Formation and propagation of cracks in cement-based repair systems induced by drying shrinkage

I. Burkart [*)], V. Mechtcherine [**)] & H. S. Müller [*)]

[*)] *University of Karlsruhe (TH), Karlsruhe, Germany*

[**)] *Technical University of Kaiserslautern, Kaiserslautern, Germany*

ABSTRACT: A numerical analysis of stresses and deformations in cement-based repair systems due to transient moisture gradients was performed. The main parameters of this investigation were the Young`s modulus, the tensile strength, the fracture energy and the thickness of the repair overlay, the moisture content of the structural member to be repaired as well as the fracture mechanical properties of the interface between the repair overlay and the substrate. The calculated results showed a good agreement with experimental results published so far and practical experiences, and could therefore be used for the evaluation of valid German guidelines concerning the design and the implementation of repair measures.

Keywords: repair system, drying shrinkage, cracking, fracture mechanics, numerical analysis.

1 INTRODUCTION

Concrete can generally be considered as a very durable building material. However, for different reasons a considerable percentage of concrete structures show severe damages long before the expiration of the expected service life.

In many cases a repair by applying a mortar or concrete layer becomes necessary, creating as a result a structural composite element. However, due to dissimilarities in the material behavior of the substrate and the repair overlay often new damages such as crack formation and delamination of the repair overlay occur, typically caused by drying shrinkage of the repair overlay. Therefore, every damaged construction requires a repair measure, which takes into account accurately the physical and mechanical properties of the substrate as well as the acting loadings including the stress and deformation behavior resulting from hygral loadings.

The regulations in the recent German guidelines referring to the design and the implementation of repair measures (DAfStb, 2001) are mainly based on observations from experimental investigations and experiences in the practice of construction, respectively. Since structural composite elements consisting of the concrete substrate and the repair layer show a complex, nonlinear stress- and deformation behavior a numerical analysis is indispensable for a better understanding of the damage mechanisms and for a technical and economical optimization of the repair measures.

Using the Finite Element Method a comprehensive analysis of the transient moisture transport as well as of the corresponding development of local stresses, their reduction due to the creep of concrete or mortar, and finally the formation and propagation of cracks is possible.

Up to now only a few research projects have dealt with the stress and deformation behavior of repair systems subjected to desiccation, while adequately considering transient moisture distributions as well as local shrinkage and creep of concrete.

Wittmann and Mueller (1993) showed that the discrete crack model of Hillerborg et al. (1976) can be applied for the analysis of the fracture mechanical behavior of the interface between repair overlay and substrate.

On the basis of their work and the preliminary work of Alvaredo (1994), Martinola (2001) developed a close-to-reality model of a repair system and showed within a parameter study the conditions for crack formation in such a system.

Within the presented study of the authors the stress and deformation behavior of common repair systems was investigated in detail following up the investigations of Martinola and own preparatory work (Huenerbein 2000). The main issue of this research project was the investigation of the influence of the material parameters and the geometrical boundary conditions on both formation and propagation of cracks (number of cracks, crack width and depth).

Based on the obtained results, the valid German guidelines referring to the design and implementation of repair systems could be discussed.

2 MODEL USED IN THE ANALYSIS

2.1 *Model geometry and calculation procedure*

In the described investigations a concrete slab with a width of 900 mm and a height of 150 mm, repaired by a 30 mm thick mortar overlay, was chosen. Figure 1 schematically shows the 2D FE mesh used for the spatial discretization of the slab as well as the defined boundary conditions. An exchange of moisture between the repair system and the environment was restricted exclusively to the topside of the repair overlay. Due to symmetry of both the system geometry and the boundary conditions, the analyses were performed on one half of the considered system. The substrate and the repair overlay were discreticized by eight-node quadrilateral isoparametric elements. The numerical solution is based on a quadratic interpolation and a Gaussian integration (DIANA 1999).

