DISCRETE CRACK ANALYSIS OF ANCHOR BOLT PULL-OUT

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Abstract
The discrete crack model is applied to both linear and non-linear fracture mechanics analyses of anchor bolt pull-out experiments. The automated mesh generation is used for remeshing at each step of crack propagation.

1 Introduction

In this paper, a fracture mechanics analyses of anchor bolt pull-out experiments using discrete crack model are presented. Both linear and non-linear fracture mechanics are used and their applicability is discussed. For linear fracture mechanics, a path independent contour integral based on the reciprocal work theorem is used to evaluate the crack tip stress intensity factors (Stern et. al. 1976). For non-linear fracture mechanics, an interface crack model is used to simulate the cohesive zone (i.e. fracture process zone) ahead of the crack tip (Červenka 1994). In the finite element model, a crack is represented by two free surfaces, which can be connected through the interface crack model for non-linear fracture mechanics. This means that for each crack extension, it is necessary to modify the finite element model by inserting additional element surfaces or interface elements. In the presented analyses, this is accomplished with an automatic mesh generator. An analysed problem is represented by its solid model (i.e. boundary representation), which is modified for each crack propagation, and a new finite element model is generated (Červenka 1994).

Two different test geometries are considered in the analysis. The general geometry of the test specimens is shown in Figure 1, and the exact dimensions and material properties for both tests are listed in Table 1. The geometry and material properties that were used in the analysis, were specified by the Japan Concrete Institute (JCI 1993) in their invitation to the round robin tests and analysis, and they are similar to the round robin analysis promoted by RILEM TC90-FMA (1991).

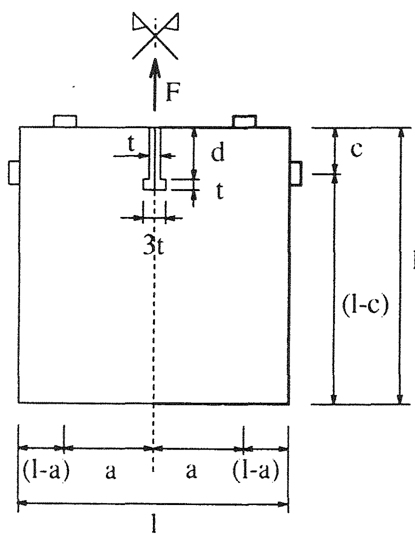

Figure 1: Anchor bolt pull out test geometry.

Table 1: Parameters of anchor bolt pull out tests.

Test	a	b	c	d	t	l	E	f_c	f'_t	G_f
			[mm]				[GPa]	[MPa]	[MPa]	[N/mm]
I	300	100	60	150	15	900	30.0	30.0	3.0	0.1
II	60	80	30	60	6	350	29.4	34.3	3.4	0.1

2 Linear elastic fracture mechanics

In the linear elastic fracture mechanics analysis, an initial crack is introduced in the direction perpendicular to the direction of maximal principal stress at the point with its highest value. The stress intensity factors are evaluated using the path independent integrals of Stern et. al. (1976). The load required for crack propagation is determined by scaling the reference load such that the crack tip energy release rate in the direction of crack propagation is equal to the specific fracture energy G_F. The direction of crack propagation is evaluated using the maximal circumferemtial stress criterion of Erdogan and Sih (1963).

The results from both tests are showed in the form of deformed finite element meshes in Figure 2 and plots of load-displacement curves in Figure 3. The load-displacements diagrams show the relationship between the force acting on the anchor and the vertical displacement of the anchor's upper edge. The force is normalized with respect to the product $b \times d \times f'_t$.

3 Non-linear fracture mechanics

In Section 2, the anchor bolt pull-out experiments were analyzed using the linear elastic fracture mechanics (LEFM). LEFM is not applicable for this problem size as it is documented on the resulting load-displacement curves (Figure 3). For both geometries the loads were overestimated if LEFM was used (see Figures 7 and 7. In this section, same problem is reanalyzed, but nonlinear fracture mechanics is used. The fracture process zone is modeled using the

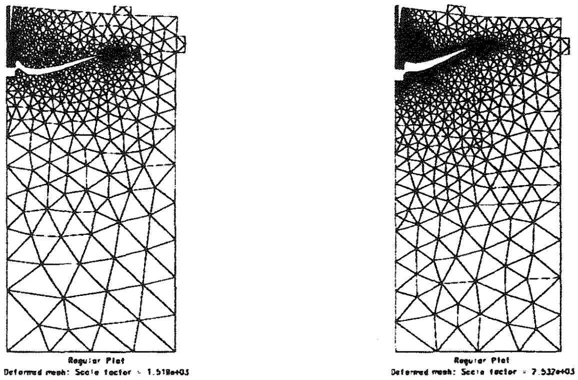

Figure 2: Final crack pattern for anchor bolt pull out tests.

