Fracture Mechanics of Concrete Structures
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APPLICATION OF FRACTURE MECHANICS TO OPTIMIZE REPAIR SYSTEMS AND PROTECTIVE COATINGS FOR REINFORCED CONCRETE STRUCTURES

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Abstract
First of all, the common technology of applying cement-based repair systems is briefly outlined. Then, the concept of separation of assignments of concrete in a reinforced concrete element is presented. Stress distributions in a drying cement-based coating are considered. Shrinkage stresses in the coating have to be balanced by fracture energy and strain softening of the material in order to avoid crack formation. Fracture mechanics parameters of the interface have to be high enough to avoid delamination. Repair systems and protective coatings can be otpimized with respect to rate of carbonation or capillary suction (chloride penetration) but also with respect to crack formation and delamination. This approach has been successfully applied to provide practical solutions.
Key words: Repair systems, protective coatings, reinforced concrete, separation of assignments, drying, shrinkage, delamination

1 Introduction

In a traditional reinforced concrete element concrete has to take over two totally different assignments. First, concrete has to provide a structural element with the required strength and stiffness. But next to the mechanical assignment concrete is to protect the steel reinforcement from corrosion. Whether this second non-mechanical assignment is really fulfilled is rarely checked. As a consequence, many concrete structures have to be repaired after a comparatively short service life.

In many cases, the carbonation depth reaches the reinforcement and/or the chloride content in the vicinity of the steel reinforcement reaches critical values. Usually in these cases, the contaminated concrete cover is removed mechanically or by high pressure water jetting. The reinforcement is freed from corrosion products and finally the concrete surface is restored. The new concrete cover is then supposed to protect the reinforcement for a sufficiently long period.

A new and more economical as well as ecological solution to this ardent durability problem is to protect the load bearing reinforced concrete structure with a cement-based coating. In this case, the two above mentioned assignments of concrete in a structural element are clearly separated. The structural concrete assures the load bearing capacity and mechanical reliability exclusively and the cement-based protective coating takes over the assignment for long-term durability.

Under theses conditions, the properties of the protective coating can be tailored according to specific requirements. The rate of carbonation and the resistance with respect to chloride penetration may be optimized for instance.

But, in any case, the repair layers and the protective coatings can fulfill their assignments only if excessive crack formation and before all delamination can be prevented. In this contribution, it is shown how non-linear fracture mechanics can be applied as to optimize cement-based protective layers for long-term durability. Hygral as well as thermal loads impose deformations on the coating which will be partly restrained. Under these conditions, strain softening of the cement-based mortar can be fully exploited.

2 Mechanics of cement-based coatings

An existing concrete structure may be covered by a cement-based mortar in the context of a repair measure or a cement-based protective layer may be particularly desigend for sufficient durability and service life of a new structure. In both cases, these thick coatings will be exposed to drying and temperature changes under usual conditions. The resulting shrinkage and thermal dilatation is at the origin of a complex and time-dependent state of stress. In this contribution, hygral stresses will be considered exclusively but it is evident that thermal stresses or a combination of hygral and thermal stresses can be treated in a analogous way.

After a certain duration of drying, the stresses in the combined system of substrate (old concrete) and overlay (new layer) can be schematically represented as shown in Fig. 1. Far from the endfaces, the shrinkage of the overlay is restraint by still humid deeper regions first and then by the substrate. Tensile stresses will occur in the x-direction of the shrinkage. If the shrinkage of the overlay is not balanced by sufficient deformability cracks will be generated in the cement-based coating. Close to the endfaces shrinkage stresses in the x-direction are released by deformation but stresses in the y-direction are built up. In addition, shrinkage in this region creates shear stresses (τ_{xy}). Under this combined state of stress delamination may occur. Once a crack through the overlay is formed far from the endfaces delamination may also occur there starting from the crack tip.

