Influence of Freeze-Thaw Micro-Cracks on Tension Stiffening Material Parameters for Reinforced Concrete

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ABSTRACT: The presented research project aims to provide a basis, on which physical and chemical loads can be included in the design process of reinforced concrete structures by means of appropriate material models which include deterioration aspects. As an example for physical and chemical deterioration mechanisms, freeze-thaw cycle loads together with the absorption of capillary water have been chosen and analyzed.

In a first step, the variation of concrete elastic modulus and bond behavior due to the applied freeze-thaw cycles are monitored and analyzed. The results of this work are then implemented in a computational model developed at the University of Waterloo, Canada. The program generates the moment-curvature relation for reinforced concrete structures subject to bending and axial loads. The model is based on a layer analysis of a cross section, where the bond behavior is particularly considered. The computed moment-curvature relation is compared with data obtained from tests on freeze-thaw damaged and undamaged beams.

Keywords: internal damage, reinforced concrete structures, freeze-thaw damage, physical and chemical loads, bond behavior, bending behavior, tension-stiffening effect, load bearing behavior under deterioration aspects

1 INTRODUCTION

The failure of reinforced concrete elements is often due to an interaction of different damages. Apart from mechanical loads, reinforced concrete structures are also subject to environmental physical and chemical loads. However, often only the mechanical loads are taken into account to calculate the changes in the load bearing behavior.

Nowadays, the physically and chemically induced damage to concrete fabric (e.g. occurring due to attack by freeze-thaw cycles) is usually considered as a problem of durability of the concrete surface only. In general , the influence of such damage on the load bearing behavior is not considered.

Within the framework of the presented research project, cycling freeze-thaw loads together with water absorption have been chosen for investigation to quantify its influence on the load bearing behavior of reinforced concrete elements. This deterioration mechanism causes an internal damage of the concrete microstructures, which can be quantified by the ultrasonic measuring technique. The freeze-thaw attack induced micro cracks in the cement paste create a relatively homogenous damage, which is suitable for formulation in terms of deterioration coherences.

2 EXPERIMENTS

2.1 *General aspects of cycling freeze-thaw loads*

There can be considerable damage to soaked concrete through freeze attack. When concrete is subjected to freeze-thaw cycles an external and also an internal damage occur. Each of them should be considered separately. The external damage contains a scaling of the concrete surface, which can be bonded by the use of thawing agents. When only a pure freeze attack occurs, the internal damage is dominant. In this case micro cracks form in the cement paste, which causes a changes in the concrete behavior.

In the first place the damage due to a freeze attack is based on the freeze-thaw induced pump effect of the concrete (Setzer et al. 2002). With each freeze-thaw cycle water from external sources will be absorbed by the concrete and the concrete becomes more and more saturated. Reaching a critical saturation there is no space in the cement paste left to compensate for the 9% expansion at the changeover from water to ice. The hydraulic pressure at critical saturation which is caused by freezing is then courbalanced by a micro crack initiation. Figure 1 and 2 show raster electron microscope images of internal damage to a freeze-thaw stressed specimen. The micro cracks, which have a width of just a few µm, propagate along the interface of the aggregate and the cement paste. Also there are micro cracks that run radially from the aggregate into the cement paste.

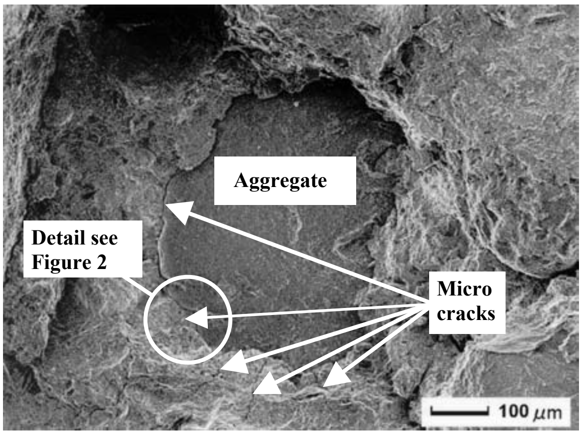


Figure 1. raster electron microscope picture of freeze-thaw induced micro cracks initiation.

