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ANCHOR BOLTS IN CONCRETE STRUCTURES - FINITE ELEMENT CALCULATIONS BASED ON INNER SOFTENING BANDS

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Abstract
A simple mixed mode fracture mechanics failure criterion have been used to model the failure mechanisms of mixed mode failure and anchor bolts in plain concrete. The model is based on the fictitious crack concept where the softening behaviour is described by a softening kinematic rule in the stress-displacement space. Finite elements based on the inner softening band approach have been used.

1 Introduction

The inner softening band (ISB) has been presented by Klisinski, Runesson and Sture (1991) and next compared with the smeared crack approach by Olofsson, Klisinski and Nedar (1994). Since the ISB is based on a discontinuous displacement jump in the element the constitutive equation can be formulated as in the fictitious crack concept introduced by Hillerborg, Modéer and Petersson (1976).

2 Constitutive Model

The constitutive model is divided in two parts, the crack initiation and the crack evolution process. The model is based on a parabolic failure surface in the normal shear stress plane which during the fracture process moves and shrinks to its residual size, see Fig 1. The softening is dependent on the effective crack opening that is determined from the softening in mode I and a shape factor that governs the dilation of the fictitious crack.

The uniaxial tensile and compressive strength determines the crack initiation locii. The softening in mode I, i.e. G_f controls the kinematic softening and in the case of a linearly varying α_e, the slope k_α determines the isotropic softening.The model and the implementation features of the Inner Softening Band concept is explained in detail in Olofsson, Ohlsson and Klisinski (1995) and in Klisinski, Olofsson and Tano (1995).

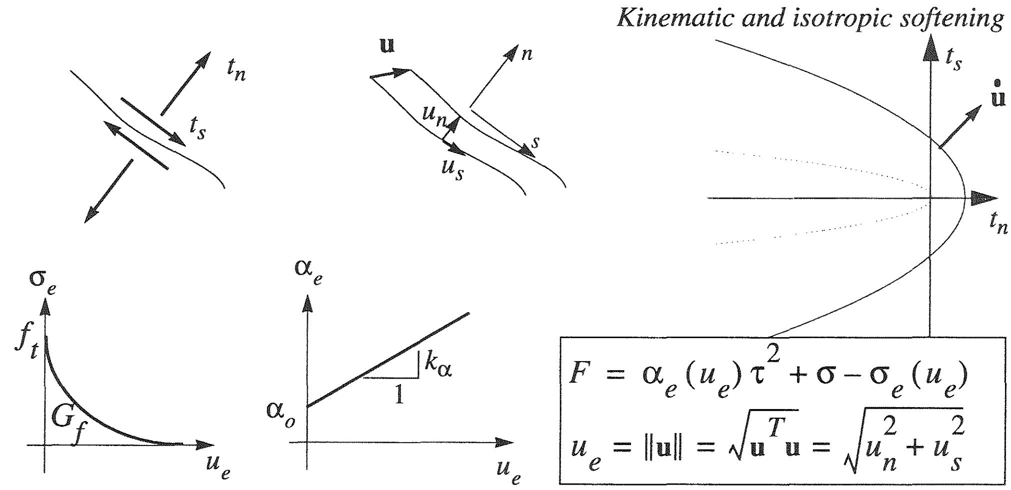


Fig. 1. Constitutive model of a fictitious crack under mixed mode conditions using Inner Softening Bands (ISB)

3 Comparison with Experiments in Mixed Mode Loading

Nooru-Mohamed (1992) conducted a series of tests on mixed mode fracture of concrete specimen. One of the loading paths was conducted in displacement control with the relation 1:1 of the normal versus shear displacement on specimens with three different sizes, (loadpath 6a), see Fig 2.

The result of the analysis are shown in Fig 3. and Fig 4. Fig 3. shows the apparent tensile stress versus the normal displacement, i.e. the applied load in the normal direction divided with the ligament length. Fig 4. shows the crack pattern at the end of the numerical test.

