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Assessment of Crack Stability in a Quasi-brittle Particle Composite

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Abstract

Fracture behaviour of a crack in a particle (silicate based) composite is studied. The crack propagation depends not only on mutual elastic mismatch of matrix and aggregate but also the influence of the interfacial transition zone (ITZ) between the matrix and the aggregate is discussed. Various combinations of materials and geometry of matrix, aggregate and ITZ can improve or degrade fracture properties of the composite. Extensive numerical simulations on a basic 3-point-bending cracked specimen via the finite element method are performed in order to analyze the stress field near the crack tip. Linear elastic fracture mechanics approach is utilized in order to assess the crack stability and summarize several conclusions.

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Keywords: Stress intensity factor; Particle composite; Interfacial transition zone; Finite elements; Crack stability

1. Introduction

Silicate based (particularly cement-based) composites are definitely the most often used building materials with a specific fracture behaviour. Their mechanical fracture properties are strongly influenced (and can be partially controlled) by the presence of aggregates (AGG) in a matrix (MTX). The aggregates as well as the interfacial transition zone (ITZ) between AGG and MTX affect the crack propagation through the matrix and cause a non-linear response of the complex material. In this paper, the particular effect of the aggregate size, thickness and elastic properties of the ITZ on the crack stability is investigated via a parametric study. Classical linear elastic fracture mechanics (LEFM) approach [1,2] is considered and application of its generalized form is discussed with respect to both higher-order terms of the Williams expansion [3] and change of the singularity level [4,5] when the crack

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reaches some of the interfaces (MTX/ITZ or ITZ/AGG). The importance of the non-singular and higher-order terms of the Williams expansion has been described for instance in [6,7].

Nomenclature

3PB	3-point-bending test
AGG	aggregate
ITZ	interfacial transition zone
MTX	matrix
a	crack length
B_1	dimensionless parameter related to the stress intensity factor
d_{AGG}	diameter of the AGG
E_{AGG}	Young's modulus of the AGG
E_{ITZ}	Young's modulus of the ITZ layer
E_{MTX}	Young's modulus of the MTX
F	applied force in the 3PB test
K_{I}	stress intensity factor (mode I)
L	half specimen length
S	half span between the supports in the 3PB test
t	thickness of the specimen
t_{ITZ}	thickness of the ITZ layer
v	depth of the aggregate centre from the free surface of the specimen
W	specimen width
ν	Poisson's ratio (used for all the materials considered)
σ	nominal normal stress in the 3PB test

2. Parametrical study

It is stated in the previous section that both the AGG and the ITZ can influence the crack behaviour. In order to investigate the effect of various properties of AGG and ITZ on the crack propagation, a parametrical study has been performed. A simplified model of a 3-point-bending specimen with a crack propagating to the ITZ and AGG was prepared and following parameters were varied:

- Thickness of the ITZ layer, t_{ITZ}: 10, 50 and 100 μm;
- Elastic properties of the ITZ layer (Young's modulus), E_{ITZ}: 10, 30 and 60 GPa;
- Diameter of the AGG, d_{AGG}: 4, 8 and 12 mm.

Moreover, the AGG was considered to be placed at various depths v from the free surface. The other material and geometrical properties were kept constant; schema of the specimen can be found in Fig. 1 (due to the symmetry, only a half of the specimen could be modelled).

The particular values of the individual parameters were considered as follows: half specimen length $L = 80$ mm, half span between the supports $S = 60$ mm, specimen width $W = 40$ mm, crack length $a = 12$ mm, applied force $F = 1$ kN, Young's modulus of the matrix $E_{\mathrm{MTX}} = 30$ GPa (corresponds to cement paste properties), Young's modulus of the aggregate $E_{\mathrm{AGG}} = 60$ GPa (corresponds to basalt properties), dimensionless Poisson's ratio for all materials $\nu = 0.2$.

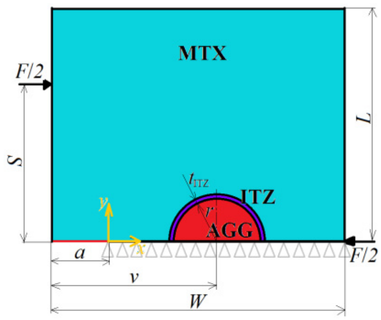

Fig. 1. Schema of the modelled 3-point-bending specimen with a crack of the length *a* approaching the ITZ layer and the aggregate.

