Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.) *Paper: 05-01*
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FLAC3D-PFC3D coupled simulation of triaxial Hopkinson bar

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1 INTRODUCTION

Dynamic loading is ubiquitous in many natural phenomena and engineering practices, such as earthquake ruptures (Aben et al. 2017), rockfall (Crosta & Agliardi 2003), tunneling (Hajiabdolmajid & Kaiser 2003) and mining (Dehkhoda & Hood 2014). Understanding the deformation and breakage behavior of rock under dynamic loading is essential in dealing with geophysical problems and protective construction design. The split Hopkinson pressure bar (SHPB) (Hopkinson 1914) or Kolsky bar (Kolsky 1949) has been widely adopted to investigate the dynamic properties of materials at high strain rates (Field et al. 2004, Ramesh 2008, Zhang & Zhao 2014). Efforts have been devoted not only to capturing the strain rate dependence of mechanical properties, but also to achieving pre-stress loading conditions because rock in the deep underground is often confined by an *in-situ* stress. Conventional approaches to apply lateral confinement have been achieved by either hydraulic chambers or a shrink-fit sleeve (Chen & Song 2011). However, the loading condition of true triaxial confining stress and high strain rate cannot be achieved using the above approaches. To overcome these limitations, a novel triaxial Hopkinson bar developed at Monash University allows for investigating dynamic behavior of geomaterials under multiaxial confinements (Liu et al. 2019). There is a demand for exploration on numerical methods simulating this advanced apparatus to overcome general experimental limitations, including boundary effects, dynamic progressive damage evolution and limited magnitude of dynamic loadings.

Numerical simulations provide a means to overcome the abovementioned problems. Modelling efforts on dynamic behavior of geomaterials have been made by using finite element method (FEM) embedded with cohesive zone models (Gatuingt et al. 2013) or rate-dependent constitutive models (Salih et al. 2016), discrete element method (DEM) (Wang & Tonon 2011), molecular dynamics (MD) (Sator & Hietala 2010), material point method (MPM) (Li et al. 2011), and smooth particle hydrodynamics method (SPH) (Rabczuk & Eibl 2003). Among these methods, DEM is believed to be an efficient tool for simulating dynamic failure process of brittle material since it has advantages of reproducing progressive fracturing as a result of initiation, nucleation and coalescence of cracks and bypassing complicated constitutive relationships. The DEM modelling of SHPB tests has experienced an extension of 2D models to 3D models so that the fracture propagation can be captured in space and the lateral confining stress can be provided. To consider the grain-scale heterogeneity of rocks, the 2D grain-based model (GBM) (Potyondy 2010) was introduced into DEM modelling of SHPB test (Li et al. 2018), which produced enhanced mechanical behavior of rock and revealed multi-scale fracturing behavior including intergranular and transgranular cracking. Although the DEM has proven to be an effective method to simulate the SHPB test on rock, the current 2D-GBM and conventional lateral confinement boundary are unable to simulate the true triaxial SHPB test as well as the 3D microstructure of rock.

This paper presents a numerical model capable of simulating the triaxial Hopkinson bar test and the 3D microstructure of rock. For the computational efficiency and the real loading boundary condition, a continuum-discrete method using *FLAC3D-PFC3D* is adopted to represent the steel bars and rock specimen. To approach the actual microstructure and mechanical property of rock in 3D, the flat-jointed material (FJM) proposed by Potyondy (2012) is utilized. The *FLAC3D-PFC3D* coupled model is first validated by checking wave propagation in the bars and dynamic stress equilibrium within the specimen. Further comparison between numerical simulations and laboratory investigations is conducted and good agreement is found.

