Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)

Prediction model for the weathering of sandstone based on fracture processes

E. Kotan & H.S. Müller
Institute of Concrete Structures and Building Materials, Universität Karlsruhe (TH), Germany

ABSTRACT: Permanently changing temperature and moisture gradients, sometimes in conjunction with frost and ice formation as well as partially arising crystallisation processes of solved salts in the building sandstones lead to a weakening of the sandstone material. For the description of the deterioration process due to these main actions, which cause primarily a gradual failure of the grain bonding proceeding from the surface to inner parts of the cross section, an appropriate model for the weathering of sandstone is presently being developed.

1 INTRODUCTION

1.1 *Background*

Sandstone is a common building and paving material. In Central Europe it is the most commonly kind of natural stone used for historical buildings. During the past century a dramatic increase of damages on historical buildings, monuments and sculptures made from natural stone has been observed. Due to these circumstances the weathering of sandstone and appropriate counter measures have been major aspects in numerous investigations in recent years. However, the past research work on natural stone weathering was primarily concentrated on the documentation of the deterioration process considering different attack conditions as well as on the investigations of chemical, mineralogical and physical sub-processes. So far analyses on theoretical aspects of strength loss and degradation during the decay processes have only been carried out to a very limited stage. Hence, no service life prediction models or similar approaches are available so far.

1.2 *Motivation*

The aim of this research project was to develop an appropriate model to describe the weathering of sandstone as a result of thermal and hygral actions. The principal idea of the proposed sandstone weathering model consists in the basic hypothesis that the weathering is primarily a result of a fatigue loading resulting from climate actions. Therefore it was essential to determine the loads due to the alternating ambient conditions using numerical methods and on the other hand to investigate the fatigue behaviour of the sandstone material by means of experimental tests. The intention of these tests was to derive Woehler curves which, in combination with an adequate failure-accumulation hypothesis allow for the specification of the intended prediction model.

2 EXPERIMENTAL INVESTIGATIONS

2.1 *Introduction*

For a realistic simulation of the deterioration process the implementation of sophisticated material characteristics and laws into the numerical analysis is essential. Besides structural data and strength values, particularly material relations who describe e.g. the crack development in sandstone are necessary. Therefore centric statical tensile tests were carried out under realistic boundary conditions. Furthermore the dynamic tensile-strength behaviour of sandstone was examined by means of centric fatigue tests.

2.2 *Fracture mechanical analysis*

In order to be able to record the entire stress-deformation behaviour also after reaching the ultimate load, notched specimens (see Fig. 1) were chosen according to (Mechtcherine 2000). The load application (v = 0,05 mm/min) occurs via stiff, rotation impeding steel plates between which the notched sandstone prisms were glued by a rapid hardening two-component adhesive on the basis of methacrylat. By means of the chosen impediment a stabile crack development was achieved over the specimens entire cross section (see Fig. 1 right). Thereby the required fracture mechanical properties e.g. the fracture energy G_F and the stress-crack-width relation could be obtained.

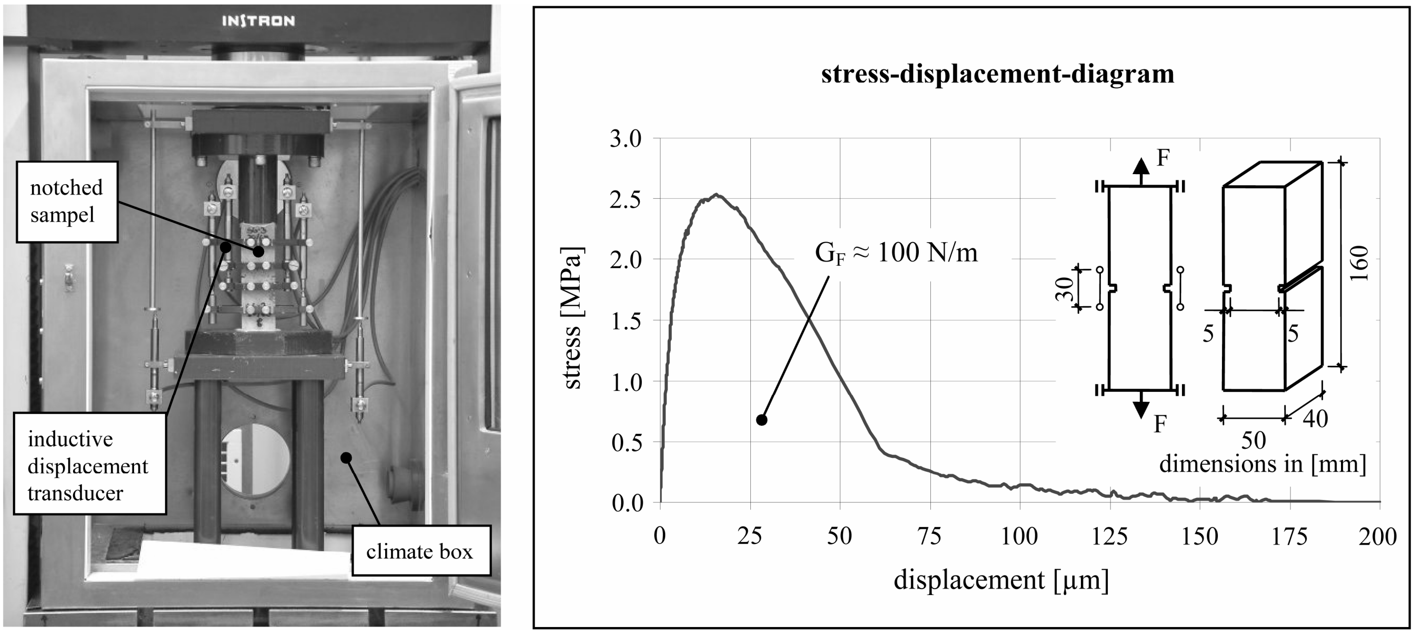


Figure 1. Experimental setup, characteristic curve progression and geometry of the notched samples.

