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**INCREASED DURABILITY OF REPOINTING IN HISTORICAL MASONRY –  
ENGINEERING MODEL AND SENSITIVITY ANALYSIS**

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**ABSTRACT**

The durability of repointing is a recurring topic in the area of building preservation. The lack of preliminary analysis of the physical and mechanical properties of stone and historical mortar often results in repointing with a limited life-span. The primary purpose of the tuckpointing is weather protection of facades. For this the mortar has to be free of cracks and it is particularly important that the bond between the mortar and stone is intact; otherwise the penetration of moisture increases. This would cause changes and damage to the material structure. Successful repointing requires a match of the new mortar to the existing masonry (stone and mortar). The composition of the mortar depends on material properties, material dimensions and environmental conditions. The scattering of material and geometric properties plays a minor role in existing prediction models. Currently a research project is developing a prediction model which takes the distribution of parameters into account. The goal is to be able to point out project-specific weak points and to identify material properties that have to be focused on. The application of an engineering model to predict the durability of a repointing is illustrated in this paper as well as the effect of taking the scattering of parameters into account.

**KEYWORDS:** *durability prognoses, repointing, historical masonry, scattering of parameters*

**INTRODUCTION**

Restorations carried out at the end of last century show, today, that it is not always possible to carry out long-lasting repointing. This tuckpointing has to be renewed already. The aim is to achieve a durability of at least 30 and up to 50 to 100 years [1]. Each repointing incurs not only a financially significant effort but irreversible dilapidations.

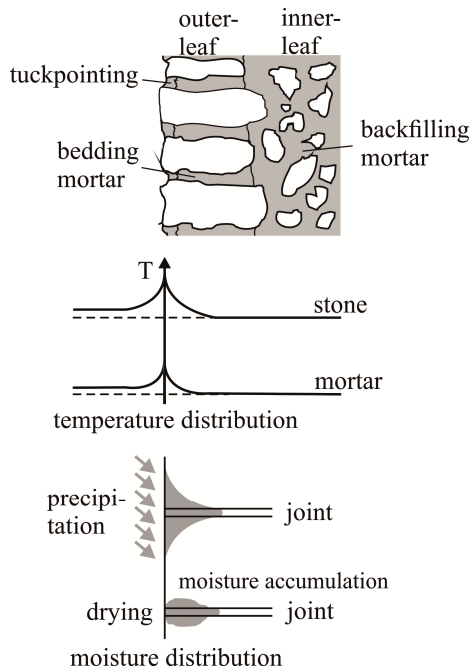
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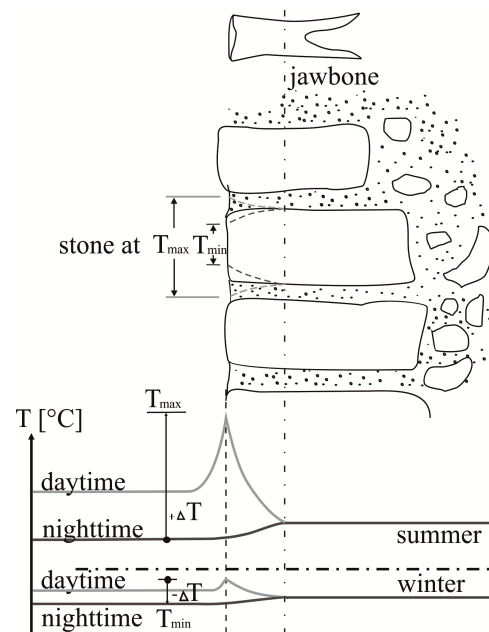
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High capillary water absorption is typical for historical mortar. The reason for structural damage can often be attributed to absorbed water that lead to chemical-mineralogical reactions. Over and above, however, the influence of changing weather conditions causes intense strain on the building materials. As shown in Figure 1 and Figure 2 the facade is subject to constant heating and cooling as well as moistening and drying within the daily and annual cycle [2]. Shrinkage and swelling of the materials is the result which, in turn, causes stress that can lead to cracks in the mortar and failure of the bond between the mortar and stone. This increases the penetration of moisture and, inevitably, the stress leading to an accelerated deterioration [3], [4], [5]. Therefore high durability of the masonry can only be ensured as long as the basic prerequisites are met: the mortar has to be free of cracks and the bond between the mortar and stone has to be intact [6], [7], [8]. To enhance the durability, the functional requirements of the mortar have to be analysed and adapted to each building with its individual materials.