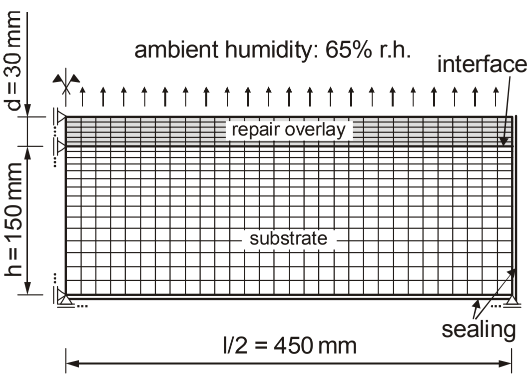

Figure 1. Spatial discretization of the repair system and the chosen boundary conditions

As high hygral gradients and therewith high stresses and crack formation could be expected not only in the repair overlay but also at the top side of the substrate the FE mesh of the substrate was refined from the bottom side to the top. A uniform transition from 15×15 mm^2 square elements to 15×5 mm^2 rectangular elements was chosen.

The interface between the substrate and the repair overlay was modeled by linear 6-node interface elements. The moisture exchange between the repair system and the ambient air was simulated by means of 2-node boundary elements, which were placed along the top side of the repair overlay.

The numerical analysis of the stresses and deformations in the presented repair system subjected to desiccation included three separate calculations. First, the place and time dependent moisture distribution was determined by means of a potential flow analysis. In the following linear and nonlinear stress analysis the data saved in the potential flow analysis were used to calculate the stresses and deformations resulting from transient moisture gradients.

2.2 *Applied material laws*

For a realistic description of the moisture transport in cement-based materials the nonlinear diffusion theory has been proved to be adequate. The temporal change of the moisture transport is defined by the following nonlinear partial differential Equation 1:

$$\frac{\partial \Phi}{\partial t} = div\left[D(\Phi) \cdot grad(\Phi)\right] \qquad (1)$$

where Φ = moisture potential, $D(\Phi)$ = moisture dependent diffusion coefficient, t = time. The chosen initial moisture distribution in the bonded system describes the initial condition for the solution of the differential equation.

Equation 2 defines the moisture exchange between the topside of the repair overlay and the ambient air:

$$q_n = H_F(\Phi_O - \Phi_A) \qquad (2)$$

where q_n = moisture flow perpendicular to the topside of the structure, H_F = the moisture transition coefficient, Φ_O-Φ_A = the difference between the moisture potential on the topside of the repair overlay and the that of the ambient air.

In addition to the moisture loss of the repair system due to desiccation, the chemical reaction of cement and water results in a further reduction of the moisture potential. However, for the given composition of the repair mortar, the effect of this autogenous shrinkage could be neglected.

The moisture transport through the repair system results in moisture gradients, leading to hygral deformations. Specifying unrestrained strains the relation of the shrinkage (or swelling) deformations $\Delta\varepsilon_{sh}$ to the moisture change $\Delta\Phi$ can be described by the following Equation 3:

$$\Delta\varepsilon_{sh} = \alpha_h \cdot \Delta\Phi \qquad (3)$$

where α = the hygral expansion coefficient.

However, due to the principle of a plane cross-section free shrinkage deformations are not possible and eigenstresses $\Delta\sigma$ according to Equation 4 develop:

$$\Delta\sigma = E \cdot \alpha_h \cdot \Delta\Phi \qquad (4)$$

where E = the Young`s modulus.

Since the moisture redistribution and the development of tensile stresses due to shrinkage is a process, which continues over years the creep behavior of the repair mortar and the concrete had to be taken into account, respectively. In the presented analysis the creep function from the CEB-FIB Model Code 1990 (1993) was applied. Some fundamentals of this local approach considering shrinkage deformation have been presented elsewhere (Mueller 1999).

The fracture mechanical behavior of the repair system was described by two different cohesion crack models.

In the repair overlay as well as in the substrate the crack location and the direction of crack propagation are unknown at the beginning of the analysis. For this reason the fracture mechanical behavior of these two components was described using the smeared crack approach, namely the Crack Band Model (Bazant & Oh 1983), see Fig. 2.