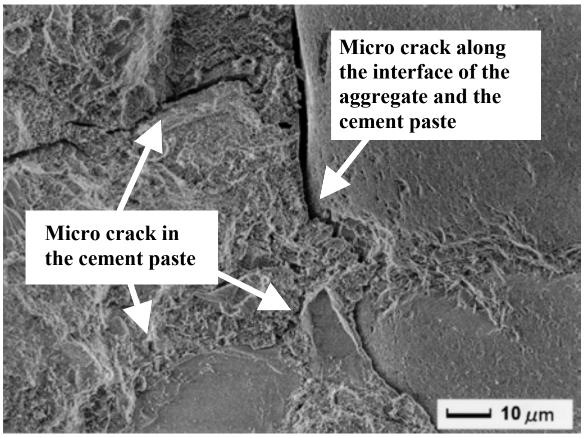


Figure 2. close-up from Figure 1.

Figure 3 shows a comparison of the pore radius distribution of an undamaged and a freeze-thaw damaged specimen measured by mercury porosimetry. The micro cracks become apparent by the obvious peaks and greater porosity in the µm-zone (horizontal axis). These investigations confirm the above presented raster electron microscope images of the freeze-thaw induced micro-cracks.

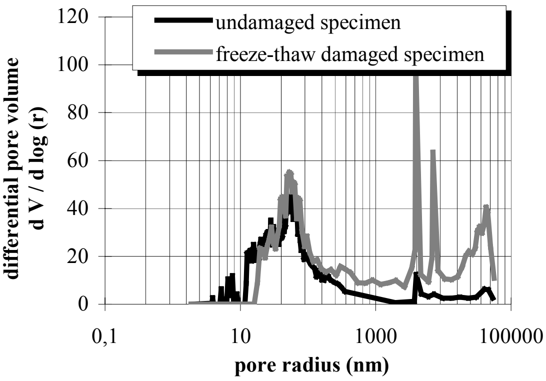


Figure 3. Comparison of the pore radius distribution of an undamaged and a freeze-thaw damaged specimen

The internal damage due to the freeze-thaw cycles lengthens the travel time of an ultrasonic wave through the concrete. From this it is possible to derive the relative dynamic modulus of elasticity, which can be used to quantify the internal damage. This quantification of the internal damage and the method of stressing the specimens with the cycling freeze-thaw load together with the water absorption was taken from the CIF-Test (Setzer 2001). In this test the freeze-thaw cycles and also the water absorption occur only on one surface, so the specimens are subjected to one axis heat and moist transport. This corresponds to the practical situation for a concrete structure under real conditions.

The internal damage due to the freeze-thaw cycles progresses from the surface subjected to the freeze-thaw action into the concrete. Because of that the damage is unevenly distributed over the cross section. Figure 4 shows the distribution of the internal damage expressed as relative dynamic modulus of elasticity at various distances from the stressed surface in relation to the number of freeze-thaw cycles. This distribution was derived from ultrasonic measurements at corresponding distances from the stressed surface. With an increasing number of freeze-thaw cycles the internal damage is more pronounced and progresses into the specimen. Further investigations of the internal damage distribution from the exposed surface into the concrete can be taken from Lohaus & Petersen (2002).

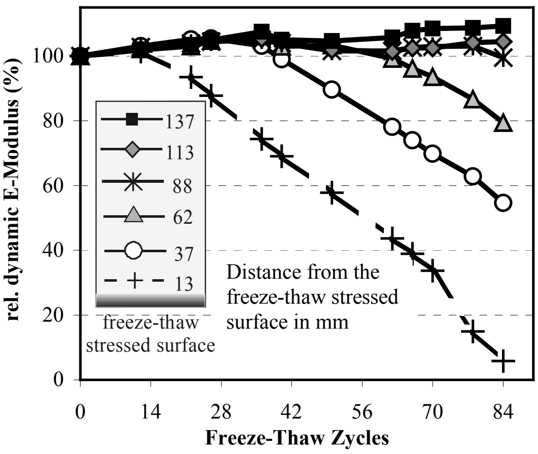


Figure 4. distribution of the internal damage over the specimen.

