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INTERACTION BETWEEN EDGE-CRACK AND AGGREGATE IN SILICATE-BASED COMPOSITE

Abstract

The paper deals with investigation of the interaction between an edge-crack and an aggregate in a silicate-based composite, because adding of aggregates into basic matrix material can improve the fracture mechanical properties of the material significantly. In this work, the three-point-bending test is modelled by means of the finite element method and the dependences of fracture parameters on various material and geometrical parameters of the aggregate and the interfacial transition zone are studied. The results are discussed thoroughly.

Keywords

Silicate-based composite, crack, aggregate, interfacial transition zone, finite element method.

1 INTRODUCTION

The presence of aggregates (AGG) in the silicate-based matrix (MTX) represents a very useful tool how to affect the fracture properties of the composite in comparison to the original material. Beside the presence of the aggregates, also the so-called interfacial transition zone (ITZ), which arises at the AGG surface as a product of chemical reactions taking place between the AGG and MTX, plays a key role. Several studies on the influence of the particle size, shape, properties etc. can be found in recent works, see e.g. [1][2][3][4]. Note that most of them are performed on polymer composites. In some of the papers referred show that the presence of the AGG and ITZ affects the crack path through the specimen. The main objective of this paper is the analysis of the interaction between the macro-crack and a circular aggregate and/or ITZ. The paper presents a parametrical study and the influence of the selected parameters of AGG and ITZ on the initial crack propagation in a three-point bending test specimen is observed and discussed. The classical linear elastic fracture mechanics (LEFM) concept [5][6] is utilized for the investigations.

2 BASIC TERMS AND PROCEDURES

The presence of a crack in a specimen/material influences its lifetime strongly, because it acts as a stress concentrator. The fracture mechanics theory deals with description of the crack behaviour and one of the basic principles assumes that three various loading modes can be distinguished: normal, shear and anti-plane shear mode, see Fig. 1.

Combination of the individual loading modes occurs very often in technical praxis. The classical one-parameter linear elastic fracture mechanics introduces the so-called stress intensity factor (SIF) that describes the amplitude of the stress concentration ahead of the crack tip and it corresponds to each loading mode. Several fracture criteria deciding about the crack stability and/or

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crack propagation direction are formulated based on the SIF concept. While the SIF values for simple geometrical configuration can be found in fracture mechanics handbooks (see e.g. [7]), more complex configurations and/or non-homogeneous specimens need to be solved via numerical methods. There exists several methods, the well-known can be for example: compliance method (the double calculation method) [8], virtual displacements method [9][10], Rice *J*-integral method [11], hybrid rack elements method [12] and others. The method using the shifted mid-side in the finite element (FE) model is applied in this work.

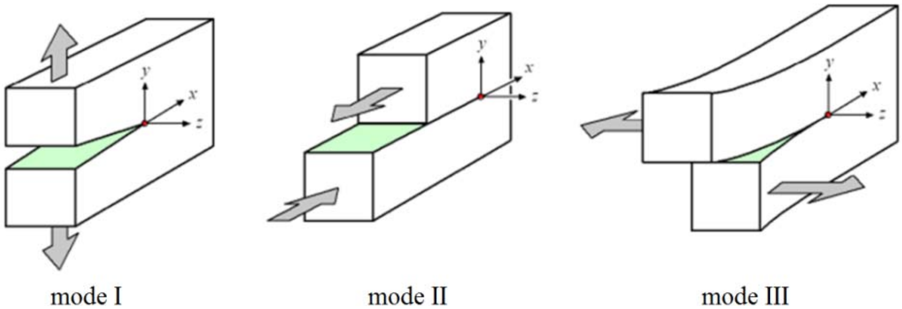

Fig. 1: Loading modes defined in fracture mechanics

2.1 The stress intensity factor

The stress intensity factor is defined in order to describe the singular stress field near the crack tip. When a plane problem is considered and the combination of mode I and II occurs, the principle of superposition can be applied and the stress tensor components can be written in a form:

$$\sigma_{ij} = \frac{K_{\mathrm{I}}}{\sqrt{2\pi r}} \cdot f_{\mathrm{I},ij} + \frac{K_{\mathrm{II}}}{\sqrt{2\pi r}} \cdot f_{\mathrm{II},ij} \tag{1}$$

where

K_{I} – is mode I stress intensity factor [MPa.m$^{1/2}$],

K_{II} – is mode II stress intensity factor [MPa.m$^{1/2}$],

r – radial distance from the crack tip [m],

$f_{\mathrm{I},ij}$ – geometrical factor corresponding to mode I and stress tensor component σ_{ij} [-],

$f_{\mathrm{II},ij}$ – geometrical factor corresponding to mode II and stress tensor component σ_{ij} [-].

3 GEOMETRY AND NUMERICAL MODEL

3.1 Geometry of the cracked specimen under study

A three-point bending test geometry was chosen for the study on the influence of the aggregate on crack propagation, see Fig. 2.

The particular dimensions were chosen as: the half specimen length $L = 80$ mm, the half supports span $S = 60$ mm, the specimen width $W = 40$ mm, the crack length $a = 12$ mm, the transition zone thickness $t_{ITZ} = 100$ µm, the applied load value $F = 1$ kN, Young's modulus of MTX $E_{\mathrm{MTX}} = 30$ GPa (corresponds to cement paste properties), Young's modulus of AGG $E_{\mathrm{AGG}} = 60$ GPa (corresponds to basalt properties), dimensionless Poisson's ratio for all the materials $\nu = 0.2$. The above mentioned values were kept constant which was based on the previous analyses [13]. On the other hand, following values were varied in the parametrical study performed:

- elastic properties of ITZ (Young's modulus), E_{ITZ}: 10, 30 a 60 GPa;
- diameter of the aggregate, d_{AGG}: 4, 8 a 12 mm;

- AGG eccentricity from the symmetry axis of the specimen, *e*: 0.1; 0.5; 1; 2; 4; 7; 10 mm see Fig. 2;
- AGG depth in the specimen, *v*: in the range from 14.3 to 21.7 mm in dependence on the AGG diameter.

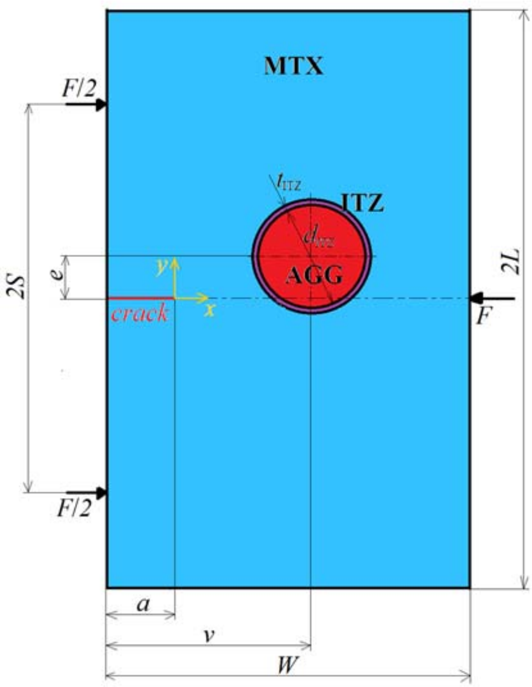

Fig. 2: Schema of the cracked specimen with an eccentrically placed aggregate subjected to three-point bending

3.2 Numerical model

A numerical model with respect to the suggested geometry was created in the finite element software ANSYS [14]. The eight-node plane elements with quadratic basis functions denoted as PLANE82 were used. The FE mesh was refined in the very vicinity of the crack tip and the first row of elements around the crack tip was meshed with the special crack elements with shifted mid-side nodes, which were proposed for fracture mechanics task when the stress singularity needs to be modelled. The plane strain conditions were accepted for the model.