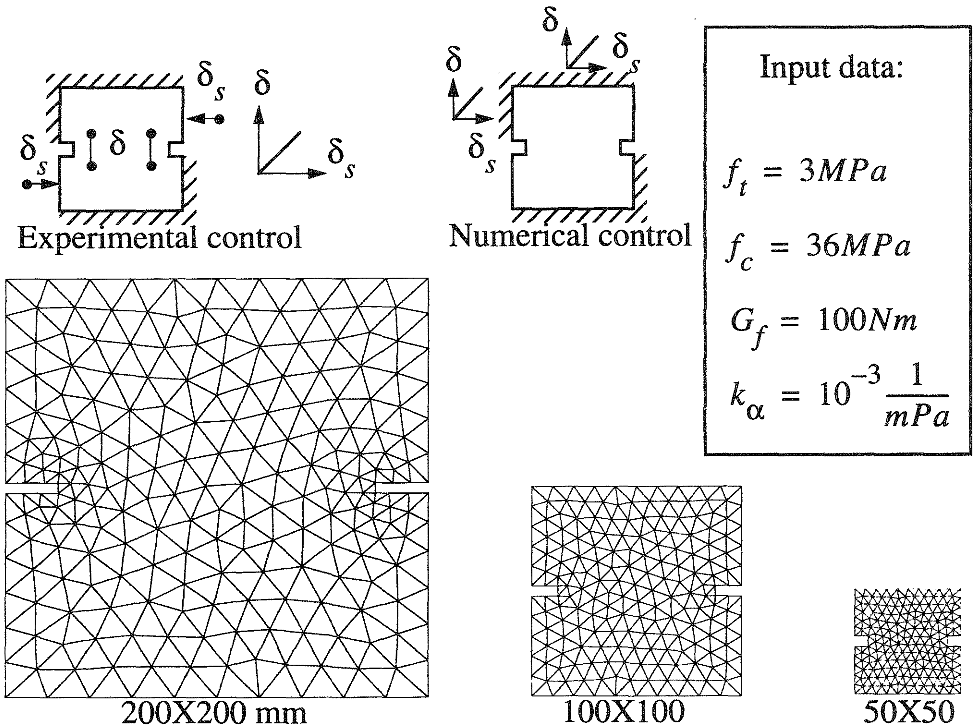


Fig. 2. FEM analysis of mixed-mode fracture test of three different sizes

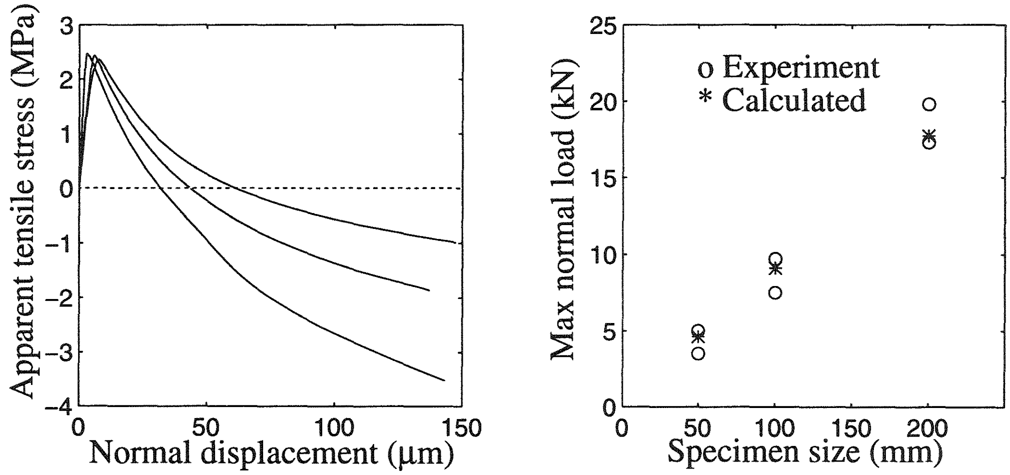


Fig. 3. Apparent tensile stress versus normal displacement and the maximum normal load as a function of specimen size