2 DESIGN AND ANALYSIS

The triaxial Hopkinson bar system at Monash University (Liu 2019) is shown in Figure 1a. It consists of a dynamic loading system including a gas gun and cylindrical striker bar (42CrMo Steel, ρ = 7850 kg/ m^3, E = 210 GPa, C_s = 5200 m/s, σ_p = 930 MPa, L = 0.5 m, ϕ = 40 mm, impact velocity up to 50 m/s), three independent pairs of square steel bars (42CrMo Steel, cross-section 50 × 50 mm^2) in three perpendicular directions, three hydraulic cylinders (pressure capacity up to 100 MPa), a strong platform, six pieces of high-strength steel reaction frame, and a multi-channel high-speed data acquisition system. The square steel bars are aligned orthogonally in the X, Y and Z directions. In the X axial direction, there is a dynamic loading system consisting of the gas gun with a striker barrel (1.5 m), an incident bar (2.5 m), a transmission bar (2 m), an absorption bar (0.5 m), a hydraulic load cylinder and a momentum-trap device . In the Y and Z axial directions, four steel output bars (2 m) are used to apply confining pressure by hydraulic load cylinders and to monitor the output waves.

Figure 1b shows the *FLAC3D-PFC3D* coupled model simulating the triaxial Hopkinson bar and rock specimen. As a continuum-based method, *FLAC3D* is well suited to simulate the six unbreakable elastic steel bars. We can apply different quasi-static pre-stresses from three different directions independently, thus the true triaxial loading condition can be satisfied. The dynamic load can be directly applied from the left end of the X incident bar through an incident wave of stress-time history. The rock specimen is simulated by the DEM software *PFC3D*, in which the most commonly used contact model is the parallel-bonded model (PBM). A comparison between the PBM and FJM is conducted and it shows that both models can reproduce proper uniaxial compression strength (UCS), Young's modulus and Poisson's ratio. However, a long-standing limitation of PBM is that the tension strength (TS) of this model is too large while the FJM can overcome this limitation (Potyondy 2018). A typical flat-joint contact is shown in Figure 1c. It consists of a finite-size, linear elastic and either bonded or frictional interface that is discretized into elements. Each element can be independently bonded or broken, thus partial damage of the interface is allowed. Such microstructure features of FJM contributes to reproducing relatively high UCS/TS ratio owing to the increasing grain interlock and moment-resistance. The calibrated micro parameters of FJM and the macro properties are listed in Table 1. The interaction between continuum and DEM model components are realized by a coupling scheme (Itasca 2017). *PFC3D* walls are created coinciding with the *FLAC3D* zone surfaces. The coupling logic (Fig. 1c) works by taking contact forces and moments with *PFC3D* wall facets and determining an equivalent force system at the facet vertices. These forces are passed to the grid points of *FLAC3D* zones along with a stiffness contribution. Note that during cycling, the mechanical computations are in large-strain mode and damping is set to zero.

Table 1. Micro- and macro-properties of FJM.

Micro-parameters			Value
Minimum particle diameter, d_{min} (mm)			1.6
Particle diameter ratio, d_{max}/d_{min}			1.5
Installation gap, g_i (mm)			0.3
Radial and circumferential elements, N_r and N_α			1, 3
Effective modulus of both particle and bond, $E_c = \overline{E}_c$ (GPa)			12.0
Bond tensile strength, σ_c (MPa)			5.2
Bond cohesion strength, c (MPa)			28.0
Friction angle, ϕ (degrees)			20
Friction coefficient, μ			0.4
	Young's modulus (GPa)	UCS (MPa)	Poisson's ratio
Experiment	9.5	40.0	0.21
Simulation	9.5	40.1	0.20