The numerical model was created in ANSYS finite element (FE) software [8]. The specimen was meshed with PLANE82 elements, where the vicinity of the crack tip was specially refined: one row of special crack elements with shifted mid-side nodes was used around the crack tip in order to model the square root singularity. Plane strain conditions were set. Details of the numerical model (matrix containing the aggregate with a very thin ITZ layer) can be seen in Fig. 2.

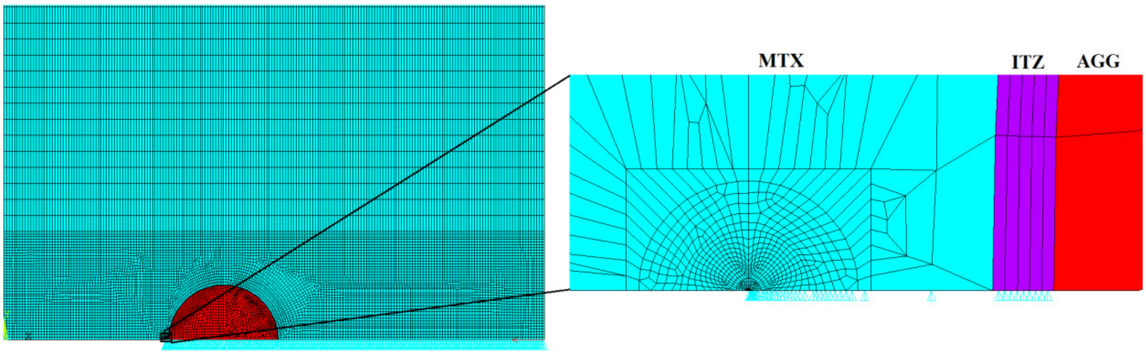

Fig. 2. Detail of the meshed numerical model of the three-phase (MTX/ITZ/AGG) cracked specimen near the crack tip.

In order to investigate how the presence of the AGG and ITZ, respectively influences the crack stability, the *K*-calibration curves have been built. Particularly, the dependences of the dimensionless parameter B_1 on the relative aggregate depth v/W were investigated. Values of the B_1 were calculated as:

$$B_1 = \frac{K_\mathrm{I}}{\sigma\sqrt{\pi a}} \quad \text{where} \quad \sigma = \frac{3SF}{tW^2}\,. \tag{1}$$

The meaning of the symbols a, S, F and W can be seen in Fig. 1; t denotes the thickness of the specimen and is considered to be equal to W; K_I represents the stress intensity factor and is determined numerically from the displacements of nodes at the crack faces directly in ANSYS FE code.

3. Results and discussion

This chapter contains the graphical results obtained and their thorough discussion. The dependences of the dimensionless parameter B_1 (sometimes also called as a geometrical factor/function) on the (relative) depth of the aggregate can be seen in Fig. 3. Various values of the ITZ thickness, AGG diameter and ITZ Young's modulus were considered and their influences on the crack stability were investigated.

