

Features of the fracture of a material representing a matrix with a low-strength inclusion in a discrete element model

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A model of fracture for a material consisting of a matrix with an inclusion is constructed using the discrete element method. A material variant in which the inclusion has significantly lower strength and elastic modulus than the matrix is considered. It is shown that the properties of the boundary between the inclusion and the matrix have a decisive influence on the fracture development. In the opposite case, when a strong inclusion is located in a plastic matrix, regardless of the interface properties, the strong bonds with a high modulus are the first to fail.

Keywords: bonded particle model, fracture, material with inclusion, stress, deformation.

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1. Introduction

The discrete element method (DEM) has been widely used so far to describe the mechanical behavior of heterogeneous materials, including rocks [1–5]. The fundamental difference and benefit of this method, compared to the continuum mechanics representation models (e.g., [6]) is that it allows to naturally model the formation of a defect (crack).

The previous study [7] offered a model that adequately described some features of heterogeneous materials destruction in cases when the main processes occurred on the grain boundaries.

In this paper, the same model is used to identify the destruction specifics for a material that is itself a homogeneous matrix with an inclusion having lower strength and modulus. The focus on this kind of studies is related to the fact that the oil-bearing rocks containing oil and gas generally do not form a continuous layer in the oil and gas-bearing horizons, but are rather interlaid with other geological formations. Such combinations of layers are called oil and gas formations. The pay zones are generally surrounded by dense, low-permeable rocks, forming a kind of natural storage [8,9]. From this standpoint, the matrix–inclusion model can be considered as a first approximation of such formations.

The objective of this study is to determine the effect of the matrix–inclusion interface (boundary) on the specifics of the destruction process evolution.

2. Computer experiment

The computer experiment was organized similar to that described in [7]. We used the bonded particle model (BPM) that is described in detail in [10]. Material (rock) model —

spherical particles of the same or different sizes simulating grains and the inter-particles bonds simulating the grain boundaries.

The simulation experiments were carried out in MUSEN freeware package [11].

Cylindrical specimens 10 mm in diameter and 20 mm in height were modelled. In all specimens, the matrix was modeled by a set of particles having the orthoclase property. In specimens of I type the interface material (bonds connecting matrix particles and inclusions) is orthoclase, in specimens of II type — it is a low-modulus material (as is the inclusion). The specimens of each type of particle matrix had the same size — 1 or 0.8 mm, the total number of matrix particles — 1800 and 3514, respectively. An inclusion of irregular shape consisting of 192 particles connected by 467 bonds was placed in the specimen's center (Figure 1, *a*). The particles and bonds of inclusion have significantly lower strength and Young's modulus compared to the matrix. Physical and mechanical parameters of the materials that constitute the particles and bonds of the matrix and inclusion are listed in Table 3.

To simulate a uniaxial compression, the specimen was placed in a virtual press, the lower plate of which was fixed, and the upper plate moved inward at a constant speed of $V = 0.02$ m/s. The experiment was finished when the specimen was broken (separated into parts). During the experiment, a large set of various mechanical parameters was recorded at equal time periods to be further used in analysis. In the present study, such parameters included the coordinates of the centers of bonds broken during the specimen deformation, the time of rupture of these bonds, as well as the deformation and stresses in the bonds.

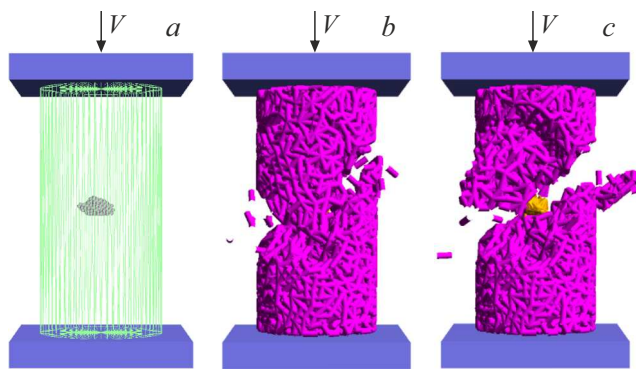


Figure 1. Specimen model with an inclusion: *a*) the inclusion is shown in gray (vertical green lines delineate the virtual cylinder); *b* and *c*) the specimen destruction images at consecutive points in time.

