A CRACK APPROACHING THE EDGE OF THE AGGREGATE

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Abstract. *In this work, the influence of a crack approaching the edge of the amphibolite inclusion on fracture behaviour of cement composite is investigated. Specimens of the nominal dimensions 40 × 40 × 160 mm with polygonal amphibolite inclusion of 8 × 8 × 40 mm were provided with an initial central edge notch with a depth 12 mm, which was made by diamond blade saw. To determine the influence of polygonal cavity on fracture behaviour, fracture tests were conducted via three-point bending. The aim of this work is to analyse the behaviour of such specimen by means of finite element method (FEM) principles in Ansys, Inc. software. For this reason, a simplified 2D model was created for plane strain conditions. The crack propagation assessment was based on generalized fracture mechanics approaches using a criterion of an average value of tangential stress determined in dependence on the polar angle coordinate θ. The results of numerical analysis indicate that the debonding in the close vicinity of the bottom edge of the inclusion occurred. In other words, imperfect compaction of the fresh mixture and a smooth surface of the aggregate leaded to the formation of poor interface with lower mechanical-fracture parameters. Further, cutting of the initial notch by a diamond saw blade results in a precrack length greater than expected.*

Keywords

Amphibolite inclusion, Average tangential stress, Finite Element Method, Fracture Mechanics.

1. Introduction

Recent serious failures of bridges and other infrastructure buildings lead material research to reveal the conditions and causes of failure initiation. The efforts to identify mechanisms of crack formation push researchers to the studies of microstructure and how the microstructure influences mechanical-fracture properties of structural materials. The influence of microstructure on the fracture behaviour of concrete, as one of the most used building material, has been the subject of research since the discovery of the interfacial transition zone (ITZ) by Farran [1]. The results of the meso-scale analysis indicate that the cracks are located mainly in the ITZs at earlier stages of analysis and thus form fracture process zone [2], [3]. Other numerical analysis [4] of a notched beam based on a three-dimensional meso-scale model of concrete fracture using cohesive interface elements shows the dependence of the beam's strength, brittleness and macro-crack propagation on the tensile strength and fracture energy of the ITZ.

The aim of this paper is to demonstrate the influence of the ITZ on the fracture behaviour of cement composite by means of finite element method principles and to estimate the ITZ's fracture parameter. Understanding the ITZ's formation and identifying ITZ's mechanical-fracture parameters are key to explaining the fracture process zone formation.

2. Theoretical background

2.1. Aggregate-matrix interface

At the aggregate-matrix interface, primarily around coarse aggregate grains or steel reinforcement, there is a layer of about 50 μm in thickness called the Interfacial Transition Zone (ITZ) [1], [5] with significantly different microstructure, than the surrounding matrix. Although ITZ is defined as a separate phase in our numerical model, it is a region of transition in fact [5]. The ITZ is formed mainly by ettringite needles and portlandite plates (see Fig. 1) while the bulk matrix is formed mainly by C-S-H gel. Basic property of the ITZ is its higher local porosity, which leads to lower values of mechanical-fracture parameters of the ITZ. Bourdette et al. [6] estimated the local porosity of the ITZ of about 3 times higher than porosity of the bulk matrix. Many of publications e.g. [7], [8] concerned with mechanical properties of the ITZ are connected with homogenization techniques, which estimate the Young's modulus value of ITZ as a 50 % value of the matrix modulus. However, the local elasticity of the ITZ used in this paper was assessed by nanoindentation technique [9].

The ITZ can be considered as the "weakest element" [5] in cementitious composites because it forms a stress concentrator which determines the structure's service life.

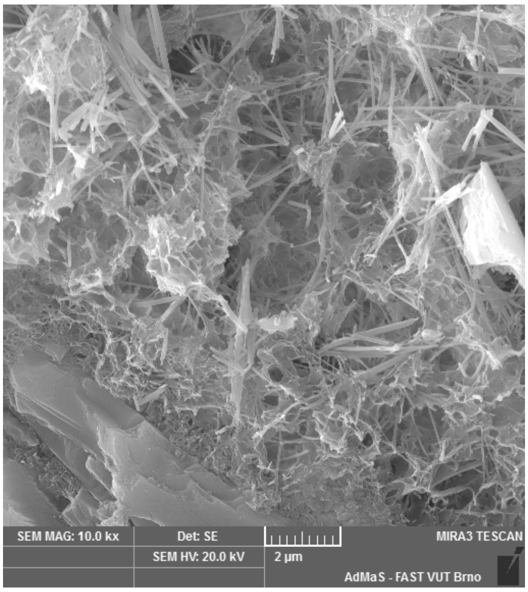

Fig. 1: Microstructure of the ITZ near an amphibolite inclusion measured by scanning electron microscopy.