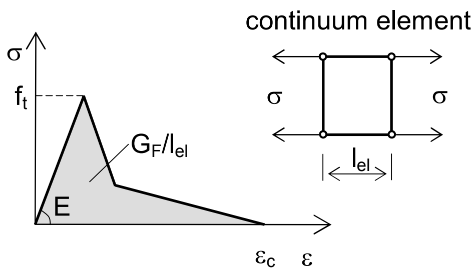

Figure 2. Crack Band Model for the fracture behavior of the repair mortar and the substrate concrete in tension

The stress-strain behavior of the undamaged concrete was described by a linear σ-ε relation defined by the tensile strength f_t and the Young's modulus E. The tension softening after the crack initiation was described by a bilinear descending branch. The area below the entire stress-strain relation corresponds to the fracture energy G_F divided by the characteristic element width l_{el}.

In order to prevent an instantaneous crack formation in all finite elements near the surface of the repair overlay as a result of equal stresses due to identical moisture gradients, concrete heterogeneity was explicitly considered by defining the input tensile strength of mortar to be a random variable following a Gaussian distribution. The elements were subdivided into 9 groups according to their tensile strength. To each group its own material law was assigned (Fig. 3). Details of this approach may be found in Mechtcherine (2000).

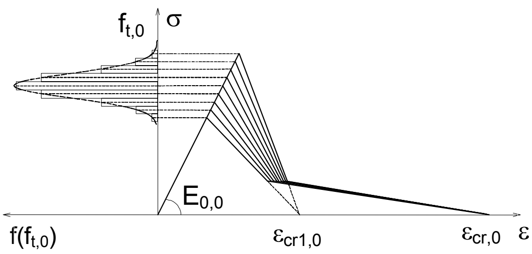

Figure 3. Variation of the material laws assigned to the finite elements representing the repair mortar and the substrate concrete

In the case of a delamination of the repair overlay the direction of crack propagation is exactly determined: The crack develops along the interface between the repair overlay and the substrate. Therefore, the fracture mechanical behavior of the interface was described using the Fictitious Crack Model by Hillerborg et al. (1976), which is particularly suitable for the simulation of the formation of discrete cracks (Fig. 4).

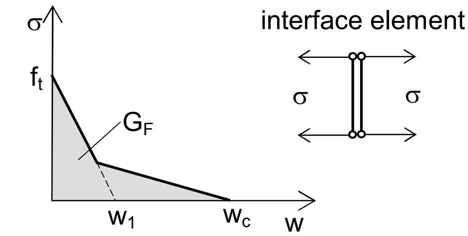

Figure 4. Fictitious Crack Model for the fracture behavior of the interface between the mortar and the substrate

As soon as the stress exceeds the tensile strength f_t, a fictitious crack develops. The softening behavior is described by a bilinear stress-crack opening relation. The area below the entire σ-w curve corresponds to the fracture energy G_F.

The numerical implementation of the described model was realized in the frame of the FE program DIANA (1999).

2.3 *Description of the reference cases*

At first the calculated results of the two reference cases with different initial moisture distributions in the substrate will be presented. The applied material properties are given in Section 2.4.

In the first case the substrate as well as the repair overlay were considered “water-saturated” at the beginning of the analysis.

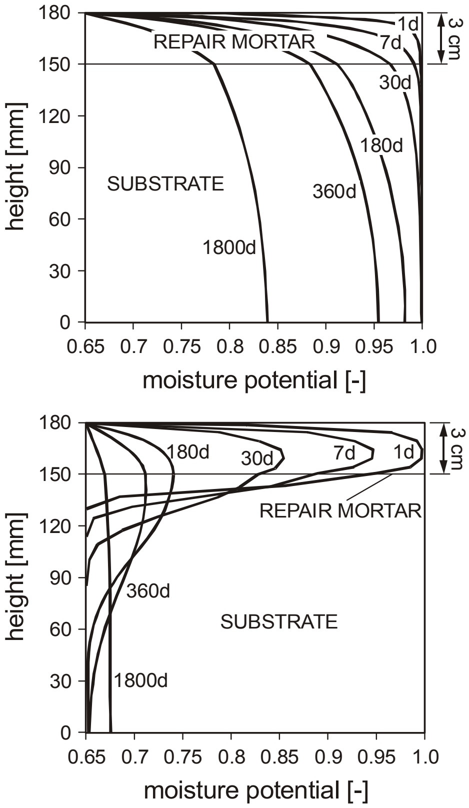

Figure 5. Moisture distributions after 1, 7, 30, 180, 360 and 1800 days of desiccation in the analysis with initially “water-saturated” (above) and “dry” substrate (below), respectively

