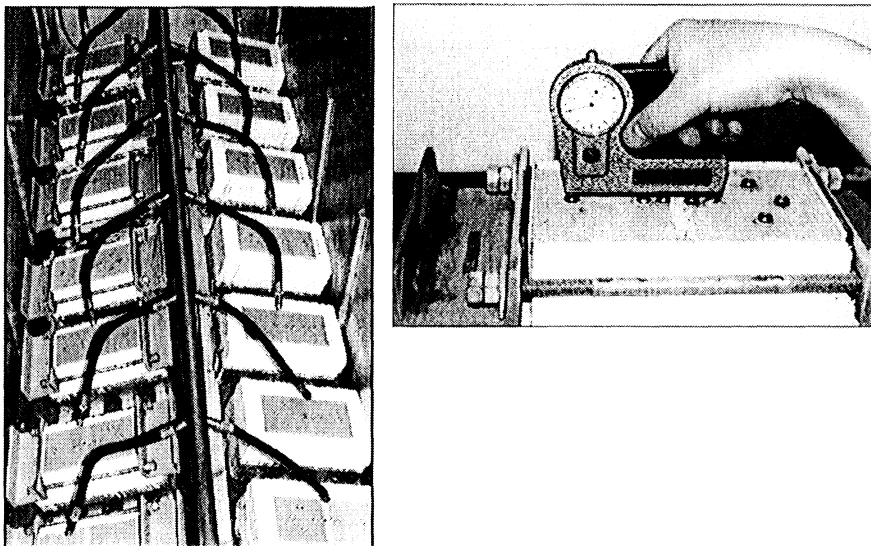


Figure 4: Look into the climatic test box and specimen during the set expansion measurement

4.4 Results and prospect

The results obtained so far allow to state the following:

- The temperature regime arranged for the test as well as the time sequence were chosen properly, the temperatures of $+20^{\circ}\text{C}$ and -20°C that were desired for the stone centre could be proved by the built-in thermosensitive element PT 100.
- In contrast to the unfastened two-stone samples, the fastened specimens showed no damages both for the mortar as well as the silicon joint in the face.

In this respect the necessity to prestress the dome surface layer should be reconsidered once again. If we follow this idea the consequence is to persistently denticulate the dome surface layer and the backing-up.

- The tests showed different failure forms of the joint at the unfastened samples with the different joint designs demonstrating different reactions. These are:
 - slight cracking at the joint flanks and in the joint centre, respectively or flaking of mortar particles in the joint areas near the surface,
 - complete separation of joint mortar at a joint flank,
 - complete separation of joint mortar at both joint flanks and
 - gapping joints at the bottom of the sample (only for silicon joints).
- In some cases the joint mortar was destroyed to a large extent. It became apparent that a mineral joint fails earlier when it is subjected to repeated stress by temperature and moisture expansions. For this reason the joint

mortar composition as well as related essential material parameters are to be optimized further with respect to the high and complex stress that acts on the dome surface layer.

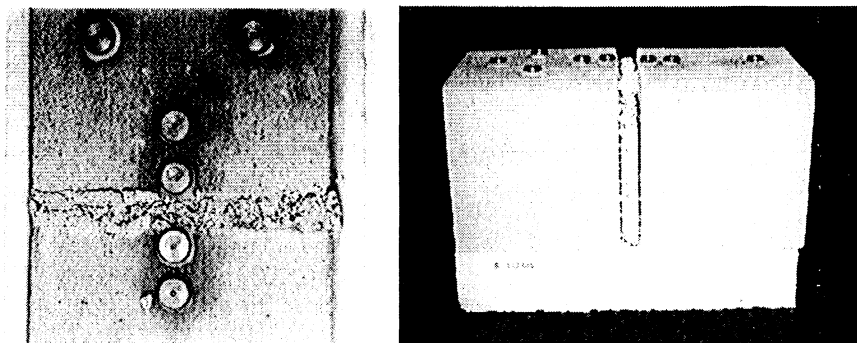


Figure 5: Damaged joint mortar after 22 freeze-thaw cycles and condition of specimen after 28 freeze-thaw cycles

Moreover tests should be made to find out whether alternative joint materials demonstrate higher resistance against the stress occurring, since the silicon-filled joints for example were still fully reliable after they had been subjected to freezing conditions.

