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Full-field measurement and fracture characterisations of rocks under dynamic loads using high-speed three-dimensional digital image correlation

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ABSTRACT

Full-field strain and strain-rate fields of rock materials under dynamic compression were studied by the high-speed three-dimensional digital image correlation (3D-DIC) method. A series of dynamic tests was conducted on Hawkesbury sandstones using a split Hopkinson pressure bar (SHPB) at three different strain rates. The real-time images of the loaded specimen were captured by two high-speed cameras at a frame rate of 200,000 frames per second (fps) with a resolution of 256 × 256 pixels. Wave propagation, dispersion and radial inertial effect on the specimen were found by DIC results. The strain rate vibration pattern on the specimen, which was visualised by DIC, found to be dependent on the input waveform. A recovery of strain in the post-peak stage was detected on the specimen by DIC, which is unrevealed in the traditional one-dimensional theory method (i.e., strain gauge signals). The results showed that strain localisation initiated from the interface of the bar and specimen with the order of tensile, shear and vertical. The initiation of crack from strain localisation is found rate-independent. Comparison between 2D- and 3D-DIC in strain measurement of the same experiment showed that the error in the strain obtained by 2D-DIC could be up to 32%.

1. Introduction

Rock deformation and breakage behaviours under dynamic loading have a significant impact on various rock engineering areas such as tunnelling [1], anti-seismic research [2], weapon penetration [3], hydraulic fracturing [4] and mining [5]. The deformation characteristics and fracture patterns of rock at high strain rate play a significant role in rock engineering safety or efficiencies such as rockburst prevention [6] and hard-rock cutting [7]. The split Hopkinson pressure bar (SHPB) technique has been recognised as the most successful loading method for determining dynamic properties of various materials [8–13] since its modern design developed in 1949 [14]. The early application of SHPB on rock was reported by Hauser [15] in which a stress-strain curve of rock was derived. After that, testing methods with SHPB were expanded to investigate various dynamic properties of rock such as tensile strength [16], bending strength [17], shear strength [18] and fracture toughness [19]. The effects of external factors such as confining pressure [20], water saturation [21] and thermal treatment [22] on the rock dynamic behaviour were also of interest to researchers. The optimisation of the experimental design and bar modification [23–26] has always been concerned for achieving constant strain rate and stress equilibrium in rock-like materials (e.g., rock, concrete and ceramics).

With regard to the deformation characteristics and fracture patterns, the investigation is more challenging than that of stress on the specimen in SHPB experiments [27]. Efforts were made, for example, to observe the residual pieces of the fractured specimen with naked eyes or the electron microscope; and to link its failure patterns and mechanisms with the strain rate or pre-stress state [28–31]. The application of high-speed photography in SHPB made it possible to visualise the real-time deformation and fracturing process of the specimen. The initial application of high-speed photography technology in SHPB tests of rock was made by Perkins and Green [32] in 1968 on Solenhofen limestone at the strain rate of 10 s^{-1}. In terms of the high-speed photography, however, the grey scale image and relatively low resolution make it hard to locate the initial cracks. The combination of high-speed photography and digital optical measurements allowed the detection of the quantitative information on the specimen surface such as photoelasticity, Moiré, caustics, holographic interferometry, infrared thermography and digital image correlation (DIC) [33,34]. The DIC technique is regarded as the most promising and ideal means to measure the dynamic deformation of rock-like materials because of its accuracy, applicability and operability [35].

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The strain localisation and evolution, and onset of fracture were examined in dynamic notched semi-circular bending (NSCB) and Brazilian disc (BD) tests with the high-speed 2D-DIC technique for the fi first time by Zhang and Zhao [36]. Chen et al. [37] studied the crack initiation, propagation and splitting failure of the granite specimen in BD test with 2D-DIC at the frame rate of 50,000 fps. Gao et al. [38] studied the crack-tip position and dynamic stress intensity factors of NSCB specimens using DIC results at 180,000 fps, where the crack propagation velocity, the fracture initiation toughness and the fracture propagation toughness were subsequently determined. Although previous studies with high-speed 2D-DIC presented post-failure results [39–41], these investigations only centred on the failure induced from a prefabricated crack or a stress concentration condition. Recently, Zhou et al. [42] studied the fracturing pattern qualitatively in the post-failure stage of granite under dynamic compression using the 2D-DIC at 100,000 fps, 192 × 192 pixels and compared the results with a model of phenomena in PFC^{2D}. However, 2D-DIC cannot detect the out-of-plane deformation which also induces errors in-plane measurement [43]. 3D-DIC was, hence, developed based on the principle of binocular stereovision [44] to overcome this restriction. A brief summary of application of high-speed 3D-DIC in dynamic tests is listed in Table 1. It has been widely employed in alloy and composite materials rather than brittle material like rock, as capturing the failure of rock under small deformation significantly relies on the high frame rate and resolution. To the best of our knowledge, the study of the full-field deformation and fracturing of rock materials under dynamic uniaxial compression has not been studied up to now. Therefore, the actual strain evolution on a rock specimen and its difference with the strain calculated from one-dimensional wave propagation theory is not clear. As SHPB has no servo system to adjust the applied loading according to the feedback from the specimen, the loading status of brittle materials like rock is uncertain during the post-peak stage. Full-field deformation and fracture characteristics of the rock in SHPB experiments remains unknown.

