RESTORATION MORTAR FOR HISTORICAL MASONRY – DURABILITY PREDICTION BY MEANS OF NUMERICAL AND ENGINEERING MODELS

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SUMMARY

The durability of historical masonry does not only depend on the behaviour of the single materials. Also it is the quality of the bond between mortar and stones that decides on the durability of the historical structure. A simple engineering model has been developed, which is based on calculations made for stresses occurring on the surface of the masonry and only requires a few material parameters. To serve it as a basis for extensive and effective structural analyses before starting rehabilitation measures a complex combined numerical model has been developed, which is able to describe both heat and moisture transport, and the complex material behavior of masonry (shrinkage, thermal strain, creep, relaxation, failure patterns) with a high degree of precision. For this model, the temperature and moisture transport is calculated by means of a FDM program. Results are then transferred to an FEM program for stress and deformation calculation.

INTRODUCTION

Conservation of historic structures normally involves rehabilitation of joints, and the jointing mortar has the function of providing weathering protection. In particular in case of in-depth

measures, the mortar also has to be able to transmit forces. An essential condition for the durability of such repair measures is that the bond between stone and joint mortar is of a good quality and does not show any cracks. The decision as to what kind of mortar to use for joint repair measures in natural stone masonry of historic buildings is usually a question of experience, while trying to give due regard to preservation requirements. Whether or not the masonry mortar or joint mortar chosen is actually suited for the given kind of masonry often does not show until it has been in place for several years. A major criterion is the weather protection of the masonry, i.e. protection against weathering of the stones and mortar destruction, which depends in particular on the crack-free bond between stone and joint mortar.

Even if a joint mortar itself has good weather protection properties, the mortar/stone flank bond region is a critical weak spot for the durability of masonry. Since the stones and the mortar in new joints tend to differ in their deformation behaviour (which is the result of differences in their thermal, hygral and mechanical properties), cracks are likely to occur between stones and mortar, or in the mortar itself. Material qualification tests alone do not suffice to predict the occurrence of cracks in the composite stone / mortar system.

In order to assess the risk of cracking, a large number of tests have to be performed on composite stone / mortar elements. Since historic buildings are made from a variety of different stones (normally natural stones whose properties tend to vary considerably), the bond characteristics would have to be examined separately for each structure requiring rehabilitation. This would not only be very costly, but also rather time-consuming. Another aspect is that different kinds of mortar are generally used in a particular structure. Mortar in the base region will not be the same as that in the rising masonry or on inclined surfaces. This large number of factors would increase the test requirements considerably.

However, if it should be possible to use models to predict the durability of new joints in historic masonry for defined boundary conditions, such costly and time consuming tests could be either limited or be avoided altogether. Broadly based parameter analyses made before starting any rehabilitation measures will then allow the suitability of a mortar to be reviewed for the application in question. Should the mortar be found to be inadequate, the properties of the mortar can be varied to decide what changes need to be made to produce a joint that is free from cracks.

CAUSES OF CRACKS

For the development of the composite structure models below, the cause for cracking must be known. The criteria primarily considered as a first step in developing the model are the mechanical/physical material properties and the residual and the restraint stress resulting from such properties. Stones and mortar are characterised by specific thermal and hygral behaviour. Irregular temperature and moisture distribution (see Figure 1), which itself is the result of atmospheric conditions, produces constrained thermal and hygric strains.

Figure 2 is a schematic representation of the thermal strains in natural stones at the surface of the masonry, which are produced by changes in ambient temperatures. During summer months, the surface of the natural stone facade heats up considerably due to its exposure to direct sunlight during the day. At night, the surface of the facade cools down to the temperature level of the ambient air. Temperature differences of up to 50 °C at the surface are

therefore quite normal. This difference in temperature produces strains in the stones and the mortar, which because of the mutual deformation restraint in turn gives rise to restraint stress. In winter, the entire facade cools down to very low temperatures. The result are tensile stresses in the mortar and in the stones, and adhesive tensile stress in the bond region.

Stresses acting on the bond primarily in near-surface regions of the masonry are hence a function of moisture and temperature fields and they are subject to stress relaxation. This means they depend from location and time as well.

