Analysis of Damage Parameters of Marble Under Uniaxial Compressive Loading Using Grain-Based Finite Element Simulation and a Damage Constitutive Model

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ABSTRACT

In this study, the damage of a type of marble under uniaxial compressive loading was investigated using grain-based finite element simulations and a damage constitutive model. Accordingly, 40 Voronoi networks with different structural configurations with low and high joint densities were generated using the Phase2 software. Then, based on the calibrated parameters, uniaxial compression tests were numerically simulated on the generated networks. Finally, by utilizing the stress-strain curves derived from the numerical simulations and extracting the initial and damage moduli, the damage variable values were calculated as a function of strain. The results indicated that with an increase in the Voronoi joint density of the networks, the average values of both the initial and damage moduli decreased. Next, it was observed that with increasing strain up to a certain threshold, the damage variable increased gradually with a gentle slope. However, after reaching a critical strain value, the damage variable increased sharply with a very steep slope. This point, at which the damage begins to increase suddenly and rapidly, represents the onset of significant damage experienced by the rock specimen under uniaxial compressive conditions. Moreover, analysis of the failure patterns showed that tensile failures in networks with high Voronoi density occurred more frequently than in those with low density. Therefore, it can be concluded that the internal grain-based structure of rocks plays a crucial role in determining the extent of internal damage, failure patterns, and the dominant failure modes of rocks under uniaxial compressive loading conditions.

KEYWORDS

Grain-based finite element simulation, Damage, Uniaxial compression, Tensile failure, Voronoi structure

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1. Introduction

The study of damage in rocks under various loading conditions is mainly conducted through laboratory methods and numerical simulations utilizing statistical techniques. Accordingly, several investigations have been carried out to examine the damage parameters of rocks with different geological origins under various loading conditions. For example, Wang et al. [1], in an experimental study, proposed a structural damage model for salt rock under uniaxial compressive loading based on the continuum damage mechanics theory. Their results showed that the proposed model can accurately describe and predict the stress-strain behavior during the failure process of rock salt at different loading rates. Du et al. [2] developed new damage models to identify the stress threshold of rocks under uniaxial compressive loading. Their findings revealed that the theoretical stress-strain curves obtained from the two structural damage models were in good agreement with the experimental data, and the differences between the two models mainly arose from the distinct evolutionary characteristics of damage variables. Meng et al. [3], by employing acoustic emission tests, proposed a primary damage model for sandstone. They demonstrated that the presented damage model performed better than the Weibull statistical strength damage model in reflecting the post-peak stress-strain curve.

Given the significant importance of studying damage in rock materials, this research focuses on investigating the damage characteristics of marble under uniaxial compression using a grain-based finite element method and a damage model. Accordingly, networks with different Voronoi joint networks were first generated in the Phase2 software. Then, uniaxial compression tests were simulated on these networks, and the stress-strain curves as well as the parameters of the initial modulus and damage modulus were extracted from the curves. Finally, using the damage model proposed by Jinhao et al. [4], the damage values at different strain levels were calculated and analyzed.

2. Grain-based model

Grain-based models constructed on Voronoi structures are among the most widely used approaches for simulating the behavior of brittle rocks. The formation of Voronoi structures begins with the distribution of points referred to as “grains”. Each Voronoi block is associated with a specific grain, and a Voronoi cell is defined as the region that is closer to its own grain than to any other grains [5].

With recent advances in numerical simulations and specialized software tools, modeling and analyzing the heterogeneity of rock materials at the microscale-such as the constituent grains and their inter-grain boundaries-has become feasible. These models are known as “Grain-Based Models (GBM)” [6].

3. Damage model

In the utilized model, it is demonstrated that the stress-strain relationship exhibits linear behavior only at the initial stages of loading for brittle materials such as rock and concrete. However, in the region approaching the peak strain (ε_μ), the curve becomes nonlinear. In this area, damage occurs within the material, expressed as follows [4]:

$$\sigma = \begin{cases} E_0(1-\omega)\varepsilon & (0 \le \varepsilon < \varepsilon_\mu) \\ E_0(1-\omega)\varepsilon_\mu & (\varepsilon > \varepsilon_\mu) \end{cases} \quad (1)$$

where (E_0) denotes the initial elastic modulus, and (ε_μ) corresponds to the strain at peak stress.