**Figure 1: Hygrothermal Exposure of Masonry cf. [3], [4]**

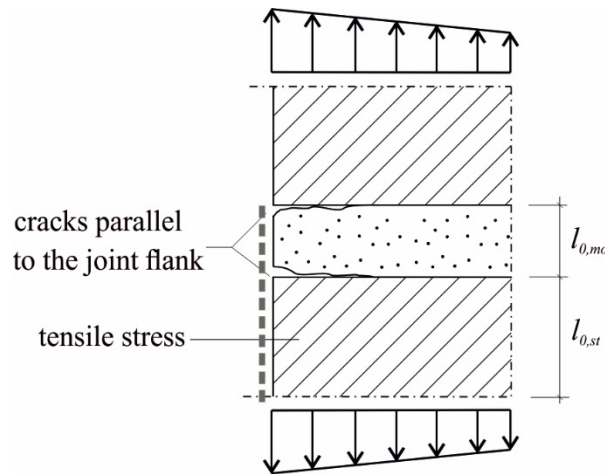


**Figure 2: Deformation of Masonry Caused by Thermal Exposure cf. [4], [5]**

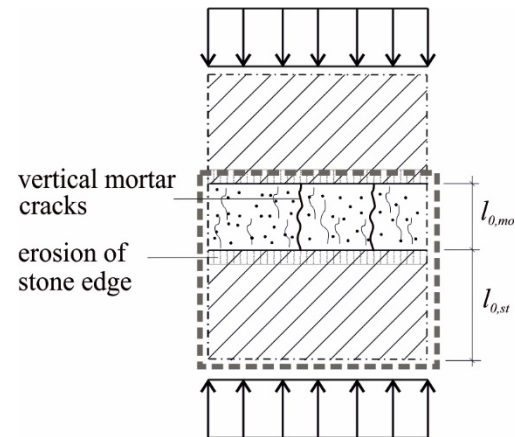
In order to choose the correct mortar composition the complex hygrothermal behaviour of the exterior building component has to be known depending on its material properties, material dimensions and environmental conditions. On the basis of this knowledge the exposure and, therefore, the required resistance can be determined.

The first prediction model which was developed uses empirical approaches. The progression was made by linear stress analysis as in and followed by non-linear finite element simulation. The latter method uses linked heat and moisture transport processes as well as models to calculate strain and stress.

Schmidt-Döhl and Rostásy [8] developed an engineering model and a research model for durability prognoses of repointing. The engineering model takes the relevant material and geometric parameters into account that are effected by weather exposure and lead to deformation. The model considers two failure criteria: cracking parallel to the joint flank (failure of bond between mortar and stone, Figure 3) and vertical cracking (in the mortar, Figure 4).