The consequence of restrained deformation normal to the joint flank can be flank failure. Deformation along the joints is limited by internal constraints. The results are residual stresses which can make the mortar crack transverse to the joint. The bond resistance is determined by the tensile strength of the stone $f_{t,St}$ and of the mortar $f_{t,Mo}$, and by the adhesive tensile strength $f_{t,a}$. The lowest value is always the decisive one. Among others the tensile strength is determined by the moisture level and, in the case of the mortar, also by the time.

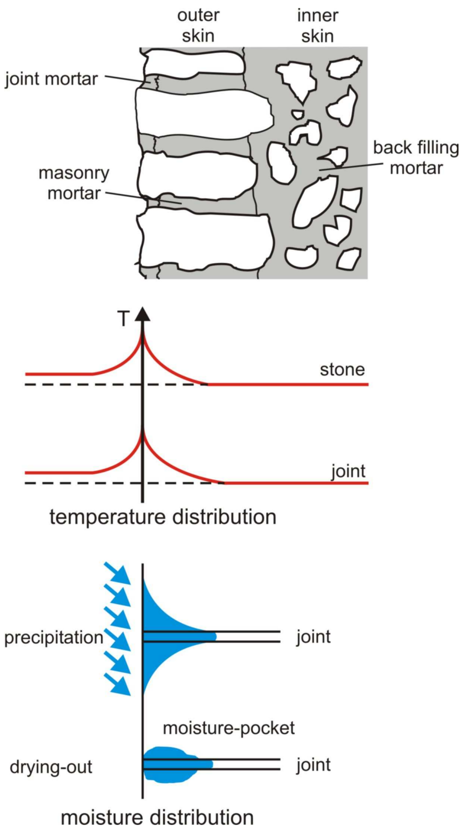


Figure 1. Thermal and Hygric Exposure of Historical Masonry

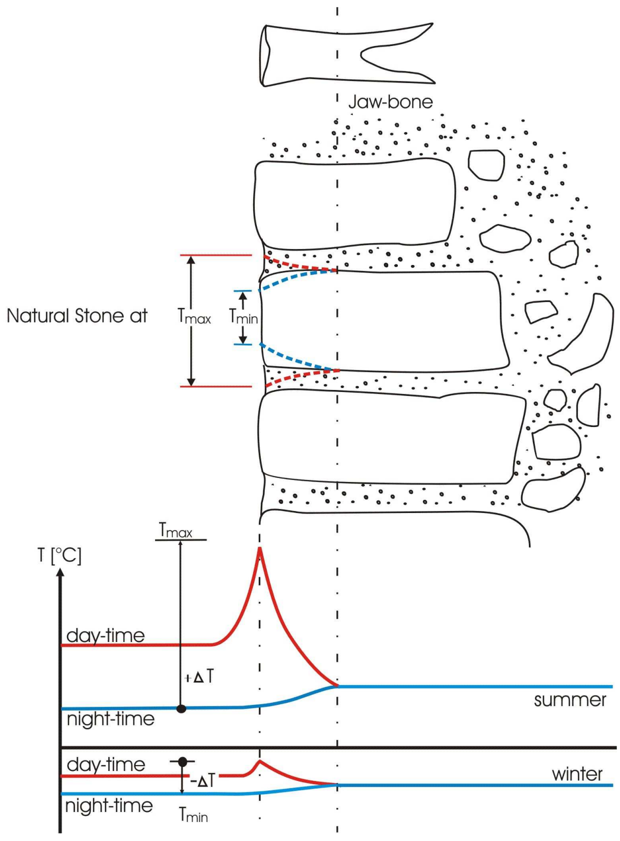


Figure 2. Deformation of Natural Stones in Historical Masonry as a Result of Thermal Elongation