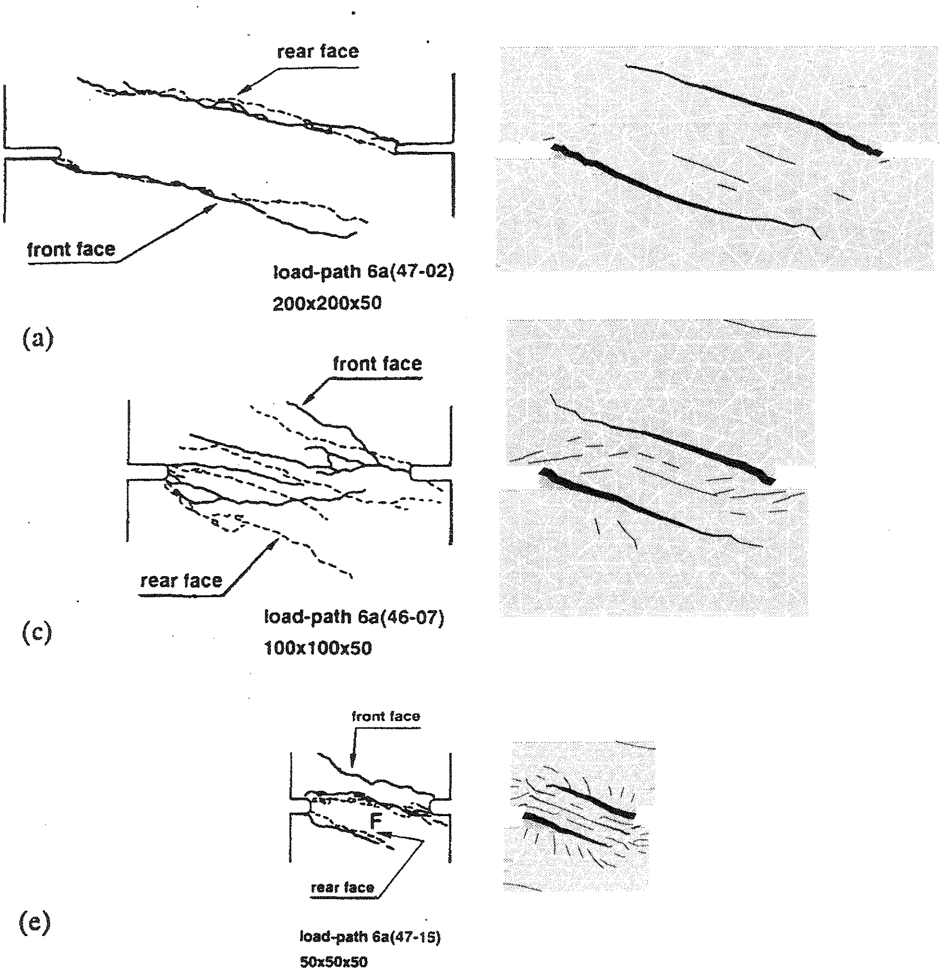


Fig. 4. To the left experimentally observed crack pattern for loadpath 6a, Nooru-Mohamed (1992). To the right calculated crack patterns at 150 μm

The apparent tensile strength shows virtually no size effect. This is probably due to the dilation effect. Since the small specimens are more confined (the displacements were measured and controlled over a smaller distance for the smallest size), the dilation will cause compressive action earlier compared to the larger specimens. At the end of the test the stress rotation in some elements, especially in the smallest size, are so great that more cracks should be introduced. However, the present implementation allows for only one crack per element.