To derive a relationship between the internal damage and the variation of the characteristic values related to the behavior of undamaged specimens, it is necessary to record the distribution of the damage over the whole specimen. From this information an equivalent internal damage must be defined for each characteristic value from the relevant ultrasonic measurement points.

In addition to the freeze induced variation of the static modulus of elasticity, which is presented in this paper, the variation of other characteristic concrete values are published by Petersen & Lohaus (2003).

The majority of the tests were done on specimens, which were cast using concrete with the same mix specification. A few complementary tests were also performed with another concrete composition to prove that the results can be used for different concretes. Detail information of the used mix specification can be taken from Petersen & Lohaus (2003).

2.2 *Freeze-thaw induced variation of the static modulus of elasticity*

The specimens were subjected to freeze-thaw cycles till they reached various defined states of damage. The distribution of the internal damage was measured at three different distances from the stressed surface. These measurements were done at two different locations along the specimens (Fig. 5).

To determine the characteristic value of the modulus of elasticity the mean value from all six ultrasonic measurement points was taken as the equivalent internal damage. Figure 5 shows the schematic of the storage during the freeze-thaw cycles and the method for measuring the modulus of elasticity.

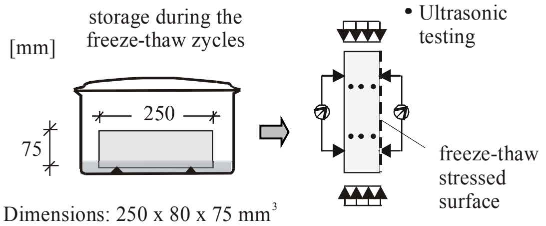


Figure 5. Schematic of the tests to determine the freeze induced variations of the static modulus of elasticity .

The modulus of elasticity decreases with increasing internal damage, which is consistent with the decrease of the relative dynamic modulus of elasticity. The test results and the relation of the variation of the static modulus of elasticity are presented in Figure 6.

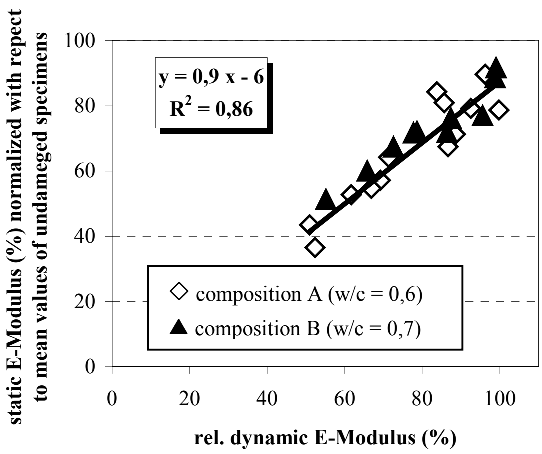


Figure 6. Freeze-thaw induced changes in the static modulus of elasticity

2.3 *Freeze-thaw induced variation of the bond behavior*

Investigations of the bond behavior were carried out using pull-out specimens with eccentrically placed reinforcing bars to simulate the bond in flexural reinforced concrete members. The freeze-thaw load was applied on the side with the smallest concrete cover.

Bond action results in a ring tension stress. At the moment of bond failure this tension exceeds the concrete strength and a crack appears along the reinforcement. This mechanism of crack initiation takes place in the concrete cover because of smallest cross section of concrete active in resisting the ring tension stress. Thus the internal damage in the area of the concrete cover is decisive for the variation of the bond behavior. Therefore the damage in the concrete cover was taken as the equivalent internal damage to compare with the variation of the bond behavior. For some further supplementary analysis also the damage in the area of the reinforcing bar was measured by ultrasonic testing. Figure 7 shows the schematic of the storage during the freeze-thaw cycles and of the pull-out test.

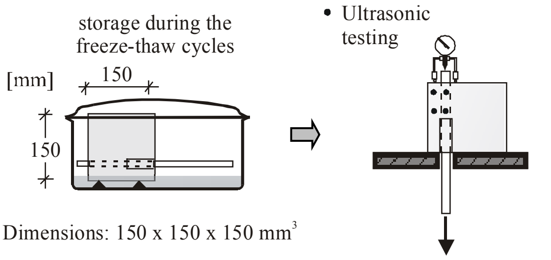


Figure 7. Schematic of the tests to determine the freeze induced variations of the bond behavior.