ENGINEERING MODEL FOR CRACKING IN NEW JOINTS

The engineering model for the durability of the composite system natural stone / mortar joint in connection with repointing of historic masonry developed by Schmidt-Döhl and Rostásy 2000 is used as a simple means of modelling the bond behaviour. The engineering model starts from the assumption that stress that can lead to cracks is the result of irregular

temperature and moisture distribution across the masonry cross section. Thermal and hygral strain at the surface is restrained by the inner masonry structure. The basic function of the model is to calculate stresses at the surface, starting from the simplifying assumption of a fully constrained composite stone / mortar element and maximum temperature difference:

$$\varepsilon_T + \varepsilon_S - \varepsilon_{el,pl} - \varepsilon_C = 0 \tag{1}$$

where ε_T = thermal strain, ε_S = shrinkage strain, $\varepsilon_{el,pl}$ = elastic-plastic strain and ε_C = creep strain.

Under conditions of full constraint, the sum total of all strain components has to be 0 at the surface. For the cases flank cracking (crack in parallel with the joint, Figure 3) and mortar cracking (crack normal to the longitudinal direction of the joint, Figure 4) the different strain components are examined more closely.

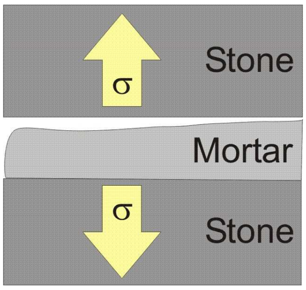


Figure 3. Cracks Parallel to the Joint

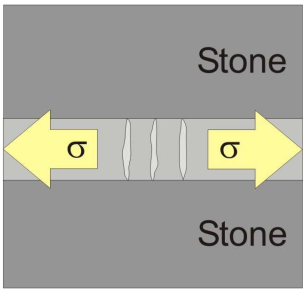


Figure 4. Cracks Normal to the Joint

Cracks Parallel to Joint (Side Cracks)

The thermal strain ε_T is calculated by means of the coefficient of thermal expansion α_T of mortar and stone, the maximum temperature difference $\Delta T_{\max}$ occurring between mortar and stone or the constraining action of the inside of the masonry (cf. Figures 1 and 2), and the percentage of area l_0 taken up by mortar and stone:

$$\varepsilon_T = \alpha_{T,Mo} \cdot \Delta T_{\max,Mo} \cdot l_{0,Mo} + \alpha_{T,St} \cdot \Delta T_{\max,St} \cdot (1 - l_{0,Mo}) \tag{2}$$

The shrinkage strain ε_S is calculated by means of the final degree of shrinkage $\varepsilon_{S,\infty}$ of mortar and stone, and the area percentage l_0 of mortar and stone. The final degree of shrinkage is used for simplification, because it is expected that the relative moisture in the mortar and stone surfaces decisive for cracking will follow very soon any changes in the relative moisture of the ambient air and that the constraint-induced shrinkage strain will be produced at the surface:

$$\varepsilon_S = \varepsilon_{S,\infty,Mo} \cdot l_{0,Mo} + \varepsilon_{S,\infty,St} \cdot (1 - l_{0,Mo}) \tag{3}$$

The elastic-plastic strain $\varepsilon_{el,pl}$ is the result of the actual stress σ_t and the secant modulus $E_{\sec}$ of mortar and stone, and of the area percentage l_0 of mortar and stone in the composite stone / mortar system. Respecting flank failure, the model starts from series arranged mortar and stone:

$$\varepsilon_{el,pl} = \frac{\sigma_t}{\dfrac{E_{\sec, Mo}}{l_{0,Mo} + (1 - l_{0,Mo}) \cdot \dfrac{E_{\sec,Mo}}{E_{\sec,St}}}} \qquad \varepsilon_C = \sigma_t \cdot \left(\frac{C_{t,Mo} \cdot l_{0,Mo}}{E_{Mo}} + \frac{C_{t,st} \cdot (1 - l_{0,Mo})}{E_{st}}\right) \qquad (4+5)$$

The creep strain ε_C is calculated from the actual stress σ_t, the creep coefficients C_t of mortar and stone, the modulus of elasticity E of mortar and stone, as well as the area percentage l_0 of mortar and stone.