The development of the moisture distributions in time over the cross section after 1, 7, 30, 180, 360 and 1800 days of drying are shown in Figure 5 (above). Since the drying of the repair system occurred exclusively over the topside of the repair overlay, high moisture gradients developed at this location decreasing with increasing distance from the topside of the repair overlay.

The second reference case simulated the application of a water-saturated repair overlay on an initially “dry” substrate (65 % r.h.), which was wetted at the surface shortly before the placement of the repair overlay. The water absorption was considered by a linear increase of the relative humidity from 65 to 100 % within two element rows on the topside of the substrate.

At its topside the repair overlay desiccated by moisture transfer into the ambient air and at its bottom side by moisture transfer into the “dry” substrate (Fig. 5, below).

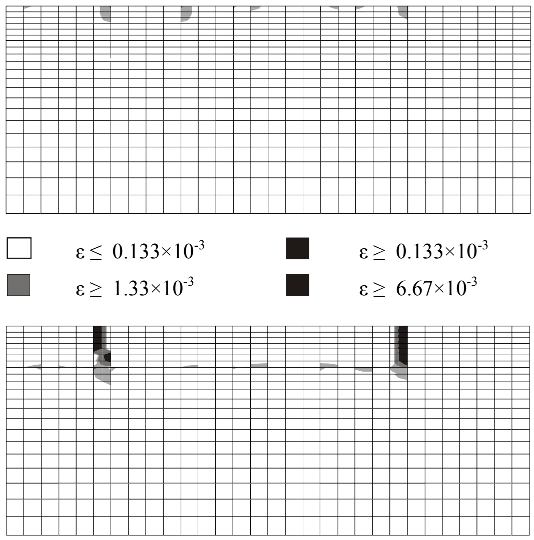

Figure 6. Strain distributions 30 days after the beginning of drying: Analyses with saturated (above) and dry substrate (below)

The analysis of both reference cases confirmed that the drying of the repair system is a long time process. Even after a period of 5 years no equilibrium was reached between the moisture potential of the repair overlay, the substrate and the ambient air.

The degree of damage in the repair system can be illustrated by means of the strain distributions calculated 30 days after the beginning of drying (Fig. 6). Those elements, which strains exceed the average ultimate elastic strain $\varepsilon = 0.133 \times 10^{-3}$ are marked in grey. The strains $\varepsilon = 1.33 \times 10^{-3}$ and $\varepsilon = 6.67 \times 10^{-3}$ correspond to the crack widths w = 0.01 and w = 0.05 mm, respectively.

At the beginning of the analysis with the dry substrate a multitude of cracks with a depth up to 10 mm developed at the topside of the repair overlay. However, afterwards two main cracks formed and grew continuously into the depth of the repair overlay. After 30 days both main cracks penetrated the entire repair overlay (Fig. 6, below). At the end of the analysis, after 5 years of drying, a maximum crack width of 0.155 mm and a maximum crack depth of 50 mm were reached, which means that the cracks also developed into the substrate.

The comparison of these results with the corresponding results obtained for the reference case with a water-saturated substrate (Fig. 6, above) shows, that the crack formation can be significantly reduced by an initial water-saturation of the substrate. First, similar to the analysis with a dry substrate initially a multitude of fine cracks emerged along the topside of the repair overlay. After 7 days three main cracks developed. However, the maximum calculated crack depths varied from 10 to 15 mm and the maximum crack width was merely 0.022 mm.