The diagram in Figure 1 shows a stress-strain relation obtained in the mentioned tests. The analysis of the illustrated curve leads to a fracture energy G_F of about 100 N/m for a sample strained parallel to its layering. An about 10 % lower fracture energy was determined from corresponding tensile tests which were performed on notched specimens strained perpendicular to their layering.

In order to consider a possible variance of the relevant material parameters as a result of different ambient conditions furthermore centric tensile tests were carried out at different temperature and moisture conditions. This variation is of relevance for the numerical analysis. For this purpose the tests were performed in an air-conditioned box (see also Fig. 1). The essential results regarding the fracture mechanical investigations are summarised in Table 1 (see also Kotan 2009).

Table 1. Summary of mechanical properties.

Setting	Average value (Standard deviation)	
	∥ to layering	⊥ to layering
Compressive strength [MPa]	59.2 (4.83)	61.2 (2.87)
Tensile strength [MPa]	2.6 (0.14)	2.2 (0.23)
Modulus of elasticity [MPa]	11,190 (827)	12,310 (424)
Poisson's ratio [-]	0.2 (-)	0.2 (-)
Net tensile strength [MPa]		
20 °C / 33 % RH	2.2 (0.07)	1.9 (0.13)
20 °C / 65 % RH	2.3 (0.13)	1.7 (0.17)
20 °C / 94 % RH	2.3 (0.09)	1.6 (0.16)
2 °C / 65 % RH	1.9 (0.16)	1.6 (0.29)
50 °C / 65 % RH	1.8 (0.27)	1.9 (0.17)
Fracture energy [N/m]		
20 °C / 33 % RH	98 (3.06)	86 (10.2)
20 °C / 65 % RH	106 (7.13)	91 (8.5)
20 °C / 94 % RH	100 (8.54)	86 (9.3)
2 °C / 65 % RH	100 (5.72)	88 (9.5)
50 °C / 65 % RH	94 (11.35)	92 (6.5)

2.3 *Cyclic tensile tests*

The determination of the dynamic tensile strength of sandstone by means of centric Woehler tests was the key part of the experimental investigations. In order to determine the related load cycles to failure N_i (see Fig. 2) preferably almost identical specimens were exposed to appropriately scaled vibration stresses. During the performance of the tests the lower stress σ_u was kept constant for all specimens of a Woehler series while the upper stress σ_o was phased from specimen to specimen so that during the course of the tests not only the descending straight line (curve) of the Woehler curve could be specified but also the fatigue resistance depending on the limit-load cycles N_{max} could be evaluated. This procedure was chosen since the compressive strength of approx. 60 MPa (see Table 1) is absolutely a lot greater than the degree of the loading observed in corresponding fatigue tests, which have been determined to 1 to 2 MPa in numerical investigations. Hence it is assumed that the deterioration contribution due to corresponding compressive loads is insignificantly small.

To accomplish the Woehler tests notched sandstone prisms with the dimensions 50x40x160 mm³ (according to the static tensile tests) were used. As ambient condition a controlled reference atmosphere of 20°C / 65% RH was maintained. In order to balance material-dependent variations 5 tests per specimen series and direction of stratification were conducted. With regard to the test duration an upper limit of 2 million cycles was defined.

For various materials it is known that the fatigue behaviour depends only slightly on the frequency of the load cycles. However as the acceleration in the tests is of highly importance in order to develop a was chosen for the derivation of the mentioned Woehler curves. Afterwards the frequency was var-

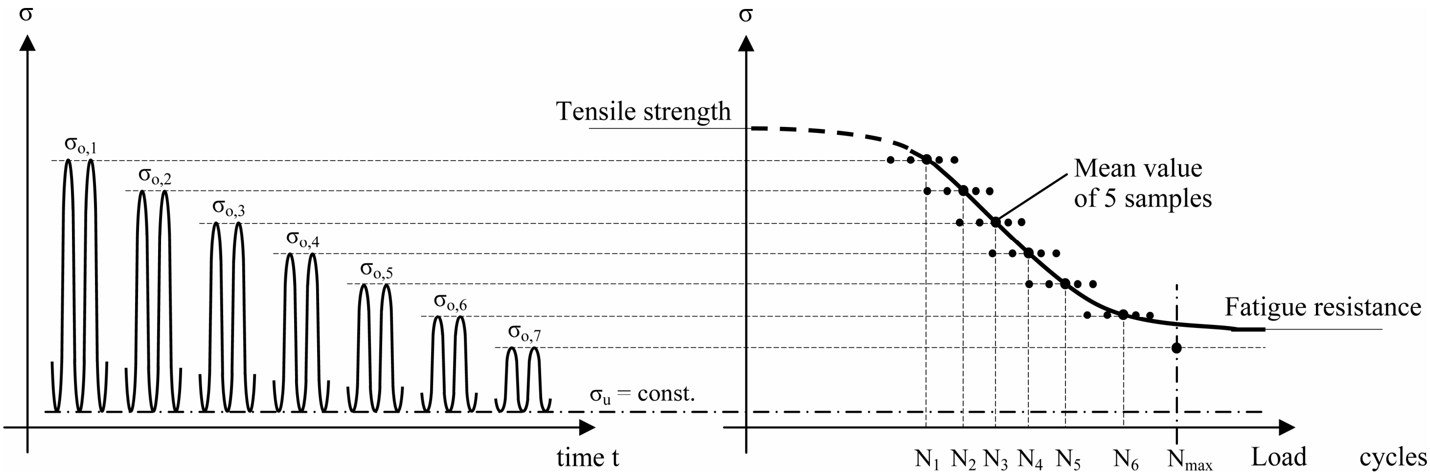


Figure 2. Evaluation of the Woehler curve with constant lower stress σ_u.

ied between 1 and 10 Hz for some representative upper stress/failure-cycle combinations. Within the examined scope the test frequency had negligible influence on the number of load cycles until failure. Therefore all following fatigue tests were performed at 5 Hz.