Plugging equations 2 to 5 into equation 1 and solving the equation for the maximum stress the composite stone / mortar system can take, or for the modulus of elasticity of the mortar, yields equations 6 and 7:

$$\sigma_t = \frac{l_{0,Mo} \cdot (\alpha_T \cdot \Delta T_{\max,Mo} + \varepsilon_{S,\infty,Mo}) + l_{0,St} \cdot (\alpha_{T,St} \cdot \Delta T_{\max,St} + \varepsilon_{S,\infty,St})}{\dfrac{l_{0,Mo} + l_{0,St} \cdot E_{\sec,Mo} \cdot 1/E_{\sec,St}}{E_{\sec,Mo}} + C_{t,Mo} \cdot l_{0,Mo} / E_{Mo} + C_{t,St} \cdot l_{0,St} / E_{St}} \qquad (6)$$

$$E_{Mö} = \frac{1}{\dfrac{\dfrac{(l_{0,Mo} \cdot (\alpha_{T,Mo} \cdot \Delta T_{\max,Mo} + \varepsilon_{S,\infty,Mo}) + l_{0,St} \cdot (\alpha_{T,St} \cdot \Delta T_{\max,St} + \varepsilon_{S,\infty,St})}{\sigma_t} - C_{t,St} \cdot l_{0,St}/E_{St} - l_{0,St}/E_{\sec,St}}{l_{0,Mö} + C_{t,Mö} \cdot l_{0,Mö}}} \qquad (7)$$

Cracks Normal to Joint (Mortar Cracks)

The risk of crack propagation perpendicular to the joint is assessed by connecting mortar and stones in parallel rather than in series. When compared with the residual stress in the mortar, the influence of the stones on crack propagation in the mortar is insignificant. This is why in this case the engineering model is restricted to the mortar and does not consider a composite stone / mortar system. Again, considerations start from a fully restrained system and the maximum temperature difference.

The thermal strain is calculated with the aid of the thermal coefficient of expansion α_T of the mortar and the maximum difference in temperature ΔT_{max} between mortar and the restraining masonry:

$$\varepsilon_T = \alpha_{T,Mo} \cdot \Delta T_{\max,Mo} \qquad \varepsilon_S = \varepsilon_{S,\infty,Mo} \qquad (8+9)$$

The shrinkage strain corresponds to the relevant final degree of shrinkage $\varepsilon_{S,\infty}$ of the mortar. The elastic-plastic strain follows from the actual stress σ_t and the secant modulus $E_{\sec}$ of the mortar.

$$\varepsilon_{el,pl} = \frac{\sigma_t}{E_{\sec,Mo}} \qquad \varepsilon_C = \frac{\sigma_t \cdot C_{t,Mo}}{E_{Mo}} \qquad (10+11)$$

The creep strain ε_C can be calculated from the actual stress σ_t, the creep coefficient C_t of the mortar, and the modulus of elasticity E of the mortar.

Plugging equations 8 to 11 into equation 1 and solving the equation for the maximum stress the mortar can take, or for the modulus of elasticity of the mortar E_{Mo}, yields equations 12 and equations 13.

$$\sigma_t = E_{Mo} \cdot \frac{\alpha_{T,Mo} \cdot \Delta T_{\max,Mo} + \varepsilon_{S,\infty,Mo}}{1 + C_{t,Mo}} \quad E_{Mo} = \frac{\sigma_t \cdot (1 + C_{t,Mo})}{\alpha_{T,Mo} \cdot \Delta T_{\max,Mo} + \varepsilon_{S,\infty,Mo}} \qquad (12+13)$$

Implementation and Application of the Engineering Model

Equations 6 and 7, as well as 12 and 13, form the kernel of the engineering model which is based on a Microsoft Access® database. Respecting the variables in equations 2 to 5 and 8 to 11 the following distinctions can be made:

1. Parameters established on the structure

   - area percentage of mortar and stone

2. Parameters established experimentally or from databases

   - coefficient of thermal expansion α_T of mortar and stone
   - final degree of shrinkage $\varepsilon_{S,\infty}$ of mortar and stone
   - maximum temperature differences $\Delta T_{\max}$ between mortar and stone
   - creep coefficients C_t of mortar and stone
   - modulus of elasticity of stone

   Should these parameters not be established experimentally, they can be assessed with the aid of the engineering model or they can be imported from the data records in the database.