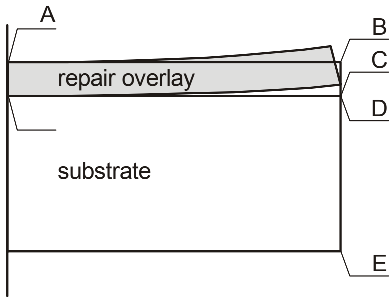

Figure 7. Geometrical points considered in the calculation of the average deformations of the repair overlay and the substrate

The average shrinkage deformations of the repair overlay and the substrate provided further information about the deformation behavior of the considered repair system. They were calculated as the arithmetic mean of the horizontal displacements of the nodal points B and C or D and E, respectively in relation to point A (Fig. 7). Figure 8 shows the results of these calculations for the two reference cases. Due to the complex deformation behavior of the repair system resulting from shrinkage deformations of the repair overlay, which are restrained by the substrate, the presented curves only serve for a comparison of the development of shrinkage deformations in time for different moisture conditions of the substrate.

In the reference case with a saturated substrate (Fig. 8, above) the average shrinkage deformations increased steadily during the entire simulation. In contrast to that the temporal development of the shrinkage deformations in the analysis with a dry substrate was characterized by two sudden decreases of the shrinkage deformations (Fig. 8, below). These discontinuities (the second is hardly noticeable due to the scale of figure 8) resulted from the relaxation of the repair overlay due to the formation of the two main cracks. Afterwards the shrinkage deformations increased continuously. The absorption of moisture by the substrate led to swelling deformations of the substrate, especially at its topside.

As the adhesive strength of the interface was defined higher than the tensile strength of the adjacent substrate, all horizontal cracks, which indicated some kind of a delamination of the repair overlay, developed in the substrate. They mainly developed at the tips of the main cracks as well as at the free edge of the repair system approx. 10 mm below the interface.

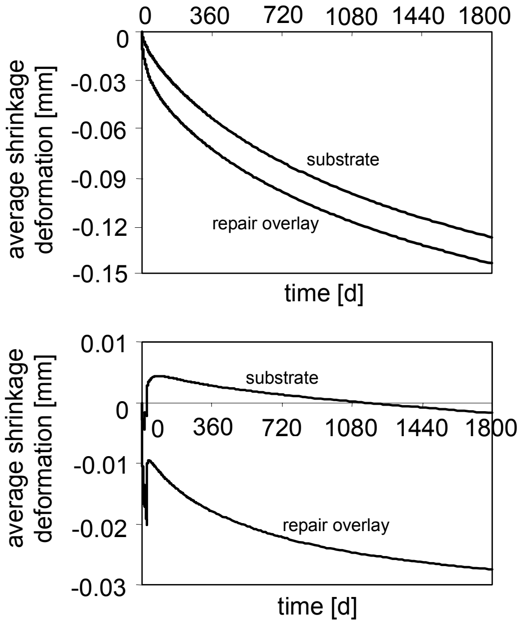

Figure 8. Development of the average shrinkage deformations of the repair overlay and the substrate: Analyses with saturated (above) and dry substrate (below)

2.4 *Overall view of the parameter study*

Practical experiences show, that the damages of repair systems due to cracking decisively depend on the mechanical and geometrical properties of the repair overlay as well as on the moisture content of the substrate. Furthermore, the fracture mechanical properties of the interface might have a crucial influence on the delamination behavior of the repair overlay.

On the basis of the reference cases with different initial moisture condition of the substrate a parameter study was performed in order to quantify the effects of the individual material and geometrical characteristics. For the reference cases the material properties of the repair mortar were defined on the basis of the German guidelines (see bold numbers in Tables 1-2). In the analysis of the water saturated substrate the effect of the Young's modulus, the tensile strength, the fracture energy as well as the thickness of the repair overlay was investigated. In each analysis only one parameter was varied as specified in Table 1.