The results of the dynamic tensile tests are shown in Figure 3. The diagram on the left represents the material behaviour for dynamic loadings applied parallel to the layering of the sandstone material. At a loading degree of about 80 % of the static tensile strength of the sandstone the samples could withstand an average of 8745 load cycles until failure. An average number of almost 200,000 load cycles was reached at a loading degree of 70 %. Finally the sample could resist 2 million load cycles without failure at a loading degree of 60 %. Per loading degree five single tests were performed. They are displayed as rhombi depending on their attained number of load cycles in the diagram. The circles represent the average value per loading degree. The static tensile strength as well as a linear relationship between the loading degree and the number of load cycles (logarithmically scaled) was taken into account in order to determine the presented best fit Woehler line.

The results for loadings applied perpendicular to the layering are shown in Figure 3 on the right side. The higher gradient of the Woehler curve for a loading perpendicular to the stratification is statistically significant and proves an increased fatigue sensitivity in this load direction. This goes along with a reduction in load cycles from more than 2 million down to 114,000 at a loading degree of 60 %.

These Woehler curves provide essential information regarding the materials fatigue resistance. Based on the working hypothesis that the weathering – excluding an entire saturation with water – represents a cumulative mechanical softening process, failure criterions due to fatigue (Woehler, Palmgren-Miner a.o.) can now be utilised. They deliver a correlation between the loading degree, which can be considerably smaller than the strength, and the time span until failure occurs. Now a prediction model can be formulated which enables to forecast of the gradual destabilization under arbitrary ambient conditions. The effect of these conditions on sandstone still has to be quantified by numerical analysis

3 NUMERICAL INVESTIGATIONS

The main aim of the numerical investigations is to quantify the loads resulting from climatical condi-

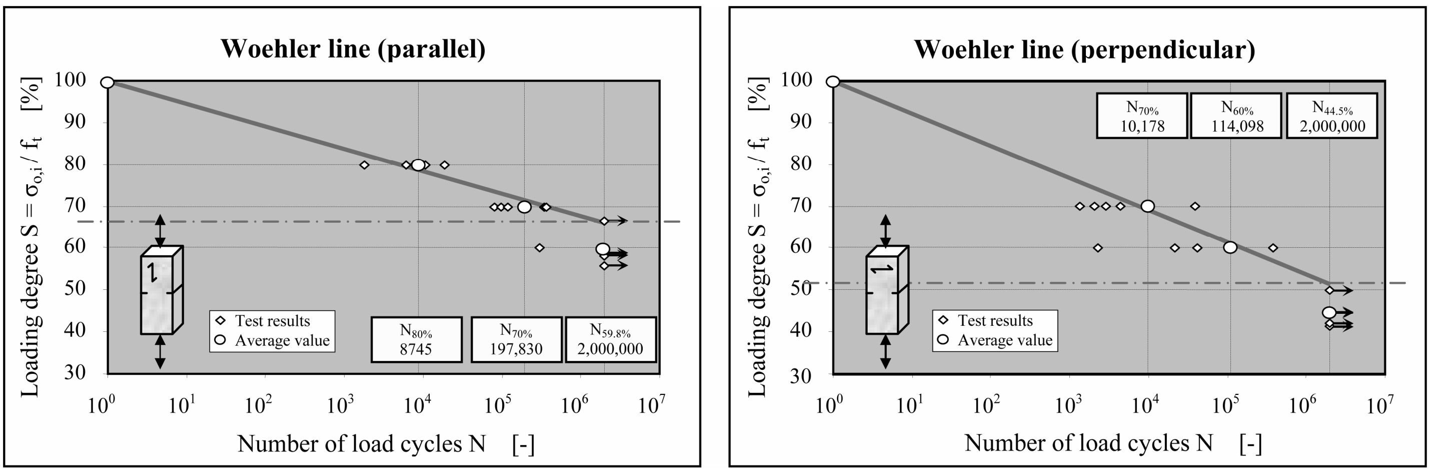


Figure 3. Test results of the dynamic tensile tests.

tions. Therefore two different numerical models are used. The quantitative determination of loads resulting from seasonal variations of temperature and moisture is carried out by a continuum model. Hereby the temperature and moisture distribution, structural stresses and potential crack development can be analysed, amongst others. The simulation of pore pressures due to frost loadings and accordingly the textural loading on the granular structure are investigated by means of a structural model. Contrary to the continuum model in this case the mesostructure of the sandstone (grains, grain bondings and structural pores) is being reproduced. For the two dimensional numerical analysis the finite element program DIANA is applied.

3.1 *Continuum model*

In order to analyse the deformations and stresses in the peripheral zones resulting from characteristic changes of temperature and humidity a FE mesh of a continuum model (macro level) was generated and tested with the help of the FE programme DIANA (see Fig. 4). The main target of the numeric computation was to gain initial values of temperature and humidity gradients and in particular to determine the resulting tensions and deformations under continuously changing climate actions.

At first a freely deformable sandstone block was examined. Hereby the moisture and temperature transport were considered decoupled. To record realistic diffusion and capillary transport characteristics of the sandstone, the humidity dependent storage and conductivity characteristics for the humidity transport were considered in the computation. To simulate the thermal and humidity transition between the ambient air and the sandstone surface appropriate convection elements were used.