2.2. Fracture Mechanics

Fracture mechanics is widely used as a requisite tool to prevent or predict catastrophic failures of man-made structures [10], [11]. Fracture mechanics deals with cracks present in structures since production or initiated in places of stress concentrations during operation. Fracture mechanics together with a finite element method (FEM) is a powerful tool for the assessment of structures behaviour and determining the durability within the structure's service life.

Generalized linear elastic fracture mechanics (GLEFM) deals with the study of stress and displacement fields and with the study of crack initiation in a vicinity of general singular stress concentrators (GSSC), such as bi-material interfaces, sharp notches, free edge singularities, etc., [12]-[16]. In this paper, the modified MTS (maximum tangential stress) criterion [17]-[23], which was designed for general singular stress concentrators, is used as a condition of stability. The stability of GSSC expresses conditions under which a crack is not initiated in the point of GSSC. The stability condition is related to the average tangential stress $\bar{\sigma}_{\theta\theta}(\theta)$ calculated across a distance d ahead of the crack tip [13], [21]. The distance d is usually chosen in dependence on the mechanism of a rupture (supposed finite crack initiation increment, the dimension of a plastic zone in fatigue metals, material grain size in case of brittle fracture etc.) [24]. The average tangential stress ahead of the crack tip is given by expression:

$$\bar{\sigma}_{\theta\theta}(\theta) = \frac{1}{d}\int_0^d \sigma_{\theta\theta}(r,\theta)dr \tag{1}$$

where $\bar{\sigma}_{\theta\theta}(\theta)$ is the average tangential stress in (MPa), d is a distance ahead of the crack tip in (m), $\sigma_{\theta\theta}(r,\theta)$ is tangential stress in dependence on polar coordinates r, θ in (MPa).

Following the theory of maximum tangential stress postulated for crack propagation path determination [25], the crack initiation direction in case of GSSCs can be determined from the maximum of the average value of tangential stress:

$$\left(\frac{\partial\bar{\sigma}_{\theta\theta}}{\partial\theta}\right)_{\theta_0} = 0 \wedge \left(\frac{\partial^2\bar{\sigma}_{\theta\theta}}{\partial\theta^2}\right)_{\theta_0} < 0 \tag{2}$$

The critical value of tangential stress depends on material and is gained for a crack propagating in homogeneous material under fracture mode I by the expression [13]:

$$\bar{\sigma}_{\theta\theta,c} = \frac{2K_{\mathrm{Ic}}}{\sqrt{2\pi d}} \tag{3}$$

where $\bar{\sigma}_{\theta\theta,c}(\theta)$ is the critical value of average tangential stress in (MPa), K_{Ic} is fracture toughness of the material ahead of the crack tip in $(\mathrm{MPa}\cdot\mathrm{m}^{\frac{1}{2}})$.

According to the criterion of critical quantity described in [26] this value can be used to determine conditions under which an existing crack propagates or new crack initiates in GSSC tip. The material ahead of such stress concentrator fails when the mean value of tangential stress in the region of the size d exceeds the critical value:

$$\bar{\sigma}_{\theta\theta} \geq \bar{\sigma}_{\theta\theta,c} \tag{4}$$

3. Experimental programme

To determine the influence of the ITZ on the fracture behaviour of cement composite, the experimental programme was carried out on specially designed beam specimens with the dimensions *40×40×160* mm and with polygonal amphibolite prismatic inclusion of *8×8×40* mm, see Fig. 2. The matrix of the test specimens was manufactured from fine-grained cement-based composite [27]. The amphibolite inclusion was fixed in its position in the moulds before the specimens casting by adhesive tape so the compaction could not be done by vibration.

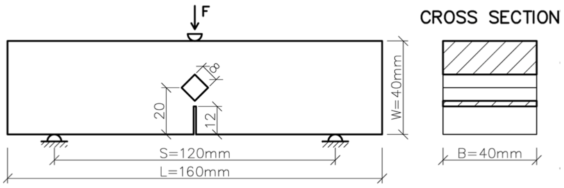

Fig. 2: Specimen geometry and the three-point bending fracture test configuration [28].

Before fracture tests, the specimens were provided with an initial central edge notch with a depth a_0 of 12 mm, which was made by a diamond blade saw. Fracture tests were conducted on these specimens via three-point bending with the incremental displacement loading. The diagrams *L–d* (load vs. displacement, i. e. deflection at midspan) and *L–CMOD* (load vs. crack mouth opening displacement) were recorded. However, only a development of the load *L* in (kN) depending on the value of crack mouth opening displacement *CMOD* in (mm) are presented in this paper. See [27] for more details.