The variation of the bond-slip behavior due to concrete deterioration with respect to the behavior of undamaged specimens versus the variation of the relative dynamic modulus of elasticity is shown in Figure 8. From the results it becomes obvious that the bond behavior changes with the deterioration. First, there is decrease of the maximum bond tension. Second, the observed slip changes at the maximum bond tension.

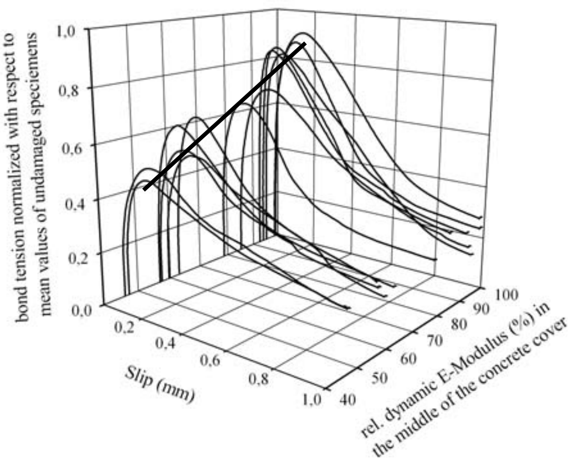


Figure 8. Freeze induced changes of the bond-slip behavior

Figure 9 shows the decrease of the maximum bond tension versus the damage in the area of the concrete cover. The relation is essentially linear (Fig. 9).

In order to explain the variation of the slip values at the maximum bond tension, four specific measured bond-slip curves are presented in Figures 10. One curve is the result from the pull-out test of an undamaged specimen. The curves A, B and C are the results from the tests of specimens with different grades of damage, increasing from specimen A to C. The related levels of damage in the concrete cover and also in the area of the reinforcing bar can be taken from Table 1.

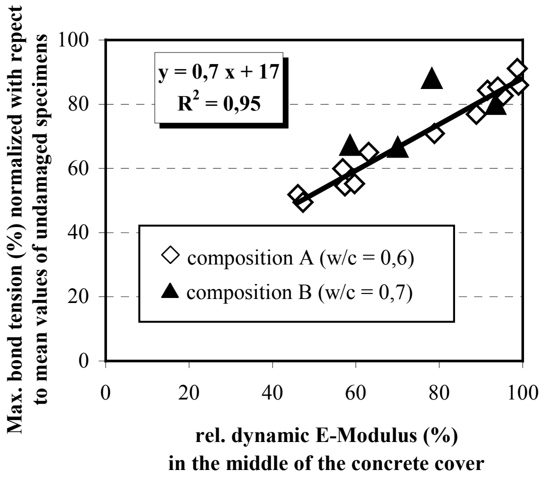


Figure 9. Freeze induced changes in the maximum bond tension

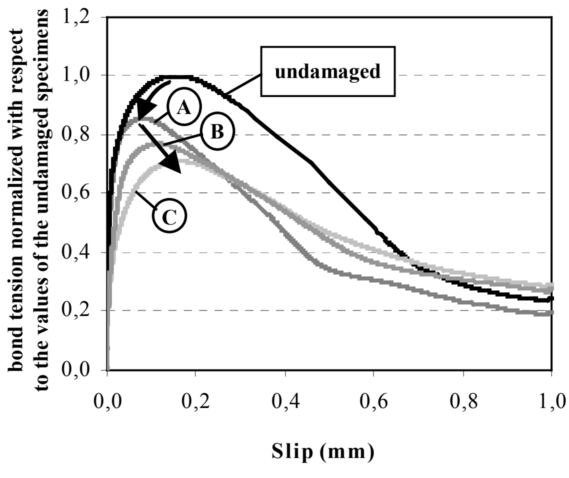


Figure 10. four specific measured bond-slip curves to show the freeze induced changes of the bond behavior

Table 1. Level of Damage of the specimens from Figures 10, subdivided in the area of the concrete cover and the reinforcing bar

	relative dynamic E-Modulus (%)	
specimen	in the area of the concrete cover	in the area of the reinforcing bar
A	94	100
B	89	95
C	85	92