Table 1. Overview of the parameter study for the repair system with saturated substrate

Parameter	Variation of parameters	
Young's Modulus E [GPa]	**30**	15
Tensile strength f_t [MPa]	**4.0**	2.0
Fracture energy G_F [N/m]	**50**	25
Layer thickness d [mm]	**30**	60

Table 2. Overview of the parameter study for the repair system with dry substrate

Parameter	Parameter variation			
Young's modulus E [GPa]	**30**	22.5	15	
Tensile strength f_t [MPa]	**4.0**	3.0	2.0	
Fracture energy G_F of the mortar [N/mm]	**50**	25	100	1000
Layer thickness d [mm]	**30**	60		
Adhesive strength f_{tG} of the interface [MPa]	**2.5**	1.0	} Variation of both parameters in one analysis	
Fracture energy of the interface [N/m]	**90**	35		

Since in the case of a dry substrate a more pronounced cracking occurs, a more extensive parameter study was performed for this moisture condition (Table 2). In addition to the parameters varied in the analysis with the water-saturated substrate, the influence of the fracture mechanical properties of the interface were investigated. Here both the adherence strength and the fracture energy of the interface were varied simultaneously.

2.5 *Results of the parameter study*

2.5.1 *Effect of the tensile strength*

In order to study the effect of the tensile strength of the repair overlay on the crack formation in the repair system due to desiccation the f_t-value was varied from 4 MPa to 3 MPa and 2 MPa, respectively. Figure 9 shows the results of the analysis in terms of the maximum total crack widths of all main cracks as well as the maximum crack depth.

In the analysis with a dry substrate no effect of the tensile strength on the crack development could be observed. However, the simulations with a water-saturated substrate provided a less pronounced cracking for higher values of the tensile strength.

The crack widths and depths obtained from the analysis with an initially water-saturated substrate were smaller than those provided by the analysis with a dry substrate.

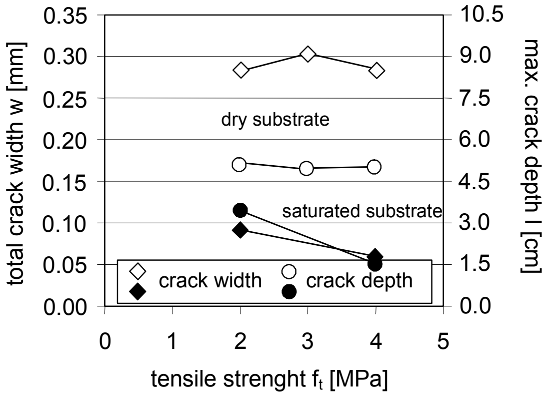

Figure 9. Effect of the tensile strength of the repair mortar on the max. crack depth and the total max. crack width

Therefore, the crack tendency can be considerably lowered by a higher initial water content of the substrate.

2.5.2 *Effect of the Young's modulus*

The Young's modulus of the repair overlay has a decisive influence on the stresses and deformations of a repair system subjected to drying.

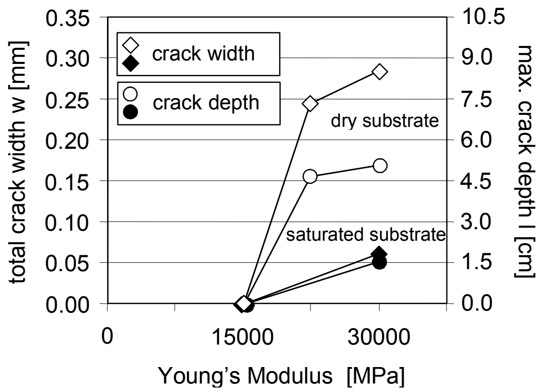

Figure 10. Effect of the Young's modulus of the mortar on the max. crack depth and the total max. crack width

In this parameter study the Young's modulus was varied from 30 GPa to 22.5 GPa and 15 GPa, respectively.

The results of the analysis with dry substrate (Fig. 10) showed a pronounced effect of the Young's modulus on the development of cracks in the repair layer. The ability of elastic deformation increases with a decreasing Young's modulus resulting in a lower crack tendency. For a Young's modulus of 15 GPa no cracks could be observed in the repair overlay.

Also in this series of calculations the cracking in the analyses with saturated substrates was less pronounced than in the case of dry substrate for the same variation of the material parameters.

2.5.3 *Effect of the fracture energy*

The fracture energy denotes the energy needed for the crack propagation in the material. Therefore, this material parameter has to exhibit a significant influence also on the cracking due to drying shrinkage.