3.1. Results of fracture tests

Figure 3 shows a development of the *L* depending on the value of *CMOD* recorded during fracture tests. The ascending branch is almost linear with the maximum force values between 0.47 and 0.60 kN. The descending branch contains local peaks with the maximal force values between 0.46 and 0.50 kN. These local extremes are not typical for quasi-brittle behaviour of cementitious composites and thus it is important to deal with them.

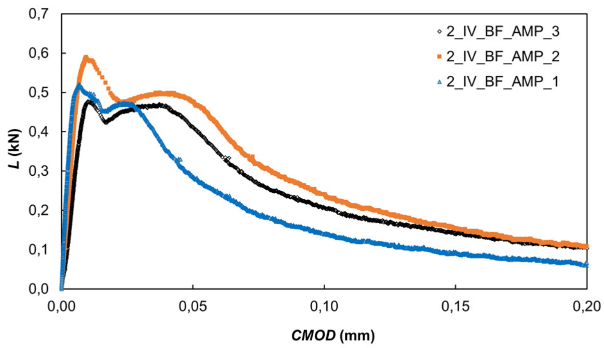

Fig. 3: Graph describing a development of the variable *L* (kN) depending on the value of *CMOD* (mm).

The observed crack propagation path during fracture test is shown in Fig. 4. Knowledge of crack propagation path is important for the design of a numerical model and for its evaluation. It will be shown in the numerical calculation that the observed crack propagation path is caused by a lower mechanical-fracture parameter of the interface than the surrounding matrix.

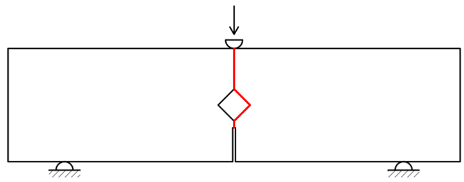

Fig. 4: Crack propagation observed during fracture tests.

The fractured specimens can be seen in Fig. 5. The interface between inclusion and matrix is very porous with cavities/pores especially in the lower part of the interface. From this figure, we suppose that the adhesion between inclusion and ITZ was very poor due to the impossibility of compaction by vibration. Lower values of adhesion could cause debonding in the areas of higher tensile stresses during fracture tests.

Fig. 5: Broken specimens.

4. Numerical study

A simplified 2D model of plane strain conditions was created in Ansys, Inc. software. The geometry corresponds to the specimen's dimensions and boundary conditions, see Fig. 6.

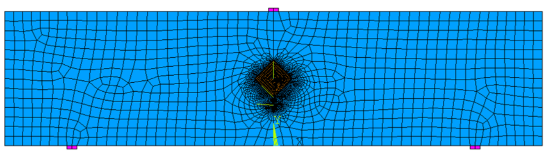

Fig. 6: A simplified 2D model of the cracked specimen.

The crack was modelled as ideally sharp with highly refined mesh around the crack tip with small elements in all directions, see Fig. 7.

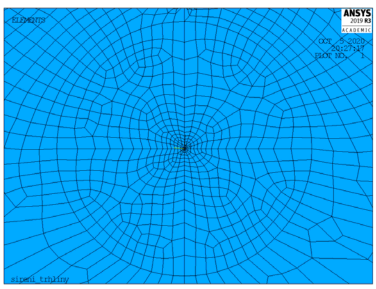

Fig. 7: Radial mesh around the crack tip.

Due to the application of the modified MTS criterion for a crack propagation assessment, the materials were modelled as linear, elastic and isotropic. Thus, only three material parameters – Poisson's ratio ν, Young's modulus E and fracture toughness – were required, see Tab. 1.

Local mechanical properties of the ITZ, such as Young's modulus, hardness and viscous properties, were assessed by nanoindentation technique. See [9] for more details.

Tab. 1: Overview of the materials' parameters used in the numerical model.

Layer	***E*** **(GPa)**	***ν*** **(–)**	K_{Ic} **(MPa·m$^{\frac{1}{2}}$)**
Matrix	44.04	0.20	0.50
Aggregate	143	0.16	3.37
ITZ	25.39 [27]	0.20	Unknown
Steel plates	210	0.30	

The force loading was applied to the top plate. When applying this force, the thickness of the model that is equal to *B=1.0* m must be considered. To achieve the same stress field in model as in real experiments, the equality of stress acting on the top plate must be satisfied.

4.1. Results of numerical study

Calculated crack propagation paths are shown in the Fig. 8. The green dashed line is for ideal adhesion between aggregate and ITZ with the fracture parameters of ITZ equal to that of matrix. On the other hand, the red line is the crack propagation path calculated for imperfect bonding. The fracture parameter of the bond was calculated from the known crack propagation path observed during fracture tests. The estimation works on the presumption that we compare known critical load at the right edge of the inclusion and the average tangential stress in the direction of the aggregate-matrix interface. The value of the fracture toughness of the ITZ was estimated as 0.37 $(\mathrm{MPa}\cdot\mathrm{m}^{\frac{1}{2}})$. This value resulted from an inverse numerical analysis with the following inputs: known experimental results and the stress field ahead of the crack propagating along the aggregate-ITZ interface.