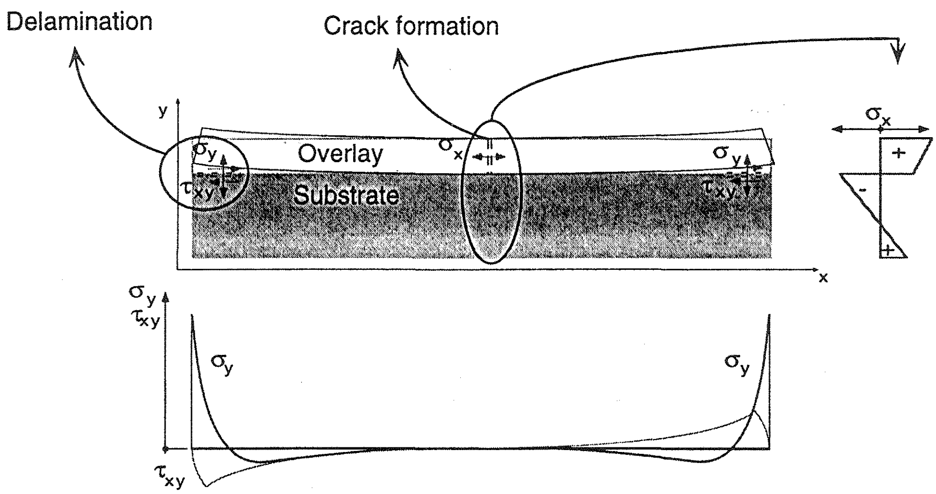

Fig. 1: Schematic representation of the complex state of stress in the combined system overlay and substrate after a certain period of drying

3 Criteria to be met for a balanced cement-based coating

In order to be able to design a reliable cement-based coating, the hygral and thermal load to be expected has to be known in the first place. In the case of a protective coating, the carbonation resistance and the chloride penetration resistance have to be taken into consideration in addition.

The hygral load is essentially given by the humidity of the environment of a structural element, the infinitesimal shrinkage, and the viscoelastic behaviour of the material (Wittmann 1993). It is a task of materials engineering to minimize the hygral load in a sytematic way. In this context, the reduction of shrinkage plays a dominant role.

In the next step, it must be checked if the coating is able to take over the time-dependent hygral load without crack formation and delamination. The requirements which have to be fulfilled can be formulated as follows:

a) the deformability of the material must be high enough in order to avoid cracking under the imposed hygral strain;

b) load and shear strength of the interface have to be high enough in order to prevent delamination.

In order to fulfill requirement (a) it is often necessary to add fibres to the coating material. Shear strength can be considerably increased by roughening the surface of the substrate. Bond strength depends both on the porosity and moisture content of the substrate during the application and the composition of the coating material.

In many cases, the thermal and hygral loads can be balanced by a cement-based coating only if the fracture energy is high enough and strain softening can be fully activated. Strength of the material is not a useful parameter to predict crack formation in this context. In Fig. 2, the required material behaviour is shown schematically. In this case, it is assumed that the material reacts linear and elastic until the tensile strength is reached. Then a fictitious crack is being formed. In the damaged zone of the fictitious crack the load bearing capacity decreases gradually. This specific material behaviour can be simulated realistically by means of non-linear fracture mechanics. This approach enables us to design and develop safe and balanced cement-based coatings, Martinola and Wittmann (1995) and Martinola et al. (1996). A simple ring test and a numerical simulation in parallel have proven to be very helpful in optimizing cement-based coatings, Martinola et al. (1997).

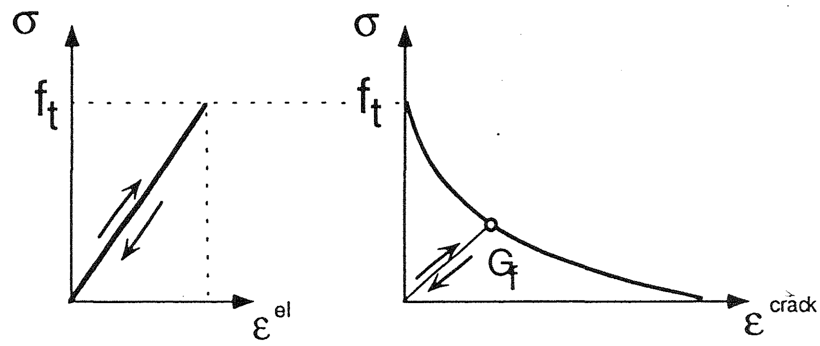

Fig. 2: Schematic representation of the behaviour of a material with strain softening