3. Results and discussion

Figure 2 shows typical mechanical stress changes during the experiment and bond breaking kinetics in both types of specimens ($t_{\text{norm}} = t/t_{\text{destruction}}$, where $t_{\text{destruction}}$ is the time when the specimen was broken into parts). Brittle fracture is observed here. In specimen of I type (interface — orthoclase), first, the low-modulus inclusion is destructed. In type II specimen (the interface consists of the low-modulus bonds) the opposite pattern can be traced: destruction begins in the matrix. This result is illustrated in Figure 3, which shows Z-coordinates (according to the height of the specimen) of the broken bonds.

To find out the reasons for the specimens different behavior the curves of maximum deformations and tensile stresses variations in the bonds were plotted (Figure 4).

In the specimen that has a strong interface up to a moment of drastic stress drop caused by the specimen's loss of load carrying capacity and separation into parts, the matrix deformation significantly exceeds the deformation

Properties of materials used for simulation

	ρ , kg/m ³	E , GPa	ν	σ_n , MPa	σ_t , MPa	η , Pa · s
Material of the matrix (orthoclase)	2560	62	0.29	420	420	1E19
Material inclusions (low-modulus)	2500	5.8	0.2	100	100	5E19
Glass	2500	50	0.22	50	50	1E40

Here: ρ — material density, E — Young's modulus, ν — Poisson's ratio, σ_n — material tensile strength, σ_t — shear strength of the material, η — dynamic viscosity.

of the inclusion. But since the strength of the inclusion is lower than the strength of the matrix, the inclusion is broken.

In the specimen with a low-modulus interface, the maximum deformation of the inclusion bonds significantly exceeds the deformation of the matrix bonds. Due to their low modulus, these bonds have the ability to deform without breaking. Therefore, first of all, the high-modulus (high-strength) orthoclase bonds of the matrix are destroyed (Figure 5).

In case of a low-modulus interface, the deformations of the interface are higher than in case of a strong interface. The bonds are most prone to deformation without breaking.

In the study [12], the destruction of a sample consisting of quartz, orthoclase, and oligoclase particles connected by strong and low-modulus bonds was investigated. In this specimen, the low-modulus bonds are randomly distributed, unlike the inclusion specimens described above. The kinetics of bond breakdown in this specimen is shown in Figure 6. It can be seen that highly strong bonds are broken first. Weaker bonds remain intact due to their deformation capability caused by low modulus of elasticity.

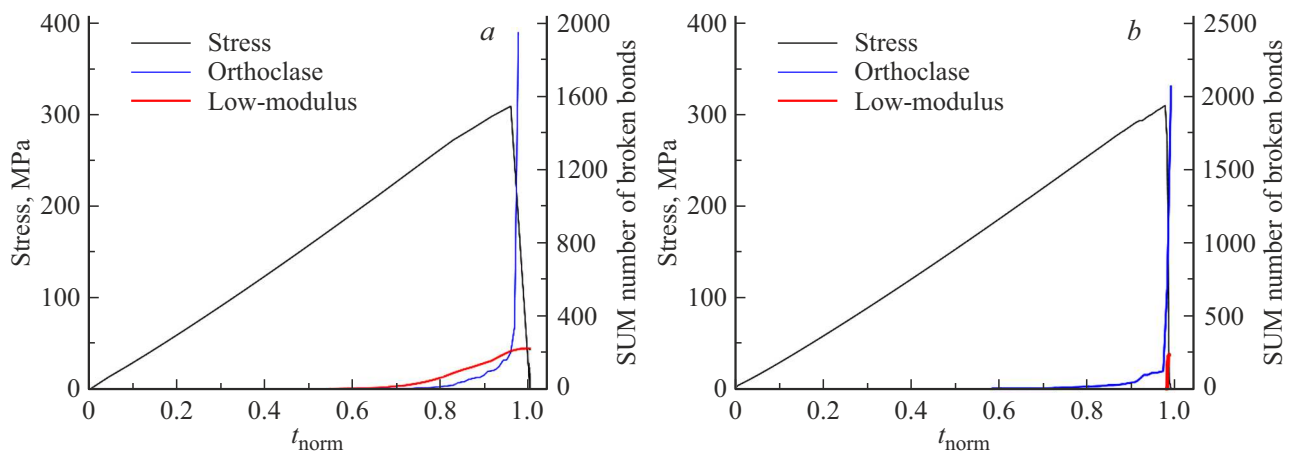


Figure 2. Typical specimens loading diagrams and kinetics of the bonds breaking: *a*) specimen of I type, *b*) specimen of II type.

