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Numerical investigation on crack branching during collision for rock-like material

Y.F. Yang [a,b], G. Li [a,*], Z.Z. Liang [c], C.A. Tang [c]

[a] Department of Applied Mechanics and Engineering, School of Engineering, Sun Yat-sen University, Guangzhou 510275, PR China
[b] Institute of Geotechnical and Underground Engineering, Fujian Academy of Building Research, Fuzhou 350025, PR China
[c] Center for Rock Instability & Seismicity Research, Dalian University of Technology, 116024 Dalian, PR China

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A B S T R A C T

In this study, a rock specimen with a single notch was used as the subject of study in edge-impact experiments. Based on the principle of elastic-brittle damage evolution, crack curving and branching mechanisms of rock-like materials under dynamic shear stress were studied through the adoption of a numerical simulation method. The numerical simulation results not only reflect the experimental trends but also permit further extension and expansion from the foundation of the physical tests. The effects of different heterogeneous rock on the crack propagation were considered. The results can provide some valuable reference for studies on the dynamic failure characteristics of rock-like material.

1. Introduction

In recent years, because of rapid development in protection engineering and the defence industry, the study of the mechanical properties of materials under the influence of impact is of critical importance to provide a fundamental basis for material selection for engineering protection and structural design. As a major tool of experimental research, the technique of loading edge cracks by edge impact (LECEI [1]) has been garnering a considerable amount of attention in terms of theory and engineering practice.

The principle of LECEI is a widely used research tool that uses pressure stress generated by the impact process to form a mode II pure stress environment in the leading tip of a crack. This approach can be used to easily study the mechanical properties of a material under shear stress. As early as 1988, Kalthoff and Winkler [2] selected maraging steel as a research specimen and were the first researchers to discover that this material, when subjected to impacts from a collision block with various speeds, can produce two types of cracking modes: the brittle fracture and shear-zone propagation modes. It can be inferred that the striking velocity has a threshold. When the striking velocity is below this threshold, brittle tensile cracking predominates in the specimen. Cracks in this mode originate at the endpoints of prefabricated cracks, with a 70-degree angle to the horizontal direction. When the collision velocity is above the threshold, the cracks form a horizontal shear zone. Since that study, materials that exhibit significantly different mechanical responses under different impact speeds have begun to attract the attention of scholars. In 2000, based on preceding studies, Kalthoff expanded his research to the study of three types of materials: epoxy resin, high-strength maraging steel X2 NiCoMo 1895, and aluminium alloy (AI7075). The results indicated that except for the high-strength maraging steel, which exhibited the previously observed transition from brittle cracking to shear-zone propagation with increasing impact velocity, the other two materials exhibited only one failure mode. Therefore, the crack-propagation mode is also related to the material properties. For example, for the brittle epoxy resin (a rock-like brittle material, often chosen as the laboratory component to produce rock-like material [3,4], within the range of impact velocities it could withstand, the crack propagation took the form of brittle cracking with a 70-degree angle to the horizontal direction. However, for the aluminium alloy material, regardless of the impact velocity, even when the loading rate was reduced to the quasi-static level, the crack propagation exhibited only the shear-zone cracking mode [1]. In 2003, Bertram and Kalthoff [5] used the LECEI method in a study that focused on brittle material, namely, Solnhofen limestone and epoxy resin (Araldite B), and studied the impact of different prefabricated crack lengths and collision velocities. The results demonstrated that within the speed range that they could withstand, both materials exhibited tensile cracks, and the results were in agreement with the statistical behaviour in epoxy resin that was observed by Kalthoff in 2000. Moreover, in LECEI tests of rock-like materials, Bertram also captured the crack-branching

* Corresponding author.
E-mail address: ligen8@mail.sysu.edu.cn (G. Li).

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behaviour under high-velocity impact. Unfortunately, the rock properties in Bertram's study lacked variety, and he did not extend the study to rocks with different properties, such as heterogeneous characteristics. In 2008, Grange et al. [6] used two types of limestone (Crinoidal limestone and Beaucaire limestone) to study the crack-propagation modes and failure mechanism for various heterogeneous characteristics using the edge-on impact test method. The test results demonstrated that although both materials were limestone, the heterogeneity difference between them was very significant. The more homogeneous the rock was, the longer was the crack-propagation path, and the primary and secondary cracks were significantly different and reticular. When the rock heterogeneity was higher, the crack propagation was less extensive. The impact failure was concentrated in the bottom region of the impact area and exhibited a nuclear-like powder shape. This result strongly established that heterogeneous characteristics are an important feature of a rock material and, indeed, are the primary factor that controls cracking behaviour. Although extensive and in-depth studies have been conducted to investigate mode II tensile cracks under loading conditions [7–10] and mode I branching cracks under dynamic tensile stress [11–14], studies of mode II cracking under loading conditions that simultaneously account for heterogeneity and crack branching have rarely been reported.

When it comes to crack branching mechanism, the research results by Ravi-Chandar have been widely recognised: when the crack propagation velocity approaches the critical value, microcrack clusters appear in the front of the main crack. In any case, the crack density featuring lateral branching increases markedly with the increase of stress. Some microcrack clusters develop to form lateral branch cracks and extend to connect with the main crack. Meanwhile, the microcrack clusters lead to the increase of roughness of the crack surface [15–18]. However, although Ravi-Chandar identified the mechanism of crack propagation, no further analytical solutions were given since the initiation and propagation of microcracks and the interaction between stress and crack are very complex. Many numerical simulations have been performed on dynamic crack propagation. However, most of them assumed the model was composed of ideally homogeneous material. The effects of the initiation and propagation of microcracks on crack propagation were neglected. However, rocks and other geomaterials are by their very nature heterogeneous materials. This heterogeneity starts from mineralogical variations on the micron-to-millimeter scale. Modelling such a multi-scale heterogeneous structure is a challenge for geomechanical engineering because of the normally very high uncertainty in the geometry of heterogeneities like microcracks, fractures, and crack/fault networks, and limited information about the geomechanical properties of the materials [19]. That is why the impact of material heterogeneity on crack initiation and propagation was ignored. For instance, many studies [14,20–22] are still limited to homogeneous materials due to high requirements on model rationality, computation efficiency and accuracy. No further analyses on the effect of internal defects on crack propagation in a material have been conducted.