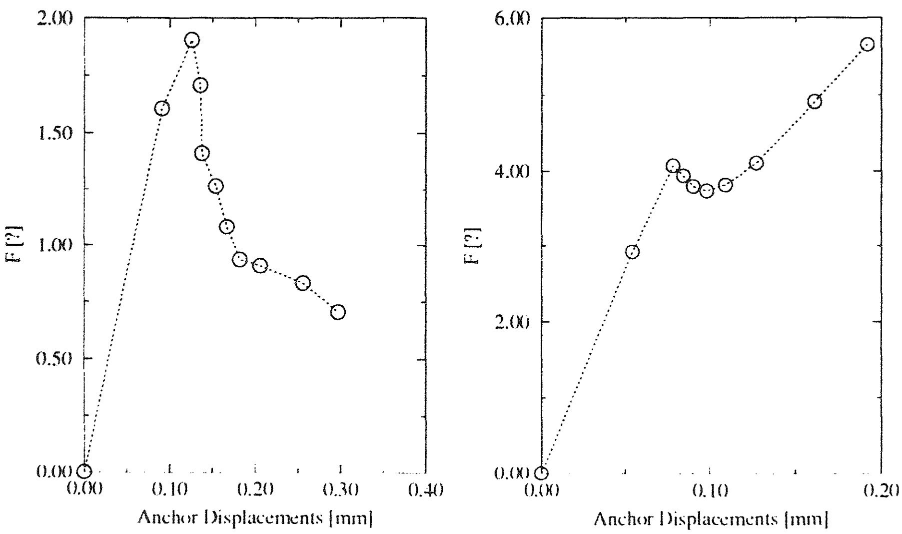

Figure 3: Load displacement curves for anchor bolt pull out tests.

interface crack model (Červenka 1994) and again automatic mesh generation is used to for adaptive modifications of the finte element model.

The finite element meshes and crack patterns for specimen type I are illustrated in Figure 4. This analysis exhibits a "zig-zag" crack

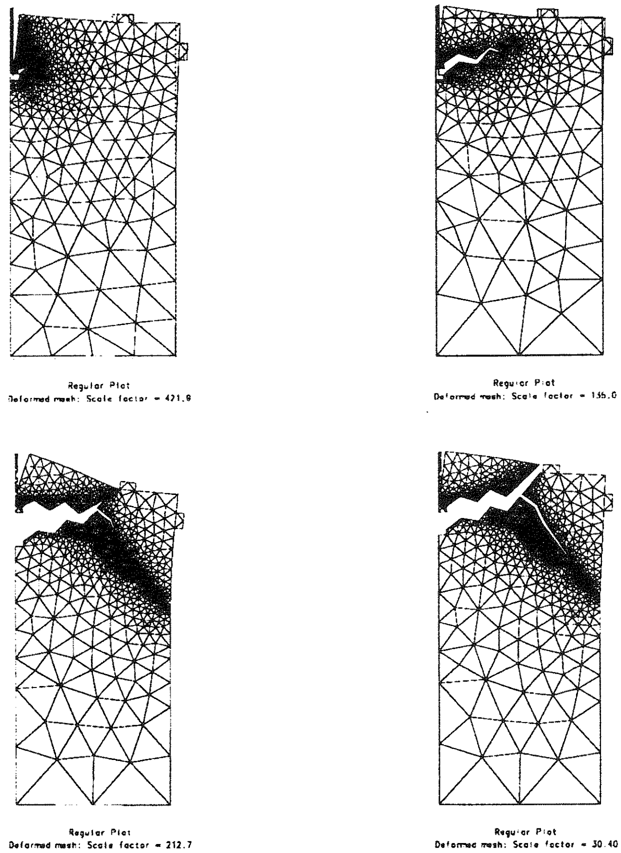

Figure 4: Crack propagation for anchor bolt pull out test I.

pattern, which indicates that the selected crack increment Δa of 50 mm was too large, and the crack tip "oscilates" around the correct path. Originally the crack propagated at an angle of about 20 degrees, but when the crack approached the support, it sharply curved down, and continued at about -55 degrees. Subsequently a secondary vertical crack developed below the vertical support causing the final failure. Eight remeshing steps were necessary in this analysis.