Initially, the internal damage is only in the area of the concrete cover and the area of the reinforcing bar is not reached (specimen A). At this level of damage the stress-strain behavior of the concrete in the contact area of the steel and the concrete is unchanged. So the curve of this specimen follows the curve of the undamaged Specimen. However, even when the concrete in the area of the reinforcing bar is undamaged the maximum bond tension decreases, because of the internal damage in the concrete cover. Therefore, the specimens with such a low level of damage show a decrease of the slip values at the maximum bond tension, however the slip values before the maximum bond tension are almost unchanged (see Figure 10, curve A).

When the internal damage rises and reaches the contact area of the steel and the concrete the bond decreases and the slip values increase very quickly (Figure 10, curve B and C).

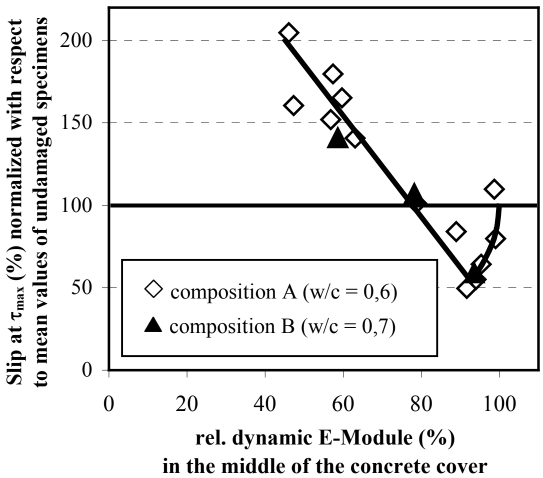


Figure 11. Freeze induced alterations of the slip at τ_{max}

Figure 11 shows the variation of the slip values at the maximum bond tension in relation to the level of the internal damage in the area of the concrete cover. When there is only a small amount of damage and only the area of the concrete cover is included, a reduction of the slip values at the maximum bond tension occurs. When the internal damage goes deeper into the concrete, reaching the area of the reinforcing bar, the bond behavior becomes less and less pronounced. At this level of damage the slip values at the maximum bond tension increase quickly.

2.4 *Freeze-thaw induced variation of the tension-stiffening effect of reinforced concrete beams*

The freeze induced variation of the load bearing behavior of reinforced concrete is analyzed on the basis of structural component tests. The comparison of the load bearing behavior of undamaged and freeze-thaw damaged beams shows the changes in the bending behavior of members subjected to freeze-thaw deterioration. The differences in the bending behavior were related to variations in the moment-curvature relationship.

The bending behavior has a special relevance for such a deterioration mechanism like the freeze-thaw attack that progresses from the surface into the concrete. The outer areas of the cross section have the greatest level of internal damage and also they are the most strained areas. Furthermore the bond behavior, which has considerable variations due to the internal damage (see above), has an essential influence on the bending behavior. For both compositions (A: w/c = 0,6 and B: w/c = 0,6) two beams were cast from the same concrete mix. So the similarity of the compositions of these two beams was guarantied. For the composition A, a beam with a small damage will be compared to an undamaged one. Only one beam was stressed with the freeze-thaw load till it showed a little internal damage.

For the composition B, both beams underwent some freeze-thaw cycles to make the comparison of the bending behavior of an average and an intensively damaged beam. The internal damage of the freeze-thaw damaged beam was recorded in three locations. At each of the locations, six different distances from the exposed surface were measured. Following the different measurement points in the beam, mean values were calculated for each of the six different distances from the freeze-thaw exposed surface.

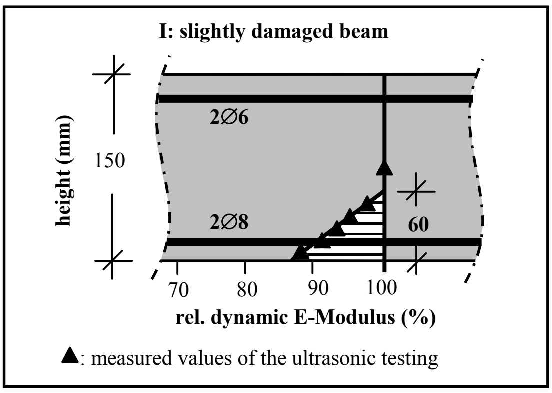


Figure 12. Level of Damage of the slightly damaged beam

Figure 12 shows the distribution of the internal damage at various distances after all freeze-thaw cycles of the slightly damaged beam (composition A). The distribution of the internal damage of the beams to the composition B is shown in Figure 13.

