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# Replicating Brittle and Hard Rocks Using 3D Printing with Applications to Rock Dynamics and Crack Propagation

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# Outline

- Background
- Identification of a suitable 3DP material for mimicking brittle and hard rocks
- Investigation of dynamic response of artificial rocks
- 3D internal crack growth under static and dynamic compression

# Motivation

1) It is fancy

2) Previous works: Pioneer application of 3DP in rock mechanics such as Ju et al. (2014)

3) A 3DP centre at HKPolyU over 20 advanced 3D printers

# Background

Problems of experimental study using natural rock specimens:

1) impossible to repeat the experimental results due to rock heterogeneity;

2) expensive to obtain rock cores from deep underground, and many samples are required during tests;

3) difficult to produce rock samples with internal 3D flaws;

4) difficult to observe and accurately detect spatial evolution of cracks inside rocks in real-time

# Background

Three-dimensional printing (3DP), also termed as rapid prototyping, builds up objects by fabricating parts layer upon layer based on a computerized 3D model data.

***Advantages***: precise fabrication;

fast and flexible preparation;

high repeatability;

no restrictions on geometrical shapes

**Typical 3DP techniques:**

Fused deposition modelling (FDM) , Powder based 3DP, Stereolithography (SLA), Selective laser sintering (SLS).

# Background

*More than 20 3D Printers at PolyU*

*20 years history,*
*3DP central facility*

**Fused Deposition Manufacturing**

**Selective Laser Sintering**

**Powder-based 3DP**

**Stereolithography (SLA)**

**SLA**

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# Five targeted available 3DP materials

The printing details of the samples

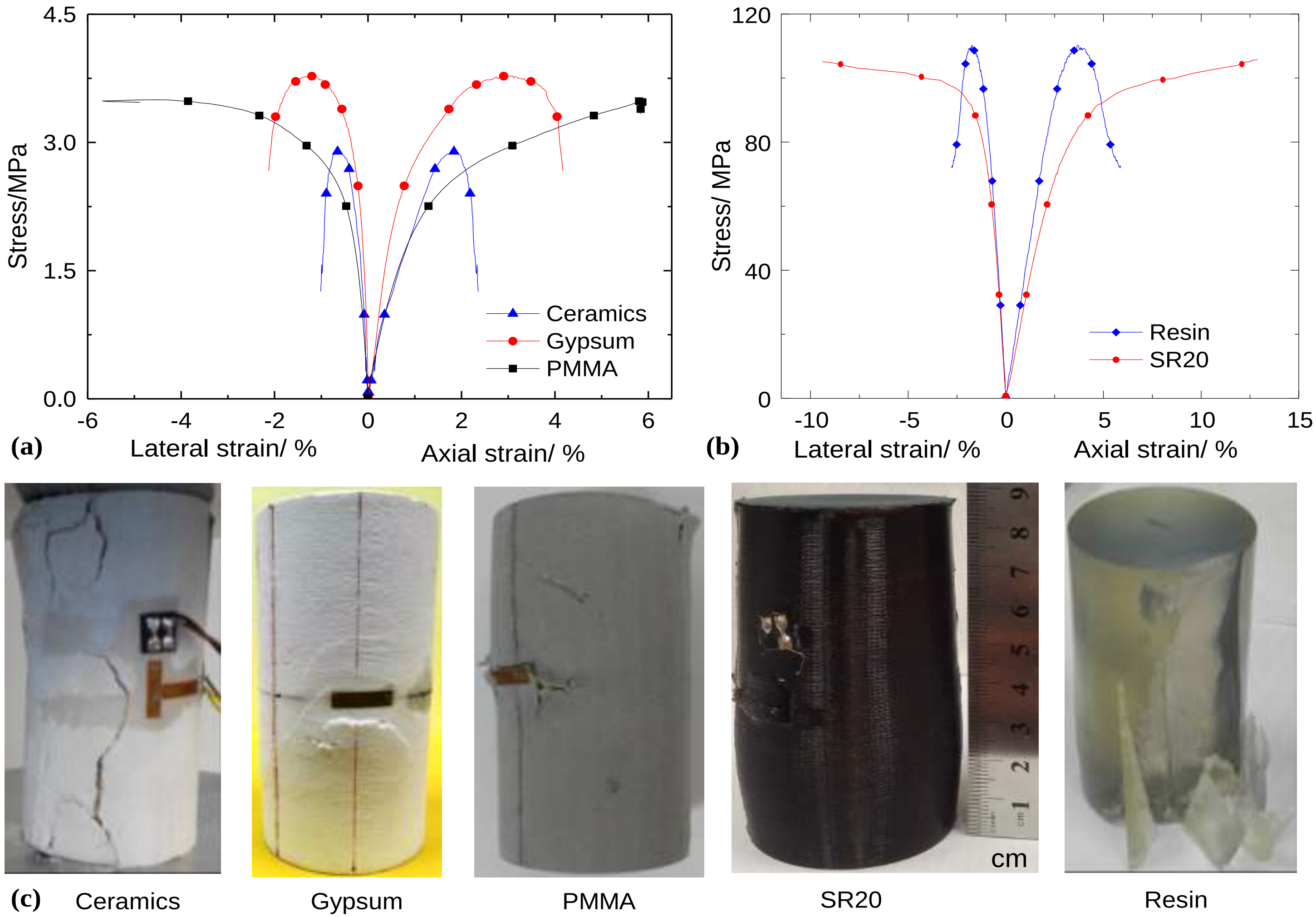
| Material | Transparency | Printer | Layer thickness | Density ($g/cm^3$) | Printing method |
|---|---|---|---|---|---|
| Ceramics | Opaque | Z Corp 301 | 0.1 mm | 1.37 | 3DP |
| Gypsum | Opaque | ProJet 860 | 0.1 mm | 1.27 | 3DP |
| PMMA | Opaque | VX200 | 0.15 mm | 0.66 | 3DP |
| SR20 | Opaque | Fortus 380 | 0.254 mm | 1.11 | FDM |
| Resin | Translucent | Viper si2 | 0.05 mm | 1.21 | SLA |

Ceramics Gypsum PMMA SR20 Resin

3DP prepared samples before testing

PMMA (poly methyl methacrylate), SR20 (acrylic copolymer), Resin (accura® 60)

# Uniaxial compression results




Stress-strain curves and the 3DP samples after testing

# Uniaxial compression results

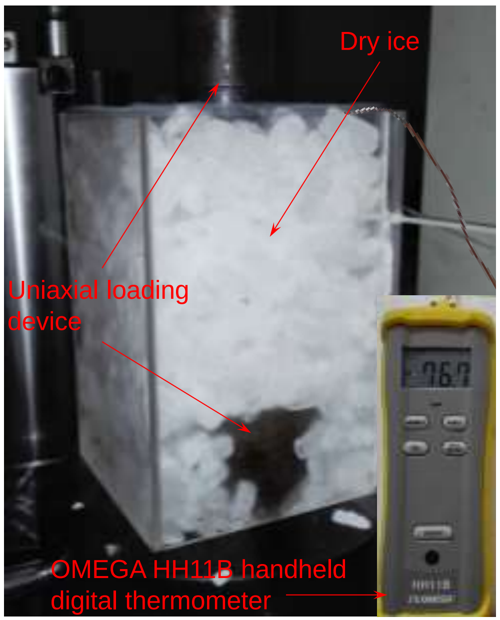
Powder-based 3DP-based specimens failed with very low loading;

FDM- and SLA-fabricated specimens yielded with high stress.

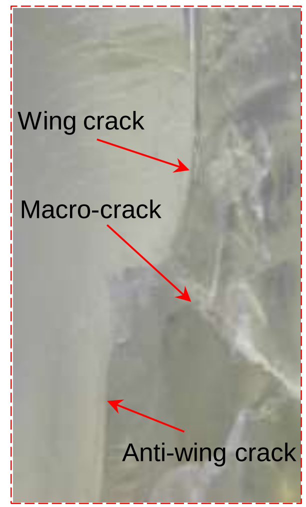
Mechanical properties of the 3DP samples

| **Sample** | **$\sigma_c$ (MPa)** | **$\varepsilon_A$ (%)** | **$\varepsilon_L$ (%)** | **$E$ (GPa)** | **$\upsilon$** | **Printing method** |
|---|---|---|---|---|---|---|
| **Ceramics** | 2.74 | 1.51 | -0.42 | 0.17 | 0.20 | Powder-based 3DP |
| **Gypsum** | 3.79 | 3.07 | -1.28 | 0.43 | 0.29 | Powder-based 3DP |
| **PMMA** | 3.50 | 5.87 | -4.36 | 0.21 | 0.33 | Powder-based 3DP |
| **SR20** | 105.56 | 12.23 | -10.05 | 2.74 | 0.36 | FDM |
| **Resin** | 110.30 | 3.60 | -1.75 | 3.81 | 0.42 | SLA |

