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Replication of internal defects and investigation of mechanical and fracture behaviour of rock using 3D printing and 3D numerical methods in combination with X-ray computerized tomography

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ABSTRACT

It is difficult to accurately visualize internal structure and characterize progressive fracture process during rock failure due to the heterogeneous and opaque features of rock. This paper focuses on providing two methods, i.e., 3D printing (3DP) and 3D numerical modelling, to replicate internal defects and study the mechanical and fracture behaviours of rock in combination with X-ray computerized tomography (micro-CT). On one hand, Stereolithography 3DP combined with the X-ray micro-CT and 3D reconstruction techniques were applied to replicate natural volcanic rocks using 3DP resin. Uniaxial compression and Brazilian disc tests were, subsequently, performed to characterize and visualize the mechanical and fracture properties of the 3DP rock. On the other hand, the digital image processing technique was adopted to integrate the microstructures of the natural volcanic rock into the rock failure process analysis code (RFPA^{3D}-digital) for characterizing the failure behaviour of rock under uniaxial compression and tension. The results showed that both the 3DP samples and the 3D numerical models can successfully replicate the internal defects and micro-structures identical to those of the natural prototype volcanic rock. The mechanical properties of the 3DP samples and the 3D numerical models, including compressive and tensile strength and the Poisson's ratio, and fracture properties are testified to be similar to those of the prototype rocks. Visualization analysis of the progressive fracture process demonstrated that the initial internal voids and cracks dominate the spatial fracture evolution and failure patterns within the rock. The proposed methods provide a promising means to quantify, replicate and visualize the pre-existing defects and mirco-structures, and to understand their influences on the mechanical and fracture behaviour of rock under different loading conditions, facilitating better understanding of failure mechanism of rocks.

1. Introduction

Rock, when viewed at a microscopic level, is heterogeneous, discontinuous and contains randomly distributed defects, e.g., cracks, voids, and joints. The failure of rock under external loading is significantly affected by these pre-existing defects and usually preceded by the development of new cracks and the growth of the pre-existing cracks.[1] Therefore, understanding the mechanical and fracture behaviours of rocks affected by the pre-existing defects is crucial for design and stability assessment of structures built on or in rock.

Laboratory experiment, as a fundamental and effective method, has been widely used to investigate the failure mechanism of rocks under various circumstances.[2] To date, many advanced techniques such as scanning electron microscopy (SEM),[3,4] acoustic emission detection (AE)[5,6] and X-ray computerized tomography (CT)[7,8] have been adopted to study the progressive failure process of rock. These advanced techniques do offer means to observe and study rock fracture behaviour. However, the failure mechanism of rock, particularly the spatial evolution of microcracks in real time, is still difficult to clearly reveal with those advances techniques. It is because they could not accurately and real-timely monitor and capture microcracks development inside rocks attributed to their inherent drawbacks, e.g., the destruction of rock samples for the SEM, the relatively low accuracy of AE source location for the AE, and the difficulty in detecting microcracks under dynamic loading for the X-ray CT.[2,9]

With a focus on the internal or spatial crack evolution during rock

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failure, some researchers have used rock-like samples produced by transparent materials such as glass,[10,11] polymethyl methacrylate[12] and epoxy resin[13–15] to investigate mechanical and internal fracture behaviours of rocks. Nevertheless, in these studies only some regular cracks, e.g., penny-shaped, elliptical and borelole cracks, are considered, which are distinct from the defects inside the natural rocks. The primary reason is that it is impossible to produce rock-like samples with internal defects identical to those in natural rocks using traditional manufacturing methods. Thereby, there is a demand for more effective techniques or methods that can be applied to conveniently prepare rock specimen with its internal defects identical to that of the natural rocks and to study real-time damage and fracture evolution within rock.

3D printing (3DP), also called rapid prototyping or additive manufacturing, is a computer-aided design and manufacturing process that fabricates objects layer upon layer using 3D graphical data.[16] It has advantages over traditional methods since it allows precise fabrication, flexible preparation and high repeatability,[17] as well as some specific applications, such as the preparation of complex geometries and internal defects.[18] Owing to these benefits, application of 3DP in rock mechanics has attracted considerable attention in recent years. Ju et al.[19] reported the replication of a natural coal with pre-existing cracks using the X-ray CT scanning and 3DP techniques. Jiang and Zhao[20] explored the possibility of simulating rock materials using the fused deposition modelling (FDM) with the polylactic acid material. Ishutov et al.[21] duplicated pore networks of the coarse-grained Idaho Grey Sandstone with a porosity of 29% using CT scan and FDM. Zhou and Zhu[22] identified the transparent resin (accura® 60) produced via stereolithography (SLA) as the most suitable 3DP material for mimicking brittle and hard rocks in view of the current 3DP techniques. Moreover, the transparent feature of the 3DP resin enables us to directly monitor and analyse fracture behaviours inside rock samples during testing. In view of this, 3DP may provide an alternative method for replicating natural rock samples and studying mechanical and fracture behaviour of rocks subjected to static and dynamic loading conditions.