4 An Example

The potential of this approach shall be demonstrated by one arbitrarily chosen example. We will compare the cracking behaviour of two different types of mortar. Let us assume that a reinforced concrete structural element has been covered by a protective layer and it shall be exposed to an average relative humidity of 60%. The moisture dependent diffusion coefficients of the coating material and the concrete have to be known or determined, Alvaredo (1994). Then the time dependent moisture distribution in the drying system can be calculated. In Fig. 3, an example is shown. A protective layer having a thickness of 70 mm is applied on a concrete element. This type of mortar, called type A, has a fracture energy of 105 N/m, an elastic modulus of 40 GPa, and a tensile strength of 5 N/mm^2. In addition, shrinkage of mortar type A has been measured as function of relative humidity (or hygral potential). With these material parameters, the time-dependent stress distribution in the overlay can be calculated.

It can be seen from Fig. 4 that this protective layer A will have a fictitious crack close to the surface already after four days of drying. The stress in the outer 5 mm is decreased because of strain softening. The length of the ficititiouss crack increases with time and at a drying time of 123 days a real crack of approximately 20 mm length has already developed. This is indicated by the stress free zone.

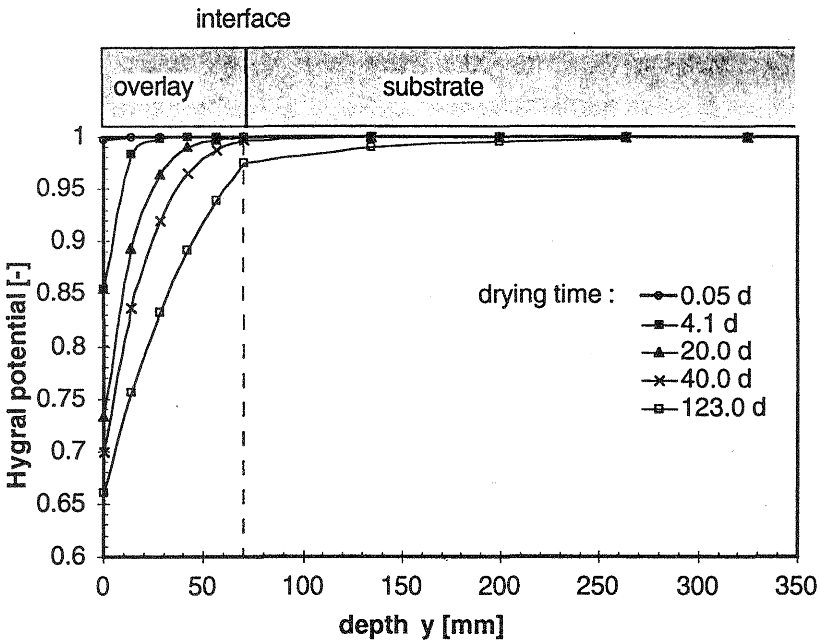

Fig. 3: Time-dependent moisture distribution in a concrete element (substrate) covered by a protective coating type A (overlay) expressed in terms of hygral potential as function of the distance from the surface

For comparison, another material called protectove coating type B has been investigated. The second protective layer is supposed to have a thickness of 60 mm. The fracture energy, the elastic modulus and the tensile strength of mortar type B have been determined to be 97 N/m, 14 GPa, and 3 N/mm^2, respectively. If we assume a structural element to be covered with this second type of mortar B and to be exposed to 60% relative humidity again the time-dependent stresses in the overlay can be calculated in the same way as just indicated in the case of mortar A. Results are shown in Fig. 5. In this case, the maximum stress never reaches the tensile strength of the protective coating and not even a fictitious crack is formed during the drying period under investigation. Delamination will not take place in both cases.