# Brittleness enhancement of 3DP resin

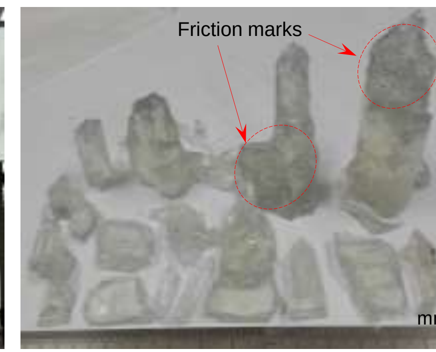



1. Freezing




(a) Failure pattern (b) Typical cracks

2. Incorporation of a macro-crack




(a) Internal fracturing (b) Fragments

3. Addition of micro-defects

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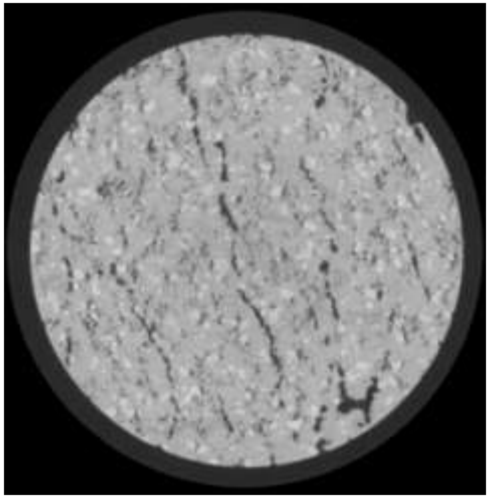
# Sample preparation

Hainan volcanic rock was used to construct 3D digital rock cores

Mechanical properties of the volcanic rock

| $\sigma_c$ (MPa) | $\sigma_t$ (MPa) | $E$ (GPa) | $v$ | $\rho$ (g/cm$^3$) | Porosity |
|---|---|---|---|---|---|
| 81.3 | 7.1 | 40.1 | 0.24 | 2.6 | 7.2% |

Volcanic rock sample



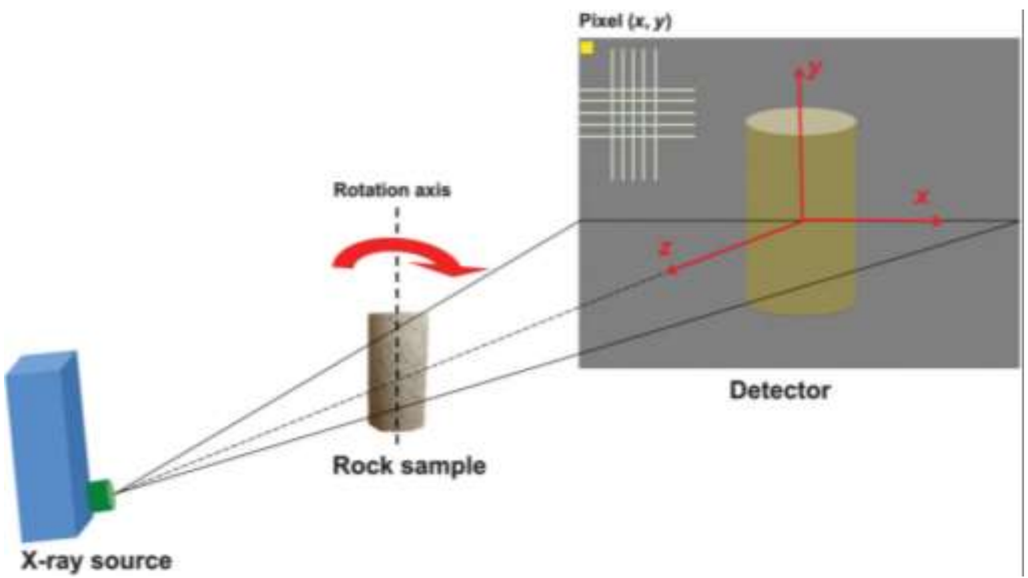
Micro-CT scan image of Volcanic rock

# Sample preparation

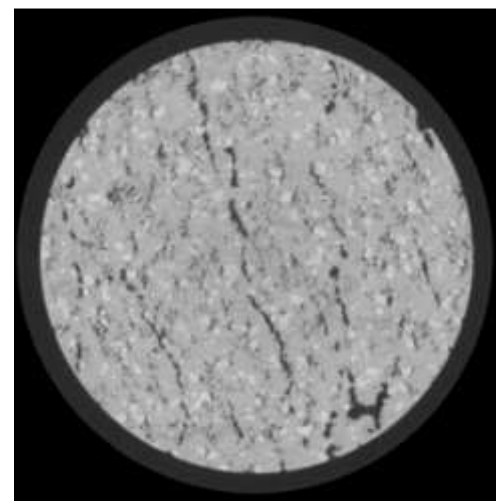
Micro-CT scanner, 3D printer

***Micro-CT scanner:*** **X-ray Micro-CT XRM 500 (RIPED, Beijing)**

Scanning range: $50\times50$ *mm*; Pixel: $2000\times2000$; Resolution: $50\ \mu m$



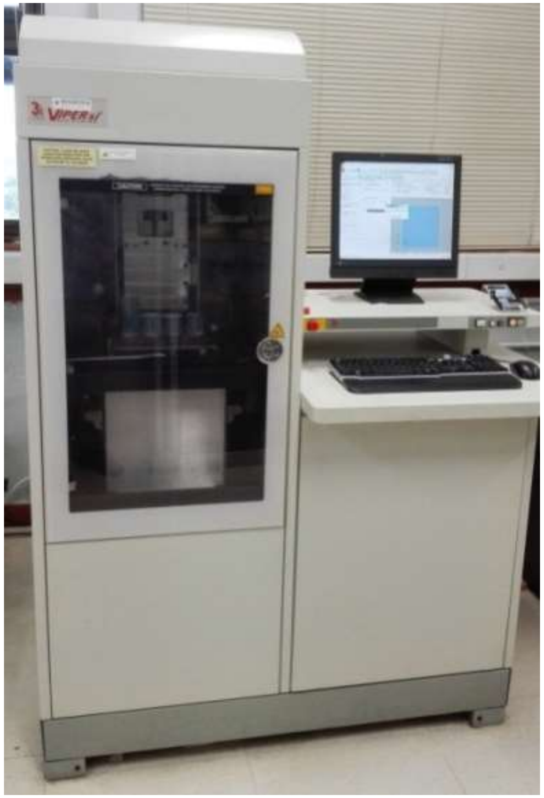

The CT scanning system (Ishutov *et al*. 2015)



Micro-CT scan image of Volcanic rock

# Sample preparation

***3D Printer:*** **3D Systems Viper si$^2$** ***(SLA)***



3D Systems Viper si$^2$

Theoretical resolution: 2.5 $\mu m$

Present layer thickness: 50 $\mu m$

***Advantages:***

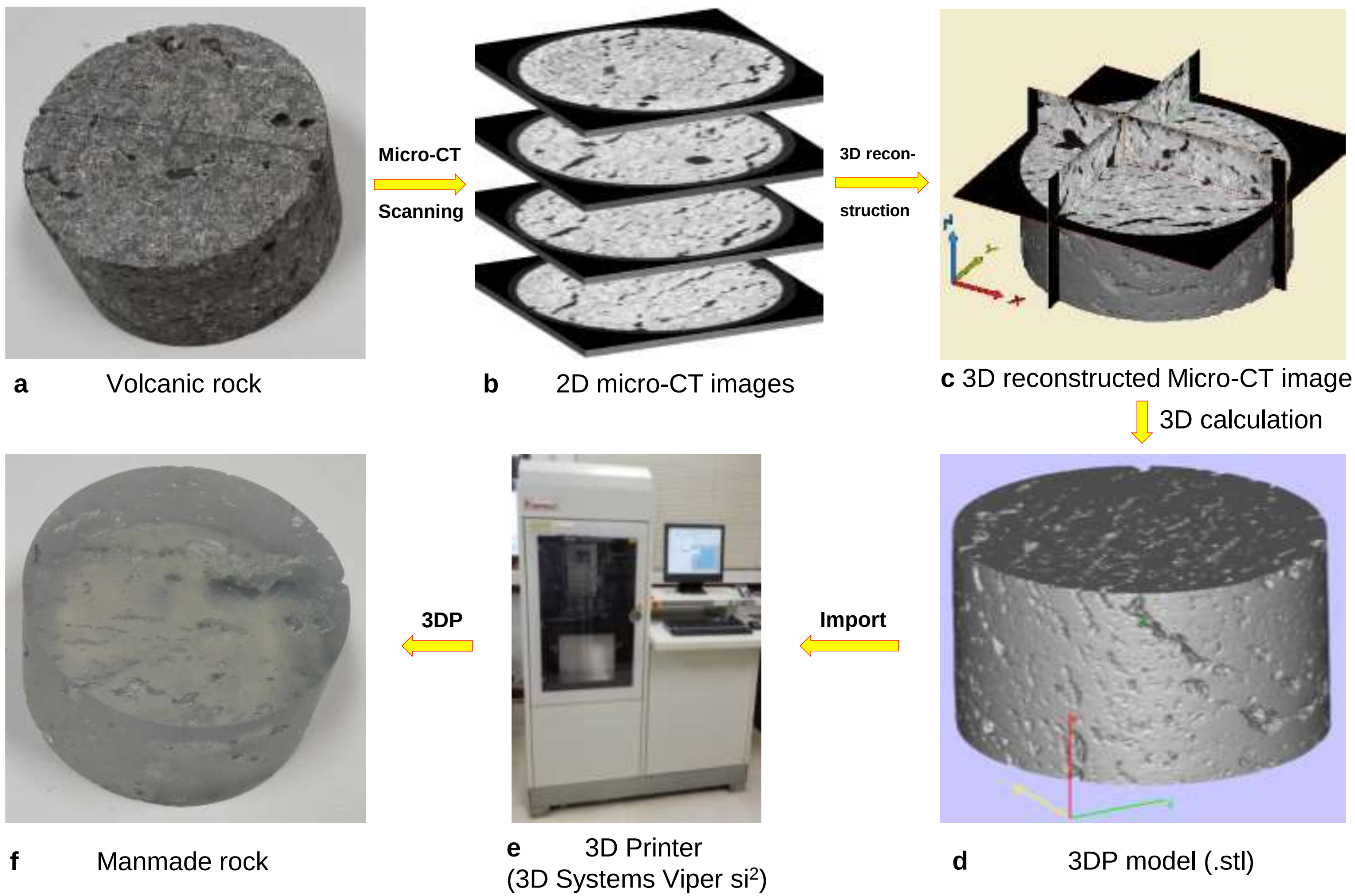
smooth surface finishing;

excellent optical clarity;

high accuracy;

excellent fine feature detail.