In order to compute the deformations caused by temperature or humidity changes, the respective thermal and hygral strain functions were considered. The strain functions were derived from literature data (Müller & Hörenbaum 2002, Schießl & Alfes 1991, Möller 1993) and cover the entire spectrum of possible moisture contents.

The calculative set of climate actions includes the usual climates as well as extreme effects like thermal shock (thundershower) and driving rain. Since the natural climate conditions do not only vary over long periods, it was necessary to run separate long-term calculations (observation period: one to several years) as well as short-time calculations (observation period: one to several hours).

The extensive computer-aided simulations on the continuum that have been performed so far provide the calculative structural stresses, type and number of the tension alternations depending on the selected characteristic values, geometrical boundary conditions as well as the simulated influences of the weather. To estimate the pore saturation degree in the peripheral zone it is also essential to record the moisture distributions.

As a result of constantly changing climate conditions a steady alternation of humidity and temperature is observed in the stones surface. The resulting moisture and temperature gradients cause distinct deformations of the sandstone, which strongly vary locally. This deformation tendency generates struc-

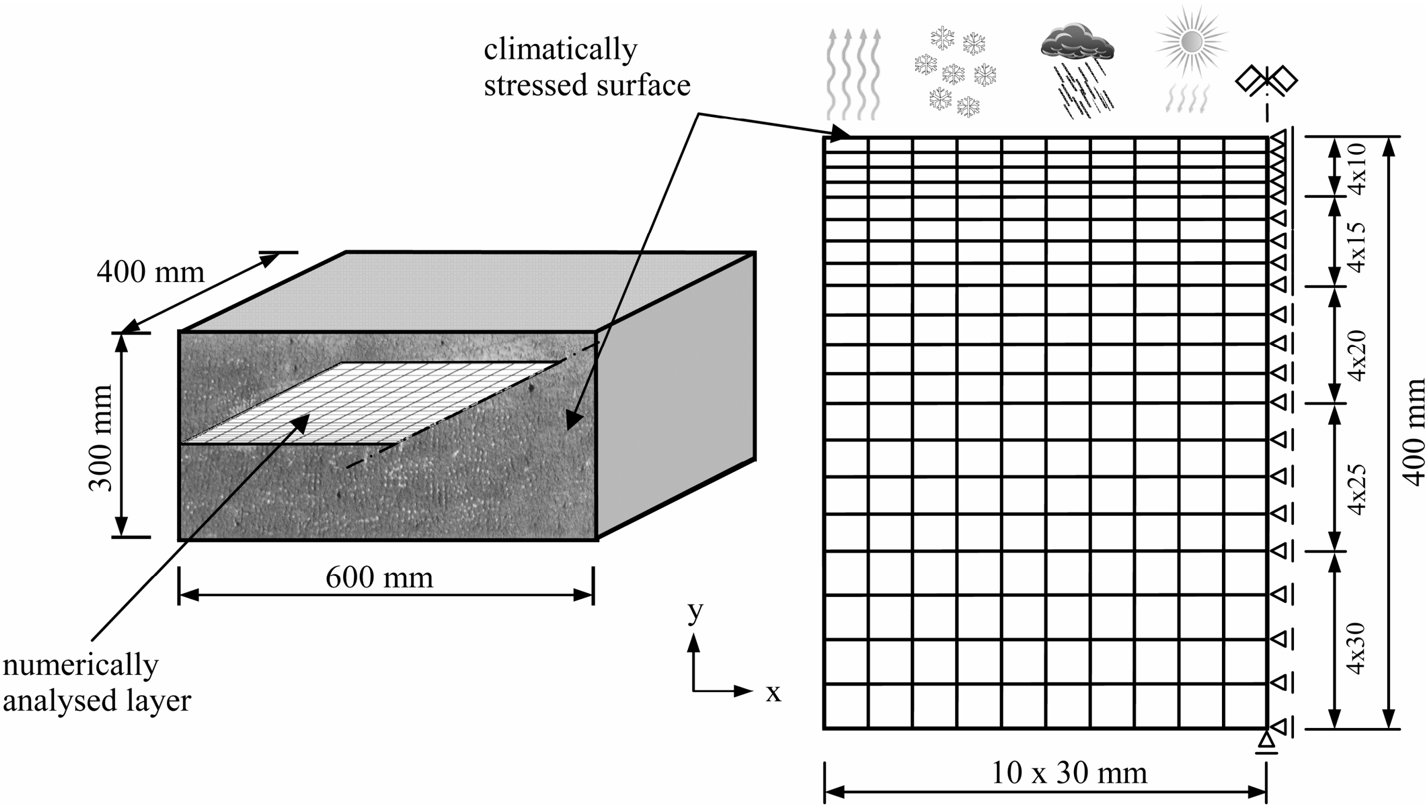


Figure 4. Numerically analysed layer of the sandstone continuum and discretised system.

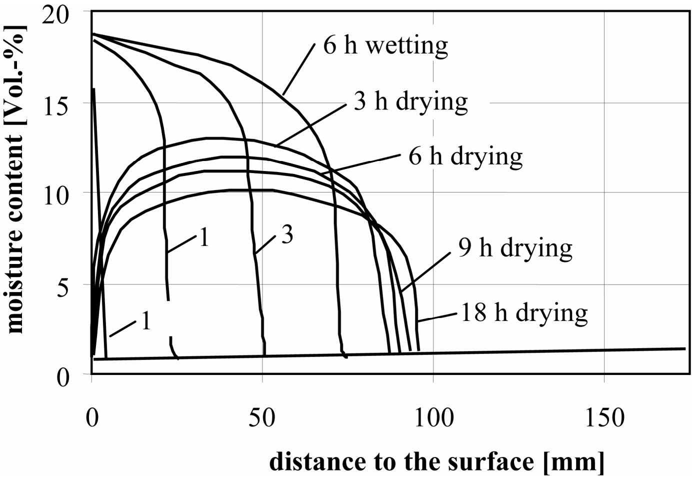


Figure 5. Moisture distribution in the stone – 6 hours of wetting followed by 18 hours of drying.

tural stresses, which can lead to a gradual failure of the grain bonding of the sandstone structure and finally to damages (Müller & Garrecht 1999).