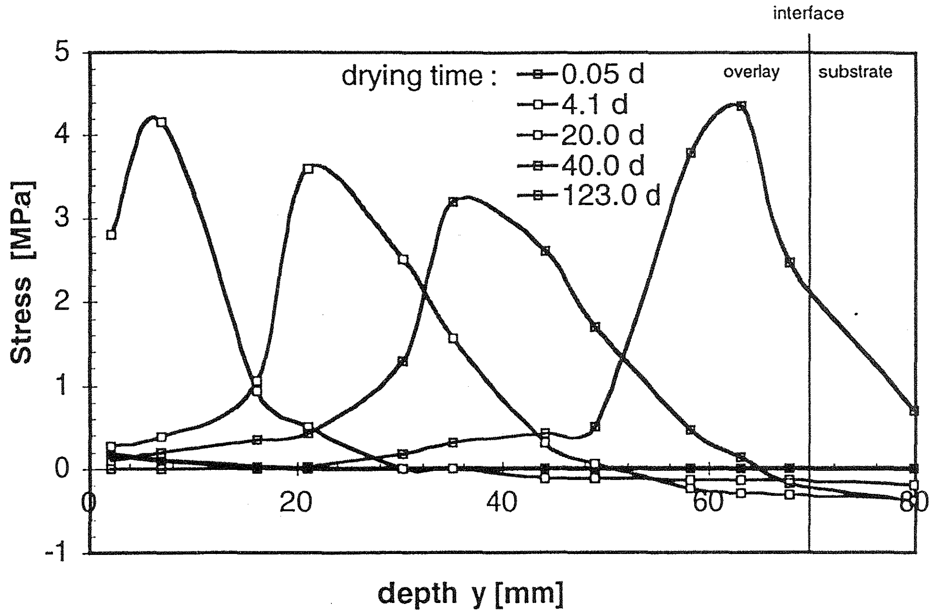

Fig. 4: Time-dependent stress distribution in the protective coating type A when exposed to an average moisture potential of 0.6

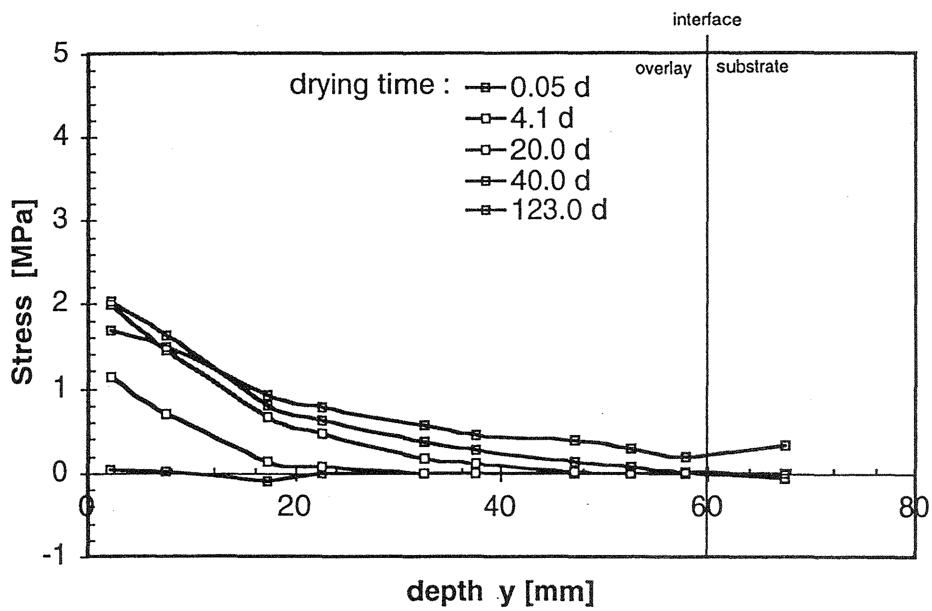

Fig. 5: Time-dependent stress distribution in the protective coating type B when exposed to an average moisture potential of 0.6

The method briefly described in this contribution allows us to predict crack formation and delamination in a system consisting of structural reinforced concrete covered with a protective cement-based coating. For given thermal and hygral loads, requirements for stable and balanced protective coatings can be formulated. This approach can at the same time be applied to design reliable coatings and to optimize material properties.

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