3. Values established with the engineering model and serving as a basis for mortar selection

   - stress σ_t normal and perpendicular to the joint flank
   - modulus of elasticity E_{Mo} of the mortar.

   Stress σ_t must not be greater than the strength of the mortar, the strength of the stone or the bond strength.

Figure 5 shows the graphical user interface which has been developed using mortar and stone data available from literature and data compiled from own investigations and analyses. This database can be used for rough parameter studies to be able to select mortars that promise to be a good choice for a given masonry, and it can alternatively be used to determine the requirements the intended mortar has to meet. For verification of the model, the cracking behaviour in the region of the joint of restrained two-stone bodies was examined for constant climatic conditions and for one-sided weather exposure.

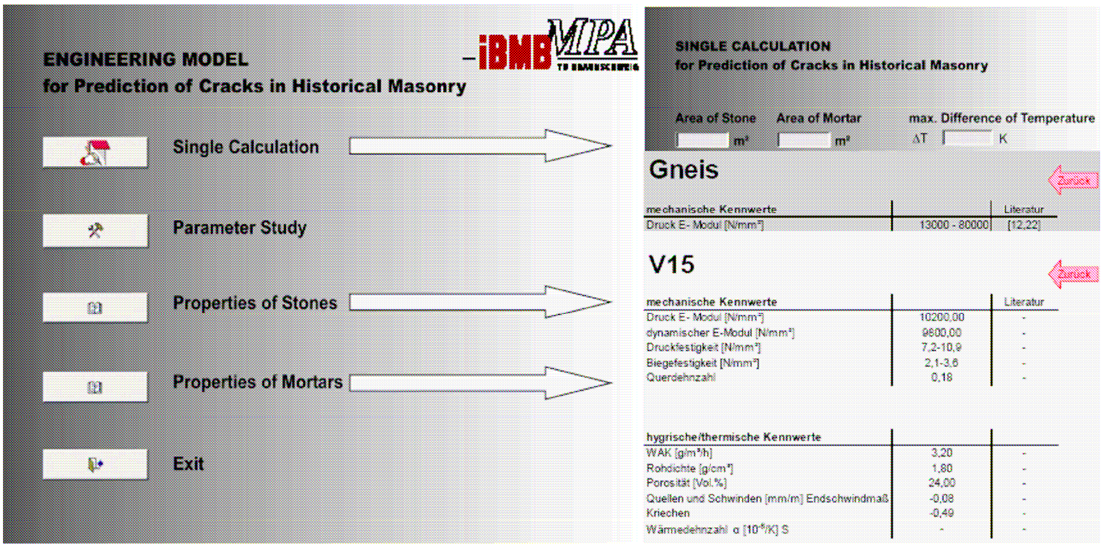


Figure 5. Database with Imposed Computation Mask for the Engineering Model

Even though the model starts from linear-elastic material behaviour (while considering time-specific deformation), experimentally determined results could be shown with a high degree of approximation. But the accuracy of the model is limited. Because it has so far been formulated as a deterministic model, it does, for instance, not account for the considerable variation of properties of natural stone. Much effort is at the moment being given to the possibility of automated parameter studies. These would also account for the variation of the mortar and stone properties, provided they have been stored in the database. Another aspect which is at the moment not included in the calculation is the bond shear strength, which is why shear stress perpendicular to the crack front is not accounted for. Neither does the model at the moment consider any chemical degradation processes and frost-induced processes, such as the degradation of mortar properties as a result of weathering.