To analyse the structural stresses, a sandstone continuum, as it is represented in Figure 4, was examined in detail. Due to the fact that the deterioration process mainly takes place on the layers close to the surface, two-dimensional numerical investigations were carried out for the calculation of the determining stresses. As an example of the calculation results, Figure 5 shows some moisture distributions in the sandstone. In this case a sandstone block, which was dry in the beginning due to a long period of dry weather, is suddenly exposed to a 6 hour period of wetting. The humidity penetration behaviour in the sandstone, being observed during the wetting, is characterised by a sharply marked sloping moisture front. In this case the penetration depth amounts to a depth of 75 mm into the stone. The following drying behaviour shows the typical well-known correlation that the drying of the material demands a multiple of the time compared to the humidification. Furthermore the calculated results show, that depending on prevalent drying possibilities at the sandstone surface, a part of the humidity is emitted in the form of evaporation back to the ambient air. At the same time a rearrangement of moisture can be observed at the moisture front within the stone. Thus a part of the humidity continues to penetrate into the stone.

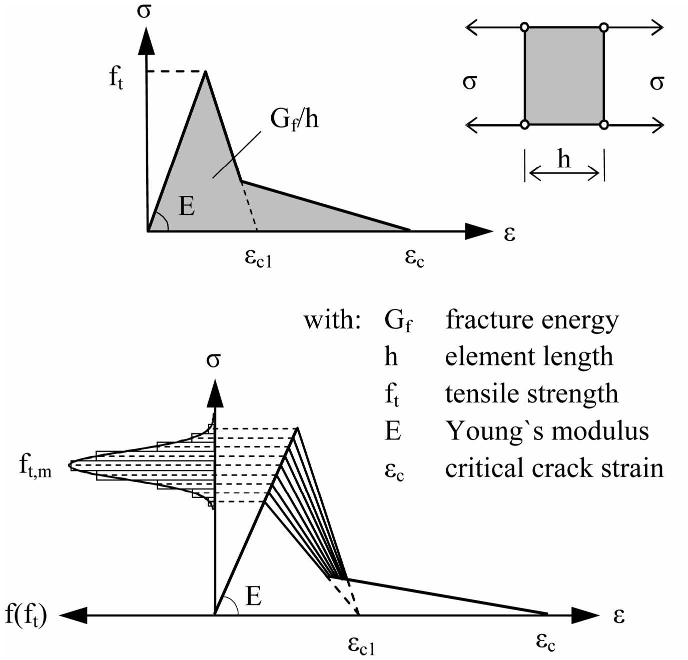


Figure 6. Implementation of the Crack Band Model in the finite element model (above) and consideration of the heterogeneity of the sandstone (below).

The implementation of adequate material laws into the FE model is important to draw conclusions about the structural stresses due to moisture and temperature gradients. The material behavior of the sandstone was modelled using the Crack Band Model developed by Bažant and Oh (Figure 6, above). The heterogeneity of the sandstone was taken into account by a variance of the material properties via a statistical distribution of the material parameters (particularly tensile strength and the frac-

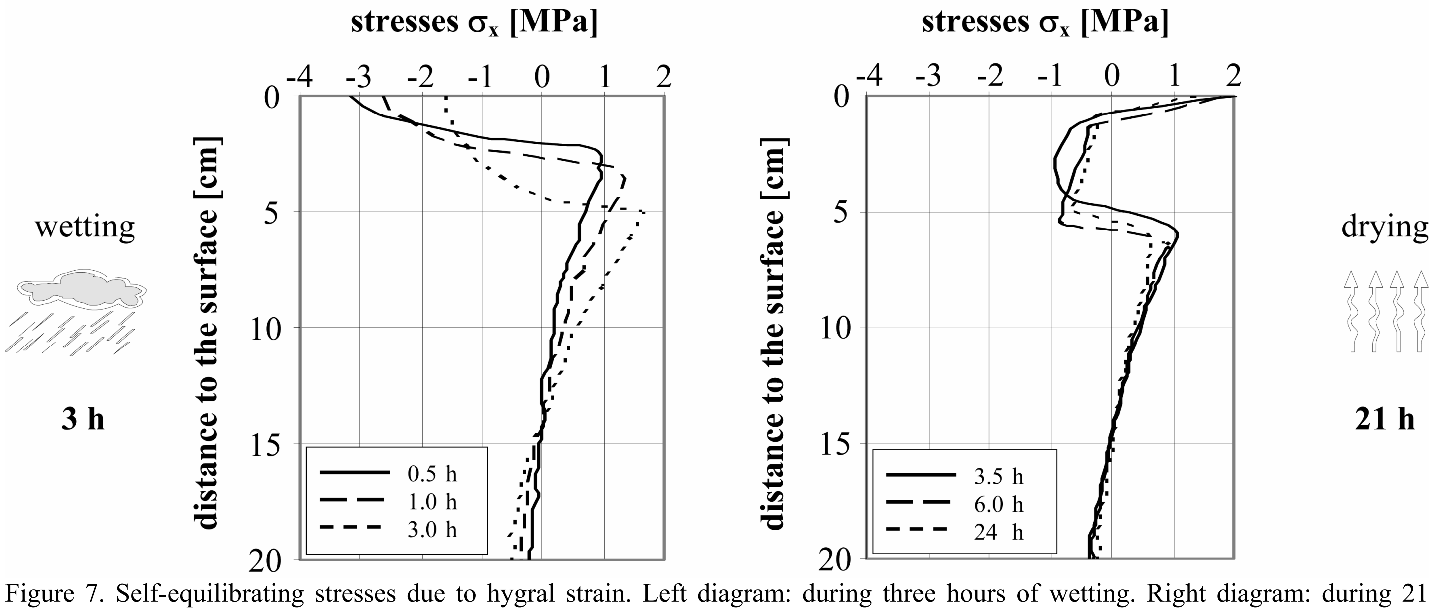


Figure 7. Self-equilibrating stresses due to hygral strain. Left diagram: during three hours of wetting. Right diagram: during 21 hours of drying.