# Sample preparation

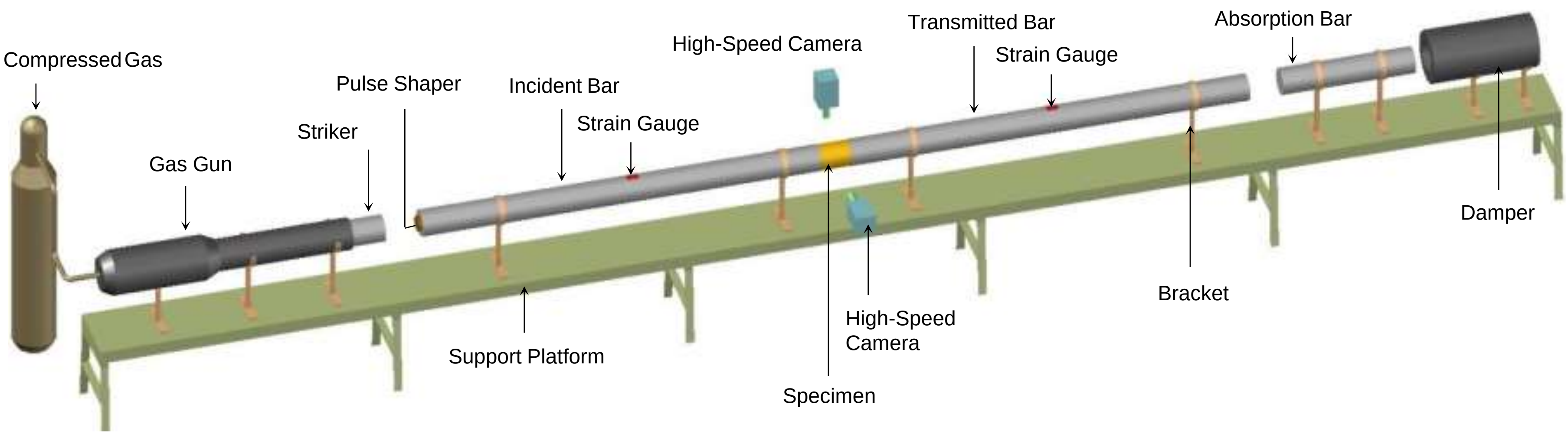



Workflow of printing resin sample

# Dynamic testing device

Split Hopkinson pressure bar (SHPB) system: Dynamic compression and Brazilian tests

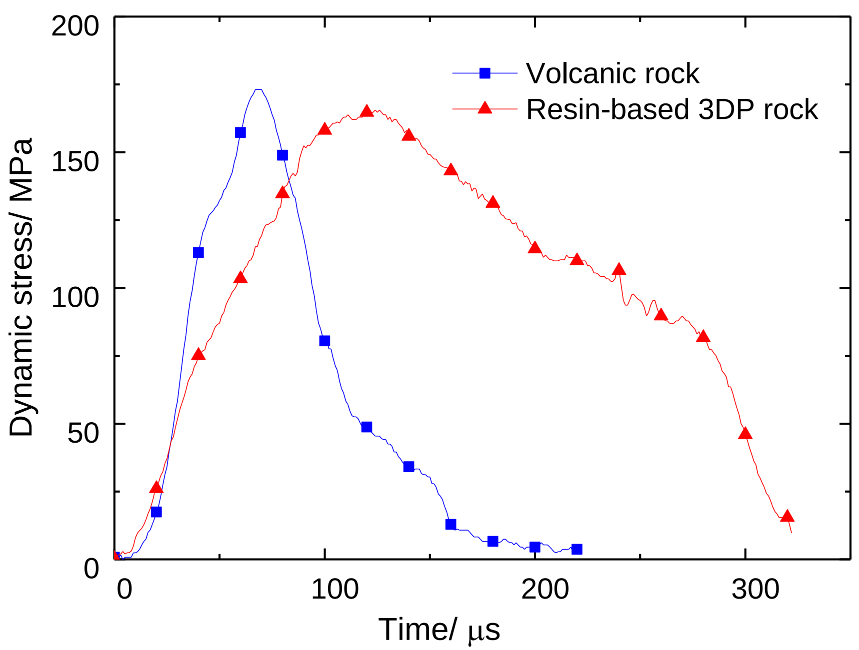
FASTCAM SA1.1 high-speed camera -100,000 frame per second



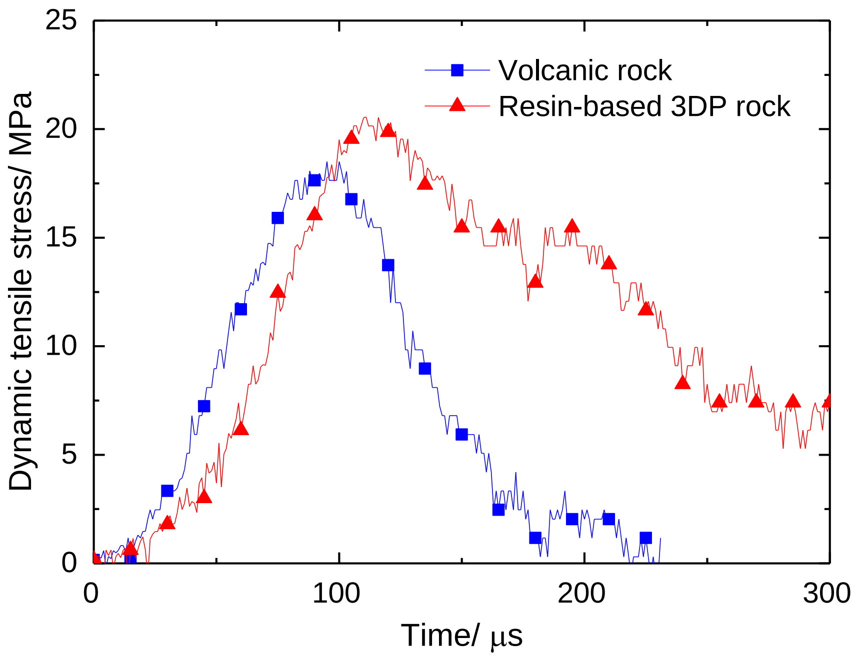

The schematic of SHPB system

# Dynamic testing results

The dynamic strength and the pre-peak stress-time behavior agree well with those of the natural volcanic rocks.




Dynamic compressive stress-time curves




Dynamic tensile stress-time curves

*Zhou T and Zhu JB (2016). The 2nd International Conference on Rock Dynamics and Applications (Conference Best Paper Award)*

# Dynamic testing results: Compression

Similar fracturing process and failure patterns

60us 80us 100us 160us 200us 250us 1000us

60us 80us 100us 160us 200us 250us 1000us

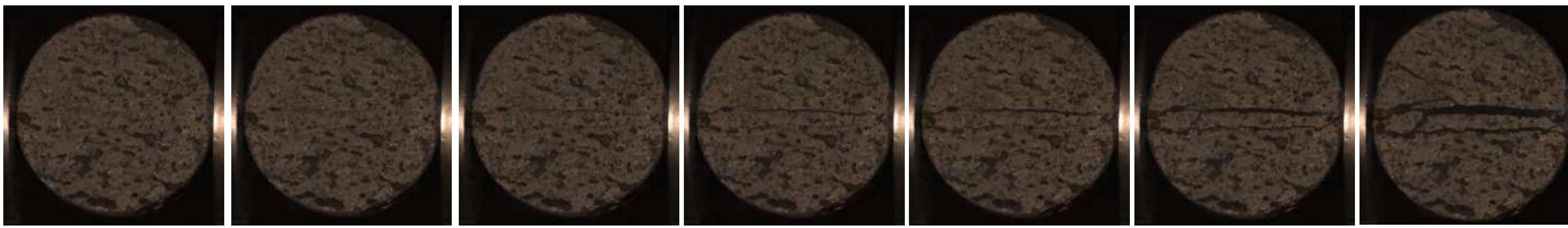
# Dynamic testing results: Compression

Fracturing process of 3DP manmade rock under compression.

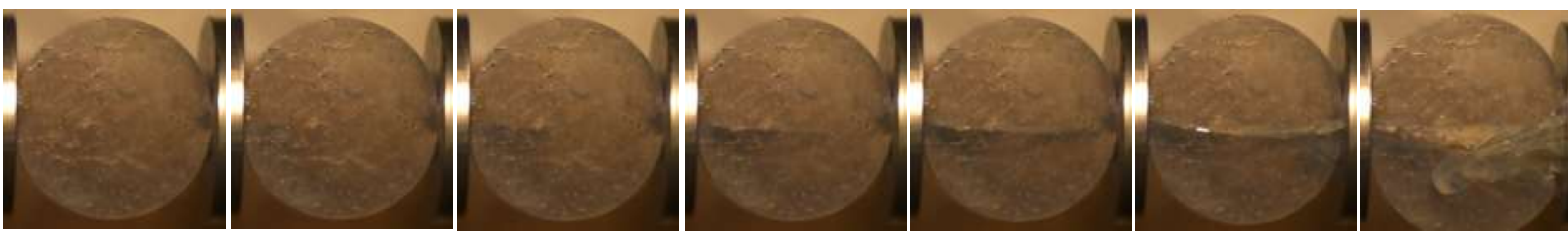
Loading direction: from right to left.