With regard to numerical simulation research, because the collision problem involves complicated contact determination and means of processing, the presently adopted methods use a simplified approach that does not consider the interaction between the impactor and the specimen and that simplifies the loading model to a velocity boundary condition. The advantage of this method is that it not only avoids complicated issues related to the contact but also ignores the mechanical response of the impactor. Therefore, it greatly reduces the computational cost. However, this type of simplification also has some drawbacks. First, although the velocity loading curve can be obtained from physical test observations, differences in the geometric sizes and mechanical parameters of different specimens and impactors can affect the velocity vs. time curve of the contact surface. Furthermore, the displacement of the entire contact surface during the dynamic response process is not consistent. If the displacement and velocity of the loading part are assumed to be consistent, this assumption will lead to a greater accumulation of error. Heterogeneity in the specimen material, the existence of cracks, and different boundary conditions will cause the difference in response at the impact region to increase. This response difference is more significant for high heterogeneity and those that have suffered damage near the contact surface. Moreover, especially for a typical asymmetric model such as a boundary single-notch crack, the deformation of the contact surface cannot be consistent. The most straightforward observation of this phenomenon is a situation in which an impactor was separated from a specimen and the separation at the end of the impactor farthest from the prefabricated crack occurred before the separation in other locations.

To further analyse the brittle tensile damage during mode II loading as a special case, based on the RFPA elastic-brittle constitutive assumption and microscopic theory, this study attempts to explain the formation process of tensile and branching cracks based on the angle of stress-wave propagation and damage evolution. This study uses a two-step method for dynamic contact processing and considers impactor parameters and velocities as influencing factors. This study begins from classical physical tests; targeted analysis was performed on the crack-propagation mode of a single-notch model, and this analysis reproduces the observed experimental trends. The results of previously published physical tests indicate that for rocks of higher homogeneity, the primary and secondary cracks differ significantly, the propagation paths at the prefabricated crack locations are longer, and there is more extensive crack bending and branching. By contrast, for rock-like material with distinct heterogeneity, a large amount of microdamage emerges during stress-wave propagation, the fracture mode is more complex, and the crack-propagation mode is significantly different [6]. The results obtained from the numerical simulation not only effectively reproduce the process of brittle fracture but also permit the systematic analysis of the impact of different levels of heterogeneity on crack propagation. This study builds upon the foundation of previous studies and provides a useful reference for studies of brittle fracture in heterogeneous materials and the complex interactions amongst microcracks during the collision process.

2. Method

2.1. Solution for dynamic finite element equations

After discretization by the finite element method, the dynamic equilibrium equation for each node in motion can be expressed as:

$$\mathrm{M}\ddot{\mathrm{u}} + \mathrm{C}\dot{\mathrm{u}} + \mathrm{K}\mathrm{u} = \mathrm{Q} \tag{1}$$

By substituting the equations relating velocity, acceleration and displacement in the Newmark method:

$$\begin{cases} \ddot{\mathrm{u}}_{t+\Delta t} = \frac{1}{\beta \Delta t^2}(u_{t+\Delta t} - \mathrm{u}_t) - \frac{1}{\beta \Delta t}\dot{\mathrm{u}}_t - \left(\frac{1}{2\beta} - 1\right)\ddot{\mathrm{u}}_t \\ \dot{\mathrm{u}}_{t+\Delta t} = \frac{\gamma}{\beta \Delta t}(\mathrm{u}_{t+\Delta t} - \mathrm{u}_t) + \left(1 - \frac{\gamma}{\beta}\right)\dot{\mathrm{u}}_t - \left(\frac{\gamma}{2\beta} - 1\right)\ddot{\mathrm{u}}_{t+\Delta t}\Delta t \end{cases} \tag{2}$$

into the dynamic equilibrium equations, the following equations can be obtained:

$$\begin{cases} \widehat{\mathrm{K}}\, u_{t+\Delta t} = \widehat{\mathrm{Q}}_{t+\Delta t} \\ \widehat{\mathrm{K}} = \mathrm{K} + \frac{1}{\beta \Delta t^2}\mathrm{M} + \frac{1}{\beta \Delta t}\mathrm{C} \\ \widehat{\mathrm{Q}}_{t+\Delta t} = \mathrm{Q}_{t+\Delta t} + \mathrm{M}\left[\frac{1}{\beta \Delta t^2}\mathrm{u}_t + \frac{1}{\beta \Delta t}\dot{\mathrm{u}}_t + \left(\frac{1}{2\beta} - 1\right)\ddot{\mathrm{u}}_t\right] \\ \qquad + \mathrm{C}\left[\frac{\gamma}{\beta \Delta t}\mathrm{u}_t + \left(\frac{\gamma}{\beta} - 1\right)\dot{\mathrm{u}}_t + \left(\frac{\gamma}{2\beta} - 1\right)\Delta t \ddot{\mathrm{u}}_t\right] \end{cases} \tag{3}$$