The damage evolution equation can be expressed as follows [4]:

$$\omega = \begin{cases} \omega_0 + A(\dfrac{\varepsilon}{\varepsilon_\mu})^B & (0 \le \varepsilon < \varepsilon_\mu) \\ 1 - \dfrac{C}{D(\dfrac{\varepsilon}{\varepsilon_\mu}-1)^\lambda + \dfrac{\varepsilon}{\varepsilon_\mu}} & (\varepsilon > \varepsilon_\mu) \end{cases} \quad (2)$$

where ω_0 is the initial damage amount, A, B, C are material constants; and λ and D represents curve parameters. Generally, D is considered to be 1.7, and the values of A, B, and C can be determined using the following Equations:

$$\begin{cases} A = 1 - \dfrac{E_\mu}{E_0} \\ B = \dfrac{E_\mu}{E_0 - E_\mu} \\ C = \dfrac{E_\mu}{E_0} \end{cases} \quad (3)$$

4. Results and discussions

After creating randomized Voronoi networks with both low and high density, and applying boundary conditions and displacement rates at each stage of the simulations, the models were solved. Stress-strain curves were then extracted from the central points of the models, resulting in 20 stress-strain curves for each density of the network.

Subsequent to calculating the initial elastic modulus and damage values for each realization of the generated Voronoi networks, the damage values resulting from uniaxial compressive loading were determined using the used damage model. The damage-strain curves for each realization in the networks with low and high density are illustrated in Figures 1 and 2.

As observed in these figures, as the strain increases up to a certain threshold, the values of the damage variable increase gradually. However, after reaching a specific strain level, the damage values increase significantly and steeply. This point, where the damage suddenly begins to increase sharply, marks the onset of severe damage experienced by the rock sample under the applied uniaxial compressive loads.

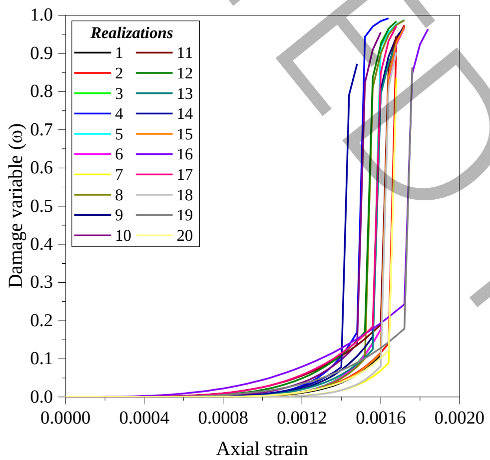

Figure 1. Damage-strain curves for different realizations of low-density networks

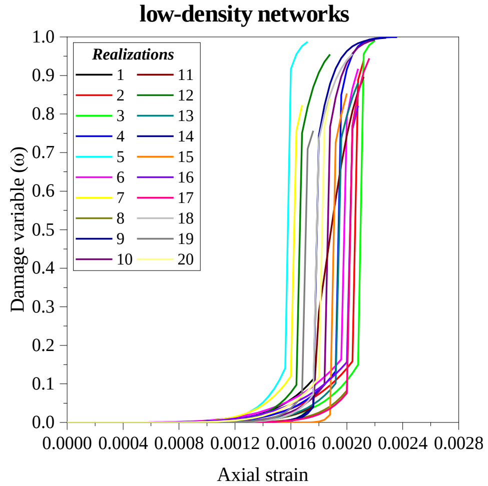

Figure 2. Damage-strain curves for different realizations of high-density networks

5. Conclusions

This study investigated the damage that occurs in the internal structure of a type of marble under uniaxial compression conditions by simulating a uniaxial compression test using grain-based finite element methods. The most significant findings of this study are as follows:

- With the increase in network density, the average initial elastic modulus and damage modulus have decreased.
- Based on the damage-strain curves, the damage variable values initially increase gradually and then very steeply.
- In different realizations within low-density networks, all three types of failure including shear, tensile, and shear-tensile are observed.

6. References

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