# Dynamic testing results: Brazilian

Similar fracturing process and failure patterns



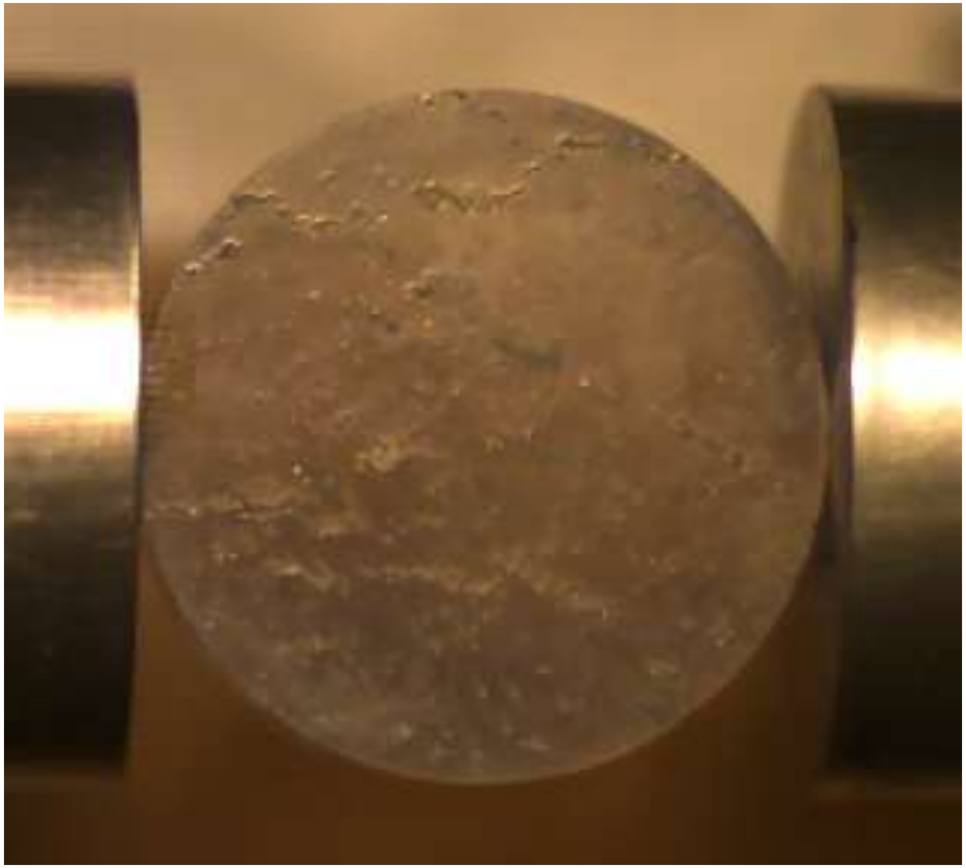
60us 100us 120us 140us 160us 200us 400us



60us 100us 120us 140us 160us 200us 400us

# Dynamic testing results: Brazilian

Fracturing process 3DP manmade rock in dynamic Brazilian test



Loading direction: from right to left.

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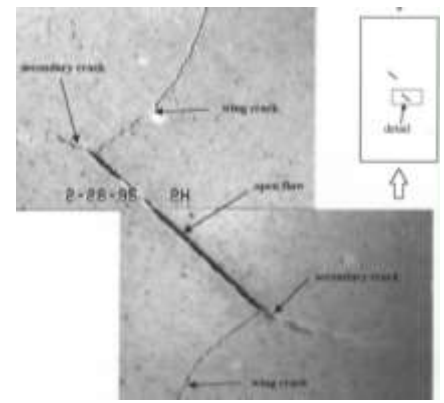
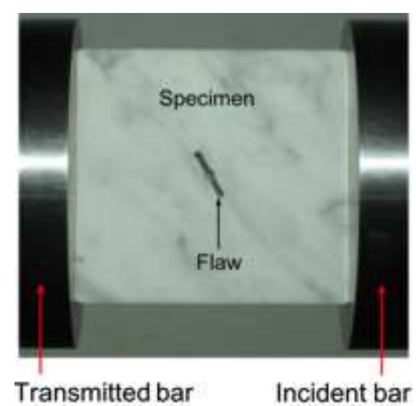
# Experimental studies on 2D crack growth

| Research group | Articles | Notes |
|---|---|---|
| Prof. H Horii and S Nemat-Nasser | Nemat-Nasser and Horii (1982); Horii and Nemat-Nasser (1985, 1986) | Studies on 2D crack propagation and coalescence in plate resin under static uniaxial compression |
| Prof. HH Einstein and his colleagues | Reyes and Einstein (1991)<br>Bobet and Einstein (1998)<br>Wong and Einstein (2009)<br>Moradian et al. (2016) | 2D crack propagation and coalescence in rock and gypsum materials have been systematically studied via static compression tests |
| Geotechnical colleagues at HK PolyU | Wong and Chau (1997)<br>Wong et al. (2001)<br>Yin et al. (2014) | 2D and surface crack growth in rock, PMMA and sandstone-like materials have been systematically studied via static compression tests |
| Other groups | Lee and Jeon (2011)<br>Yang and Jing (2011)<br>Zou and Wong (2012)<br>Li et al. (2016) | 2D crack fracturing in rock and gypsum materials have been studied through conducting static and dynamic compression tests |



Bobet (2000)

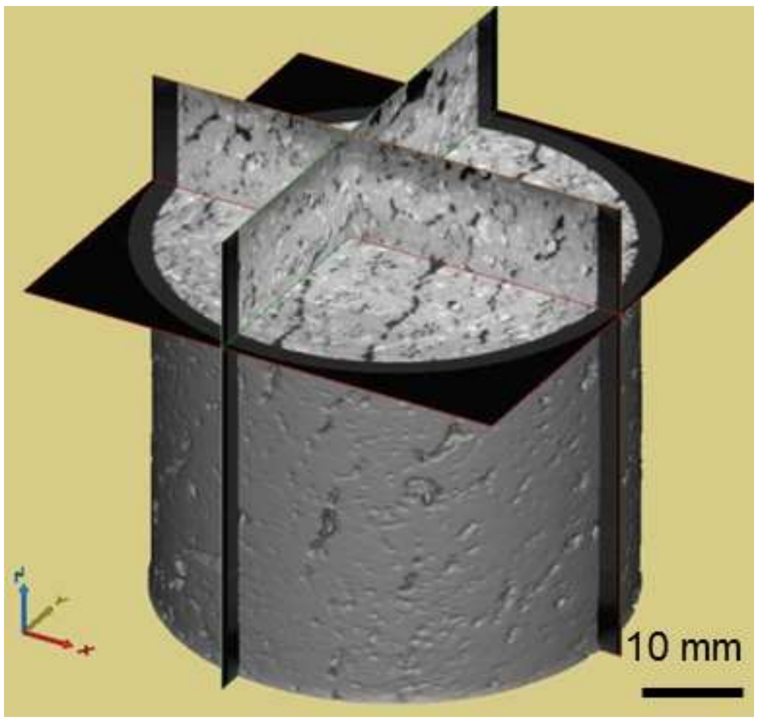
Static compression test




Li et al. (2016)

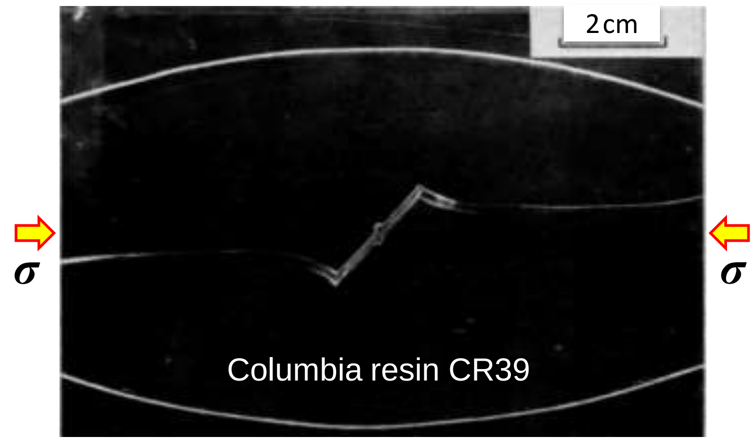
Dynamic compression tests

## 3D cracks exist in natural rocks

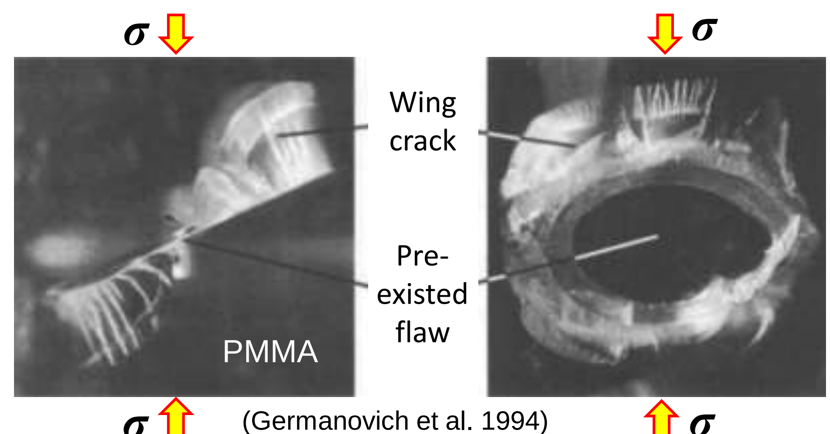



3D reconstructed CT images of volcanic rock

## Difference between 2D and 3D crack growth




(Horii and Nemat-Nasser 1985) 2D case



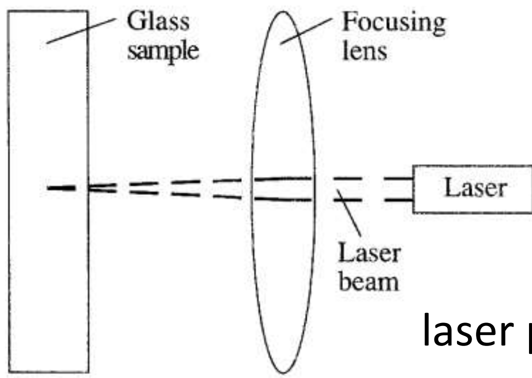

(Germanovich et al. 1994)