4 Analysis of Anchor Bolt Specimen

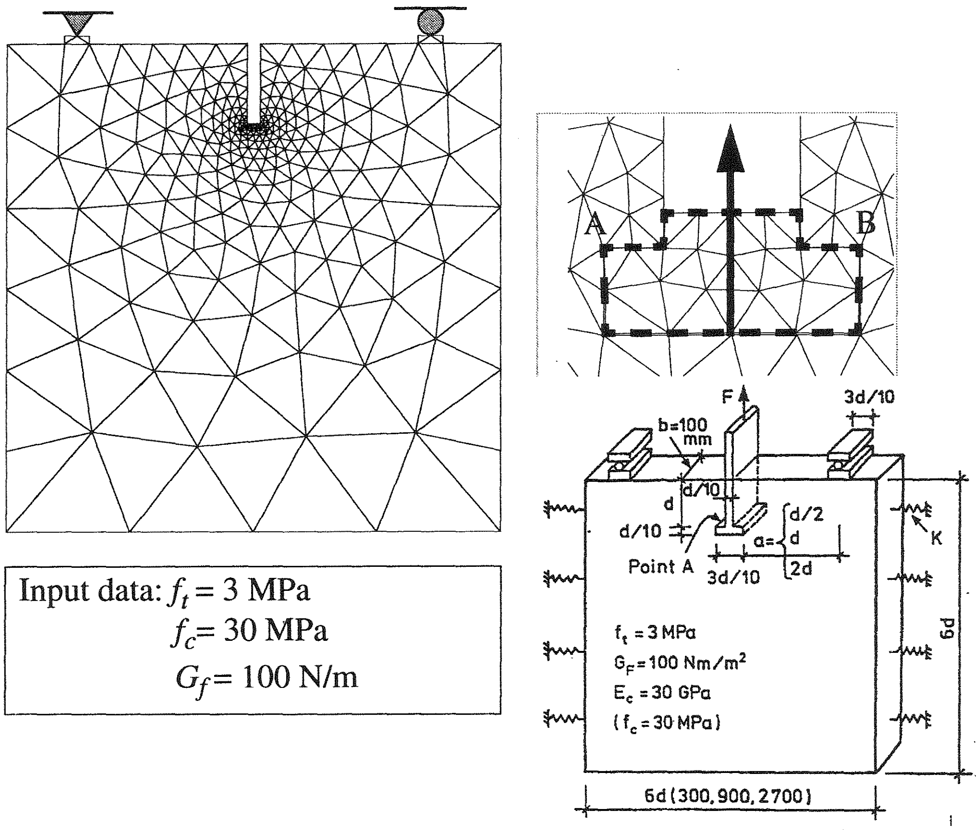


Fig. 5. Finite element model and geometry of anchor bolt specimen

In the RILEM Round-Robin Analysis and Tests, anchor bolts have been used, in order to compare different numerical analyses with actual test results, RILEM TC 90-FMA (1991).

The geometry and material properties of the specimen are shown in figure 5. Here, the case with d = 50 mm, a = 2d and K = 0 is studied.

A model with 440 CST elements was used in the analysis. The finite element mesh is shown in figure 5.

The shaft of the anchor bolt was not modelled. On the upper surface, the bolt was assumed to be fixed to the concrete. The other sides were free. The loading was applied in displacement control at the central node on the bottom surface of the bolt. This node was free to translate in the horizontal direction and to rotate. The load displacement curves show the displacements of both points A and B on top of the anchor head.

The elements modelling the anchor bolt were linear elastic. The concrete elements were of ISB type. A parabolic failure surface was used.

Calculations were also made with a prescribed crack path. The elements crossed by the prescribed crack had an ISB constitutive model. The other elements were linear elastic.

Figure 6 shows deformed finite element meshes at different stages of cracking. A non symmetric crack pattern was early formed. Before peak load, the displacements of both sides of the anchor head were of the same size. At peak load, the anchor head rotates and the displacements in points A and B diverge.

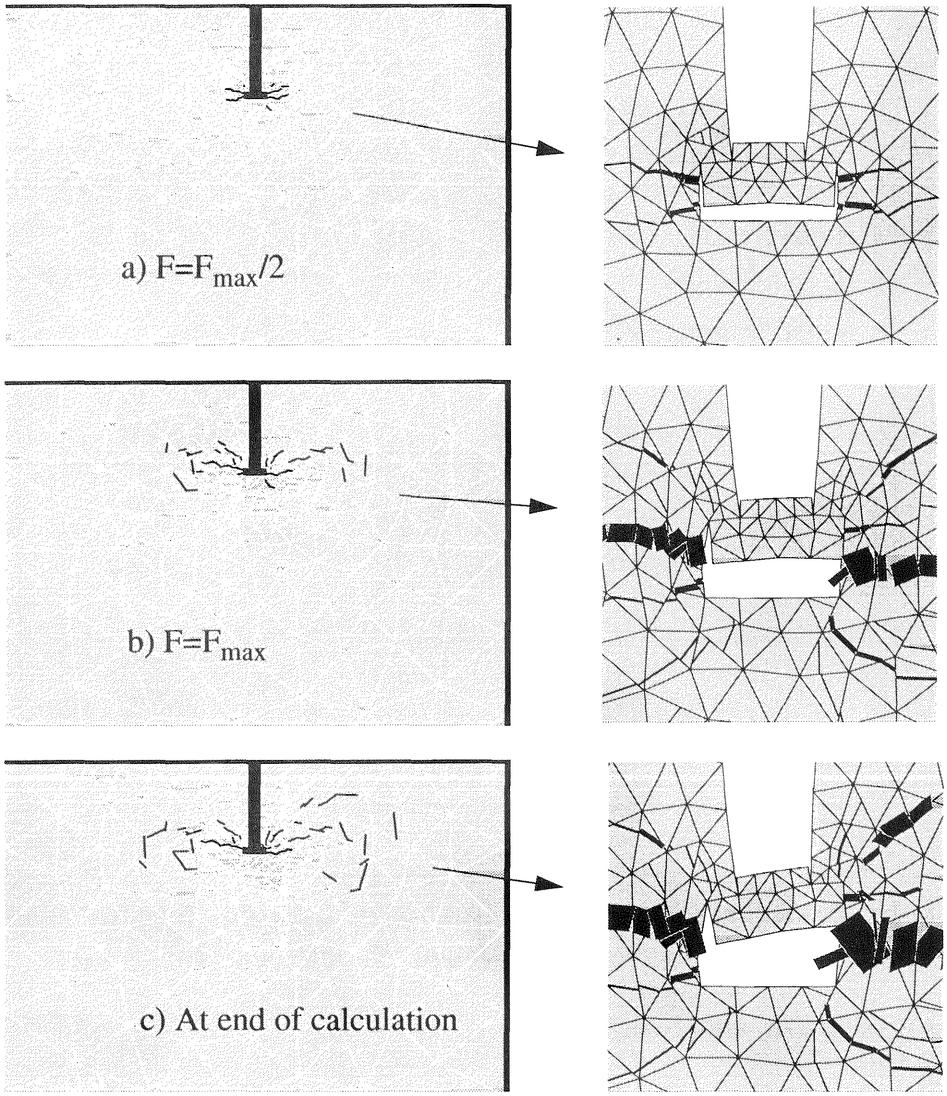
Final crack patterns obtained in experiments, see figure 6, can not be reproduced with the present implementation. After peak load, the stress rotations along the crack path are so large that more cracks should be introduced in already cracked elements.