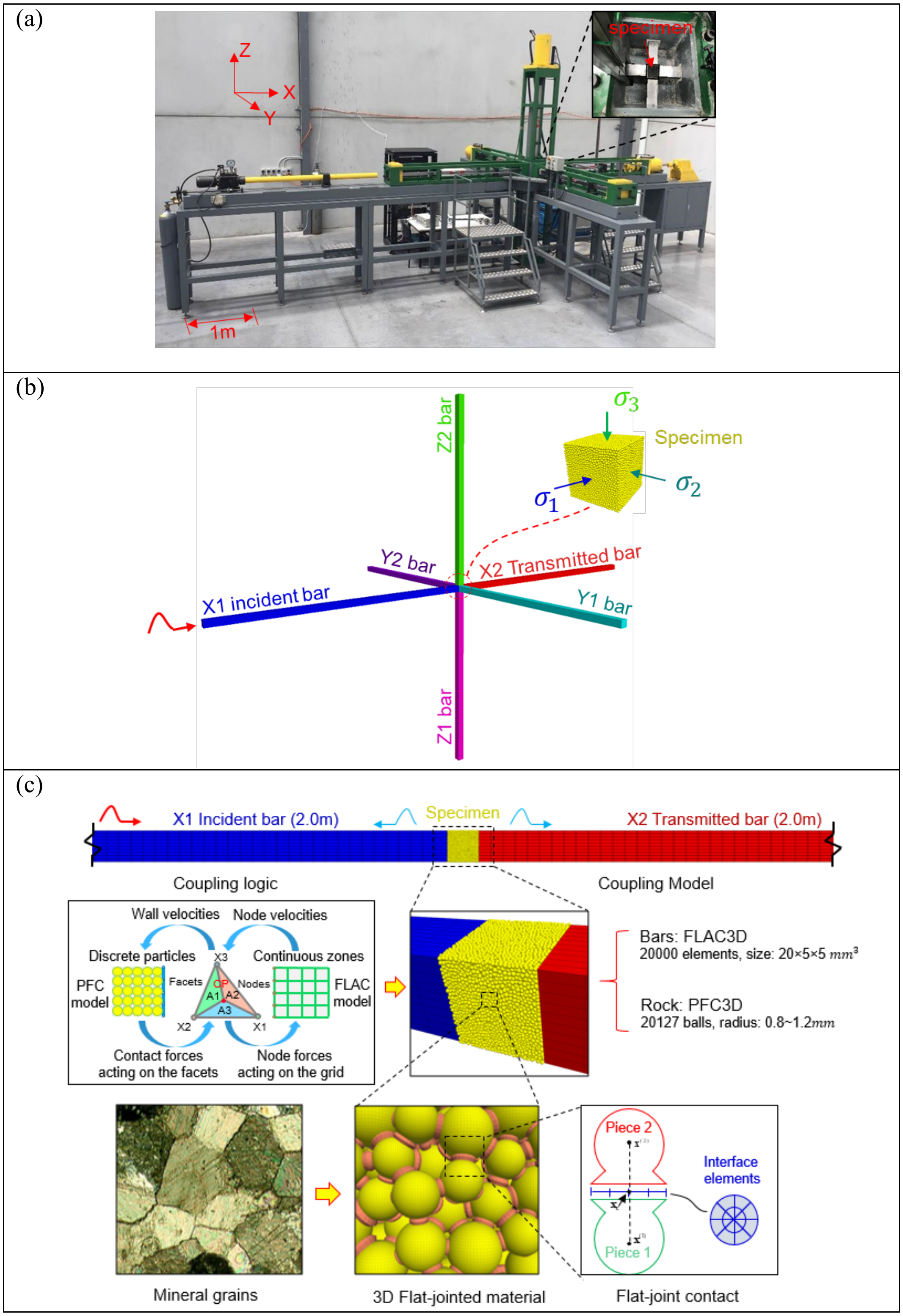

Figure 1. Triaxial Hopkinson bar system at Monash University (a); *FLAC3D-PFC3D* coupled model (b); and coupling logic and flat-jointed material (after Potyondy 2018 and Itasca 2017) (c).