3D case

# Limitations of existing methods for producing 3D internal cracks

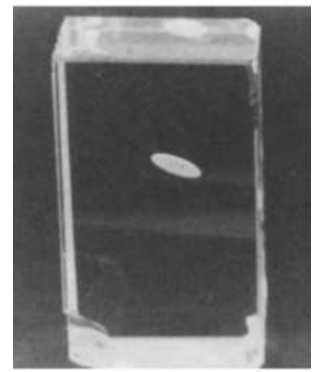
①

Generated by high-energy laser pulse




laser pulse

(Germanovich et al. 1994)



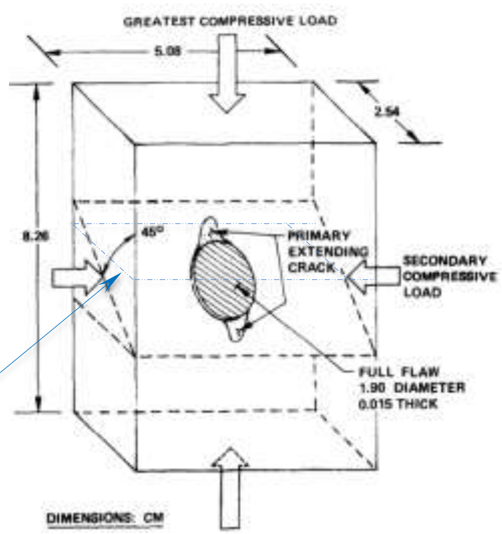
Silica glass sample

*Sophisticated skills are needed to operate the laser pulse generator*

②

Cementing two blocks together

*Unavoidable cutting plane*




Adams and Sines (1978)

Wing cracks

Cotton threads

3D flaws

Tang et al. (2015)

③

Hanging aluminium foil disks

*Difficult to guarantee the crack position; Remain in sample*

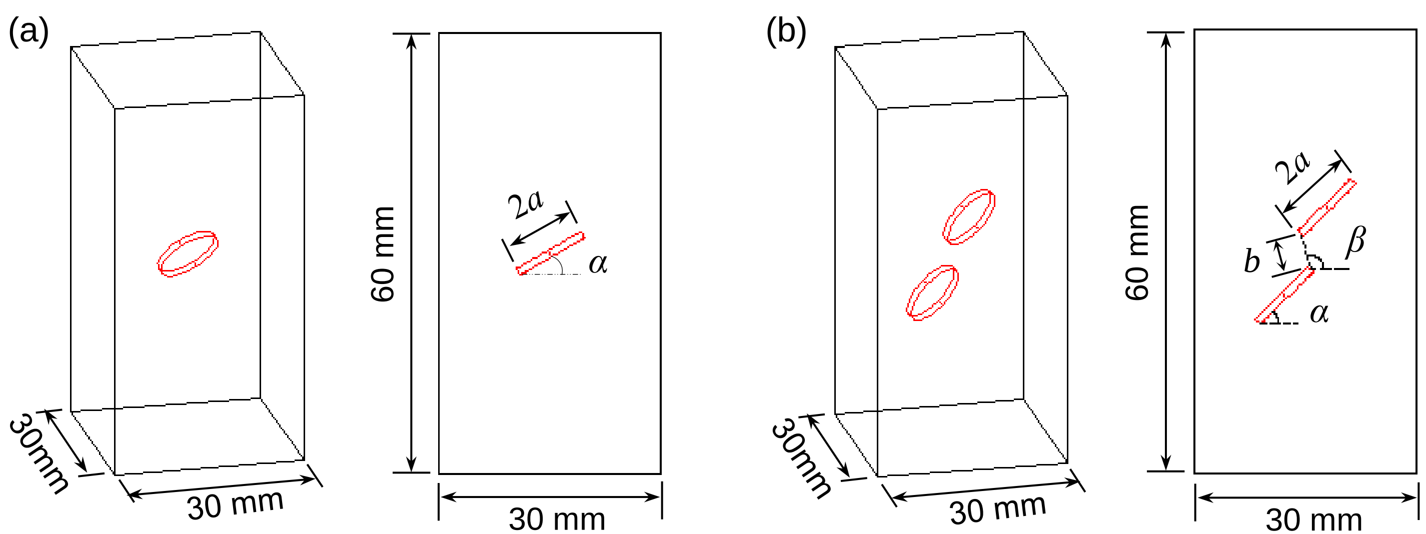
# Producing 3D internal flaws using the SLA-based 3DP

***Prismatic 3DP resin Samples***

***Two high-speed cameras***

Group and test information of samples

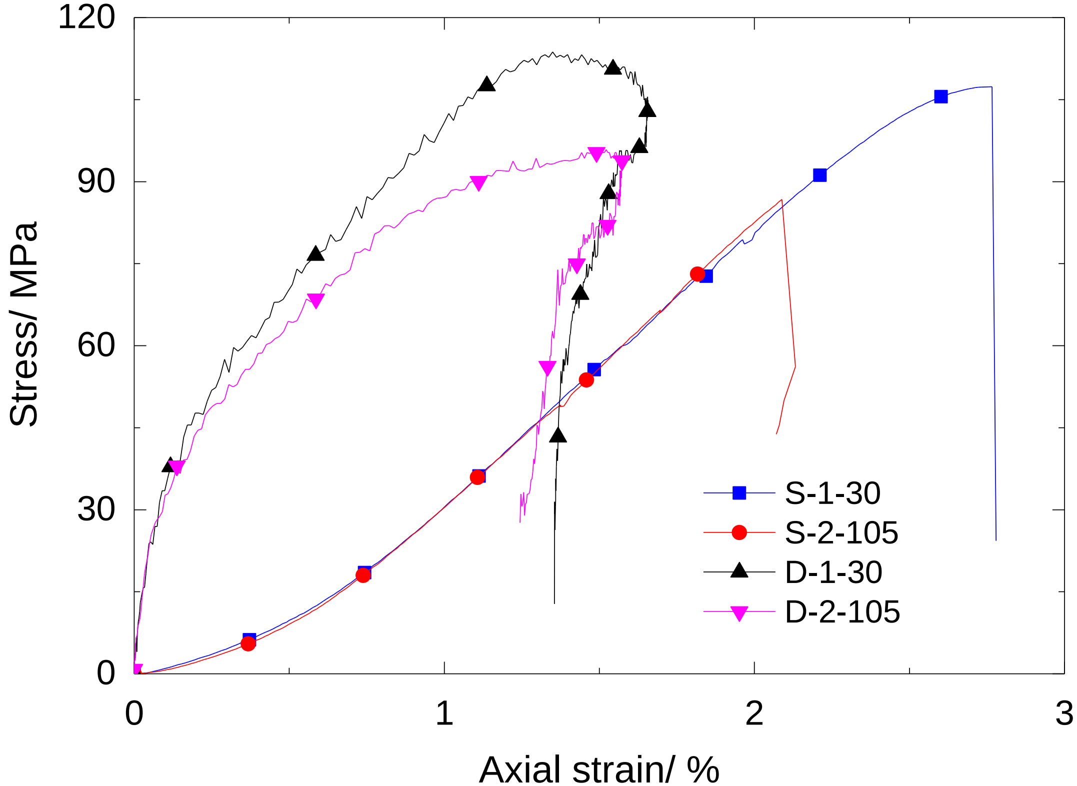
| Loading type | Sample no. | $\alpha$ | $\beta$ | Device |
|---|---|---|---|---|
| Static | S-1 | 30° | - | TAW-2000 rock testing system |
| | S-2 | 45° | 105° | |
| Dynamic | D-1 | 30° | - | SHPB system |
| | D-2 | 45° | 105° | |




Geometry of the pre-existing single flaw and double flaws in 3DP resin samples, where $\alpha$ is flaw angle, $\beta$ is ligament angle, $2a$ is flaw length, and $b$ is ligament length.

