OPTIMIZING CEMENT-BASED COATINGS WITH RESPECT TO SHRINKAGE CRACK FORMATION

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ABSTRACT

Cement based layers are frequently used for the repair of reinforced concrete structures nowadays. They may restore the protection of the reinforcement, after contamination and removal, against the penetration of aggressive substances. In this way the service life of the repaired structure can be improved. To provide protection and to prevent the transport of harmful substances inside the reinforced concrete structure these layers have to be free from cracks during the planned service life. Under usual conditions such layers are submitted to different actions like thermal, hygral and autogenous shrinkage or swelling. These processes create a complex state of eigenstresses inside the system layer-substrate. The tensile stresses can lead to the formation of cracks and delamination of the protective layer after several years. This paper suggests an approach for the optimization of repair systems. For this purpose a modern tool i.e. numerical model is used in order to determine the time dependent stress distribution and the crack formation due to different loads and boundary conditions. On this basis the requirements for a layer can be formulated ad hoc as a function of the probabilistic properties of each damaged building and the risk of failure can be minimized.

KEYWORDS

cement-based layer, repair system, protective coating, shrinkage, crack formation, fracture mechanics, delamination, durability, numerical model, optimization

1. INTRODUCTION

In a traditional reinforced concrete element concrete has to take over two totally different assignments [1]. First, concrete has to provide a structural element with the required strength and stiffness and it has to anchor the steel reinforcement. At the same time, the concrete cover has to prevent corrosion of the steel reinforcement. Whether this second non-mechanical assignment is really fulfilled is rarely checked. As a consequence and because of bad execution, many concrete structures have to be repaired after a relatively short service life. This is the reason for the increased of expenditures for maintenance and repair of buildings and structures.

In many cases, carbonation depth reaches the reinforcement and/or the chloride content in the neighborhood of the steel reinforcement reaches critical values too rapidly. In order to restore the initial state the contaminated covercrete is removed. The reinforcement is freed from corrosion products and finally the concrete surface is restored with a new layer. In order to assure mechanical reliability and a long-term durability of the repaired concrete structure, both the mechanical and non-mechanical assignments must be fulfilled. It is also possible to apply cement based protective coatings in order to protect new reinforced concrete structures. In this case the structural concrete assures the load bearing capacity and the coating takes over the protection of the reinforcement. To offer protection and to prevent the transport of harmful substances into the reinforced concrete structure these layers have to be free from cracks during the planned service life and show low permeability and low capillary suction.

Mistakes in design, selection of materials and execution lead to crack formation with a drastic reduction of the durability of the repaired structures. One basic problem is that engineers so far have no quantitative tools to evaluate if a proposed repair design is appropriate for a given situation.

The use of durable repair materials does not ensure the durability of the system substrate (old concrete) / overlay (repair material), because the effectiveness of a repair measure is also related to the dimensional compatibility between overlay and substrate.

Overlay and substrate are subjected to different external and/or internal loads. Under usual conditions such systems are submitted to different actions like thermal and hygral gradients and autogenous shrinkage or swelling. If the resulting deformations of both components are different restraining action will give rise of stresses and eigenstresses inside the system layer-substrate. Failure of the repair system will occur when the stresses due to restraint or the imposed deformations can not be absorbed by the system. In this case crack formation will appear. The capacity of the materials of the system to absorb restraining actions is contained in its elastic deformation, creep deformation and strain softening. The complex competition between loads and the material is illustrated in Fig. 1.