ture energy). Therefore nine material classes were defined and assigned randomly according to a Gaussian distribution to the finite elements (Fig. 6, below).

As a numerical result of a chosen hygral strain over a period of 24 hours Figure 7 shows exemplarily the self-equilibrating stresses in a sandstone block. For simplification purposes the temperature conditions were assumed to be constant. The left illustration shows explicitly the self-equilibrating stresses appearing after irrigating a sandstone which was completely dry to start off with. The stress ratio during the following 21 hour drying process is shown in the diagram on the right hand side.

As a result of the moisture absorption compressive stresses in the already humid stone are observed. At the moisture front the signal of the stress changes from pressure to tension. This fact is a result of the restrained deformation caused by the lower and drier stone layers. Due to a further ingress of moisture into the stones interior the tensile stresses arise and can exceed the material tensile strength (see Table 1).

On the right hand side of Figure 7 the stress distribution due to the following 21 hour drying period is illustrated. As a result of moisture dissipation the layers close to the surface tend to exhibit shrinkage deformations. However, this deformation tendency is being restrained by the more humid lower layers. Thus, tensile stresses in layers close to the surface occur. Especially at the beginning of the drying process, when the moisture gradient is high, the tensile stresses can almost reach the material strength.

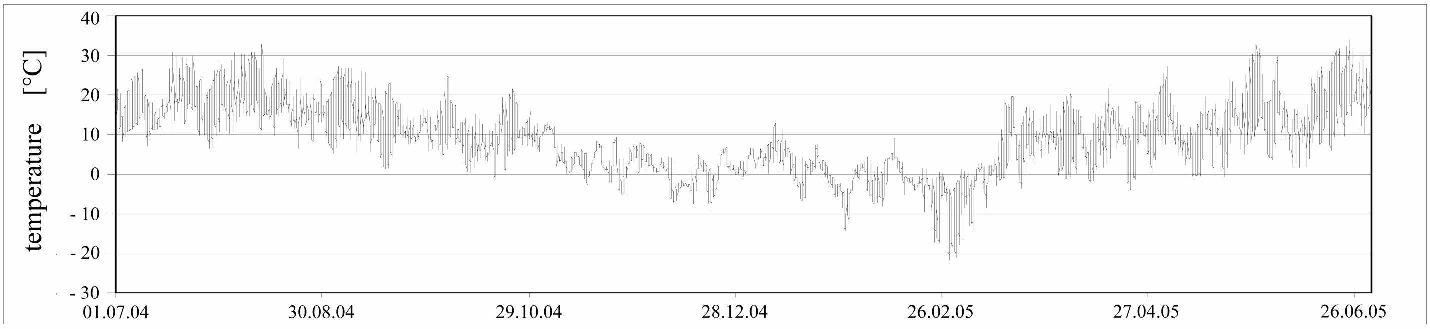
Essential in order to investigate the fatigue behaviour due to climatical influence is a quantitative survey of the stress alteration on the individual stone-layers. Therefore seasonal climate actions (temperature and moisture) were examined and corresponding seasonal distributions of stress were determined. These distributions were subsequently evaluated by using statistical counting procedures (rainflow or reservoir counting method). Afterwards frequency distributions were developed and finally compiled in a profile of stress collectives (see Fig. 8).

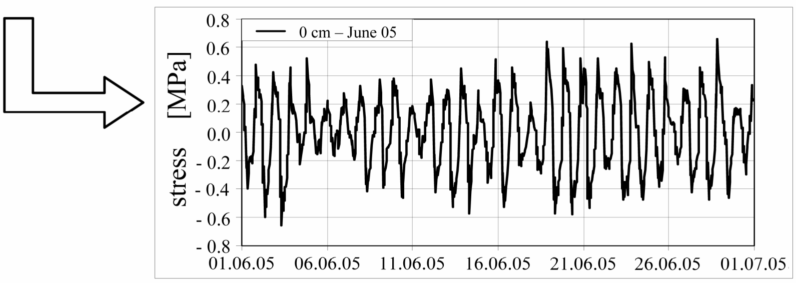
The stresses given in Figure 8 have to be superposed with the stresses due to seasonal hygral actions. Furthermore structural stresses as a result of a frost attack have to be taken into account by load collectives. For this purpose the investigations are performed on the structural model, which is specified in the following.

3.2 *Structural model*

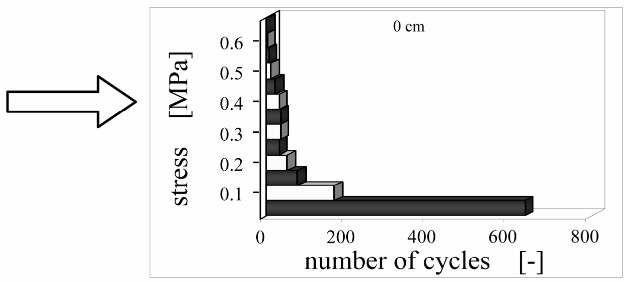
For the weathering during a frost attack the degree of pore saturation with water is of major relevance. The formation of ice for low degrees of saturation leads to reversible structural deformations. In contrast to this irreversible deformations appear during saturated conditions due to the bursting pressure of the freezing water. So far a quantitative investigation of these structural loadings within the texture of the sandstone has only been carried out rudimentarily. In particular the level of the arising stresses and the stress cycles require a quantitative analysis, in order to be able to reproduce the deterioration potential during the frost loading by means of a model.