3 RESULTS AND DISCUSSION

A dynamic triaxial test with the pre-stress state of (30, 20, 10) MPa is conducted via experiment and simulation. During the test, the quasi-static stresses are first applied to the specimen in all three directions. After the specimen reaches the state of stress equilibrium, the dynamic loading is then applied from the front end of the X incident bar. Figure 2a,b) shows the stress wave distribution in the six bars and wave propagation in X direction. The generated compressive pulse propagates along the X incident bar and impacts the specimen. A portion of the compressive pulse travels through the specimen and then transmits into the X transmission bar, while the remaining portion is reflected into the X incident bar as a tension pulse. It is observed that the impact in the X direction results in the generation and propagation of compressive pulse along the Y and Z bars due to the lateral expansion of the rock specimen, which is attributed to the Poisson effect. The stress histories of measurement elements located in the middle of each bar are shown in Figure 2c. The dynamic stresses are extracted from these original stresses subtracted by static pre-stresses for further analysis.

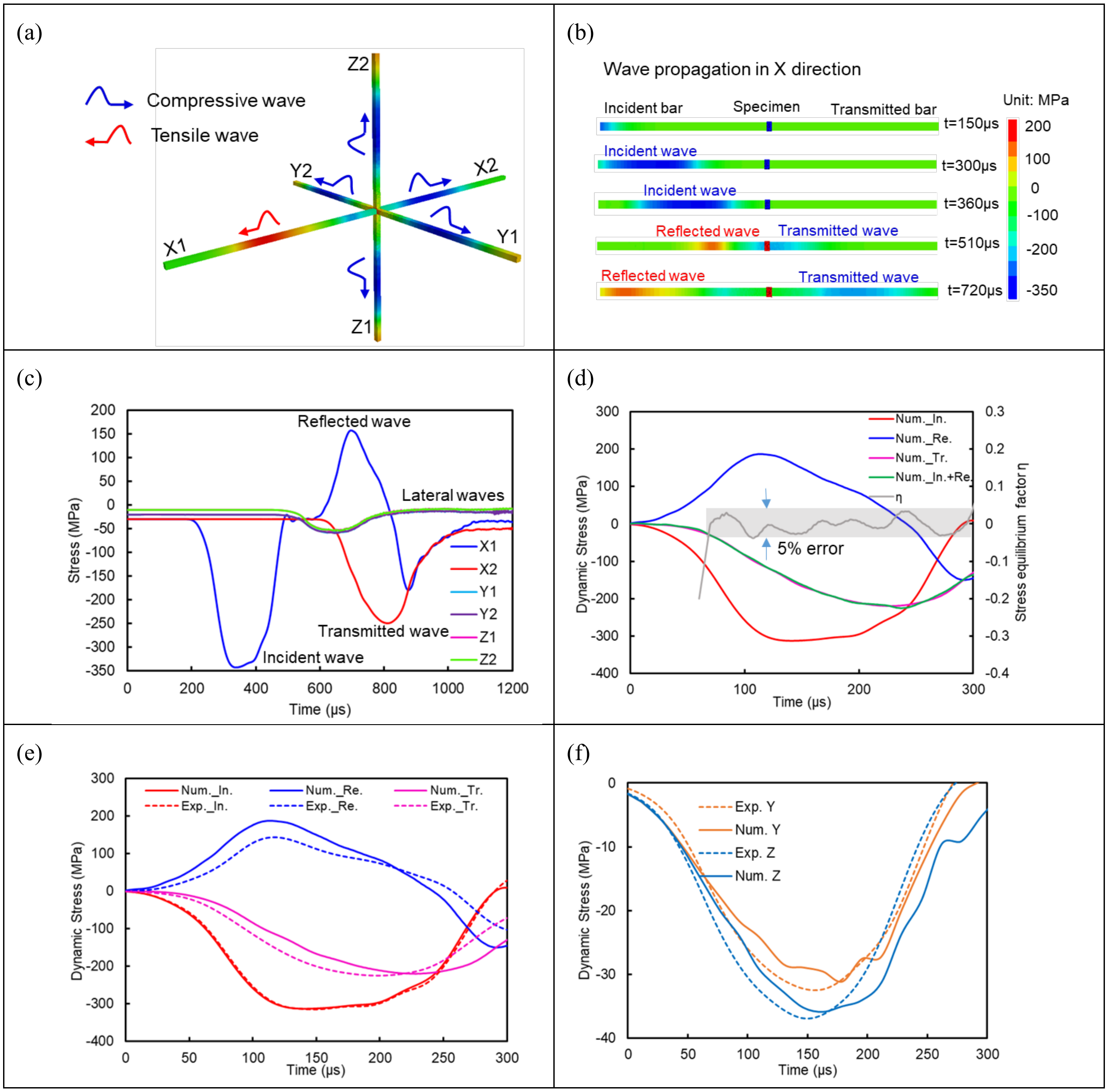

Figure 2. Typical results at pre-stress conditions (30, 20, 10) MPa: Stress waves in the six bars (a) and wave propagation and reflection in X direction (b); stress histories in the six bars (c); dynamic stress equilibrium check (d); comparison between simulation and experiment in X direction (e); comparison between simulation and experiment in Y/Z direction (f) (Num. and Exp. represent numerical and experimental results, respectively; In., Re., and Tr. represent incident, reflection, and transmission waves, respectively).

For a valid SHPB test, the dynamic stress equilibrium of the specimen during the time of interest is required. As shown in Figure 2d, the superposition of the incident and reflected waves $\sigma_{In.+Re.}$ agrees well with the transmitted wave $\sigma_{Tr.}$ and the oscillation of the stress equilibrium factor $\eta = 2(\sigma_{In.+Re.} - \sigma_{Tr.})/(\sigma_{In.+Re.} + \sigma_{Tr.