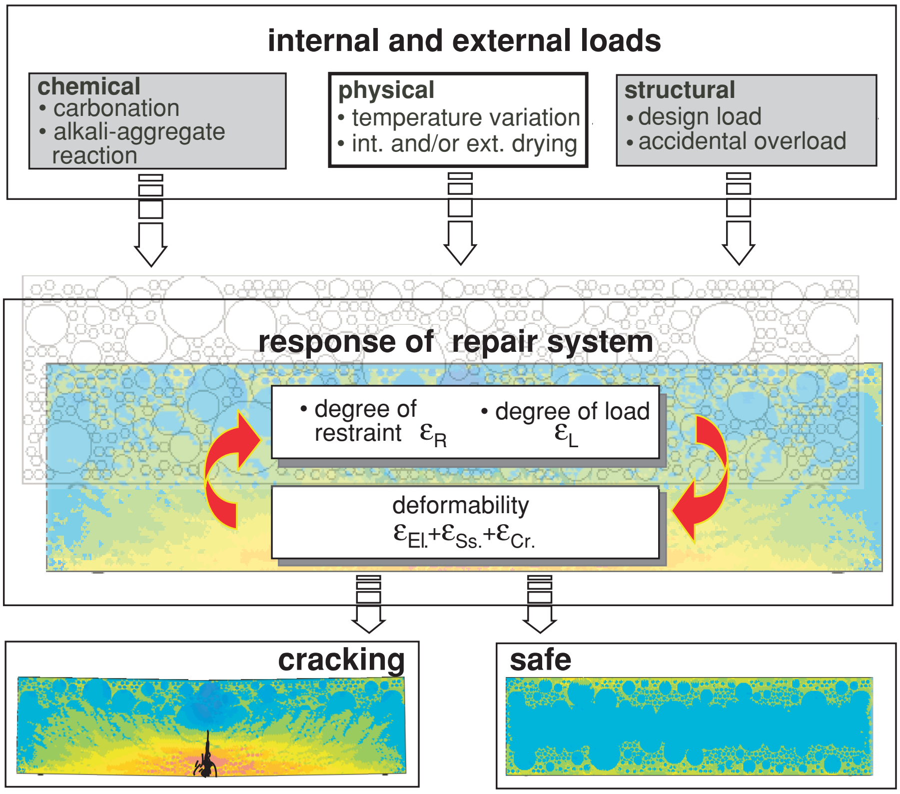

Figure 1: Analysis of the principal loads acting in a repair system and failure criteria. ε_{El}, $\varepsilon_{Ss.}$. and $\varepsilon_{Cr.}$ are the elastic, crack (strain softening) and creep strains respectively

A linear elastic stress analysis shows in Martinola [2] that, the most important factor influencing the state of restraint of the system is the hygral load and thermal load or a combination thereof. During drying or a rapid cooling tensile stresses until 20-25 MPa are induced in the system. Under these conditions practically every cement based material will be damaged. Usual structural loads can provoke failure of the system only in combination with physical loads. The chemical load can be avoided by the correct choice of the mix components of the overlay material and a detailed analysis of the environmental conditions.

A rigorous analysis based on the knowledge of material science (realistic constitutive laws) is an essential step in order to assess this problem. The effectiveness and the durability of concrete repair depend also of the environmental and mechanical boundary conditions. Such rigorous analysis can be carried out only with modern tools like FEM or BEM that are able to solve systems of non-linear differential equation.

The behavior of repair systems is investigated in this work with the Finite Element Method. A validated numerical model [3] that allows us to calculate crack formation and crack propagation in such systems under different kind of solicitations (mechanical, thermal and hygral load) is applied for a parametric study. The results of the sensitivity analysis are used to formulate criteria for crack prevention in such layers. This criteria can be used for the optimization of the properties of the layer and in this way provide solutions for the design of repair of concrete structures.

2. EXAMPLE FOR A DAMAGE MECHANISM: RESTRAINED CEMENT BASED COATINGS

A typical concrete repair system consisting of a superposition of an old concrete element and a new concrete or mortar repair layer is shown in Fig. 2. Initially, the new material layer is in a quasi saturated state. Generally the upper surface of the composite system is in contact with the environment. If the surrounding relative humidity is low, compared with the pore humidity of the material of the new layer, the system begins immediately to dry. Cracks can occur in the upper layer due to the hygral gradients generated during the drying process. Simultaneously, the entire new layer is subjected to a global volume change. Depending on the composition of the cement-based material used for the repair layer, the volume variation can be much larger at an early stage if the material is subjected to endogeneous drying. This volume variation is generally restrained by the old concrete element. It must be underlined, that the degree of restraint depends not only on the compatibility of the hygro-mechanical parameters of both materials but also on the actual moisture gradient between the two materials and on the thickness of the new layer. As a consequence of the restraint, normal tensile stresses σ_y and bond shear stresses τ_{xy} will be induced in the interfacial zone. Fig. 2b shows schematically the state of the stresses and the possible damage, i.e. cracking of the overlay and decohesion of the interface. If the stresses are higher than the bond cohesion, then delamination will occur (see for example photo in Fig. 2b).