For this purpose a two-dimensional structural model that takes the structural data of the real sandstone (porosity, grain size distribution) into account was generated and tested. Primary target of the nu-





Stress magnitude on various levels of the specimen can be determined by means of numerical analysis on the continuum model (the variation of stress on the stone surface is exemplarily shown for a period of one month)



Seasonal tensile stresses presented as stress collectives (the results of the thermal stresses at the stone surface over a period of one year; exemplarily)

Figure 8. Presentation of exemplary test results on the continuum model.

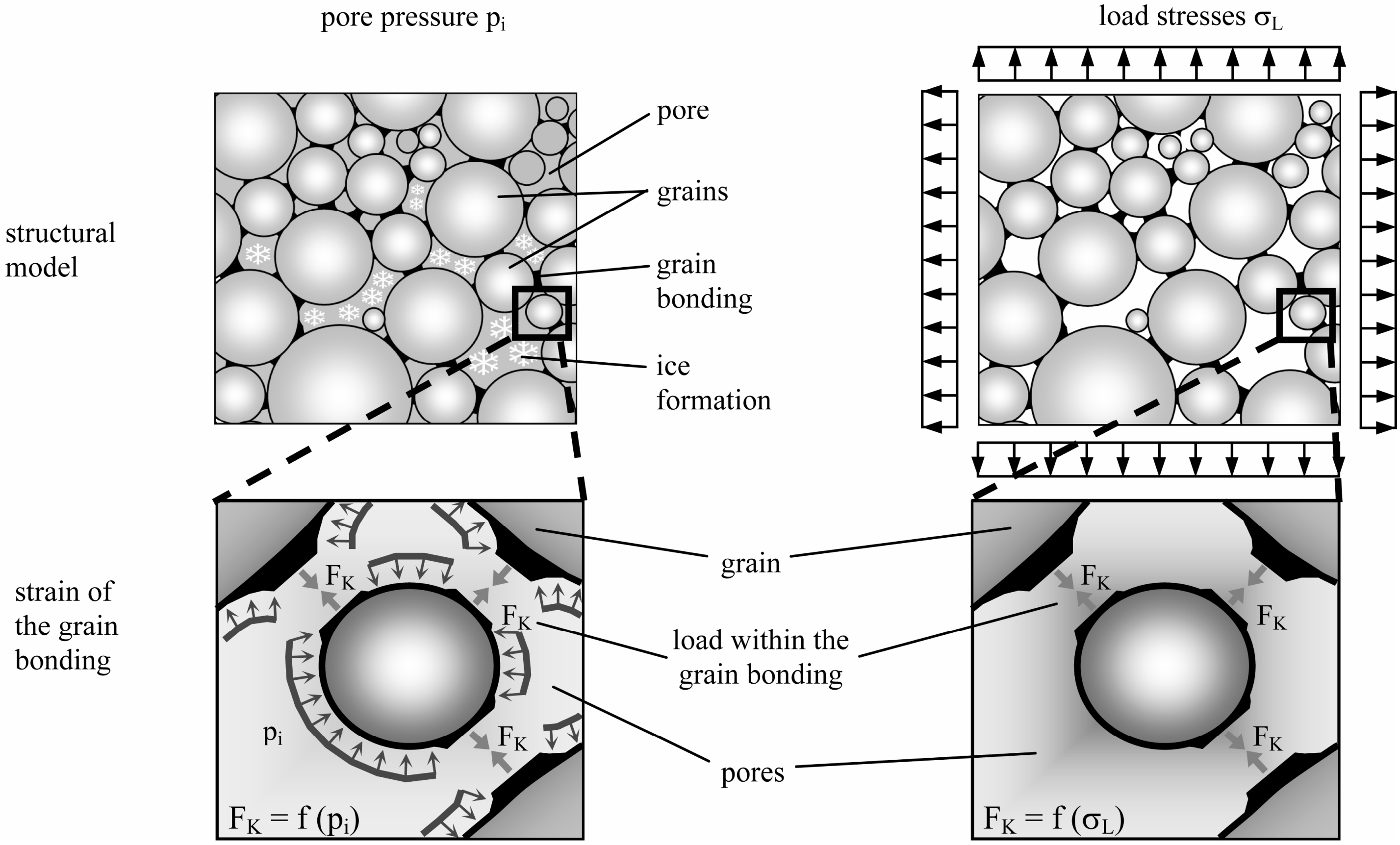


Figure 9. Exposure of the structural model to the effect of pore pressure due to ice formation (left) and load stresses (right).

merical analysis was a quantitative evaluation of external dummy loads (load stresses). The stress condition due to these external loads has to be equal with the bursting effect due to icing in the pores (see Fig. 9)

One of the applied finite element meshes which are randomly generated corresponding to the total porosity and the grain size distribution is exemplarily shown in Figure 10. The variation of the material properties is included via a statistical distribution of characteristic values (tensile strength, fracture energy) for each single element. In order to be able to reproduce a realistic crack development the cohesive crack model is applied for the material behaviour of the grain matrix and implemented in the numerical model respectively. In order to simulate the bursting pressure due to the formation of ice, the pores within the numerical model are filled with an adequate material. This material has equal mechanical properties as ice and reproduces the volumetric expansion during icing by an adequate temperature-strain curve. Thereby also the degree of pore saturation is considered as a major influence.