})$ during the time of interest is within 5%, which ensures the stress equilibrium within the specimen and negligible axial inertial effect. To further validate the *FLAC3D-PFC3D* coupled model, the evolutions of the three principle stresses acting on the rock specimen are compared with experimental results (Fig. 2e, f). The dynamic stress histories are intrinsically associated with the deformation and fracturing properties of rock materials. It should be pointed out that the stresses of the peak point are the most important values that can be used to calibrate dynamic constitutive models (Liu 2019). According to the transmitted wave $\sigma_{Tr.}$ histories (magenta lines in Fig. 2e), the numerical dynamic stress peak point (219, 31, 36) MPa is close to the experimental dynamic stress peak point (225, 33, 37) MPa. After adding the pre-stresses (30, 20, 10) MPa, the original stress point is (249, 51, 46) MPa for simulation and (255, 53, 47) MPa for experiment. Overall, the *FLAC3D-PFC3D* coupled model satisfies fundamental requirements and reproduces reasonable mechanical behavior of the triaxial Hopkinson bar. With this model, the progressive damage under various multiaxial loading condition will be captured during the short duration of the impact.

4 CONCLUSIONS

A novel triaxial Hopkinson bar developed at Monash University is capable of recreating specified quasi-static stress states on rock and followed by applying dynamic loadings. To promote the investigation of dynamic behavior of rock under various pre-stress conditions and overcome experimental limitations, numerical simulation of the triaxial Hopkinson bar is conducted in this study. To ensure computational efficiency and the real loading boundary condition, a continuum-discrete method using a *FLAC3D-PFC3D* coupled model is adopted to represent the steel bars and rock specimen. The 3D microstructure of rock is mimicked by the FJM which provides grain interlock and moment-resistance by allowing partial damage of cement between grains. A typical impact test case is conducted both numerically and experimentally. It is demonstrated that the *FLAC3D-PFC3D* coupled model satisfies fundamental requirements and reproduces reasonable mechanical behavior of the triaxial Hopkinson bar. Further study will investigate various multiaxial loading conditions including uniaxial, biaxial and triaxial compression as well as the effect of loading rate on the damage-evolution process.

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