# Results

## Influence of pre-existing flaws and loading types on mechanical properties

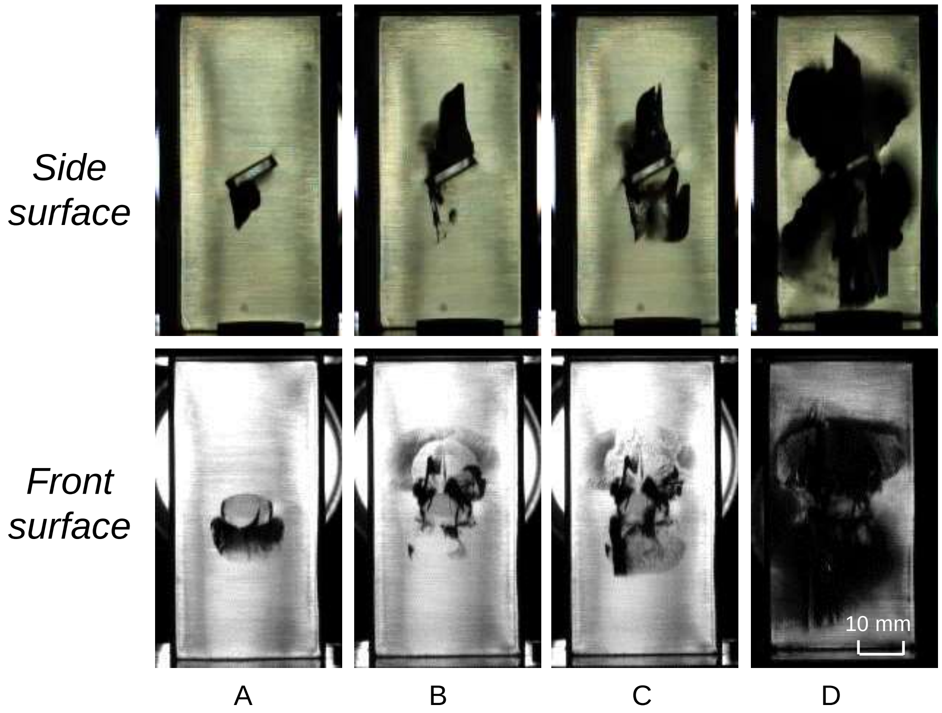


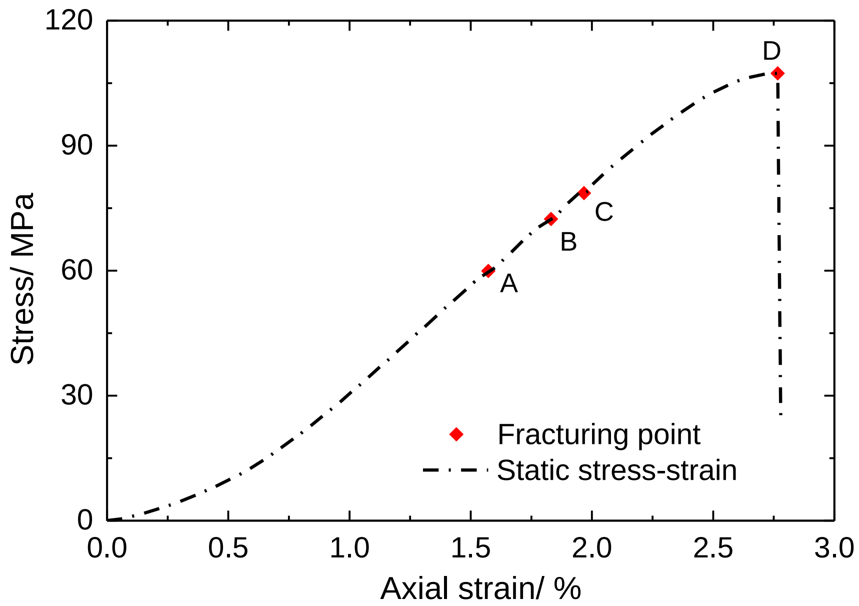

*Zhou T and Zhu JB (2016). The 9th Asian Rock Mechanics Symposium (Conference Best Paper Award)*

Results

***Single flaw***

## 3D crack growth under static compression



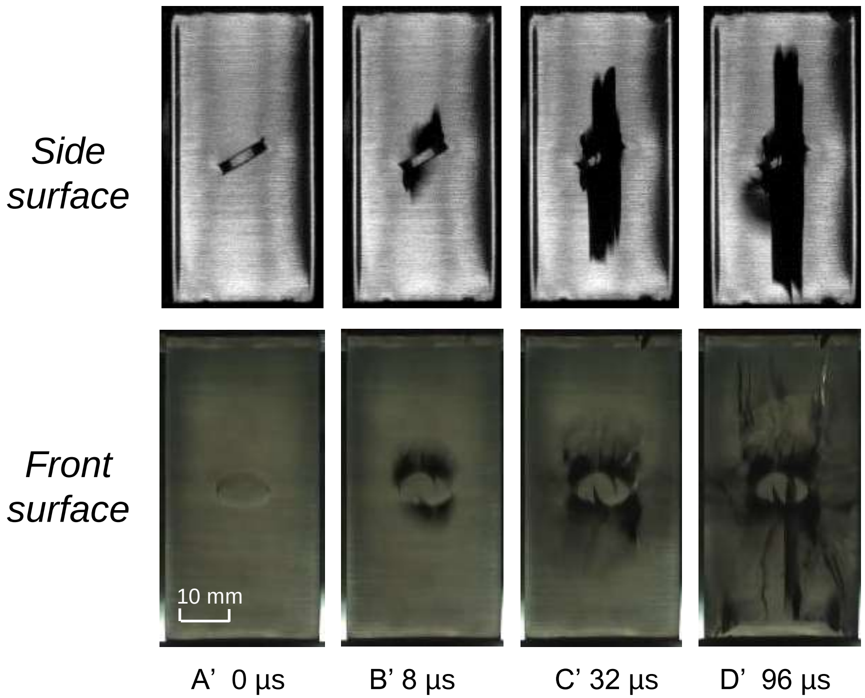



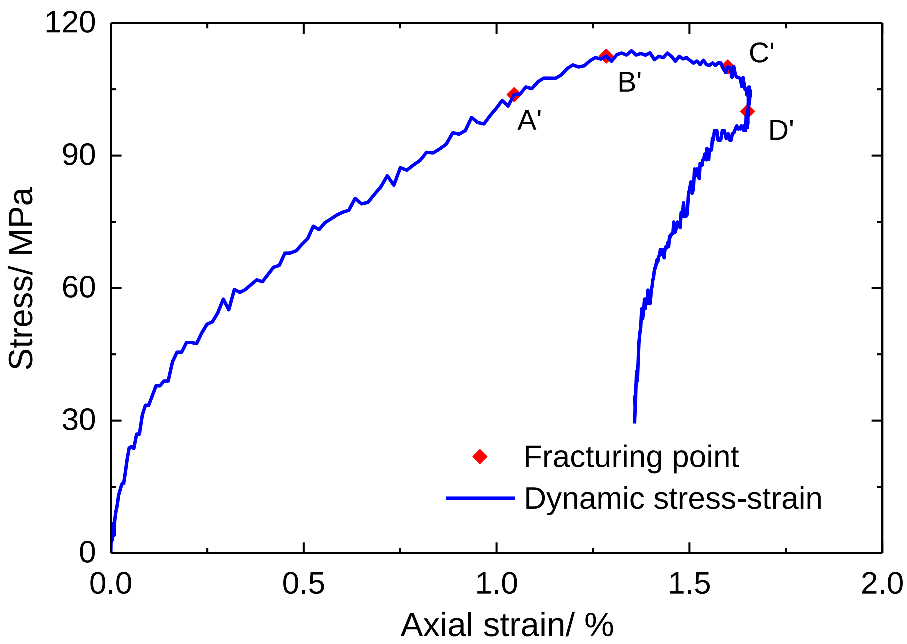

Wing and anti-wing cracks intermittently generated. The fracturing process from A to D is approximately 1 minute.

Results

***Single flaw***

## 3D crack growth under dynamic compression



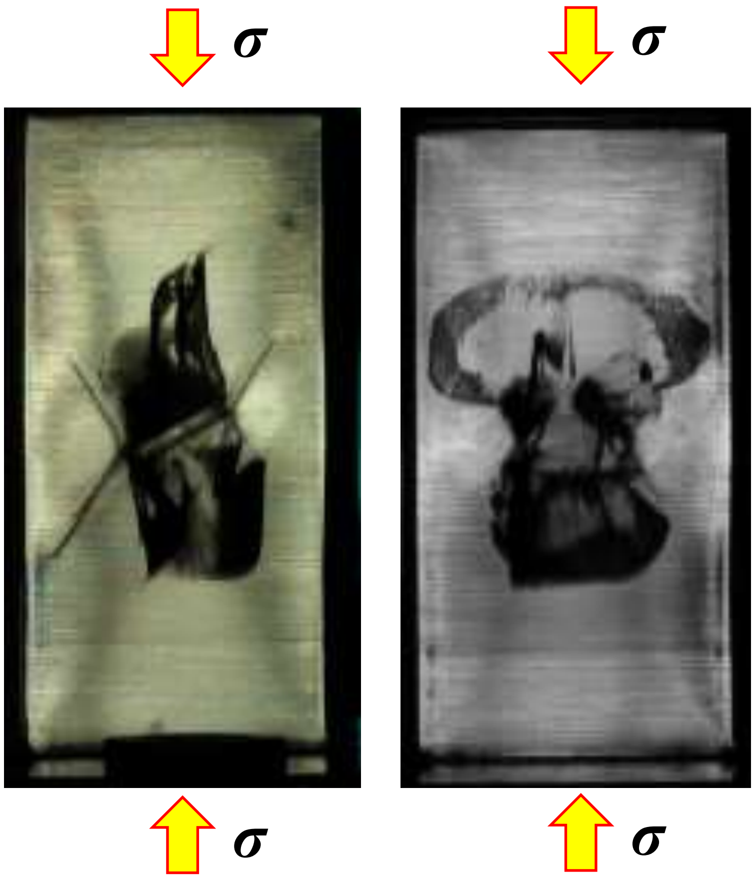




Wing cracks continuously propagated. The fracturing process from A' to D' is approximately 100 μs.