4 RESULTS AND DISCUSSION

It was already mentioned in the previous sections that the intensity of the singular stress field ahead of the crack tip can be described by means of the stress intensity factors. Therefore, these values were observed within the numerical study in dependence on various selected parameters, see Fig. 3 and 4. Only few representative configurations were chosen for presentation and discussion of the results in this paper.

Fig. 3 shows the normalized stress intensity factors $K_{\mathrm{I,norm}}$, i.e. the K_{I} values divided by the $K_{\mathrm{I,hom}}$ value (value of the stress intensity factor corresponding to the homogeneous specimen without AGG and ITZ). On the other hand, Fig. 4 shows the dependences of the K_{II} values, which are not normalized, because there does not occur the shear mode in the homogeneous cracked configurations. Both figures are plotted for AGG diameters 12 and 4 mm and Young's modulus of ITZ 10 and 60 GPa. The study presents the dependences of the $K_{\mathrm{I,norm}}$ a K_{II} values on the relative distance of the AGG from the specimen surface taking into account various AGG eccentricities from the axis of symmetry of the specimen.

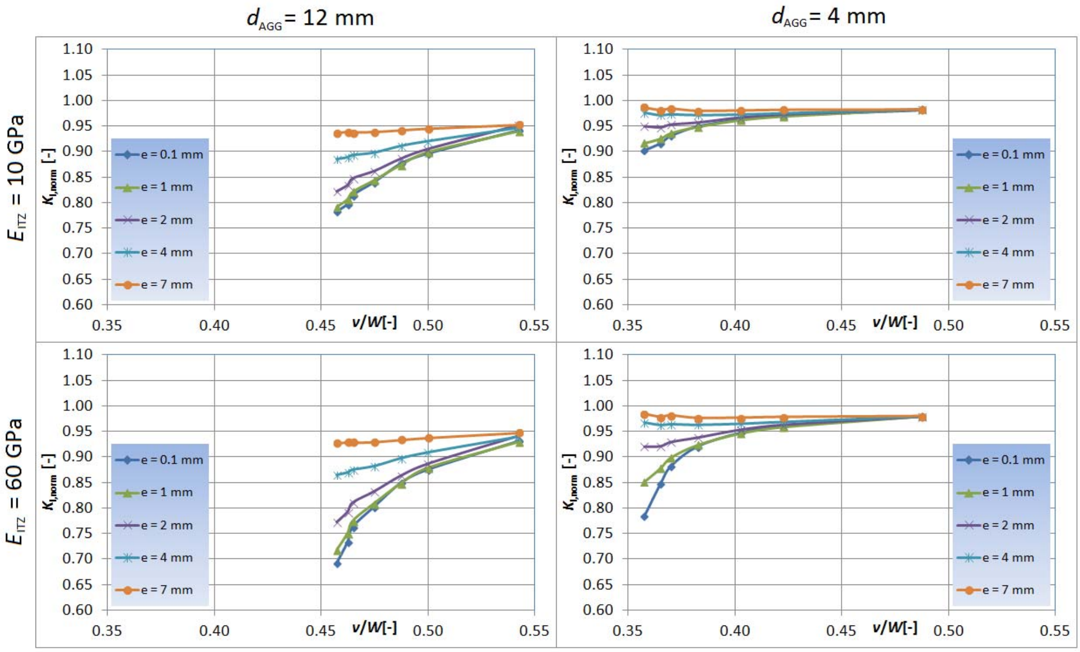

Fig. 3: Dependences of the normalized SIF $K_{I,norm}$ on the relative depth of AGG from the specimen surface. The individual colour curves correspond to configurations with different AGG eccentricities; configurations with AGG diameter of 12 mm on the left, with AGG diameter of 4 mm on the right; the upper plots correspond to E_{ITZ} = 10 GPa and the lower plots to E_{ITZ} = 60 GPa