By means of the described model it is possible to analyse structural stresses as well as crack development due to icing. The effective grain bonding forces can be determined via an integral examination of the stresses within the grain bondings (Fig. 10, right).

According to the principle idea for the development of the prediction model, the structural stresses due to the formation of ice are transformed into load induced stresses. Their cyclic deterioration effect is to be described on the basis of fatigue laws. However the performed calculations indicated that the transformation of the computed structural stresses

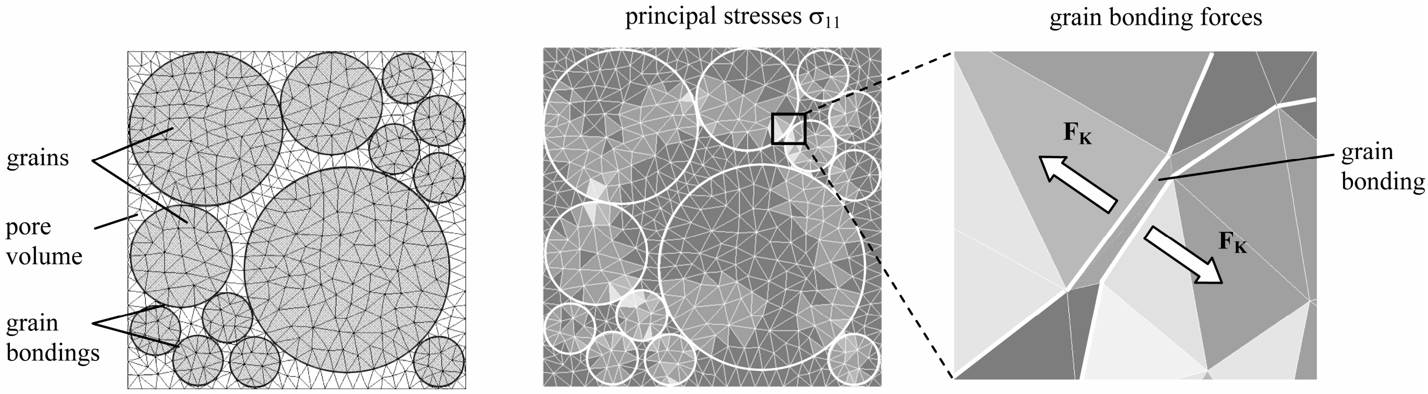


Figure 10. Randomly generated structural model depending on porosity and grain size distribution of the real sandstone (left) and exemplary presentation of computation results of grain bonding forces (right).

into external load induced stresses is more extensive than estimated. The approach using grain bonding forces seems to be feasible but requires high efforts. Therefore the investigations concerning the possibility of transformation are not yet accomplished and continue at the present time.

4 ONGOING RESEARCH AND OUTLOOK

The exemplarily shown calculation results of the previous chapter still have to be completed with regard to the total bandwidth of the seasonally prevalent climatic conditions. In this context, not only the maximum occurring stresses but also and more important, the capture of the stress changes, number and duration of the single stress amounts have to be surveyed. This is necessary to be finally able to acquire the mechanical fatigue load – i.e. the actual reason for the crack initiation, respectively decompression, even caused by stresses far below the short-term strength – occurring on the edge zone during a long period of time.

The conversion of the structural stresses into load-induced stresses takes place according to the principle that stresses acting in the internal profiles are attached as external loads by taking equilibrium conditions into account. In an integral consideration this is equivalent to external loads producing the same stresses as the self-equilibrating stress condition. In this context, fundamental considerations have to be taken into account as far as depth-dependent stresses and the corresponding load distributions – in particular due to frost actions –, respectively, are concerned.

Permanently changing climate conditions cause variable structural stresses. Upon completion of the simulation calculations, all the calculated stresses (due to thermal, hygral and frost actions) have to be summarized in classes like incidence, frequency, medium stress amount and amplitude via the established mathematical methods.

Finally bursting pressures during ice forming and their transformation into load-induced stresses have to be investigated. These stresses then must be superimposed to the frequency distribution of the single stress amounts. Using the stochastically generated structural model (meso level), which is capable of representing grains, grain bondings and structural pores, it is also possible to transform the internal disruption forces between grains due to the ice formation into load induced stresses. On the basis of the hypothesis that the thermal and hygral induced weathering takes place in a first approximation as a mechanical fatigue process, the formulation of a life time prediction model may be derived in conjunction with a damage accumulation hypothesis like e.g. the Palmgren-Miner rule. On the basis of already existing experimental results on the durability of sandstones the parameters of the weathering model of sandstone can finally be calibrated.

5 SUMMARY AND CONCLUSIONS

The physically dependent sandstone weathering is investigated within the framework of this research project. The target is to describe the time development of the stone weathering process depending on climatic parameters and material properties, finally ending up in a lifetime prediction model. For this purpose the loads resulting from continuously changing climatical conditions have to be compared with the fatigue behaviour of the sandstone material.

The time-dependent prediction of deteriorations, respectively the possibly remaining useful life expectancy of a building, is of very large economic importance for the scheduling of repair works. In case of a well-timed implementation of appropriate precautionary measures, the repair costs can be kept to a minimum. By creating an almost realistic forecast model for the time-dependent physical deterioration process of sandstone it will be possible to set up an evaluation of the “lifetime” of the most commonly used natural stones in Central Europe. Also it has to be taken into account that due to such a model the considerable consequential costs of an existing building can be estimated.

ACKNOWLEDGMENT

The work described in the present paper was part of the DFG Priority Programme SPP 1122 – “Vorhersage des zeitlichen Verlaufs von physikalisch-technischen Schädigungsprozessen an mineralischen Werkstoffen“. The financial support from the German Research Foundation is gratefully acknowledged.

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