FLAC3D-PFC3D Coupled Simulation of Triaxial Hopkinson Bar

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OUTLINE

• Introduction
  – Dynamic loading resources
  – Experimental and numerical methods

• 3D Triaxial Hopkinson Bar

• Numerical Modelling

• Summary and Future Study
Natural and Human-induced Hazards: Confinement and Impact

- **Surface**
  - Intact rock: Barringer Meteor Crater
  - Granular materials: Rock fall, High-risk area, Kalgoorlie Super Pit

- **Underground**
  - Coal burst
  - Outburst of coal
  - Austar Coal Mine, NSW, Australia

- **Lab scale**
  - Compression
  - Tension
  - Single Shear
  - Double Shear

**Fracturing (primary)**
- Liu PhD thesis
- Liu PhD thesis

**Fragmentation (secondary)**
- Multi-particle impact: Parab 2017
- Single particle impact: Shan et al. 2018
- Particle chain impact: Liu et al. 2016

**Impact velocity (v)**
- 1.2km

**Confinement (σ₁, σ₂, σ₃)**
- Pressure
- Projectile

**Different loading conditions**
- Earthquake fault
- San Andreas fault at California
- Rempe et al. 2013
- Kenkmann et al. 2014
- Shan et al. 2018
- Parab 2017
- Austar Coal Mine, NSW, Australia
- Barringer Meteor Crater
- Kalgoorlie Super Pit
Dynamic Experimental Techniques

- Pneumatic-hydraulic Machines
- Drop Weight Machines
- Split Hopkinson Bar
- Plate Impact Techniques

\begin{itemize}
  \item 1D Split Hopkinson pressure bar ($\sigma_1 > 0, \sigma_2 = \sigma_3 = 0$)
  \item Conventional confining boundary ($\sigma_1 > \sigma_2 = \sigma_3$)
  \item Multiaxial loading boundary ($\sigma_1 > \sigma_2 > \sigma_3$)
\end{itemize}
Numerical Modelling Methods

- **Continuum-based methods**
  - RFPA, AUTODYN, LS-DYNA
  - Incorporation of rate-dependent constitutive models
  - Phenomenological representation of failure

- **Discontinuum-based methods**
  - UDEC, PFC, ESyS-Particle
  - Explicitly modelling of fractures formed by microcracks
  - Limited scale
  - Insufficient strain rate effects

- **Hybrid Methods**
  - FDEM, FDM/DEM
  - Computational efficiency
  - Fracture and fragmentation
  - Stress wave propagation
OUTLINE

• Introduction
• 3D Triaxial Hopkinson Bar
  – Components and Capabilities
  – High-Speed Imaging and Micro-CT Scan
• Numerical Modelling
• Summary and Future Study
Dynamic Behaviours under Multiaxial Loading

- Impact velocity up to 50 m/s
- Specimen size from 50 mm
- Triaxial quasi-static loads up to 100 MPa

Liu et al. 2019, RMRE

Schematic of 3D Triaxial Hopkinson bar at Monash University
Dynamic Behaviours under Multiaxial Loading

Polycrystals Composites Porous media
Granite Concrete Sandstone

Uniaxial (UC) Biaxial (BC) Triaxial (TC)

Internal (X-ray CT)

Surface (3D DIC)

Multiple contacts

Micro scale (SEM)

- Fracture surface energy
\[ E_s = W_{\text{in.}} - W_{\text{Re.}} - W_{\text{Tr.}} - E_k \]
\[ G = E_s/A \]

Granite Marble Sandstone

- Internal (X-ray CT)
- Microstructure
- Failure mechanism

- Kinetic energy of the flying fragments
\[ E_k = \frac{1}{2} m v^2 + \frac{1}{2} I w^2 \]
OUTLINE

• Introduction
• 3D Triaxial Hopkinson Bar
• Numerical Modelling
  – A coupled continuum-discrete method
  – Flat-jointed model
  – Verification and comparison
• Summary and Future Study
A Coupled Continuum-discrete Model for 3D SHPB

Steel Bars: continuum
20000 elements, size: 20x5x5 mm$^3$

Rock: discontinuum
20127 balls, radius: 0.8–1.2 mm

Mineral grains 3D Flat-jointed material

Coupling logic

Model Components

- 3D grain microstructure
- Partial damage
- Rotation resistance

Flat-joint contact
Verification and Comparison

Wave propagation in X direction

Stress-time history

Comparison in X direction

Impact from multiple directions
**Damage Pattern**

- **Flat-jointed model (FJM)**
  - Particle 1
  - Interface cement
  - Full damage after breakage

- **Parallel-bonded model (PBM)**
  - Particle 2
  - Interface elements
  - Partial damage is allowed

**Damage ratio (%)**

\[
\text{Damage ratio} = \frac{\text{Broken contact elements}}{\text{All contact elements}} \times 100\%
\]

**CT slice 3D fragments**

**Z displacement (mm)**

**Z velocity (mm)**
Double Impact on Rock Spheres

- **Local crushing zone**
- **Surface fracture**
- **Meridian fracture**
- **Fragment slice**
- **8 major fragments**
- **Powders**

- **High speed cameras and DIC techniques**
- **CT slices characterizing fracture and damage**

Marble - impact velocity = 9.17 m/s
Numerical Modelling of Double Impact Test on Sandstone

Contact force chain

Fragments

Tensile/Shear Cracks

Different loading stages
Summary and Future Studies

Summary

- The coupled continuum-discrete method can be used to simulate the triaxial Hopkinson bar
- Consideration of rock microstructure represented by 3D FJM contributes to an enhanced dynamic strength
- Similar V-shaped and orange-slice failure pattern of cubic and spherical rock can be observed

Future Studies

- Dynamic constitutive relationship under true triaxial loading condition
- Dynamic fragmentation models considering rock heterogeneity
- Application in prediction of blasting and crushing during mining operations