**Figure 3: Cross Section; Cracks Parallel to the Joint Flank as a Result of One-sided Cooling [6]**



**Figure 4: Exterior View; Cracks Vertical to the Joint Flank as a Result of One-sided Heating [6]**

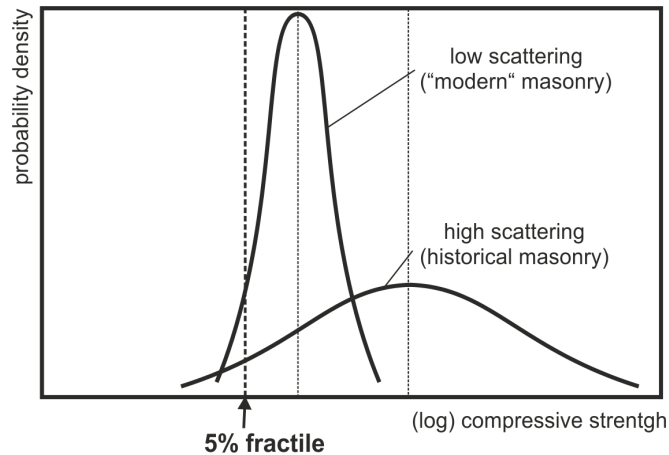
The prognosis models use the arithmetic mean of the material and geometric properties. Measurement errors of each parameter and ultimately measurement uncertainties that result in scattering can have a great impact on the prognoses due to error propagation. Kaptan [9] already mentioned that the engineering model should be further developed to incorporate automated parameter studies.

The engineering model developed by Schmidt-Döhl and Rostásy [8] is being enhanced. The enhancement allows scatterings of each parameter to be dealt with. An integrated algorithm makes it possible to run a sensitivity analysis. In this way, the parameters that have the greatest impact on the durability can be detected. In the course of restoration planning the focus can be shifted to the project-specific weak points. Their parameters can be verified statistically in laboratory tests. The enhanced model provides an adjusted and optimized restoration plan that meets the specific requirements of the given building for high durability. Besides saving costs the building structure will be sustainably protected due to the extended intervals between repeated repointing.

## SCATTERING OF PARAMETERS

First thoughts about the scattering of compressive strength of stones and mortar were published by Franke et al. [10]. The research focused on how the scattering of compressive strengths would have an impact on the load-bearing behaviour. Especially older materials often show a wider distribution than newer materials. The distribution density of the compressive strength of a

historical brick in comparison to a “modern” brick is shown in Figure 5. Even though the characteristic strength is the same, the distributions can vary significantly.



**Figure 5: Probability Density of a “Modern” and a Historical Brick with the Same Characteristic Strength [10]**

Steinbach [11] developed basic approaches of a safety concept for construction physics calculation parameters. Based on his work, the influence of scattered material and geometrical properties on construction physics verifications was assessed and the importance demonstrated in [12], [13].

## ENGINEERING MODEL BY SCHMIDT-DÖHL AND ROSTÁSY

### *Overview*

As part of a research project, Schmidt-Döhl und Rostásy [8] developed an engineering model and a research model to check possible cracking in the mortar and in the mortar/ stone interface. As a result mortar optimizations can be made in advance to achieve the most durable repointing possible.

External exposure causes a temperature and moisture gradient through the cross section of the building component. The gradient leads to strains at the masonry surface. The engineering model is based on the assumption that crack formations are the result of tensile stress caused by the external exposure exceeding the tensile strength of resistance at the masonry surface. To achieve highly durable repointing the aim is to calculate the necessary tensile strength of the mortar as well as the tensile bond strength of the mortar/stone composite.

Stress calculations on the masonry surface (grey dashed line in Figure 3 and Figure 4) are the basis of the engineering model. The calculations relate to a masonry section that is seen as a fully constrained system with uniform strains. Therefore the total sum of strain is 0 and consists of strains caused by temperature  $\varepsilon_T$ , shrinkage  $\varepsilon_S$  and creepage  $\varepsilon_C$  as well as elastic-plastic  $\varepsilon_{el,pl}$  strains:

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

The strains are calculated using the required input data. The input data include actions, geometry data and material data as seen in Table 1. The material data can either be obtained experimentally in laboratory tests or taken from literature and databases. To calculate the tension in the mortar and the tension at the bond of the mortar/stone composite that leads to cracking, two separate calculation runs are needed and shown below [8].

### ***Stress calculations on the masonry surface – cracking parallel to the joint flank***

Using the input data the strains can be calculated with the following equations (2) to (4). Since creeping and elastic-plastic strains are, among other parameters, a result of tension, the equation has to be solved for the tension. The outcome is the maximum resisting tension shown in (6). An outcome higher than the tensile bond strength of the mortar/stone composite indicates bond failure and crack formation. In that case the mortar has to be optimized to increase its tensile bond strength. Alternatively, other parameters can be calculated, e.g. the secant modulus of elasticity of the mortar, if the tensile bond strength cannot be changed. The distinction between the parameters of mortar and stone in the equations are indicated by the subscripted characters “mo” or “st”.