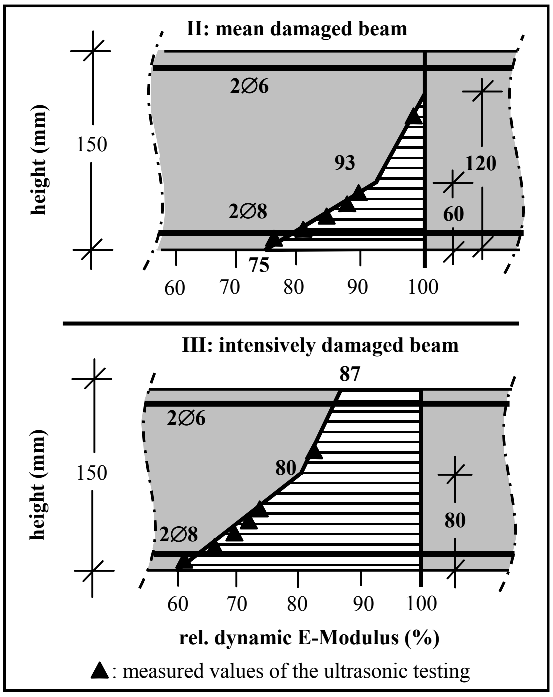


Figure 13. Level of Damage of the mean (II) and the intensively (III) damaged beam

The beams were tested in a 4-point-bending test. A schematic of the test is given in Figure 14. Along the beam, five inductive sensometers were placed. The curvature was calculated from the different measured deflections at the five gauging points.

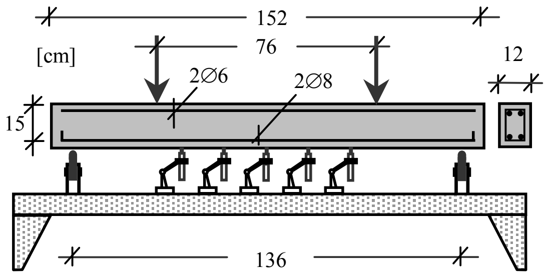


Figure 14. Experimental setup for flexural tests.

Figure 15 shows the results of the composition A, the moment-curvature relation of slightly damaged to the undamaged beam.

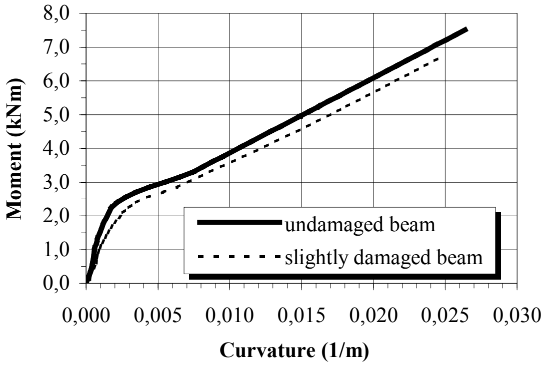


Figure 15. Moment-curvature relation of the small freeze-thaw damaged and an undamaged beam

Even with this small freeze-thaw damage the clear decrease in stiffness before and after cracking, as compared to the undamaged beam, is apparent. Before cracking the differences in the curvature and therefore also in the deflections is due to the freeze induced variation of the modulus of elasticity i.e. the flexural rigidity. But also after cracking the curve of the damaged beam is visibly below the undamaged one. In this area, the curves run nearly parallel to each other. Tension-stiffening effect is less for the damaged beam. The decrease of the tension-stiffening effect is the result of the freeze induced variation of the bond behavior (see section 2.3).