Besides laboratory testing, attributed to the advantages of repeatability and visualization of internal damage and fracture evolution process, numerical simulation has also been widely utilized in studying mechanical and fracture characteristics of heterogeneous rocks.[23–29] For instance, Tang et al.[30] studied the effects of heterogeneity and microstructure on progressive failure of rocks under compression using the finite element modelling (FEM)-based rock failure process analysis code (RFPA); Fang and Harrison[31] developed a local degradation approach to model the brittle fracture in heterogeneous rocks. In these studies, however, the heterogeneity and microstructure of rocks were usually characterized by the statistical distribution of properties (e.g., Weibull distribution) which may inadequately reflect the actual local geometrical and constitutive variations of microstructures in rock.[25]

To more realistically reflects the physical characteristics and the microstructure of the actual rock, Yue et al.[32] proposed to build the numerical specimens using the digital image processing (DIP) technique which could take the material heterogeneity and mesostructures into account during numerical model establishment; Mahabadi et al.[33] quantitatively modelled geomaterials by incorporating their real microscopic heterogeneity using the X-Ray micro-CT, micro-indentation and micro-scratch techniques; Zhu et al.[25] integrated the DIP based local rock heterogeneity and microcracks into RFPA and studied their effects on the damage evolution and hydromechanics of fractured rocks. Their results demonstrated that models considering the real 2D meso- or microscopic heterogeneity can more accurately predict the mechanical and fracture response of rocks.[25,32–34]

However, few 3D numerical studies of mechanical and fracture behaviours of rock with the consideration of effects of initial defects have been carried out so far. Recently, Zhao et al.[9] incorporated the 3D microstructures of Gosford sandstone obtained from high-resolution X-ray micro CT, into numerical model. Although the sample model was small, it was found that the strain rate dependency of uniaxial tensile strength of Gosford sandstone was caused by the microstructures. Yu et al.[35] converted a physical jointed rock sample into a corresponding numerical model in RFPA^{3D} in combination with CT scan and DIP techniques, which provides a novel and effective means to study the mechanical and fracture behaviour of jointed rock.

In this paper, experimental and numerical tests were performed using the 3DP and RFPA^{3D}-digital methods, respectively, aiming to provide two methods to replicate pre-existing defects of natural rocks and to investigate mechanical and fracture behaviours of rock using these two methods in combination with X-ray micro-CT. Firstly, natural volcanic rock specimens were replicated using the SLA 3DP and X-ray micro-CT techniques. Then, comparative experimental tests, i.e., uniaxial compression and indirect Brazilian disc tests under static and dynamic loading conditions, were conducted on both the 3DP man-made rocks and the prototype rocks to validate the applicability and accuracy of the proposed 3DP methods. Meanwhile, numerical tests of the uniaxial compression and indirect tension under static loading were carried out using the RFPA^{3D}-digital code by incorporating the real microstructures of the natural volcanic rock samples detected by X-ray micro-CT. Subsequently, the pros and cons of these two methods were compared and discussed. Finally, potential means to facilitate the application of these two methods in studying rock failure were suggested. The findings in this paper could provide a promising means to quantify, replicate and visualize the pre-existing defects and micro-structures, and to understand their influences on the mechanical and fracture behaviour of rock under different loading conditions, facilitating better understanding of failure mechanism of rocks.

2. Experimental and numerical setups

2.1. Rock sample preparation

In this study, Hainan volcanic rock (Basalt), collected from the Crater Park in Haikou, China, is chosen as the prototype natural rock. It is an igneous rock with a porosity of 7.2%. Optical microscopy analysis shows that the main mineralogical constituents are plagioclase, pyroxene and opaque mineral, with volume percentages of 58.5%, 35.4% and 6.2%, respectively. Their grain sizes are between 0.1–1.3, 0.1–0.9 and 0.1–0.2 mm, respectively.

During fabrication, rock cores with a diameter of approximately 49 mm were firstly drilled from a large volcanic rock block, which were then cut into standard rock samples. According to the International Society for Rock Mechanics Suggested Methods[36,37], the ratio of length to diameter of specimen for the indirect Brazilian disc tests is 0.5:1, and the ratios for static and dynamic compression tests are 2:1 and 1:1, respectively. All the specimens were ground and polished to have a surface roughness smaller than 0.02 mm.

2.2. X-ray micro-CT scanning of rock samples

In nature, rock contains numerous pre-existing micro-defects such as fissures, voids and inclusions. The existence of these micro-defects significantly affects the mechanical and fracture properties of rocks.[1] Thereby, to effectively study the deformation and failure behaviours of rocks, the pre-existing defects shall be duplicated in the replicated rock samples and the 3D numerical models. To fulfil this requirement, an X-ray Micro-CT XRM 500 scanner was used to precisely image and map the surface and internal defects of the volcanic rock specimens. The scanner has a 160 kV X-ray light source with an exposure time of 18 s. The maximum scanning range is 100 × 100 mm, and the corresponding pixel of its charge coupled device is 2000 × 2000.

During scanning, when the cone-shaped X-ray beam generated by an X-ray source penetrates rock sample, the signal is attenuated and absorbed due to the density and composition variation through the section. By rotating the specimen incrementally to 360°, the X-ray projection data in different orientations can be obtained by the