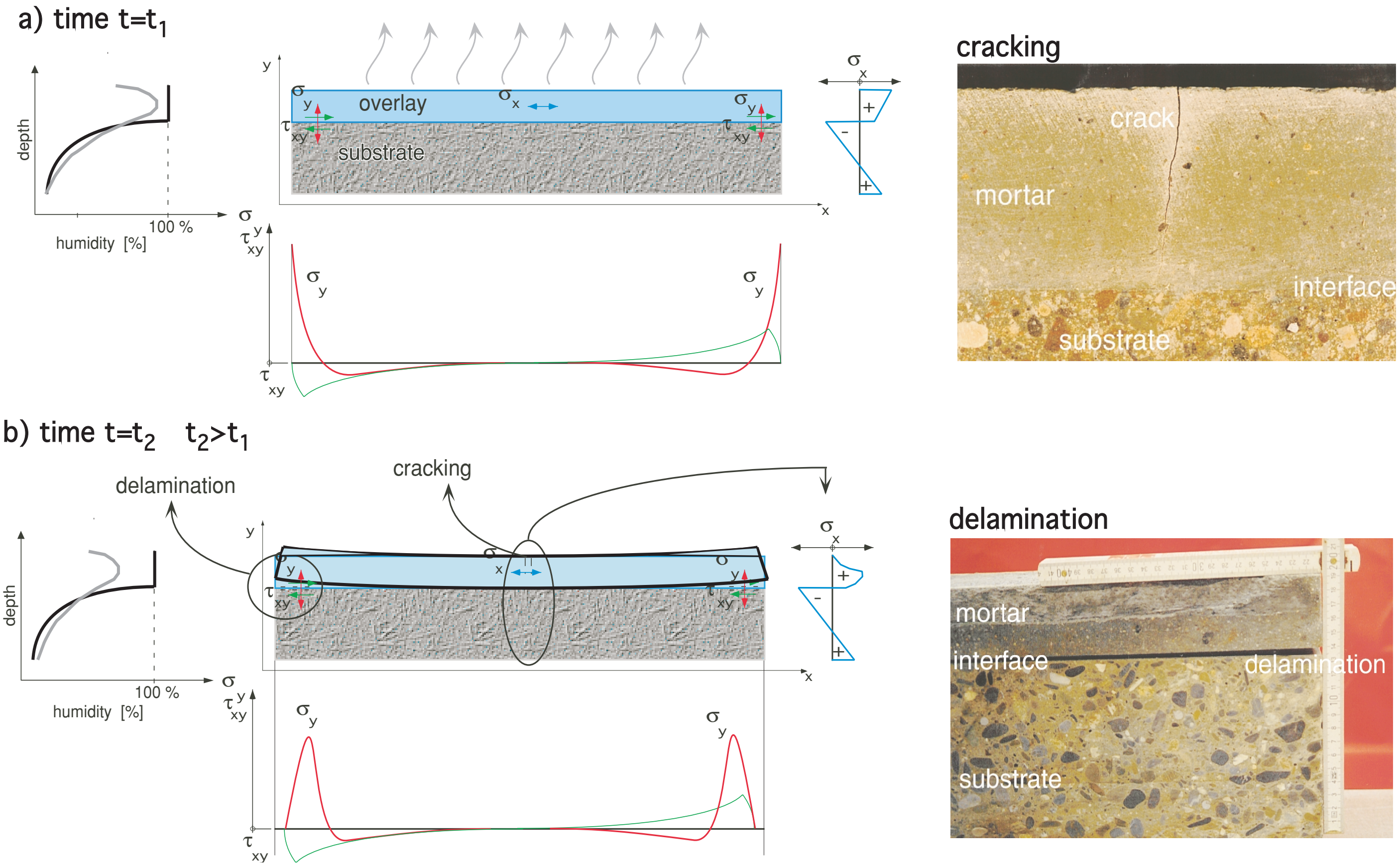

Figure 2: a) Schematic representation of a drying repair system and moisture distributions at different drying times b) Hygral-induced cracking and delamination and stress distributions

3. CRITERIA FOR MINIMIZING THE RISK OF SHRINKAGE CRACKING

Based on the reasonable agreement between the observed results obtained from different experiments performed on different materials and the numerical results, the proposed model has been used to carry out a parametric study [2]. The objective of this study is to identify the most relevant material parameters influencing shrinkage cracking and consequently to be able to decide which material parameter(s) must be optimized in order to reduce the risk of surface cracking as far as possible.