In the case of hygric exposure it might be necessary to take creeping effects of the mortar and stone into account; otherwise the calculated tension could become unrealistically high [2]. To calculate using a time-dependent modulus of elasticity, the secant modulus of elasticity has to be reduced in accordance with the equation (7) and applied instead in (6).

$$\varepsilon_T = \alpha_{T,mo} \cdot \Delta T_{\max,mo} \cdot l_{0,mo} + \alpha_{T,st} \cdot \Delta T_{\max,st} \cdot (1 - l_{0,mo}) \quad (2)$$

$$\varepsilon_S = \varepsilon_{S,\infty,mo} \cdot l_{0,mo} + \varepsilon_{S,\infty,st} \cdot (1 - l_{0,mo}) \quad (3)$$

$$\varepsilon_{el,pl} = \frac{\sigma_t}{E_{\text{sec},mo}} \cdot \frac{l_{0,mo} + (1 - l_{0,mo}) \cdot E_{\text{sec},mo} / E_{\text{sec},st}}{1} \quad (4)$$

$$\varepsilon_C = \sigma_t \cdot (\varphi_{mo} \cdot l_{0,mo} / E_{mo} + \varphi_{st} \cdot l_{0,st} / E_{st}) \quad (5)$$

$$\sigma_T = \frac{l_{0,mo} \cdot (\alpha_{T,mo} \cdot \Delta T_{\max,mo} + \varepsilon_{S,\infty,mo}) + l_{0,st} \cdot (\alpha_{T,st} \cdot \Delta T_{\max,st} + \varepsilon_{S,\infty,st})}{l_{0,mo} + l_{0,st} \cdot E_{\text{sec},mo} \cdot (1/E_{\text{sec},st}) / E_{\text{sec},mo} + \varphi_{mo} \cdot l_{0,mo} / E_{\text{sec},mo} + \varphi_{st} \cdot l_{0,st} / E_{\text{sec},st}} \quad (6)$$

$$E_{\text{sec},t} = \frac{E_{\text{sec}}}{(1 + 0,8 \cdot \varphi)} \quad (7)$$

### ***Stress calculations on the masonry surface – cracking vertical to the joint flank***

The stone has a minor influence on crack formation in the mortar compared to the internal stress of the mortar. Therefore the stress calculations that lead to cracking in the mortar are limited to the

internal stress of the mortar. If the calculated tension is higher than the tensile strength of the mortar, cracking will set in. If the masonry is exposed to moisture the secant modulus of elasticity has to be reduced as mentioned above.

### SENSITIVITY ANALYSIS USING AN ENHANCED ENGINEERING MODEL

The engineering model developed by Schmidt-Döhl und Rostásy [8] has been enhanced in order to run sensitivity analyses on the parameters. Scilab, which is a software for numerical computations, was used to take the scattering of parameters into account by running a numerical algorithm. The scattering is seen as uniform distribution so that each parameter is described as a vector in the range of the upper and lower tolerance value  $\overline{a_- a_+}$  (8). The algorithm of the computation includes loops to calculate the resisting tension for the vector of each parameter one after another. As an outcome, the effect of each parameter on the resisting tension and, consequently, on the durability of the repointing can be shown graphically.

$$a_- = \bar{a} - \Delta a_- = \bar{a} - \bar{a} \cdot v \quad ; \quad a_+ = \bar{a} + \Delta a_+ = \bar{a} + \bar{a} \cdot v \quad (8)$$

$a_- / a_+$	Lower/ upper tolerance value of individual parameter
$\bar{a}$	Mean value of individual parameter
$v$	Coefficient of variation of individual parameters in [%]

In the following, the outcome of a computation of possible crack formation parallel to the joint is represented using the example of the St. Nikolai Memorial in Hamburg, Germany, which is being repointed. The restoration planning for repointing started in 2014 and went on for about a year. The Memorial is shown in Figure 6 and Figure 7.