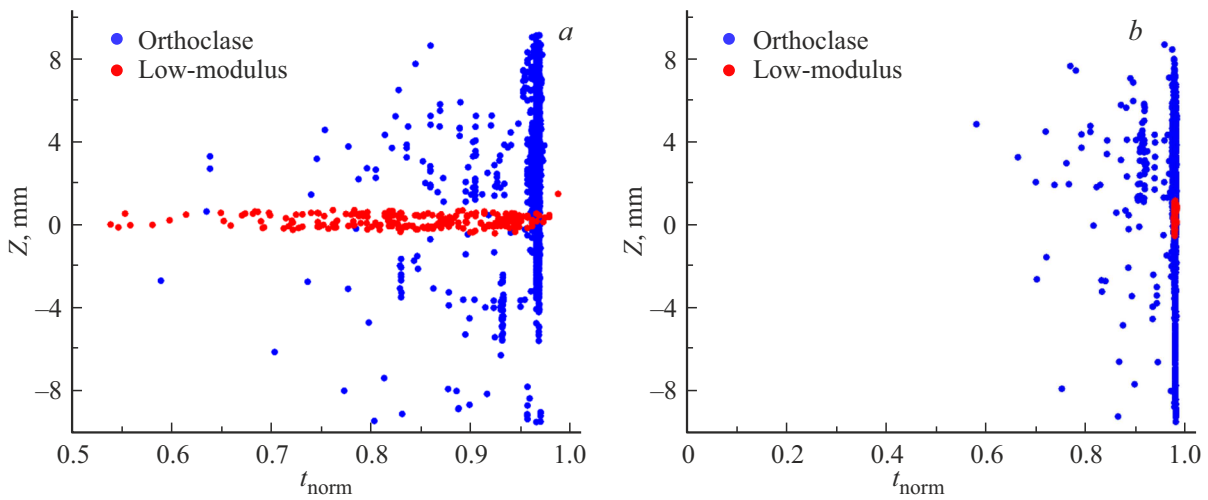


Figure 3. Z-coordinates of the destructed bonds during the experiment: a) specimen of I type, b) specimen of II type.