Nevertheless, two more corrections were included in the analysis. The first one was the change of the initial central edge notch depth. In the previously published paper [28], it was found out that the real depth is between 13 and 13.5 mm instead of 12 mm. In the current model, crack depth was considered as 13.5 mm. The extension of the initial crack length from 12 to 13.5 mm is due to the small distance between the crack tip (front) and the bottom edge of the amphibolite inclusion, which cannot resist the load that is caused by cutting the specimen by diamond saw blade and must inevitably lead to its partial failure. See [28] for more details.

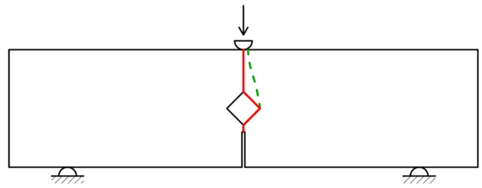

Fig. 8: Crack propagation path observed from numerical model for ideal (green dashed line) and imperfect (red line) bond.

The second correction is realized by an initial one-side debonding in the vicinity of the bottom edge of the inclusion. The debonding was included in the model because of imperfect compaction of fresh mixture and a smooth surface of the inclusion. One-side debonding of approximately 75 % of the inclusion's dimension was considered.

Final calculated diagram of *L* depending on the *CMOD* is shown in Fig. 9. The second peak point corresponds to the change of the crack propagation direction at the right edge (corner) of the inclusion. As it can be seen, the values of the load *L* are similar to the measured ones, while the values of the crack mouth opening displacement *CMOD* are different. The inaccuracy of the calculations is caused by an application of the linear elastic fracture mechanics (LEFM) principles, which do not take tensile softening into consideration. Since we do not know all the mechanical-fracture parameters needed for advanced material models, this simple engineering criterion appears to be the best choice for the initial estimation of the fracture behaviour of specimens with inclusion and for the quantification of the mechanical-fracture parameters of the ITZ.

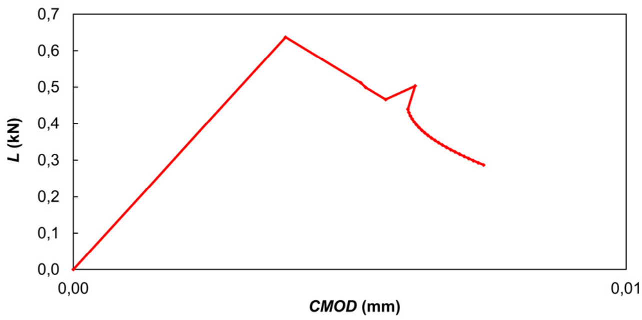

Fig. 9: Results of the FE simulation – A graph describing a development of the variable *L* (kN) depending on the value of *CMOD* (mm).

5. Discussion

The similar results as in our study were obtained by Vervuurt and Van Mier in **Chyba! Nenalezen zdroj odkazů.**. In their case, the interface fracture was obtained by a splitting load under *CMOD* control. They have also performed a real-time crack propagation measurement by a high-resolution long-distance optical microscope. In their diagrams of *L* depending on *CMOD* also two peaks can be distinguished similarly as in our current paper. The first peak was observed as soon as the crack initiated at the notch of the specimen. After a drop of the load, a second ascending branch was observed with a peak which occurred when the crack changed its propagation direction. These results are almost identical to the results of numerical simulations presented in this paper.

6. Conclusion

From the detailed numerical analysis of the described fracture test, we conclude that the process of debonding between inclusion and matrix occurred and that the actual crack depth a_0 had to be greater than expected. This phenomenon was observed also in the case of specimen with cavity – see [28]. In other words, the diamond saw blade damaged the specimen more than expected. This damage is due to the small distance between the bottom edge of the amphibolite inclusion and the crack tip (front), which is approximately 2.34 mm. It is obvious that such a small area above the crack tip cannot resist the load that is caused by cutting the specimen by diamond saw blade and must inevitably lead to its partial failure. Debonding of the aggregate and the matrix is caused by the smooth contact area between the inclusion and the surrounding matrix with poor adhesion and imperfect compaction of the fresh mixture. Fracture toughness of the interface was estimated as 0.37 $(\mathrm{MPa}\cdot\mathrm{m}^{\frac{1}{2}})$ at the most.

From the numerical analysis, we also conclude that the second peak of diagram of load depending on crack mouth opening displacement occurred when the crack changed the propagation direction at the right edge of the inclusion.

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