The results of this sensitivity analysis [2] showed that the shrinkage coefficient, the fracture energy and the Young‘s modulus are the most important parameters influencing cracking. It is of interest that tensile strength plays a minor role in the damage process.

By compiling the obtained numerical results, a diagram that shows the risk of crack formation as function of the above mentioned material parameters can be plotted as shown in Fig. 3a. In this figure, the z axis represents the mean value of the coefficient of shrinkage $\bar{\alpha}$. In many standard codes the shrinkage is defined by the strain measured on a specimen during drying from 100% to 65% or 50% R.H. According to the presented theory a corresponding value can be approximated by the following expression:

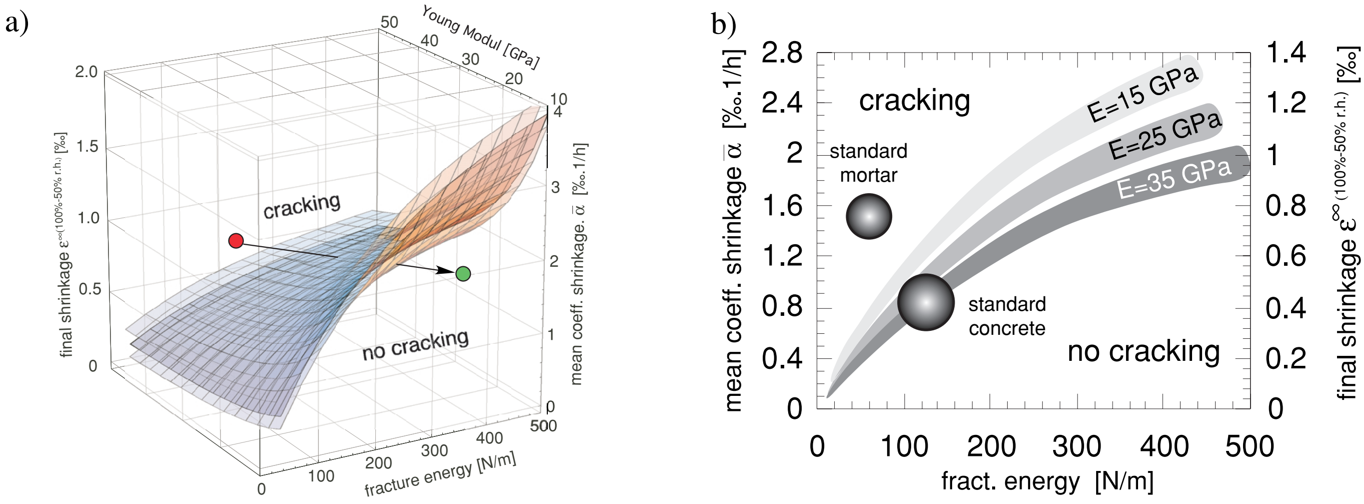

Figure 3: a) Surface separating conditions for cracking and no cracking of the repair layer as function of fracture energy, coeff. of shrinkage and Young´s modulus b) 2D representation of the risk of crack formation as function of fracture energy, coeff. of shrinkage and Young‘s modulus

$$\varepsilon_{meas}(100\%–65\%\ (50\%)) \cong \varepsilon(t \to \infty) = \bar{\alpha} \cdot (h_2 - h_1) \tag{1}$$

with ε ($t \to \infty$) being the final shrinkage strain measured when the test specimen, initially at 100% RH, reaches a hygral equilibrium with 50% RH. If the combination of material parameters of a given mortar are localized above the surfaces shows on Fig 3a they will crack during the drying process. Fig. 3b) shows a 2D contour plot of the plane fracture energy versus shrinkage obtained from Fig. 3a). In order to introduce a safety factor for the interpretation and the utilization of the diagram which covers the variation of the results, a transitional area between the cracking and the crack free zone is defined.