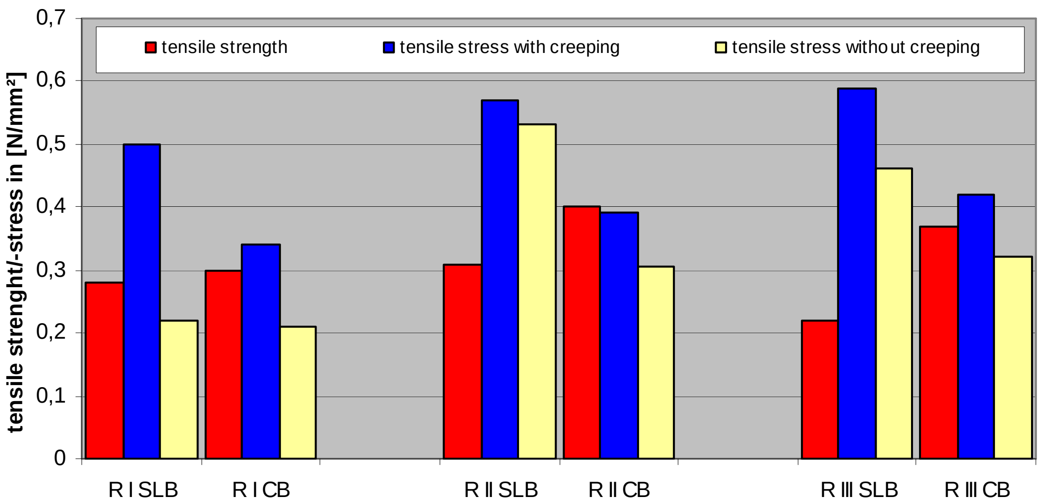


Figure 6. Calculated Results of Flank Cracking of Three Different Gypsum-Lime-Mortars (R) and Two Different Bricks (SLB = sand-lime brick – CB = clay brick)

Figure 6 shows the results of comparative calculations using the engineering model for flank failure due to the temperature load case $\Delta T = 5$ K. In this case, the bond between three different gypsum-lime mortars and calcareous sandstone or highly absorbent bricks is

considered. Once the maximum stresses exceed the measured bond strength, the flanks will fail. It is evident that the stress-reducing effect of the creep deformation of gypsum mortar has been considered in a very realistic manner. Masonry samples exposed to this temperature load case showed flank failure in the same specimens as it had been forecasted in the model.

RESEARCH MODEL

The research model is to serve as a basis for extensive and effective analyses before starting rehabilitation measures, while allowing the number of pre-rehabilitation tests to be reduced substantially. Quantitative determination of the deformation and stress components, sensitivity analyses etc. give more detailed insight into the possible cause of cracks. The research model also permits the moisture distribution to be assessed for the entire cross section as a function of time. For the time being, no model is available that would be able to describe both heat and moisture transport, and the complex material behaviour of masonry (shrinkage, thermal strain, creep, relaxation, failure patterns) with a high degree of precision. One reason is the highly complex dependence of the material behaviour on moisture and temperature. This dependence pattern produces coupled differential equations that have so far not been solved satisfactorily with the FEM method (Van Zijl 2000). In the following a complex numerical model is presented, which offers the consideration of such effects. Up to the point at which cracking starts, hygral and thermal transport can be assumed to be a process that is independent of the mechanical condition of the system. This is why a model has been developed which combines the detailed submodels (see Figure 7).