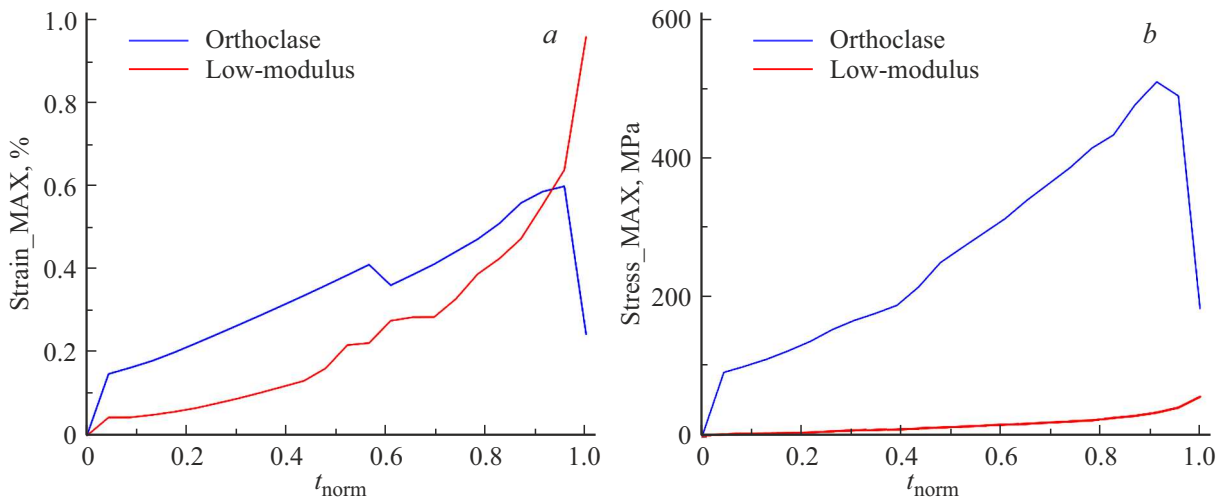


Figure 4. Changing the deformation and stress on the bonds during the specimen deformation with a strong interface.

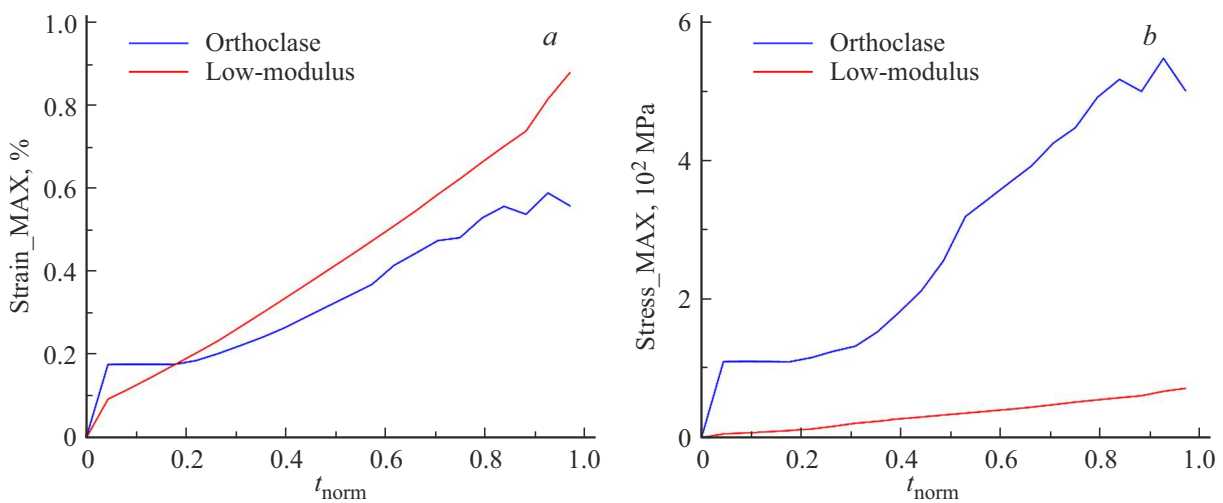


Figure 5. Changes of deformation and stress in the bonds during deformation of a specimen with a low-modulus interface.

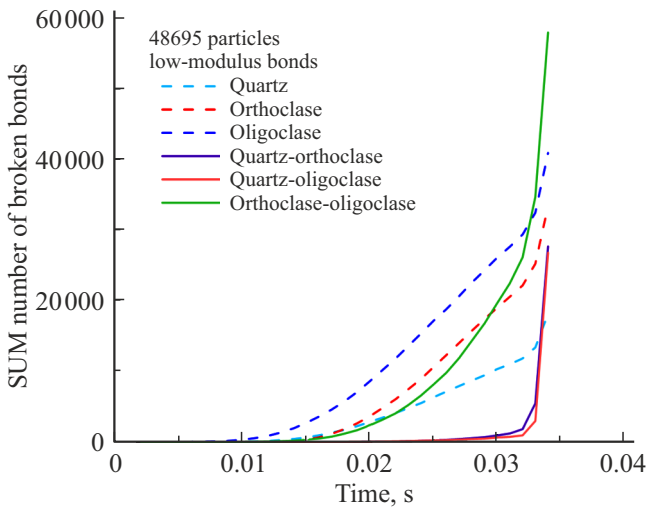


Figure 6. Kinetics of bond breakdown in a heterogeneous specimen without inclusions.