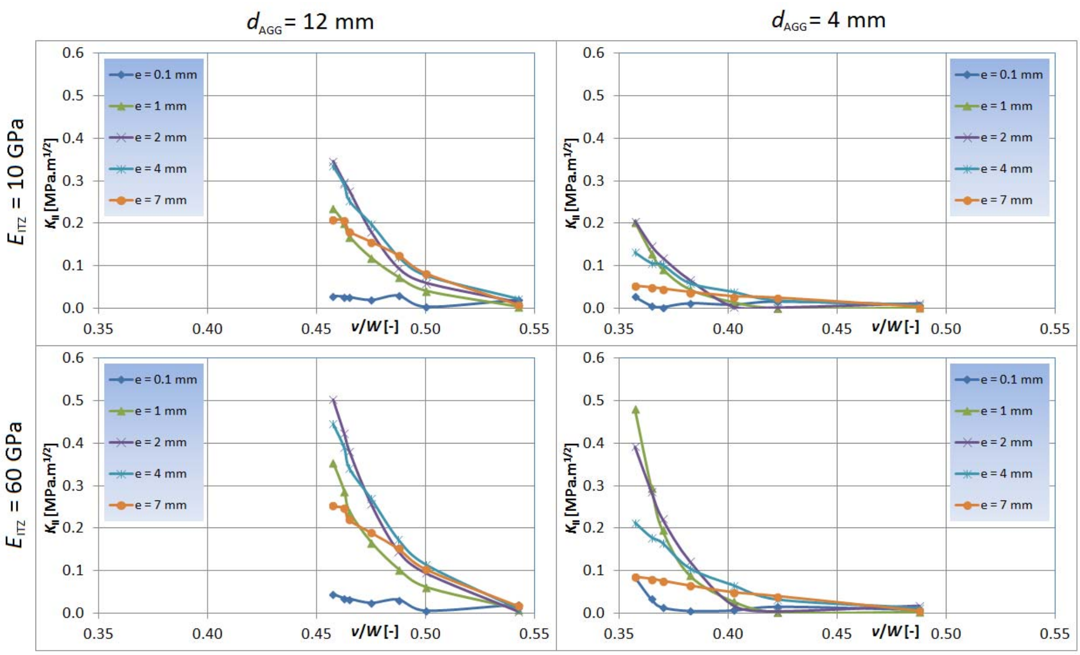

Fig. 3: Dependences of the SIF K_{II} on the relative depth of AGG from the specimen surface. The individual colour curves correspond to configurations with different AGG eccentricities; configurations with AGG diameter of 12 mm on the left, with AGG diameter of 4 mm on the right; the upper plots correspond to E_{ITZ} = 10 GPa and the lower plots to E_{ITZ} = 60 GPa

The following conclusions can be stated from the dependences obtained:

- Presence of the eccentrically placed aggregate ahead of the crack tip results in adding mode II to the pure I mode typical for a homogeneous specimen.
- Presence of the stiff aggregate ahead of the crack tip decreases the stress intensity factor value, K_I, i.e. it defends its propagation/slows it down.
- The larger the stiff aggregate, the higher influence on the stress intensity factor values: K_I values decrease, K_{II} values increase.
- The stiffness of the ITZ affects the K_I and K_{II} values as well: the stiffer ITZ causes higher decrease of K_I and higher increase of K_{II}.
- As it can be expected, it holds that the lower distance between the crack and aggregate produces the higher influence on the stress field distribution.
- In the case of mode I there exists also the unambiguous dependence on the eccentricity: the larger eccentricity of the aggregate, the lower effect on the stress redistribution near the crack tip.
- When mode II is observed, the biggest increase of the stress intensity factor is typical for configurations with the eccentricity between 1 and 4 mm (depending on other parameters).
- Based on the observed dependences, it can be seen that the existence of the aggregate in a cracked specimen can influence its behaviour: crack stability, crack propagation rate, crack path.