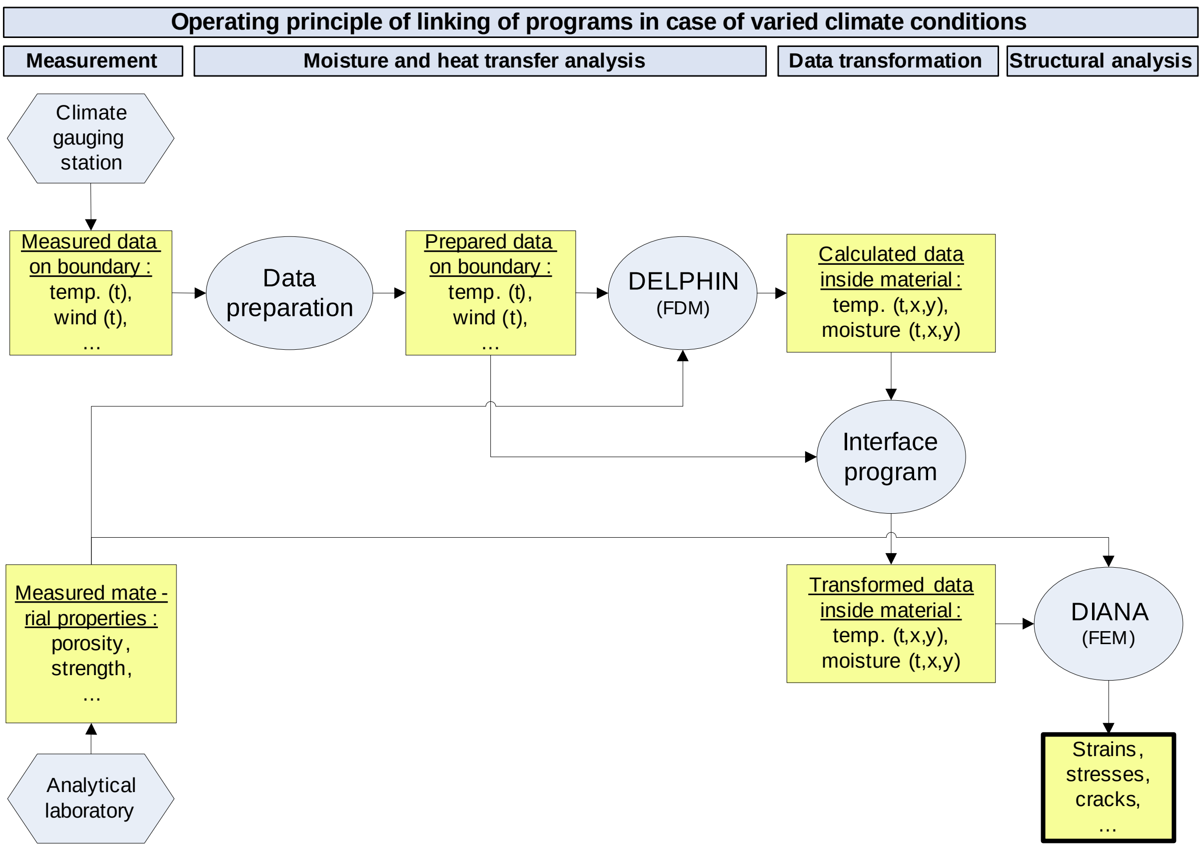
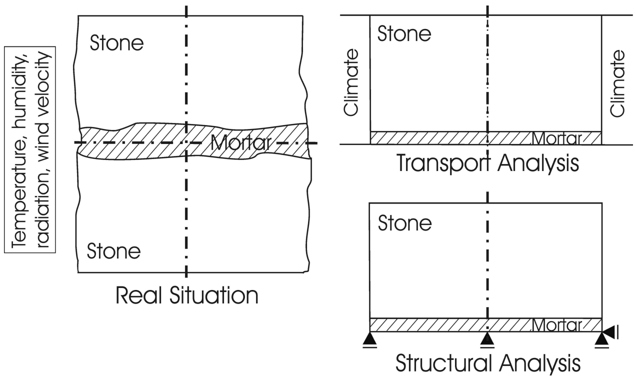


Figure 7: Linking of Programs in Case of Variing Climate Conditions as Flow Chart

The program DELPHIN®, based on the finite difference method (FDM), provides the possibility to determine the transport processes realisticaly including effects of solar radiation, driving rain and of course variable time-dependent climatic conditions. Especially to simulate experimental outdoor test, measured data from the climate gauging station can be prepared and used as realistic occured boundary conditions in the transport calculation.

Results of the time-dependent thermal and moisture fields are transmitted to a developed interface-programm. This interface transformes data from the FDM-mesh to a FEM-mesh, which is generated from the FEM-program DIANA® using the material models of Rots 1997, Lourenço 1996 and Van Zijl 2000 to calculate the resultant deformations, stresses, and cracking, due regard being given to viscous and plastic material behaviour.

So far, the model has been used to describe two-stone bodies (see Figure 8), in which heat and moisture transport processes were still simulated separately by making use of the symmetry (see Figure 9).