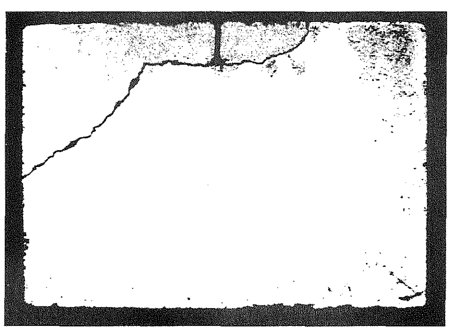
The peak load of the analysis was 23.4 kN, see the load displacement curve in figure 7. Tests with similar geometry and material properties give results which are in reasonable correspondence with the analysis. In two tests by Ohlsson and Ghasemlou (1993) on specimen with the thickness 50 mm, F_{max} were 9.39 kN and 11.42 kN respectively. If assuming plane stress conditions this correspond to a maximum load of 18.78 kN and 22.84 kN. In a test by Alvaredo et. al. (1992) F_{max} was 18.3 kN. Tests by Vervuurt et. al. (1993) gave maximum loads of 11.8, 13.8, 14.0 and 14.1 kN.

In order to study the influence of different α_0, a number of calculations with a curved prescribed crack was carried out. Experiments and calculations show that the cracks in general grow unsymmetrically on both sides of the anchor bolt. Such a crack trajectory also form a perfect cracking mechanism. Figure 8 shows load displacement curves for different α_0.

The size of α_0 influences the maximum load. For a large α_0 the slope of the parabolic failure surface is small and only small shear stresses are developing when the principal stresses rotate during the calculations.

Calculations with a prescribed crack path gives a lower maximum load than the calculations with ISB-properties in all elements. Reason for this is that the prescribed crack path allows the forming of a cracking mechanism. The interlocking effects in the elements due to stress rotation are smaller.





Example of final experimental crack pattern.

Ohlsson and Ghasemlou (1993)

Fig. 6. Deformed finite element meshes together with example of final experimental crack pattern