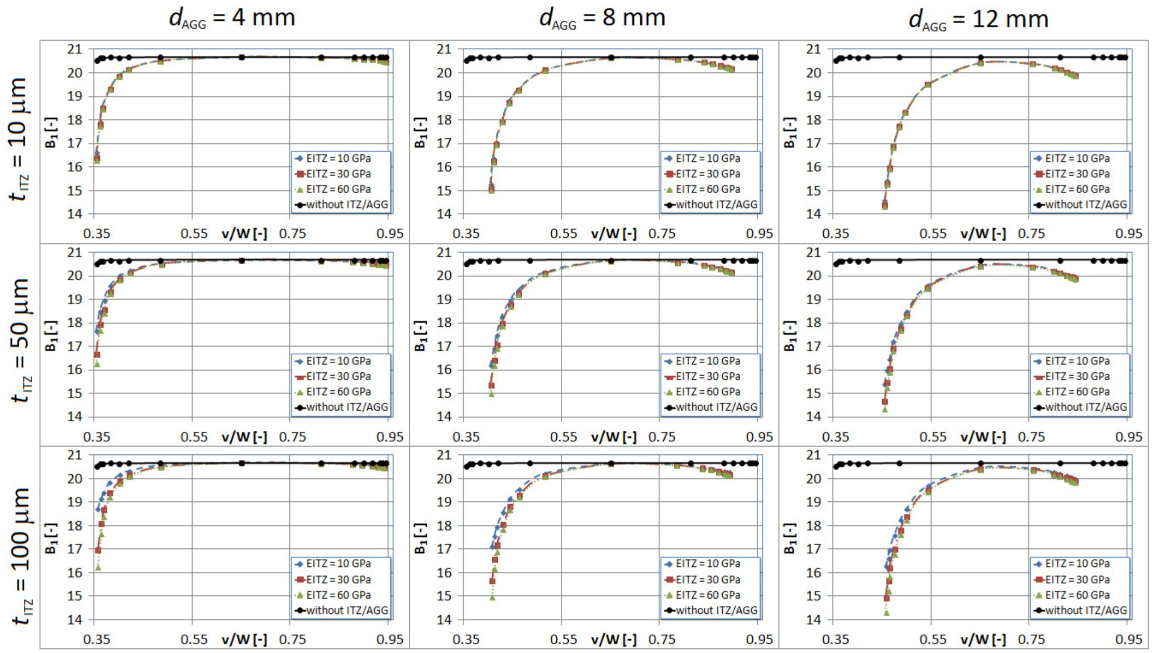

Fig. 3. The dependences of the dimensionless parameter B_1 (corresponds to the stress intensity factor K_I) on the relative depth of the aggregate for various values of the ITZ thickness, AGG diameter and ITZ Young's modulus.

Based on the curves plotted in Fig. 3, the following statements can be concluded:

- Regardless of the value of any other parameters, the presence of the stiff aggregate in the matrix (close to the crack) decreases the level of the stress concentration ahead of the crack tip, i.e. the stiff aggregate increases the crack stability and prevents the crack from its further propagation. This fundamental conclusion can be made by comparing the black curves for a crack in a homogeneous matrix (without ITZ and AGG) with the other ones in Fig. 3.
- The bigger (stiff) aggregates (with larger diameters), the lower stress intensity factors (and B_1) considering the same aggregate depth.
- The lower distance between the crack tip and the aggregate, the more significantly the AGG and ITZ affect the stress state ahead of the crack tip.
- If the aggregate is relatively small (d_{AGG} = 4 mm) and is located further from the crack tip, it does not influence neither the stress distribution at the crack tip nor the crack behaviour.
- The properties of the ITZ layer (thickness and Young's modulus) seem to have rather small effect on the crack stability among all the variables studied – it is caused probably by its very low thickness (in order of microns).
- If the ITZ layer is very thin (t_{ITZ} = 10 µm), it does not matter what its elastic properties are – the crack behaves always in the same manner.
- With increasing ITZ thickness the Young's modulus of the layer becomes more significant, where the low E_{ITZ} values support the crack propagation towards the ITZ layer. This can be sometimes desirable: the crack goes through the compliant layer, the energy is released and the crack is blunted when it reaches the ITZ/AGG interface and the aggregate can be fully debonded.

- It is always important to find a balance between the required mechanical fracture properties of the composite material (strength, fracture toughness, etc.).

It should be noted that the elementary results presented in the paper are going to be enhanced by a further research soon, primarily in the field of:

- Consideration not only the first singular term (stress intensity factor) of the series expansion derived for the crack-tip stress distribution because it has been proved that the higher-order terms can be very significant. It is expected that the interaction between the crack tip and the aggregate with the ITZ layer can be described better by means of the multi-parameter fracture mechanics approach.
- Applying the generalized fracture mechanics in the sense of considering the crack terminating directly at the MTX/ITZ and ITZ/AGG interface, respectively. Then, the crack behaviour can be studied in more complex way. Nevertheless, this very special configuration of a crack with its tip at the bi-material interface requires more advanced fracture-mechanics methods for assessment of the crack stability because the stress singularity differs from the ½ value. Based on the generalized fracture criteria, it can be decided if the crack stops at the interface, penetrates into the following layer or debonds the aggregate.

4. Conclusions

A numerical parametric study of a 3-point-bending cracked specimen has been performed in order to investigate the influence of the geometrical/material properties of the aggregate and the interfacial transition zone (ITZ) on the crack behaviour in the matrix. The pilot analyses show that the presence of a stiff particle near the crack tip in the matrix can enhance the crack stability because it decreases the values of the opening stress and stress intensity factor, respectively. Moreover, if the ITZ is thick enough, its low Young's modulus can lead to attracting the crack towards the AGG. When the crack reaches the interface, it can stop, penetrate or debond the aggregate and thus, the global fracture toughness of the composite increases. The crack behaviour directly at the interface will be studied intensively by means of the generalized fracture mechanics approach in the next step of the research.

Acknowledgements

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