4. USE OF THE PROPOSED CRITERIA FOR THE OPTIMIZATION OF A CEMENT BASED COATING

Using this 2D representation a minimization of the risk of shrinkage cracking of a particular cement-based material can be achieved. For instance a mortar A exposed to an external relative humidity of 65%, with a Young´s modulus of E=40 GPa, a fracture energy G_f=105 N/m and a final shrinkage strain of 1 ‰ (see point „mortar A“ in Fig. 4a) will crack during the drying period, in the case of restrained mechanical boundary conditions. In order to avoid crack formation the properties of this mortar have to be changed. The mortar A has to be modified and moved from the critical zone (cracking) to the safe zone (no cracking). All combinations of the material parameters, that will lead to a shift of mortar A into the safe zone, are possible of course. For instance the mortar A may be modified by reducing the cement content and reducing the Young´s modulus to 14 GPa. In this way the shrinkage strain is reduced to 0.8 ‰ (see point „mortar B“ in Fig. 4a). A second possibility of optimization can be carried out by the addition of steel fibers. The mechanical behaviour of the mortar is completely changed. The fracture energy is increased to more then 500 N/m (see point „mortar C“ in Fig. 4a).

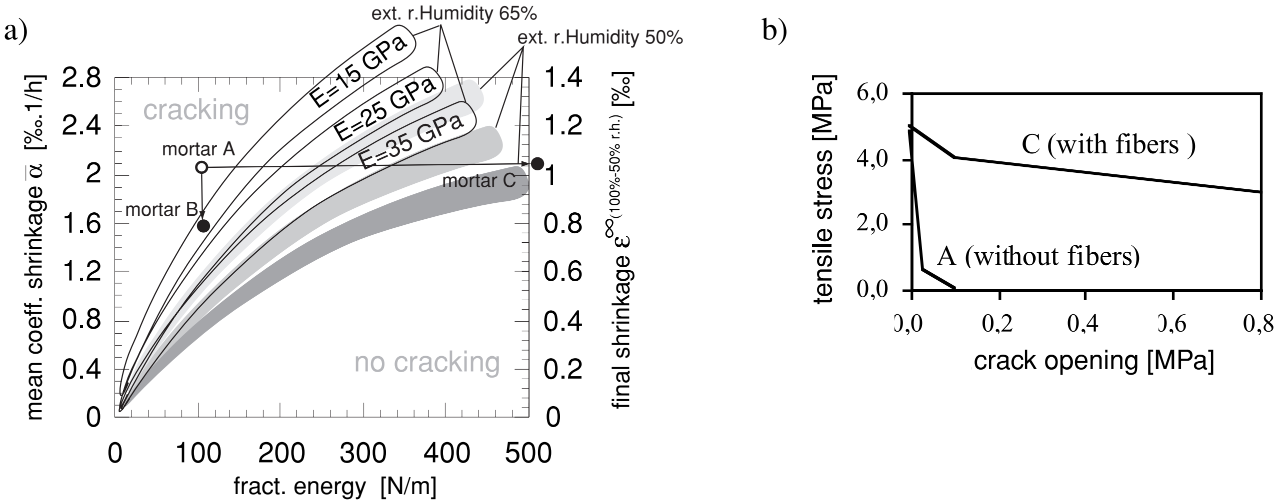

Figure 4: a)2D representation of the risk of crack formation for two different boundary conditions (ext. R.H of 50 and 65%) b) Mechanical behaviour of the mortar A and mortar C

In order to demonstrate the influence of the different combinations of material parameters with respect to crack formation under hygral variation, the numerical model is used to analyze these 3 different mortars when applied on the same substrate. The other relevant materials parameters of the repair mortars and of the old concrete which are needed in the numerical model have been held constant for the three analyses. In Fig. 5 results