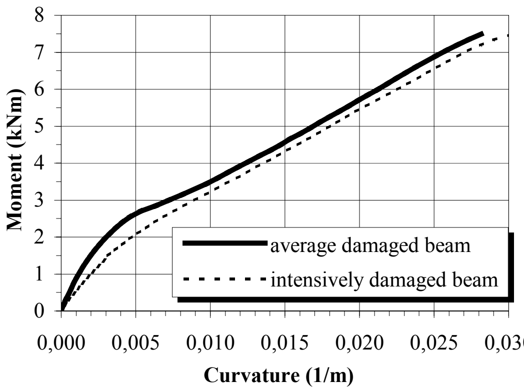


Figure 16. Moment-curvature relation of the mean and the intensively freeze-thaw damaged beam

The tests with composition B show the same deterioration effects (Figures 16). The bending behavior of the intensively damaged beam is softer than the bending behavior of the beam with the average level of damage.

3 COMPUTATIONAL MODELING OF THE FREEZE-THAW INDUCED VARIATION OF THE BENDING BEHAVIOR

The experimental verification shows that physical and chemical loads influence the bending behavior. Therefore, as the next step, the theoretical studies were undertaken which included both the variations of the modulus of elasticity and of the bond behavior. The freeze-thaw induced variations in the above material parameters were implemented into a computer model for the calculation of the bending behavior of reinforced concrete elements. This model was created at the University of Waterloo, Canada by Polak & Blackwell (1998). It computes moment-curvature relations for members subjected to bending and axial loads. The model considers tension-stiffening effect, which is described in terms of bond characteristics of the member.

The formulation consists of a model for concrete before cracking, model for concrete after cracking, bond model and method for predicting crack spacing.

The program divides the cross section of a beam into finite horizontal layers. The program works by iterative searching for a linear strain distribution corresponding to equilibrium of internal and external loads. Once a strain distribution is found, the curvature of the cross section is calculated and referred to the external load. A linear elastic concrete behavior is assumed for uncracked portions of concrete. For concrete in compression the program uses a nonlinear stress-strain relation.

The method for including tension stiffening is as follows. After exceeding the crack strain for concrete in tension in the first layers from the bottom, the layer is considered to crack completely and thus cannot transfer any axial stress directly across the crack, but a certain distance away from the crack the remaining pieces of concrete remain strained to a value of a cracking strain. Thus the cracked layers contribute to the overall calculated bending behavior. In the analysis of the layered cross section, the force developed in this cracked layer is then applied to the uncracked layer adjacent to it (e.g. second from the bottom, if cracking starts on the bottom of the member). When the crack tip reaches the reinforcing steel, it is assumed that all forces from all cracked layers are projected to the reinforcement due to the bond behavior. Thus the considering forces from the cracked layers in the described way, the tension-stiffening effect is considered in the computation. Figure 17 shows the principal concept of the computation after the crack tip passes above tension reinforcement.

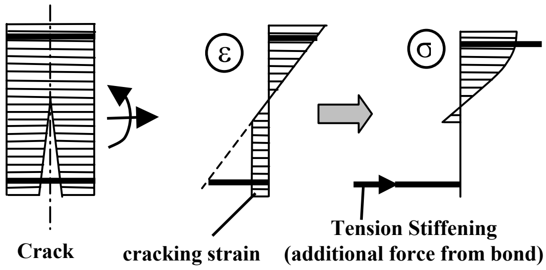
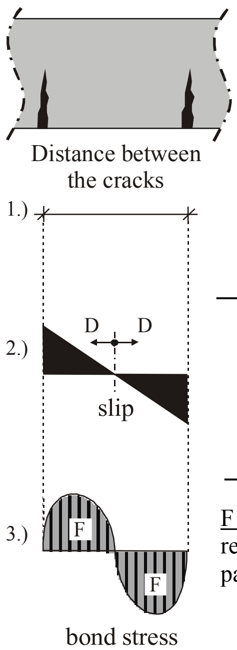


Figure 17. Strain and Stress after Crack Tip passes above Tension Reinforcement

The formulation for the calculation of the bond force is shown in Figure 18. The crack spacing can be calculated with the equation (1) and depends on the distance from the neutral axis to the compression face of a member of the cross section. The slip can be calculated with the equation (2). It changes in a linear way between the cracks. In addition to the slip the bond force can be calculated with a bond-slip relation that can be taken from Petersen 2004.