The results for specimen type II are shown in Figure 5, which shows the crack patterns and shaded areas of maximal principal stresses at remeshing steps 2,6,9 and 10. Altogether, ten different finite element meshes were used.

Two cracks were considered in this analysis. One started at the top edge of the anchor head, and second at the bottom edge. The first crack proved to be the dominant one, and as for specimen I, it first propagated in an almost horizontal direction (10-20 deg.), but below the support, the crack again sharply turned downward, and continued at the angle of approximately -45 degrees. Again, a secondary vertical crack eventually developed under the support.

The crack paths for both specimens are plotted in Figure 6, and they show a good agreement with the experimentally observed ones. It should be noted however that the experimental crack patterns in this figure are only approximate, since no quantitative data about the exact crack patterns are reported in the literature.

The load-displacement curves are shown in Figure 7 and 8 for specimen I and II respectively. These figures show comparison of this analysis with experiments and numerical simulations by other researchers. The experimental curves are adopted from Shirai (1993) and Slowik (1993), and the numerical curves correspond to the best results reported by Shirai (1993).

4 Conclusions

The fracture mechanics analysis of two anchor bolt pull-out experiments were presented. The discrete crack model was used for both analyses, and it was shown that the automatic mesh generation can alleviate one of the major drawbacks of the discrete crack model, which is the need to modify the finite element mesh at each step of crack extension. In addition, the model successfully simulated crack branching and propagation of multiple cracks. For anchoring problems it is, however, necessary to complement the fracture mechanics model with an appropriate constitutive formulation for compressive behaviour as is indicated by the results of test II.

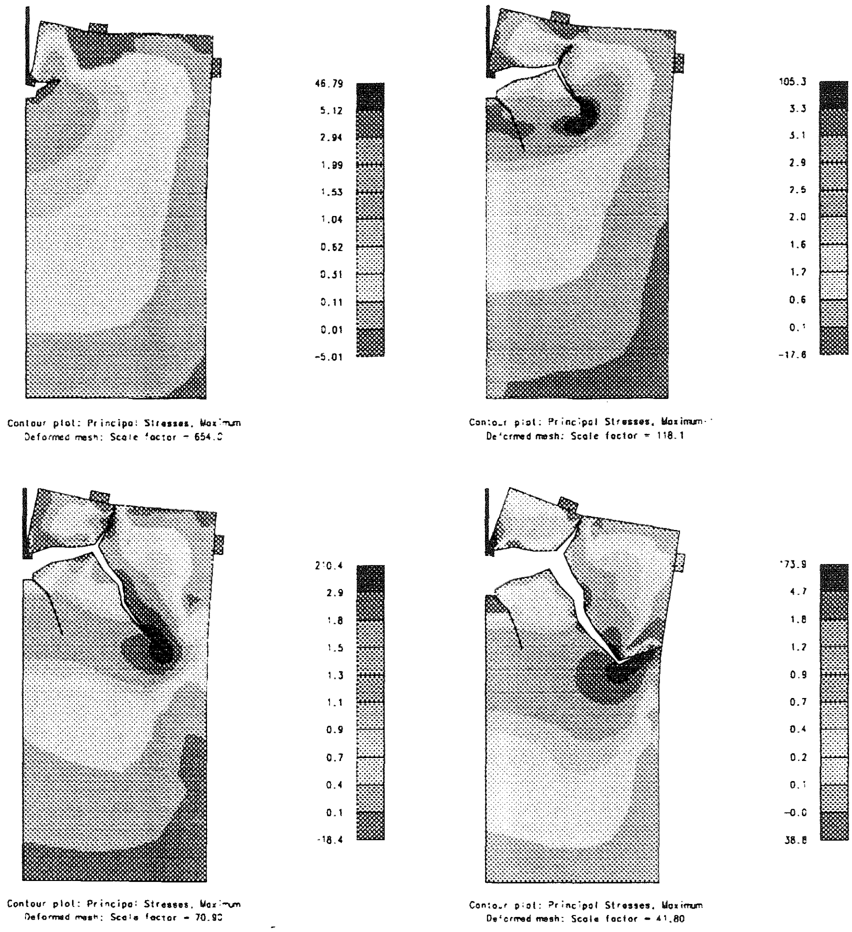

Figure 5: Crack propagation for anchor bolt pull out test II.