**Figure 6: Exterior View of the Steeple of the St. Nikolai Memorial**



**Figure 7: Mortar Erosion at the St. Nikolai Memorial**

The characteristic parameters of the existing sandstone and assorted samples of mortar compositions were tested in the laboratory of the Institute of Material Science at the Jade University of Applied Sciences in Oldenburg. The contracting authority is the Freie und Hansestadt Hamburg. The test results of the material and geometry data for the engineering model

are shown in Table 1. Each test procedure is documented in the final analysis report [14]. The scattering of each parameter is considered using the coefficient of variation of the series of measurements with a 90% confidence interval of its Student-t-distribution.

**Table 1: Input Parameter for the Modified Engineering Model**

Input parameter	Variable	Arithmetic mean [14]	Coefficient of variation
<b>Actions</b>			
Maximum difference of the temperature gradient through the cross section of the building component	$\Delta T_{\max, st}$	15 [K]	10* %
	$\Delta T_{\max, mo}$		
<b>Geometry data</b>			
Area ratio of the mortar vertical to the joint flank	$l_{o, mo}$	0.09 [-]	33.7* %
<b>Material data for the mortar</b>			
Linear thermal expansion	$\alpha_{T, mo}$	$1.03 \cdot 10^{-5}$ [1/K]	10* %
Final degree of shrinkage	$\varepsilon_{S, \infty, mo}$	$1.71 \cdot 10^{-4}$ [-]	17.1 %
Creep coefficient	$\varphi_{mo}$	6.5** [-]	10* %
Secant modulus of elasticity	$E_{sec, mo}$	11100 [N/mm <sup>2</sup> ]	9.5 %
<b>Material data for the stone</b>			
Linear thermal expansion	$\alpha_{T, st}$	$1.1 \cdot 10^{-5}$ [1/K]	1.5* %
Final degree of shrinkage	$\varepsilon_{S, \infty, st}$	$7 \cdot 10^{-5}$ *** [-]	10* %
Creep coefficient	$\varphi_{st}$	0.8** [-]	10* %
Secant modulus of elasticity	$E_{sec, st}$	20000 [N/mm <sup>2</sup> ]	21.8 %

\* Assumption

\*\* Estimated according to Schmidt-Döhl and Rostäsy [8] and Hörenbaum [2]

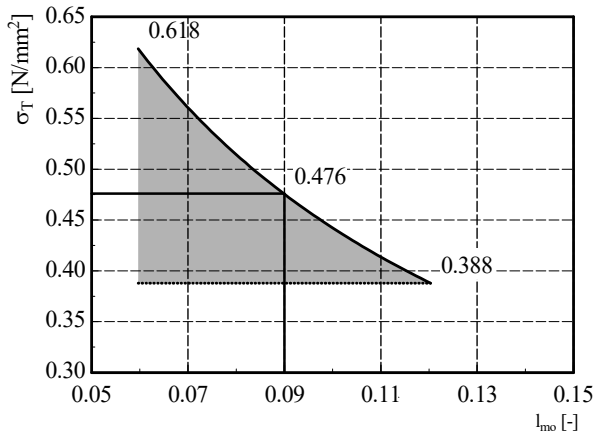
\*\*\* Estimated according to Schmidt-Döhl and Rostäsy [8] and Alfes and Schießl [15]

The calculated resisting tension is shown as a function of the iterated parameter in its individual value range. The higher the slope of the curve the higher the impact of the scattering. In this example the parameters that have the highest impact on the resisting tension are the area ratio of the mortar, secant modulus of elasticity of the mortar and the creep coefficient of the mortar. The creep coefficient of the stone has one of the lowest impacts. The curves of the parameters are shown in Figure 8 to Figure 11.