In order to more clearly identify the role of the boundary material between a low-modulus inclusion and a strong matrix, an experiment was conducted where the inclusion particles and the matrix were bound by brittle glass bonds (properties are shown in the table). In this case, as expected, the glass bonds are broken first (Figure 7), then the strong bonds of the matrix and the inclusion itself are destructed.

It is of interest to compare the destruction specifics of specimens with low-strength inclusions in a strong matrix and specimens with strong inclusions in a low-strength matrix, which is typical for composite materials with a plastic matrix reinforced with brittle strong inclusions. For this purpose, experiments were conducted with specimens in which the particles and bonds of the matrix had the properties of a low-modulus material (see the table), and the particles and bonds of the inclusion behaved like in orthoclase (see the table). In this case, as in the experiments described above, two types (boundaries

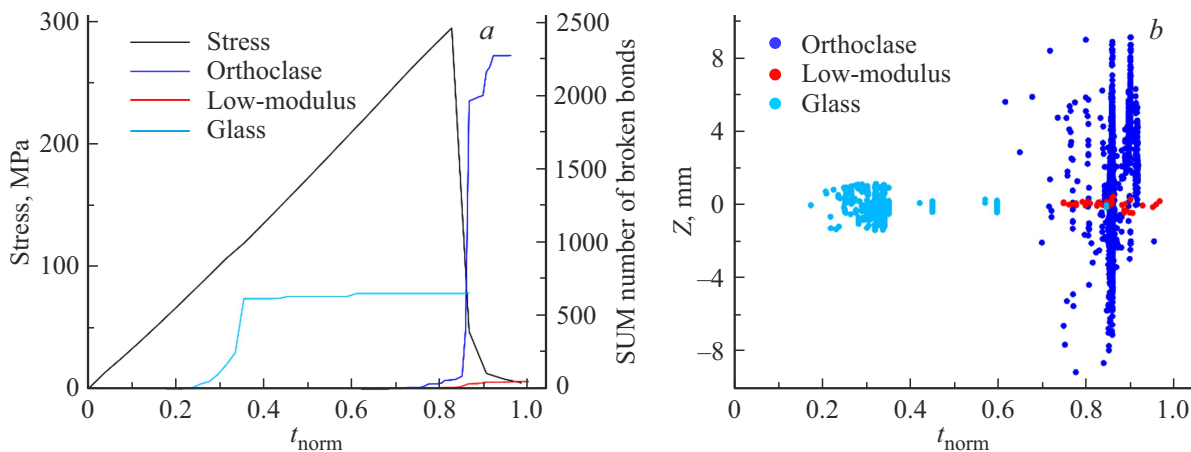


Figure 7. Deformations of a specimen with a glass interface between the inclusion and the matrix: *a*) voltage change and bond breaking kinetics; *b*) Z-coordinates of the breaking bonds.

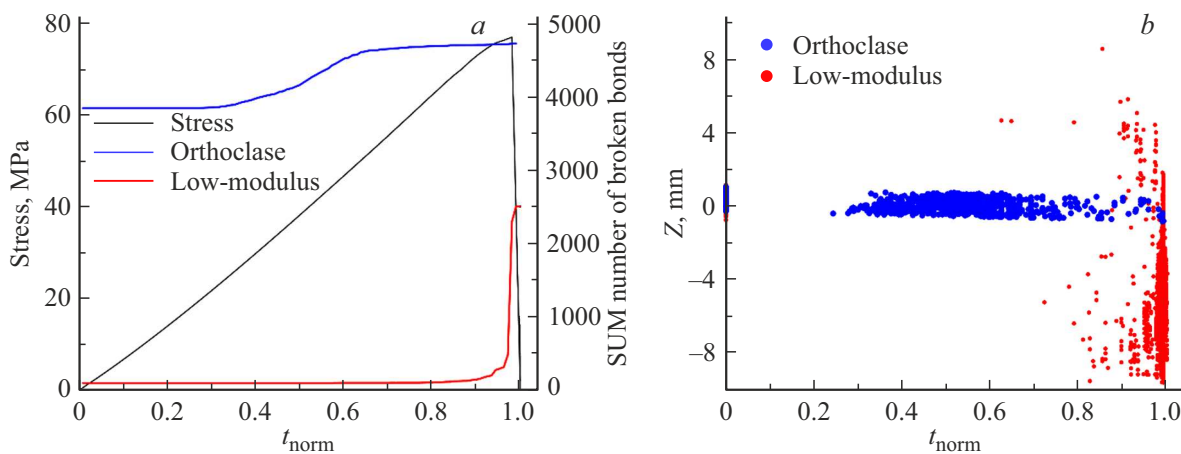


Figure 8. Deformation of type III specimen: *a*) voltage change and bond breaking kinetics; *b*) Z-coordinates of the breaking bonds.