$$cs = cs_y \cdot \left(1 + \frac{c}{H}\right)^2 \quad (1)$$

according to Polak & Blackwell (1998)

$$s(D) = (\varepsilon_s - \varepsilon_{cr}) \cdot D \quad (2)$$

according to Polak & Blackwell (1998)

F = Bond force from bond slip relation with integrated damage parameters

according to Petersen (2004)

where cs = crack spacing; cs_y = crack spacing at yield; c = Distance of the neutral axis to the compression face of member; H = height of the member; s = slip; D = distance of lug i from the centerpoint between two cracks; ε_s = strain in reinforcement; ε_{cr} = cracking strain of concrete

Figure 18. Principle procedures to calculate the bond force.

The distribution of the internal damage measured by ultrasonic testing at various distances from the freeze-thaw stressed surface can be included in the program. Following the distribution of the internal damage, the concrete modulus of elasticity varies over the height of the section. The relation between modulus of elasticity and the internal damage with respect to the relative dynamic modulus of elasticity can be taken from section 2.1. Furthermore, the variations of the bond behavior (see section 2.2) were implemented into the computation considering the internal damage in the concrete cover. Details about the mathematical formulations of the bond deterioration can be taken from Petersen (2004).

4 COMPUTATION IN COMPARISON WITH THE TEST

The comparison of the computation and the test results for the composition A, undamaged and the slightly damaged beam, is shown in Figure 19. Both comparisons show a good correlation between computation and test. The experimentally detected difference in the bending behavior due to a small amount of damage is confirmed by calculations.

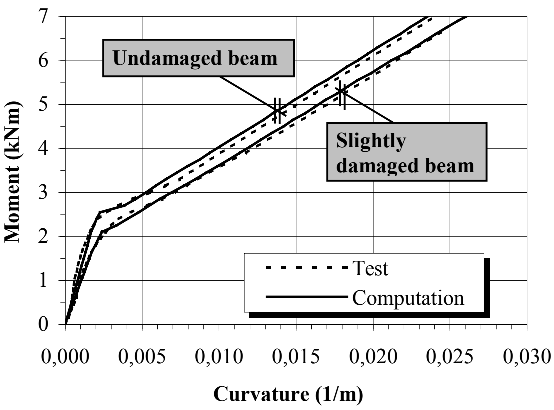


Figure 19. Comparison of theoretical and tests results for the tests to the composition A (w/c = 0,6)

In Figure 20 the experimental moment-curvature relations of beams with an average and an intensive level of damage are compared with the corresponding computations. The comparisons for this composition also show good correlation between test and computation. In addition to those comparisons between test and computation a calculated undamaged moment-curvature relation is also presented in this Figure.

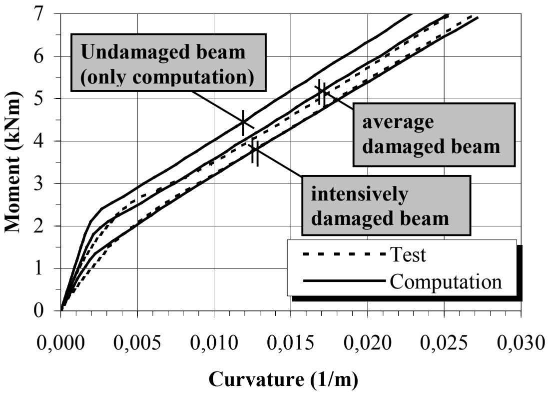


Figure 20. C Comparison of theoretical and tests results for the tests to the composition B (w/c = 0,7)

5 CONCLUSIONS

The variation of the concrete modulus of elasticity and the bond behavior due to free-thaw deterioration were successfully implemented into a formulation for predicting flexural behavior of reinforced concrete elements. For this purpose the formulation by Polak & Blackwell (1998) was extended to the deterioration influence of internal freeze-thaw damage.

The moment-curvature behavior generated with the computational model was compared to the data obtained from tests with a freeze-thaw damaged and undamaged beams. These comparisons show very good correlation between theoretical and experimental results.

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