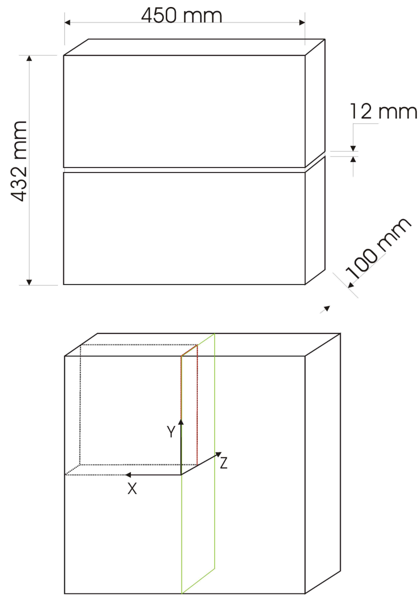
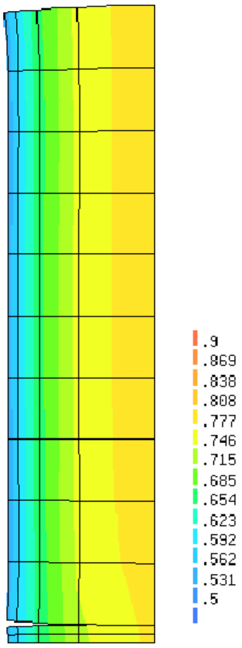


Figure 8: Geometric Model and Deformation Conditions in the Research Model

Figure 9: Two-Dimensional Illustration for the Wall Cross Section

Figure 10 and Figure 11 show the results of moisture distribution, stress distribution and deformations for a two-stone body when dried for 100 days (initial situation: masonry with 90 % rel. air humidity; air with 50 % rel. air humidity). The expected cracking pattern as a result of intensive dryness could be approximated with a high degree of precision, a result which measurements during test programmes cannot achieve. Another advantage is that climatic conditions can be simulated at random and that the numerical model can be used to investigated a wide range of climate variations as well as specific climate situations. In this way it can also be determined under what conditions the bond between mortar and stone is particularly likely to fail.



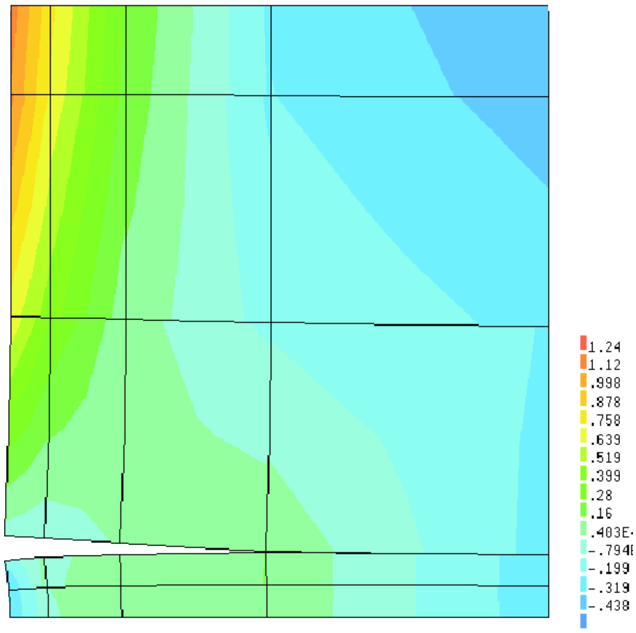


Figure 10. Moisture Content and Deformation Pattern Across the Cross Section

Figure 11. Detail Stone-Joint: Resulting Stress in y-Direction and Deformation Pattern

CONCLUSIONS

The simple engineering model offers a tool that permits the probability of cracks in new joints to be assessed in a realistic manner. There is good agreement between the results calculated with the engineering model and the results of experimental tests. On the whole, the cracking pattern for chosen combinations of different mortars and bricks was forecast correctly.

First coupled calculations using the more complex research model also produce plausible results. Model development aims at providing an instrument that permits a better understanding of the failure mechanisms in the bond between natural stone and mortar joint. More broadly based experiments are essential for verification of both models.

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