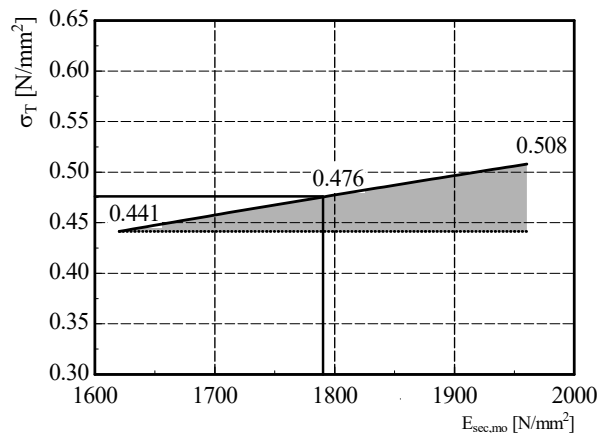
The calculated mean resisting tension is 0.48 N/mm<sup>2</sup>. Consequently, the tensile bond strength of the mortar/stone composite should be higher than 0.48 N/mm<sup>2</sup> or bond failure and crack formation would set in. The higher the tensile bond strength the higher the probability of achieving highly durable repointing. In this case the mean tensile bond strength of the tested mortar and the existing

sandstone is 0.3 N/mm<sup>2</sup>. Using the Student-t-distribution with a 90% confidence interval, the lower and upper tolerance value describe a range between 0.20 N/mm<sup>2</sup> and 0.34 N/mm<sup>2</sup>.

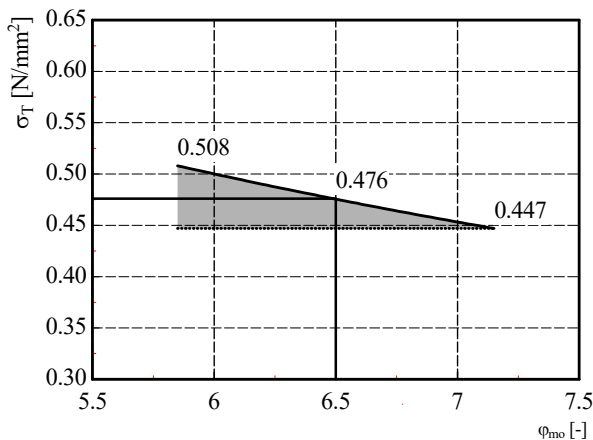
In this case the tensile bond strength was tested again with an adhesion promoter which increased the mean tensile bond strength to 1.03 N/mm<sup>2</sup>. The lower and upper tolerance value range is 0.37 and 1.69 N/mm<sup>2</sup> considering a Student-t-distribution with a 90% confidence interval. The outcome is, in this case, that it is necessary to use the adhesion promoter to achieve a high probability and, thus, a high durability.



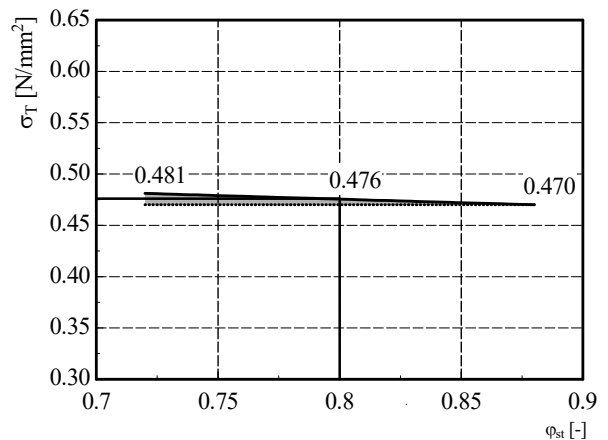
**Figure 8: Resisting Tension as a Function of the Area Ratio of the Mortar**



**Figure 9: Resisting Tension as a Function of the Secant Modulus of Elasticity of the Mortar**



**Figure 10: Resisting Tension as a Function of the Creep Coefficient of the Mortar**



**Figure 11: Resisting Tension as a Function of the Creep Coefficient of the Stone**

To clearly illustrate the specific lower and upper tolerance value of the mean resisting tension in relation to each other and, therefore, the most influential parameter, the equation (9) is applied. Table 2 shows the result of the sensitivity analysis on the St. Nikolai Memorial. The calculated lower and upper tolerance value of the mean resisting tension are indicated as a percentage of the mean resisting tension.