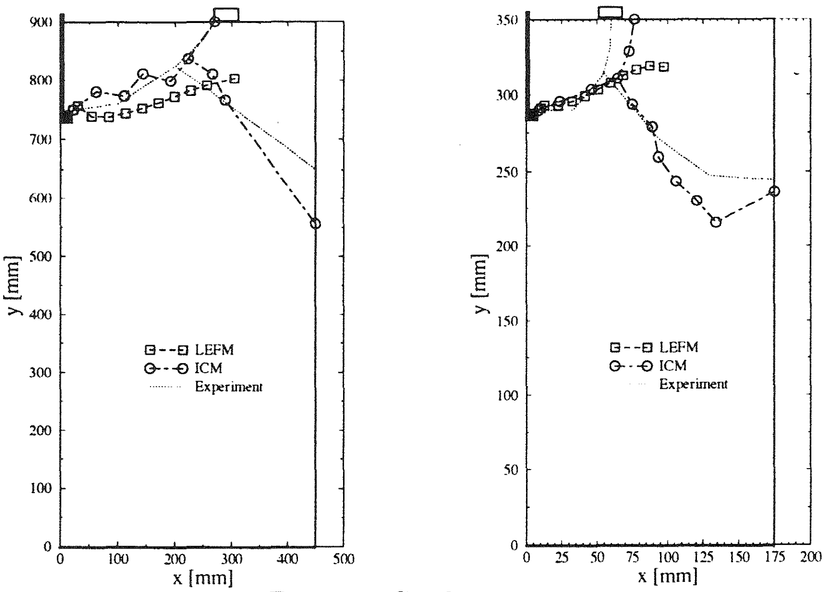

Figure 6: Crack patterns.

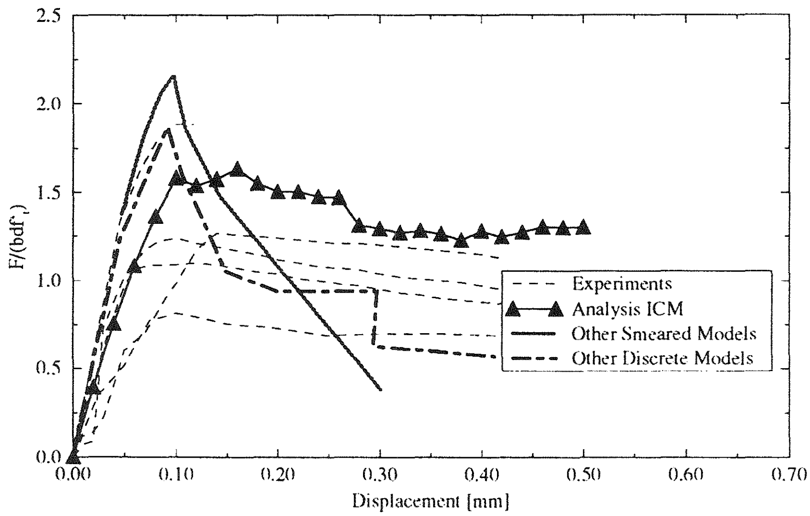

Figure 7: Load displacement curve for test I.

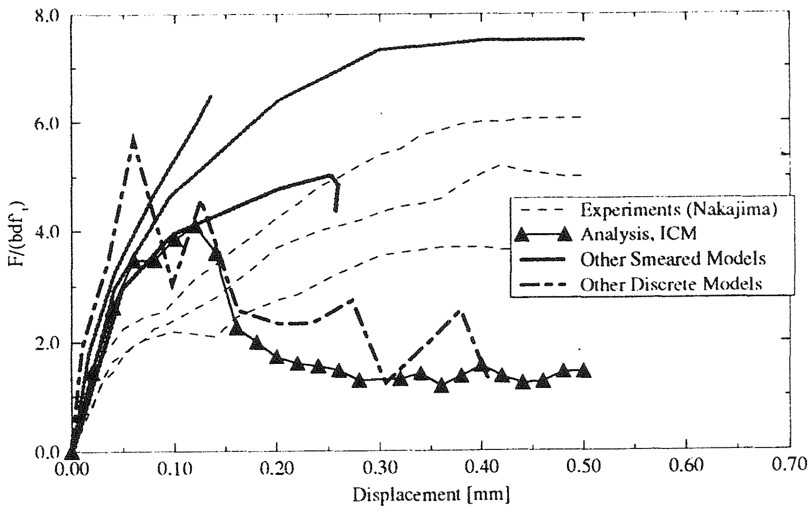

Figure 8: Load displacement curve for test II.

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