Generally, several cases of crack propagation through a composite can be observed: 1) the crack can deflect from the original direction when it is approaching the stiff aggregate and then it propagates through the matrix or 2) the crack can be attracted by the compliant ITZ, where the crack can be arrested or blunted as a result of debonding of the AGG and ITZ. The numerical analysis can help to decide about the crack behaviour, which can improve the process of designing of new advanced composite materials.

5 CONCLUSIONS

The contribution introduces a parametrical study when the basic fracture-mechanical properties are investigated (stress intensity factors K_I a K_{II}) in dependence on various material and geometrical characteristics of the cracked specimen. The analysis is performed considering the three-point bending test conditions. The crucial idea is the presence of an aggregate with a thin surface interfacial transition zone near a crack tip. The paper shows how the stiff aggregate together with ITZ influences the crack behaviour. Particularly, the influence of the aggregate size, ITZ stiffness and position (in two directions) of the aggregate in relation to the crack tip. It is shown that the mutual position between the crack and aggregate is fundamental for their interaction, i.e. the crack tip needs to be located close enough to the aggregate in order to observe the effect of the aggregate on the fracture behaviour of the crack (crack stability, crack propagation rate, crack path).

ACKNOWLEDGMENT

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LITERATURE

[1] TOGHO, K., FUJJI, T., KATO, D. and Y. SHIMAMURA. Influence of particle size and debonding damage on an elastic-plastic singular field around a crack-tip in particulate-reinforced composites. *Acta Mechanica*. 2014, 225, pp. 1373–1389.

[2] CHO, J., JOSHI, M.S. and C.T. SUN. Effect of inclusion size on the mechanical properties of polymeric composites with micro- and nanoparticles. *Composites Science and Technology*. 2006, 66, pp. 1941–1952.

[3] HUTAŘ, P., MAJER, Z., NÁHLÍK, L., ŠESTÁKOVÁ, L. and Z. KNÉSL. Influence of particle size on the fracture toughness of a PP-based particulate composite. *Mechanics of Composite Materials*. 2009, 45, 281–286.

[4] MAJER, Z., HUTAŘ, P. and L. NÁHLÍK. Determination of the effect of interphase on the fracture toughness and stiffness of a particulate polymer composite. *Mechanics of Composite Materials*. 2013, 49, 475–482.

[5] ANDERSON, T.L. *Fracture Mechanics: Fundamentals and Applications*, Boca Raton: CRC Press, 2004. ISBN 978-084931656-2. 640 p.

[6] ERDOGAN, F. and G.S. SIH. On the crack extension in plates under plane loading and transversal shear. *International Journal of Basic Engineering*. 1963, 85, pp. 519–527.

[7] MURAKAMI, Y. and Co-editors. *Stress intensity factors handbook Vol. 1*, Tokyo: Pergamon Press, 1987.

[8] DIXON, J. R. and J.S. STRANNIGAN. Determination of energy release rates and stress intensity factors by the finite element method. *Journal of Strain Analysis*. 1972, 7, pp. 125–131.

[9] HELLEN, T.K. On the method of virtual crack extensions. *International Journal of Numerical Method in Engineering*. 1975, 9, pp. 187–207.

[10] PARKS, D.M. A stiffness derivative finite element technique for determination of crack tip stress intensity factors. *International Journal of Fracture*. 1974, 10, pp. 487–502.

[11] RICE, J. R. and G. J. ROSENGREN. Plane strain deformation near a crack tip in a power-law hardening material. *Journal of the Mechanics and Physics of Solids.* 1968, 35, pp. 379–386.

[12] TONG, P., T.H.H. PIAN and S.J. LASRY. A hybrid-element approach to crack problems in plane elasticity. *International Journal for Numerical Methods in Engineering*. 1973, 7, pp. 297–308.

[13] MALÍKOVÁ, L., J. KLUSÁK and Z. KERŠNER. Assessment of crack stability in a quasi-brittle particle composite. *Procedia Engineering*. 2017, in print.

[14] ANSYS Program Documentation. User's manual version 10.0. Swanson Analysis System, Inc., Houston, 2005.