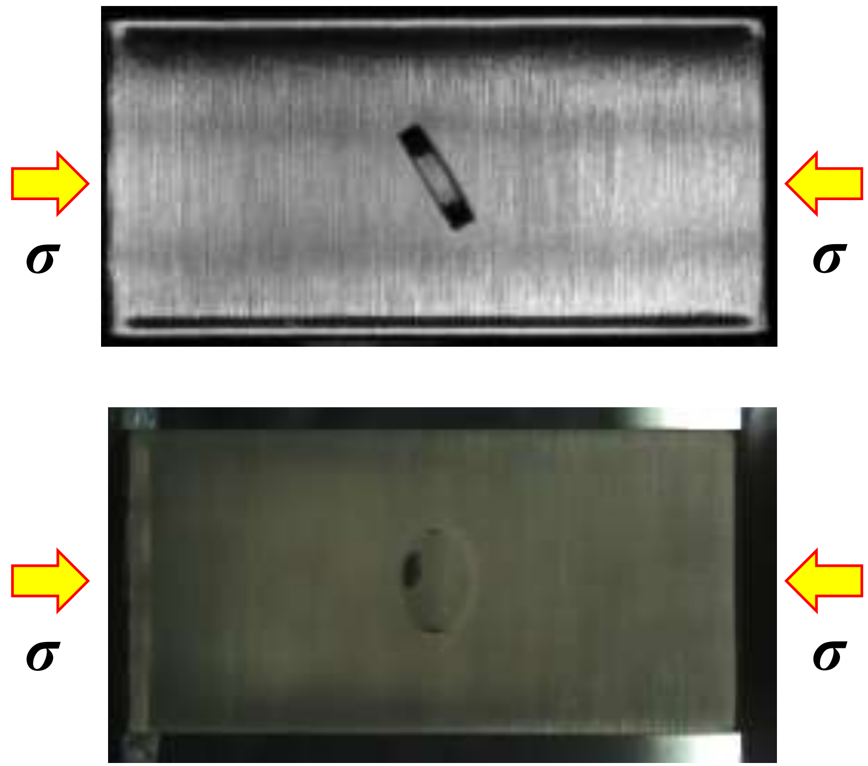
Results

***Single flaw***

## 3D crack propagation under static and dynamic compression




Static (final fracturing)




Dynamic fracturing

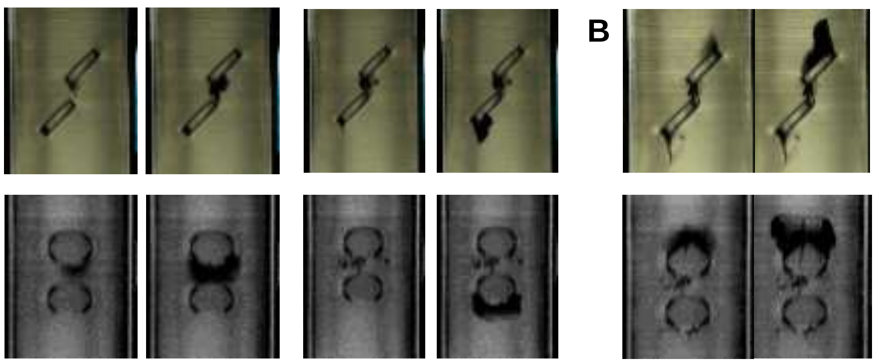
# Results

***Double flaws***

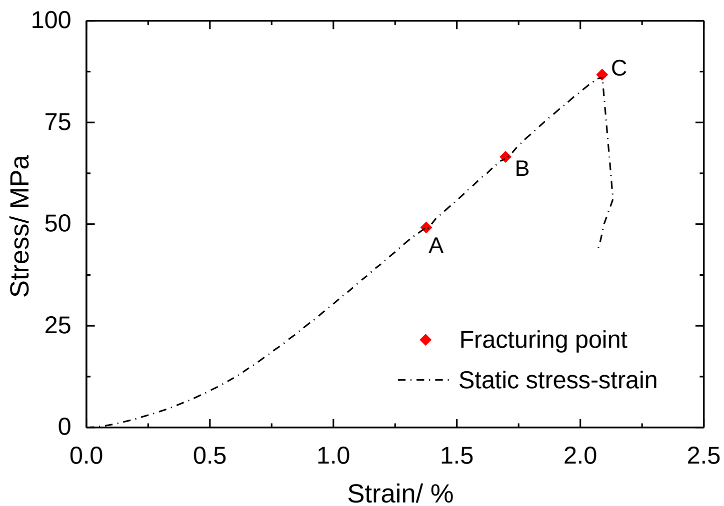
## 3D crack propagation and coalescence under static compression