$$\Delta\sigma_{T,-} = \frac{\bar{\sigma}_T - \sigma_{T,tol,l}}{\bar{\sigma}_T} \quad ; \quad \Delta\sigma_{T,+} = \frac{\sigma_{T,tol,u} - \bar{\sigma}_T}{\bar{\sigma}_T} \quad (9)$$

**Table 2: Output Data of the Enhanced Engineering Model; Percentage of Lower and Upper Tolerance Value of the Mean Resisting Tension**

		$\Delta\sigma_{T,-}$	$\bar{\sigma}_T$	$\Delta\sigma_{T,+}$
<b>Actions</b>				
Maximum difference of the temperature gradient through the cross section of the building component	$\Delta T_{\max,st}$	94%	100%	106%
	$\Delta T_{\max,mo}$	99%	100%	101%
<b>Geometry data</b>				
Area ratio of the mortar vertical to the joint flank	$l_{0,mo}$	130%	100%	82%
<b>Material data of the stone</b>				
Linear thermal expansion	$\alpha_{T,st}$	99%	100%	101%
Final degree of shrinkage	$\varepsilon_{S,\infty,st}$	97%	100%	103%
Creep coefficient	$\varphi_{st}$	101%	100%	99%
Secant modulus of elasticity	$E_{sek,st}$	93%	100%	105%
<b>Material data of the mortar</b>				
Linear thermal expansion	$\alpha_{T,mo}$	99%	100%	101%
Final degree of shrinkage	$\varepsilon_{S,\infty,mo}$	99%	100%	101%
Creep coefficient	$\varphi_{mo}$	107%	100%	94%
Secant modulus of elasticity	$E_{sek,mo}$	93%	100%	107%

## CONCLUSIONS AND RECOMMENDATIONS

The example demonstrates the importance of considering a certain scattering range of the parameters instead of taking the arithmetic mean for granted. Especially the plotting of the resisting tension as a function of different parameters emphasizes their influence. The impact of the area ratio of the mortar vertical to the joint flank is non-linear and stands out clearly. The implication is that the focus has to be put on accurate measurement of the area proportions of mortar and stone. This could perhaps be optimized using photogrammetry. The secant modulus of elasticity and the creep coefficient of the mortar should be tested in the laboratory in a high quantity. In this way, the Student-t-distribution of the results is brought more into line with the standard normal distribution and, thus, the precision increases. Therefore the probability statement is of a higher quality and the chosen repointing mortar ensures higher durability. The engineering model is being enhanced so that the results can be transferred to probabilistic concepts.

Further developments of the engineering model by Schmidt-Döhl und Rostàsy [8] should not only include material effects caused by thermal exposure but moisture exposure too. In addition, a

closer look should be taken at how time-dependent creeping affects the materials. Another aspect that should be considered is Poisson's ratio.