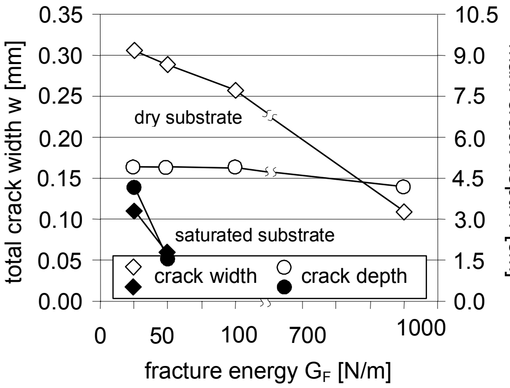

Figure 11. Effect of the fracture energy of the repair overlay on the max. crack depth and the total max. crack width

This expectation was clearly confirmed by the results of the calculations (Fig. 11). The crack width w increased significantly with a reduction of the fracture energy. However, the effect of the fracture energy on the crack depth was found to be less pronounced. Analogous to the results presented in the previous sections the crack development in the repair system with an initial water-saturation of the substrate was more moderate in comparison to that in the corresponding analysis with a dry substrate.

2.5.4 *Effect of the thickness of the repair overlay*

Besides the mechanical properties of the mortar the cracking behavior of the repair system depends on the thickness of the repair overlay.

The results of the analysis with two different thicknesses of 30 mm and 60 mm, respectively, for the case of a dry substrate are presented in Figure 12. As expected the crack depth increased with increasing proportion of shrinking material when a larger layer thickness was chosen. However, with increasing thickness of the repair overlay the drying process proceeds longer and the resulting stresses due to shrinkage deformations can be partly reduced by the creep of the repair mortar. For that reason, and because of the shifting of the drying front into the interior of the slab at the advanced period of desiccation, smaller maximum crack widths could be observed in the analysis with a layer thickness of 60 mm.

The crack tendency can be lowered by a higher initial water content of the substrate. Contrary to the analysis with a dry substrate the crack widths occurring in the analysis with a water-saturated substrate were unaffected by the layer thickness.

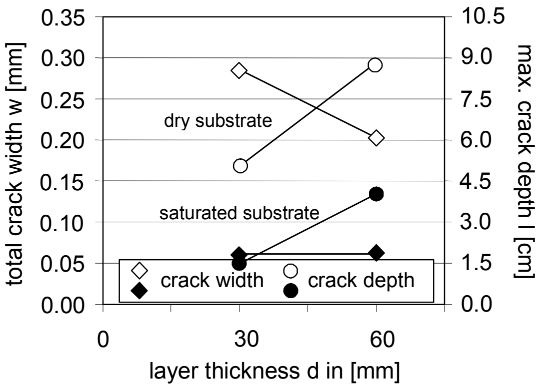

Figure 12. Effect of the thickness of the repair overlay on the max. crack depth and total max. crack width

2.5.5 *Effect of the fracture mechanical properties of the interface*

Contrary to the expectations even after a reduction of the fracture energy and the adhesive strength of the interface by the factor 2.5 (From 2.5 MPa to 1.0 MPa) no delamination of the repair overlay could be observed directly at the interface. The horizontal cracks occurred in the adjacent substrate about 10 to 12 mm below the interface at the right edge of the repair system as well in front of tips of the main cracks. An explanation might be the specific development of the moisture distributions in time. As the pretreatment of the substrate with water was considered by a linear increase of the moisture content in the two top element rows of the concrete slab, the transition zone from swelling to shrinking was shifted into the substrate. Due to a pronounced mutual obstruction of the developing swelling and shrinking deformations in this area horizontal cracks adjacent to the interface became possible.

The fracture mechanical properties of the interface had no effect on the formation and propagation of the vertical cracks in the repair overlay and into the concrete substrate.