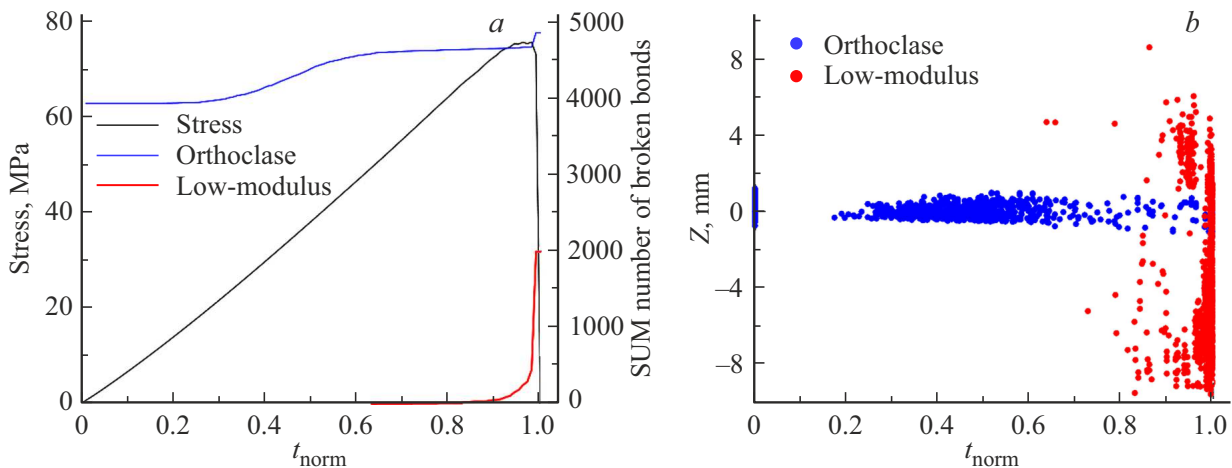


Figure 9. Deformation of IV type specimen: a) voltage change and bond breaking kinetics; b) Z-coordinates of the breaking bonds.

between the inclusion and the matrix) were considered: in specimens of type III, the interface material is low-modulus, the specimens of type IV have a strong interface (orthoclase).

Figure 8, a shows the change in stress and the kinetics of bond failure during deformation of a type III specimen. It can be seen that highly strong bonds connecting the inclusion's particles are broken first. This result is illustrated in Figure 8 b, which shows Z-coordinates (according to the height of the bonds being broken).

We see a similar pattern in case of damage of IV type specimens (Figure 9).

Thus, in case of a strong inclusion in a low-module matrix, regardless of the properties of the interface, strong bonds with a high module are destroyed first.

4. Conclusion

A computer model based on the discrete element method is constructed, which makes it possible to identify the features of fracture development in materials that are a homogeneous matrix with an embedded inclusion differing in physical and mechanical properties. The influence of interface properties (matrix-inclusion boundary) on the development of the destruction process is studied. Two types of materials are considered: I type — the inclusion has a lower modulus of elasticity and ultimate strength compared to the matrix material; II type — strong inclusion in a plasticity matrix.

It was found that in I type material, in case of a strong interface, low-modulus inclusion is primarily broken. If the interface has a lower modulus and strength compared to the matrix, then the high-modulus (high-strength) bonds of the matrix are broken first. Thus, the computer experiments made it possible to identify the determining role of the properties of the inclusion-matrix boundary and the matrix in progress of destruction.

In material of II type regardless of the properties of the interface, strong bonds with a high modulus are destructed first.

Conflict of interest

The authors declare that there is no conflict of interest.

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