**A** *Side surface* / *Front surface*

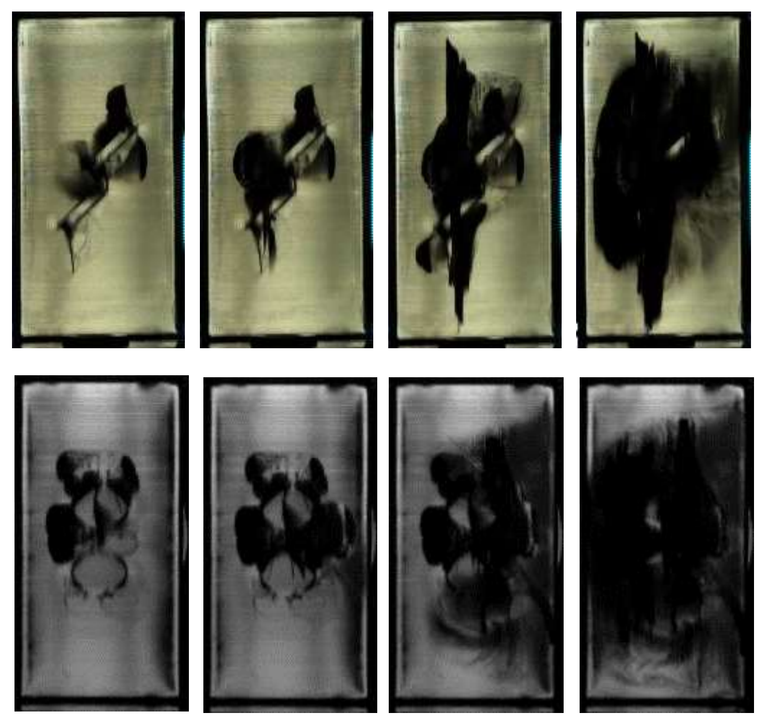
**B**



6.67 µs 13.33 µs / 6.67 µs 20 µs 6.67 µs 20 µs




**C** *Side surface*



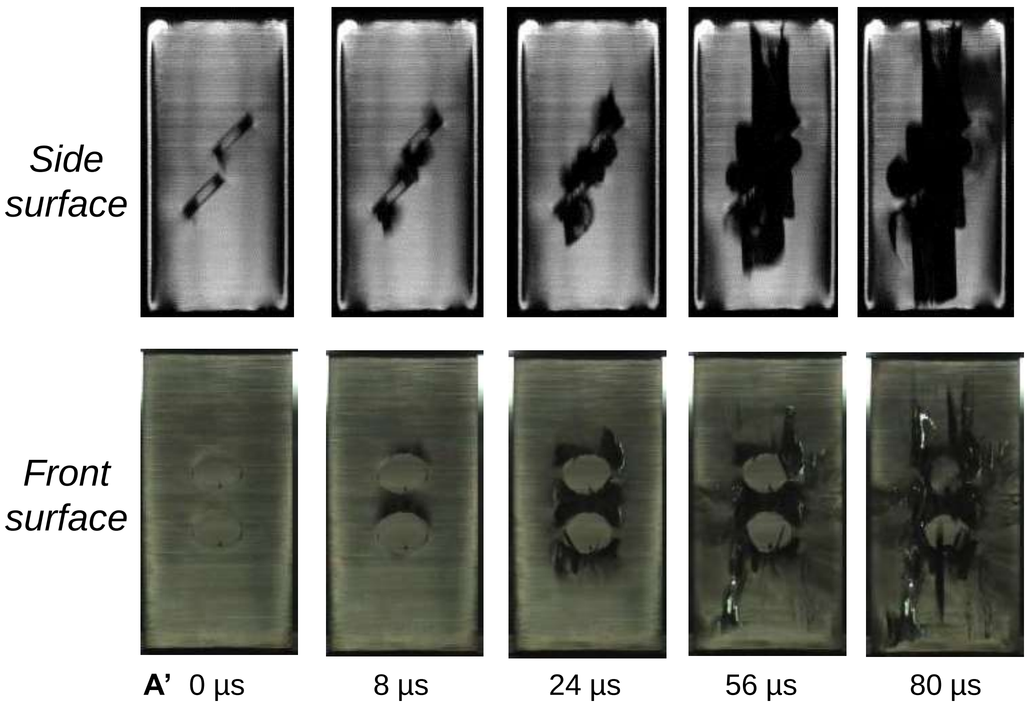
0 µs 30 µs 70 µs 130 µs

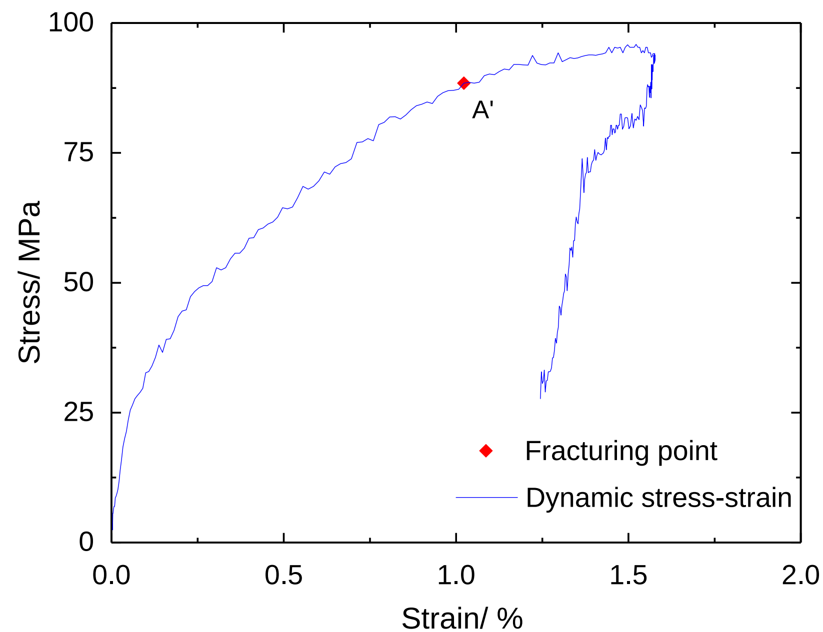
*Front surface*

## Results

***Double flaws***

# 3D crack propagation and coalescence under dynamic compression



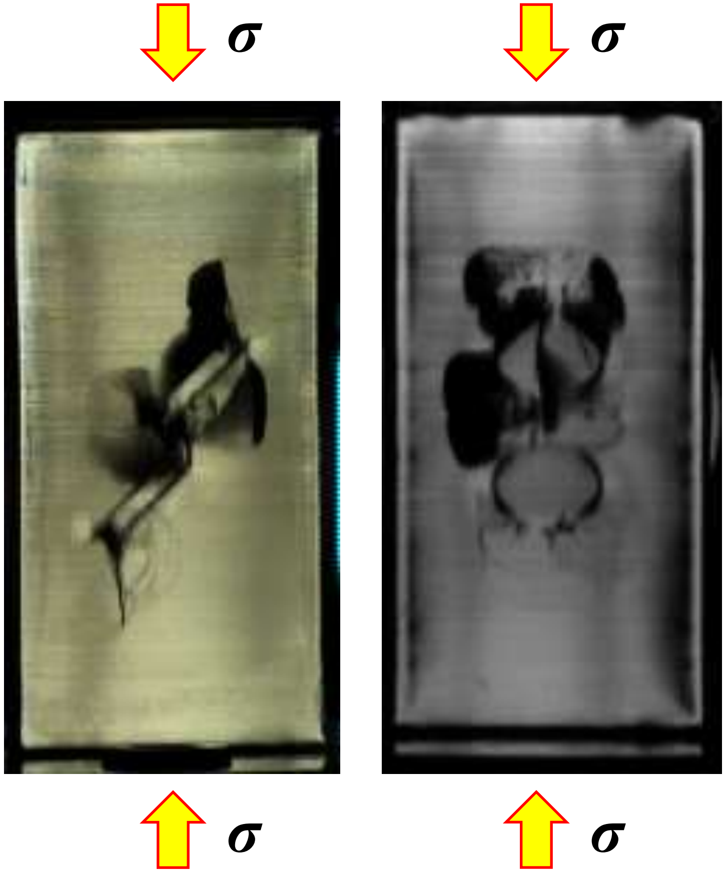




Wing cracks continuously propagated.

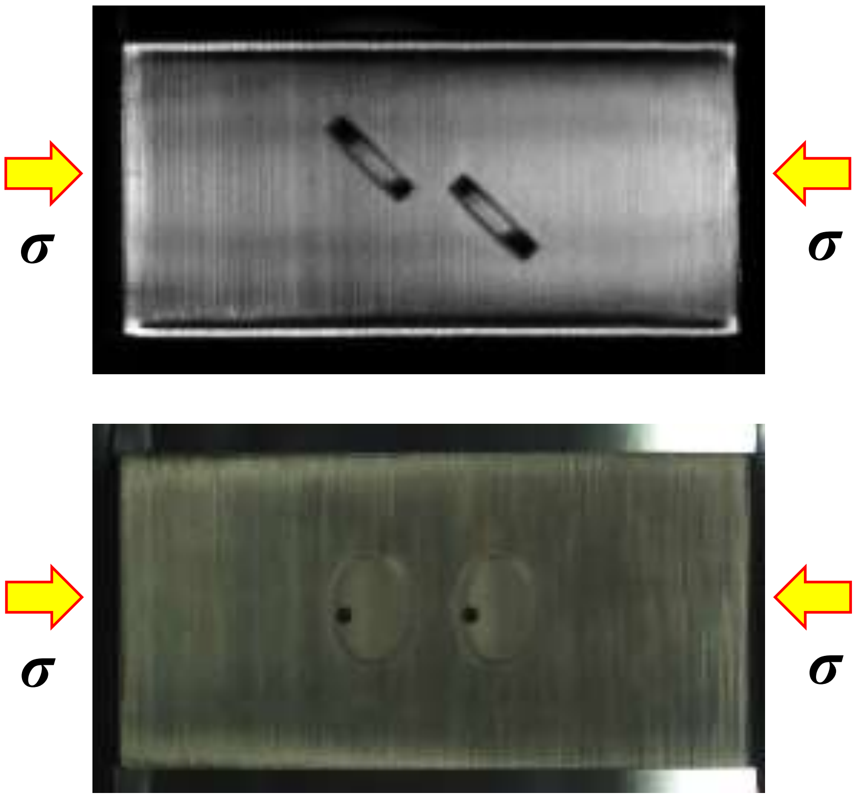
Results

***Double flaws***

## Comparison of 3D crack propagation in static and dynamic tests




Static (final fracturing)

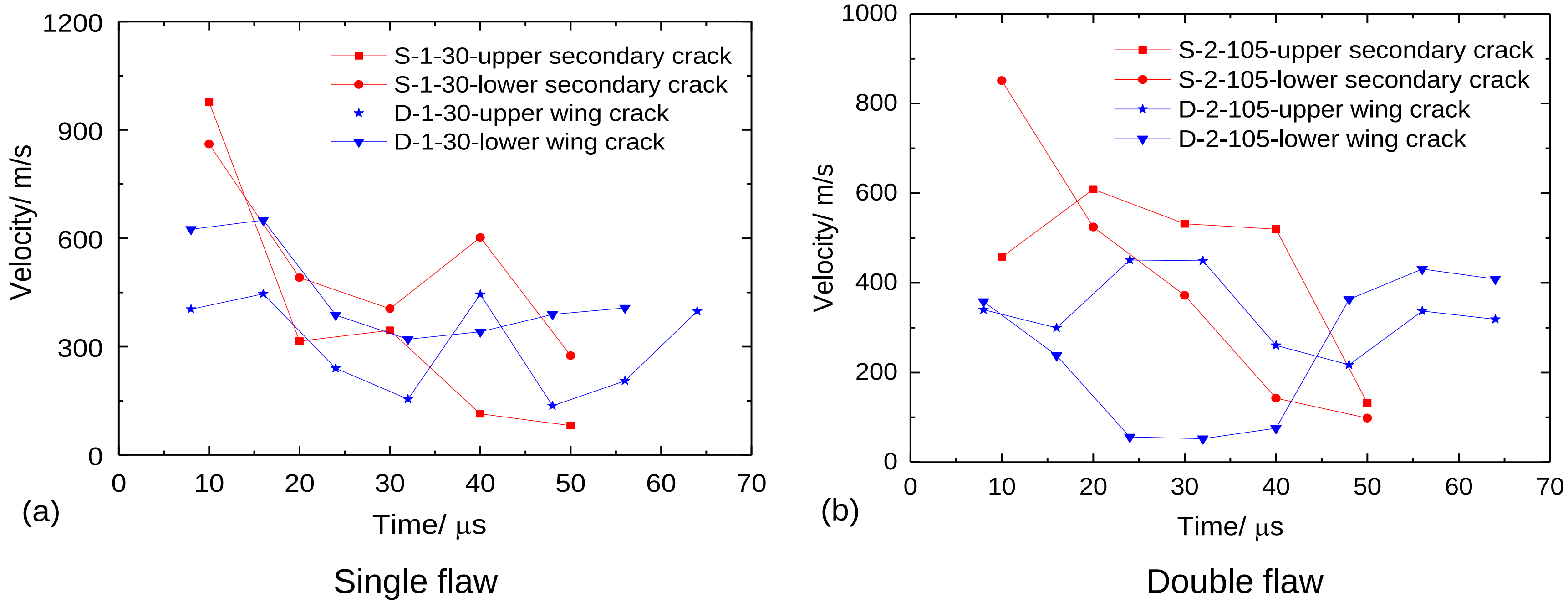



Dynamic fracturing

# *3D crack propagation velocity*

Unstable for static test, more stable for dynamic test.

The maximum velocity is higher in static test.




3D crack propagation velocities in static and dynamic compression tests

## Conclusions

1) The transparent resin fabricated by SLA is the most suitable 3DP material among the five targeted 3DP materials for mimicking brittle and hard “intact” rocks, particularly after brittleness enhancement.
2) Combined with micro-CT scanning and 3D reconstruction technologies, 3DP resin can effectively replicate dynamic behavior of natural rocks
3) The SLA-fabricated resin is suitable for studying 3D crack growth
4) 3D crack growth behaviors appear to be loading rate dependent:

   Static loading: secondary cracks lead to burst-like failure;

   Dynamic loading: wing cracks lead to splitting failure.

***Thank you for your attention!***

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