3 SUMMARY AND CONCLUSIONS

In this research project the stress and deformation behavior of repair systems subjected to hygral loads was analyzed numerically. The following conclusions could be drawn:

- The formation and propagation of cracks in the repair layer can be considerably reduced by an increased initial water content of the substrate.
- In the case of a dry substrate, the delamination of the repair overlay occurred in the substrate adjacent to the interface, independent of the fracture mechanical properties of the interface. In the analyses with an initially saturated substrate no delamination could be observed.
- A reduction of the Young's modulus of the repair overlay generally reduces the cracking.
- A lower tensile strength of the repair mortar increases the risk of crack formation, as it was observed in the analyses with a saturated substrate. However, in the analyses with a dry substrate this phenomenon was probably covered by other effects, so that no obvious effect of the tensile strength on the cracking behavior could be observed.
- An increase of the fracture energy of the repair mortar results in smaller crack widths whereas the crack depths are almost unaffected by this material parameter.
- A larger thickness of the repair overlay leads to a prolongation of the drying process of the repair system. Therefore stresses induced by shrinkage deformations can be partly compensated by creep of the repair layer and the substrate concrete. As a result, in the case of a larger thickness of the overlay smaller crack widths could be observed, while the crack depth increased in comparison to the case of a smaller thickness.

The results of the performed analyses qualitatively confirmed the observations in the practice. Therefore, they could be used for an evaluation of the valid German guidelines.

The comparison of the results obtained from the analyses with saturated and dry substrate clearly confirmed the necessity of the prescription of the substrate pre-treatment with water as required in the guideline. However, the guideline may be revised concerning the optimization of the kind and duration of the pre-treatment.

In order to ensure an adequate carrying capacity of repair overlays for load bearing constructions, the Young's modulus of the repair overlay should be chosen according to that of the substrate. For minimizing the crack formation in repair overlays on non-load bearing constructions a reduced Young's modulus should be recommended.

Since with increasing thickness of the repair overlay the depth of cracks induced by shrinkage increases, the limitation of the thickness required in the guideline seems to be justified.

The presented research project showed that the used numerical approach is adequate for the analysis of the stress and deformation behavior of repair systems. However, the evaluation and improvement of the existing guidelines or the safe design of repair measures necessitates an extension of the performed parameter study and a refinement of the numerical model. Of particular interest is the analysis of further initial and boundary conditions as well as different geometrical and material parameters.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Alessandra Alvaredo for basic assistance concerning this research approach on repair systems and the help by the numerical implementation of the model.

4 REFERENCES

Alvaredo, A.M., 1994. PhD Thesis, Drying Shrinkage and Crack Formation. Eidgenössische Technische Hochschule (ETH) Zürich.

Bazant, Z.P., Oh, B.H., 1983. Crack Band Theory for Fracture of Concrete. Materials and Structures, Vol. 16, pp. 155-177.

CEB, 1993. CEB-FIB Model Code 1990, Bulletin 'Information, No. 213/214, Lausanne.

DAfStb (2001). Guidelines for Protection and Repair of concrete structures (Rili-SIB). Beuth Verlag, Berlin (in German).

DIANA (1999). Finite Element Analysis, User's Manuals release 7.2. TNO Building and Construction Research, Delft.

Hillerborg, A., Modéer, M., Petersson, P.-E., 1976. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research, Vol. 6, pp. 773-782.

Huenerbein, R., 2000. Stress and deformation behaviour of cement based repair systems. Student thesis, Institute for Concrete Structures and Building Materials, University of Karlsruhe (in German).

Martinola, G., 2001. Formation of cracks and delamination of cement based overlays on concrete. Building Materials Reports No. 12, AEDIFICATIO Verlag (in German).

Mechtcherine, V., 2000. Fracture mechanical and fractological investigations on crack development in concrete. Institute for Concrete Structures and Building Materials, Vol. 40, University of Karlsruhe (in German).

Mueller, H.S., 1999. Prediction of shrinkage deformations in concrete constructions. In R. Eligehausen (ed.), Construction Materials - Theory and Application -, ibidem Verlag Stuttgart, pp. 363-374 (in German).

Wittmann, F.H., Mueller, T., 1993. Adherence and Fracture Energy, Adherence of Young on Old Concrete. AEDIFICATIO Verlag, pp. 97-106.