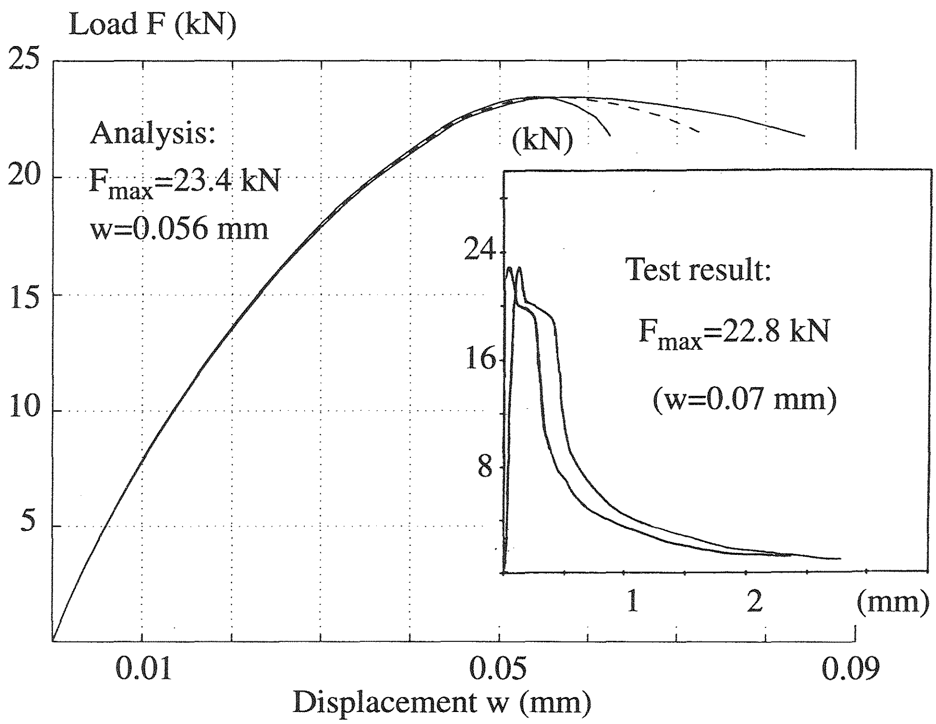


Fig. 7. Load displacement curve from the analysis together with experimental data from Ohlsson and Ghasemlou (1993)

5 Discussion and conclusions

In the analysis of mixed mode fracture, the model reproduces crack pattern and nominal stress displacement curves. The compressive stresses due to dilation are also captured. The stress rotations are generally small. In the final stage of the test, the stress rotation increases in some elements, especially for the smallest element size, so that more cracks should be introduced in order to avoid interlocking effects.

The analysis of the anchor bolt specimen reproduces deformations at maximum load and crack pattern at an early stage of the test. Peak loads are slightly overestimated. The post peak behaviour is not properly captured due to large stress rotations causing stress interlocking even before the peak load is reached. The possibility to introduce more then one crack in an element seems to be essential for the anchor bolt analysis.

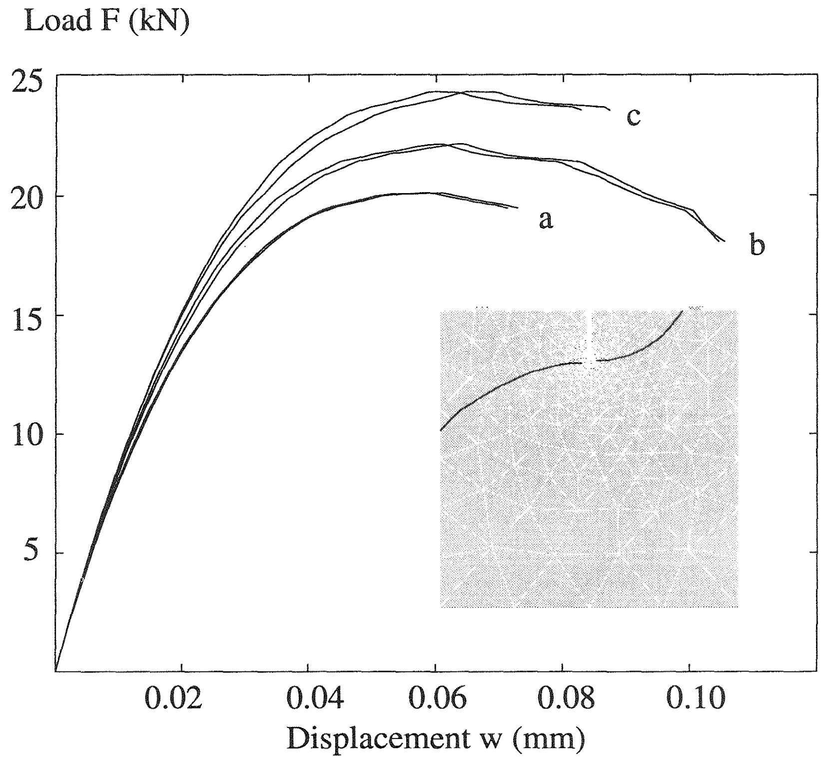


Fig. 8. Load displacement curves for different values of α_0
Curve a: $\alpha_0 = 6.2 \cdot 10^{-7}$ F_{max}=20.11 kN
Curve b: $\alpha_0 = 6.2 \cdot 10^{-8}$ F_{max}=22.11 kN (normal case)
Curve c: $\alpha_0 = 6.2 \cdot 10^{-9}$ F_{max}=24.31 kN

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