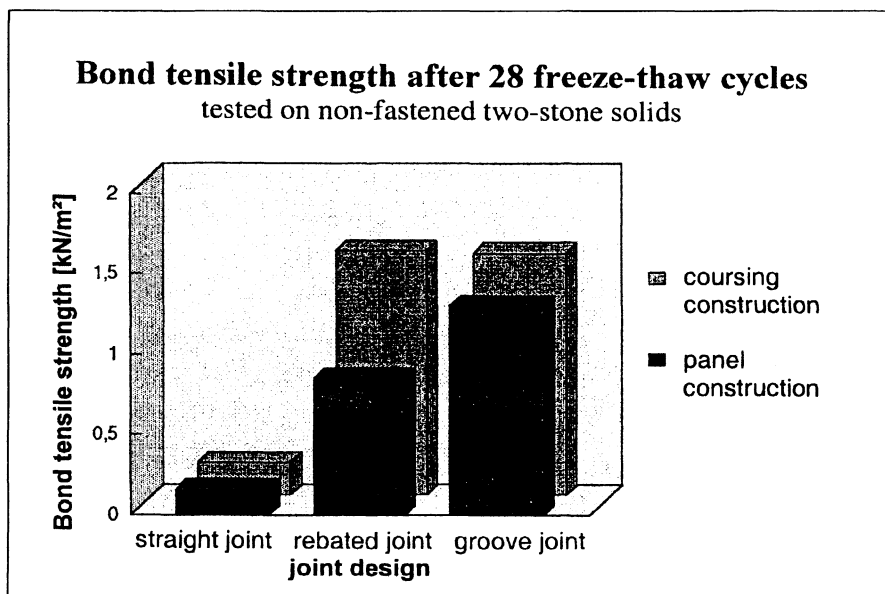


Figure 6: Determined bond tensile strength after 28 freeze-thaw cycles

- Presently we cannot draw any valid conclusions about the influence the joint design has. On the one hand there is clear evidence that the most serious damages, even optical damages, occurred at the straight joint and that on the other hand the bond tensile tests showed the clearly higher values for the joint profiles "groove" and "rebate". Further tests should be planned to investigate the effect of the flow distance using stones that are already covered with patina (where the stone surface is considerably denser). In this case we can start from the assumption that the water moves across the joints only.

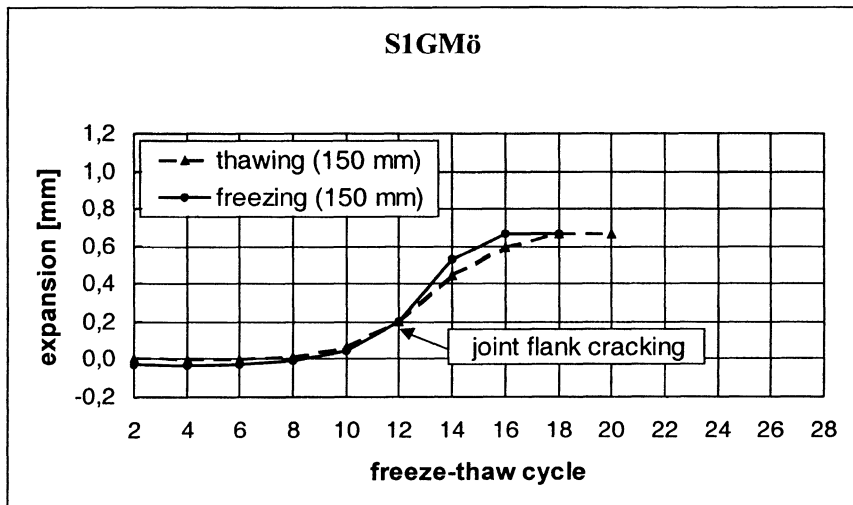


Figure 7: Determined expansions for instance of an unfastened specimen

- The sandstone itself did not show any wear and tear. It is not new that Posta sandstone is frost-resistant. However its high water absorption capacity (after storage in standard climate and a subsequent immersion test an average of 6-7 M-% had been recorded before the test started) should not be underestimated as far as the moisture protection of the dome structure is concerned.

5 Acknowledgement

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