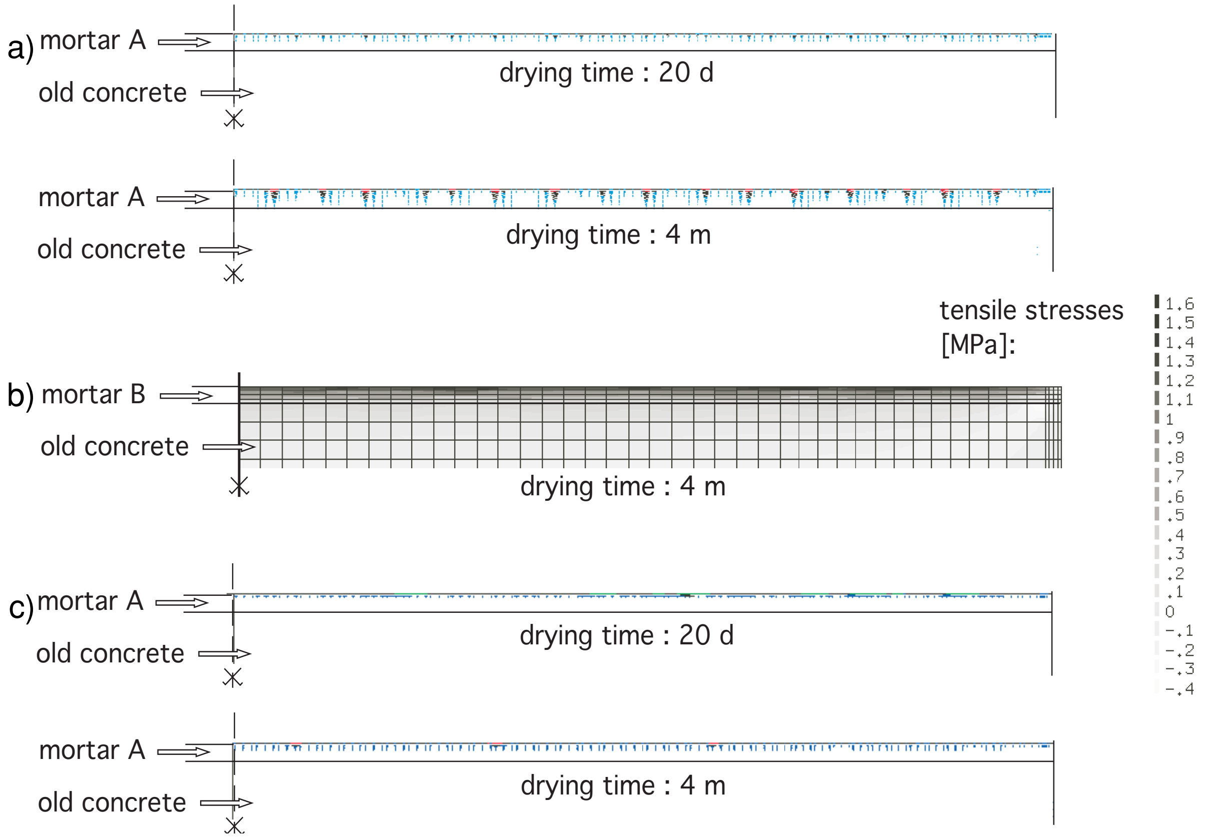

Figure 5: a) crack distribution for the repair system with the mortar A after 20 days and 4 months drying
b) stress distribution in the system with the mortar B after 4 months drying
c) crack distribution for the third repair system (mortar C) after 20 days and 4 months drying

are presented the of the hygro-mechanical analysis of the 3 repair systems are presented. As assumed the mortar A cracks under the imposed hygral load. After 20 days of drying many fracture process zones (FPZ) are activated near the surface of the mortar. As the drying proceeds, a limited number of FPZ becomes wider and wider and moves gradually towards the old concrete. Other process zones close due to stress redistribution. After an advanced drying time of 4 months, real cracks are developed in the outer layer of the overlay (see Fig 5a).

Fig. 5b shows the stress distributions in the global system (mortar B) after 4 months of drying. In this case, during the performed analysis, tensile stresses were always lower than the tensile strength. This means mortar B remains cracks free.

In the third analysis (mortar C) a lot of fracture process zones have been developed after a drying time of 20 days (see Fig. 5c) in the same way as in the case of mortar A, due to restrained shrinkage deformations. But after 4 months drying the situation is different as compared with mortar A. Due to the fact that steel fibers lead to a better distribution of the FPZ, most of those which have already been formed after 20 days of drying increased in depth and fictitious crack opening but none of them exceeded maximum fictitious crack opening. Therefore no real cracks have occurred in the mortar C. That means that the durability of the repair systems can be enhanced significantly by increasing fracture energy.

5. CONCLUSIONS

A numerical model based on realistic material laws has been developed. This model allows us to study damage evolution in new and repaired concrete structures subjected to different types of loading.

By applying the numerical model, a parametric study has been carried out. The results of this study allow us to define criteria for the risk of damage. The criteria can be use as a basis for optimizing cement-based materials in particular with respect to the prevention of shrinkage cracking and delamination.

The life-cycle of repaired structures can be considerably enhanced by an accurate design of the durability and a stringent quality control.

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