This paper aims at identifying the full-field strain and strain rate fields directly on the rock specimen in SHPB tests with the high-speed 3D-DIC method. The full-field deformation pattern during the pre-failure stage is visualised and extracted from the strain field by DIC method. The comparison of strain and strain rate results determined by DIC method and one-dimensional wave theory is discussed. The strain localisation and fracture development characteristics are identified together with the error analysis in 2D-DIC.

2. Experimental set-up

2.1. Rock specimens

Hawkesbury sandstone from Sydney, Australia was selected for this study, which is a popularly favoured building material in Australia. Cylindrical specimens were extracted from coring the same rock block without obvious bedding, and were examined by ultrasonic scanning to guarantee a good agreement in properties. The specimens are homogeneous with the following properties: density $\rho = 2.21\ \mathrm{g/cm^3}$, P-wave velocity $C_L = 2110\ \mathrm{m/s}$, elastic modulus $E = 8.39\ \mathrm{GPa}$, Poisson's ratio $\nu = 0.21$, uniaxial compressive strength $\sigma = 41\ \mathrm{MPa}$. The specimens were manufactured to a diameter of 48 mm, and the length to diameter ratio was 1.0 as suggested by International Society for Rock Mechanics (ISRM) [10]. Two ends of the specimen were ground to be flat to 0.02 mm tolerance and not depart from perpendicularity to its axis by more than 0.001 rad. The side surface of the specimen is smooth and free of abrupt irregularities and straight to within 0.02 mm. A total of 15 specimens were examined in three groups corresponding to different strain rates.

2.2. Loading and data acquisition system

The principle of SHPB is based on the theory of one-dimensional (1D) stress wave propagation, and the dynamic pressure on the incident (P_1) and transmitted (P_2) ends of specimen are [14,52,53]:

$$P_1 = \frac{A_B}{A_s} E_B(\varepsilon_i + \varepsilon_r),\ \ P_2 = \frac{A_B}{A_s} E_B \varepsilon_t \tag{1}$$

where E_B is the Young's modulus of bars; A_B and A_s are the cross-sectional area of the bar and specimen; ε_i, ε_r and ε_t are the incident, reflected and transmitted strain signals, respectively.

The velocities at the incident bar end (v_1) and the transmitted bar end (v_2) are:

$$v_1 = C_B(\varepsilon_i - \varepsilon_r),\ \ v_2 = C_B \varepsilon_t \tag{2}$$

where C_B is the wave velocity of the bar.

The average engineering strain rate $\dot{\varepsilon}$ and strain ε in the specimen are calculated as:

$$\dot{\varepsilon} = \frac{v_1 - v_2}{L_s} = \frac{C_B}{L_s}(\varepsilon_i - \varepsilon_r - \varepsilon_t),\ \ \varepsilon = \int_0^t \dot{\varepsilon}\,dt = \frac{C_B}{L_s}\int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t)dt \tag{3}$$

where t is time and L_s is the length of the specimen.

When the pressures on both ends of two bars reach an equilibrium, namely $P_1 = P_2$, Eq. (1) leads to:

$$\varepsilon_i + \varepsilon_r = \varepsilon_t \tag{4}$$

Eqs. (2) and (3) can thus be simplified as follows,

$$\dot{\varepsilon} = -2\frac{C_B}{L_s}\varepsilon_r,\ \ \varepsilon = -2\frac{C_B}{L_s}\int_0^t \varepsilon_r dt \tag{5}$$

The schematic of the experimental setup is shown in Fig. 1. SHPB system in Swinburne University of Technology consists of a gas gun, a striker (0.4 m), an incident bar (2.4 m), a transmitted bar (1.4 m) and a momentum bar (0.8 m). The striker and bars made with high strength 40Cr steel, and share the diameter of 50 mm and have a nominal yield strength of 800 MPa, the P-wave velocity of 6100 m/s, and elastic modulus of 208 GPa. The striker launched by the gas gun impacts the incident bar to generate a compressive wave which propagates through the specimen and afterwards to the transmitted bar. The strains induced by the wave on the bars are measured by two sets of strain gauges attached on the incident and transmitted bars; the voltage signals from strain gauges were then amplified by a differential amplifier through a Wheatstone bridge (half bridge circuits).

Table 1
Brief summary of high-speed 3D-DIC in dynamic tests.

Type of material	High-speed camera	Testing method	Frame rate (fps)	Resolution (piex^2)	Area of interest (mm^2)	Reference
TC4 Alloy	N/A	Direct tension	100,000	208 × 96	18 × 5	[45]
Polymeric foams	Photron SA-X2	Compression	100,000	384 × 264	42 × 39	[46]
Carbon/epoxy composite	Photron SA1	Implosion	50,000	1024 × 1024	76 × 51	[47]
Reinforced carbon-carbon	Phantom v7	Ballistic impact	26,900	256 × 256	355 × 355	[48]
Aluminium and steel	Phantom v1610	Airblast	21,000	896 × 800	4000 × 4000	[49]
Braided composite	Photron SA5	Ballistic impact	15,000	896 × 560	Ø 120	[50]
Steel	Photron APX-RS	Double Lap Shear	10,000	1024 × 1280	600 × 22	[51]