In the course of a current dissertation research project called "Durability Prognoses of Repointing in Historical Masonry in Consideration of Scattering of Material Properties" which is carried out by the first author, a prognosis model is being developed. Previous research models are the basis of the current research project. This study however, takes the research one step further and takes the scattering of material properties into account. The probabilistic-based assessments for failure prognoses of repointing are going to be carried out using the engineering tool SARA. First, masonry sections are going to be simulated as a finite element model in ATENA. The probabilistic software FReET is going to be used to simulate uncertainties. Since it is not possible to simulate coupled heat and moisture transport in ATENA the software DELPHIN is going to be used in addition. Currently the relevant parameters are being tested and statistically assessed. Furthermore, a constant re-evaluation between the simulations and long-term measurements on masonry section in the laboratory is going to take place.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] Maurenbrecher, A.; Trischuk, K. and Rousseau, M. Z. (2001). "Review of factors affecting the durability of repointing mortars for older masonry." *Abstracts of Proceedings & Final Program, 9<sup>th</sup> Canadian Masonry Symposium*, Fredericton, NB, Canada, p. 1–12.
- [2] Hörenbaum, W. (2005). *Verwitterungsmechanismen und Dauerhaftigkeit von Sandsteinsichtmauerwerk*. Dissertation, Universität Fridericiana zu Karlsruhe (TH), Karlsruhe.
- [3] Schmidt-Döhl, F. and Rostásy, F. S. (1997). "Dauerhaftigkeitsmodell von Verfugungen." Rostásy, F. S., Wigger, H., editors. *Tagung Konsolidierung von Historischem Natursteinmauerwerk. 6. und 7. November 1997*, Braunschweig, IBMB, Heft 135, p. 191–201.
- [4] Twelmeier, H. (2011). *Dauerhaftigkeitsprognose der Verfübung von gipshaltigem historischem Mauerwerk*. Dissertation, Technische Universität Braunschweig, Braunschweig.
- [5] Budelmann, H.; Weiß, D. and Rostásy, F. S. (1993). "Der Verbund zwischen Fugenmörtel und Naturstein- Anforderungen und Prüfung." TA Esslingen, editors. *Internationales Kolloquium Werkstoffwissenschaften und Bausanierung. Tagungsband*, p. 1080–1091.
- [6] Franke, L. and Bentrup, H. (1991). "Schädigung von Mauerwerksbauten durch Umwelteinflüsse- Beurteilung und Instandsetzung." *Bauphysik*, 13. Jahrgang.
- [7] Meyer, U. and Schubert, P. (1991). "Mauer- und Verfügmörtel (Restauriermörtel) für die Instandsetzung von Natursteinbauwerken." *Jahresberichte aus dem Forschungsprogramm Steinerfall - Steinkonservierung 1989*, Ernst & Sohn.

- [8] Schmidt-Döhl, F. and Rostásy, F. S. (2009). *Ingenieurmodell zur Dauerhaftigkeit des Verbundsystems Naturstein/Mörtelfuge mit Bezug auf die Neuverfugung historischen Mauerwerks*. DFG Abschlussbericht, TU Braunschweig, Braunschweig.
- [9] Kaptan, K. (2016). *Engineering Models of Masonry by Joint Repairing Techniques*, Beykent University, Civil Engineering Dep., Istanbul, Turkey.
- [10] Franke, L.; Deckelmann, G. and Goretzky, W. (1993). *Einfluß der Streubreiten von Stein- und Mörtelqualität bei der Festigkeitsbestimmung von bestehendem Mauerwerk, insbesondere bei historischen Bauten*, Fraunhofer IRB Verl., Stuttgart.
- [11] Steinbach, S. (2010). *Ansätze zur Entwicklung eines Sicherheitskonzeptes für bauphysikalische Bemessungsgrößen*. Dissertation, Bauhaus-Universität Weimar, Weimar.
- [12] Westermann, C. (2013). *Einfluss unsicherer Daten bei bauphysikalischen Nachweisen*. Masterthesis, Jade Hochschule, Oldenburg.
- [13] Schulz, J.-U.; Westermann, C. and Wigger, H. (2013). "Unscharfe Daten." Schwickert, S., editors. *Detmolder Bauphysiktag 2013*, Aachen, Shaker, p. 65–113.
- [14] Wigger, H.; Twelmeier, H.; Schmidtman, I.-M. and Westermann, C., Verein zur Förderung der Materialprüfung an der Jade HS e.V. (2016). *Abschlussbericht. Nr. 0675/14, Versuchsergebnisse der Mörtel- und Steinuntersuchungen*. Mörtelkonzept Mahnmal St. Nikolai.
- [15] Alfes, Ch.; Schießl, P. (1994): "Spannungsdehnungsverhalten, Schwinden und Kriechen von Sandsteinen." *Jahresberichte aus dem Forschungsprogramm Steinzerfall und Steinkonservierung*, Berlin, Ernst und Sohn, p. 3-17