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TECHNICAL NOTE

Strength of Rock-Like Specimens with Pre-existing Cracks of Different Length and Width

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1 Introduction

Discontinuities play a key role in the failure process of rock and rock mass. Small fractures can decrease the strength of rock while large-scaled joints can have a significant effect on the overall stability of rock mass (Eberhardt et al. 2004). Discontinuities are often separated by intact rocks, which are known as "rock bridges". These rock bridges contribute to the stability of jointed rock mass by providing a strength reserve (Gehle and Kutter 2003) that needs to be broken first before failure can take place. In recent years, a number of experimental studies have been performed to investigate the mechanism of crack propagation in rock-like material under uniaxial (Shen et al. 1995; Wong and Chau 1998; Sagong and Bobet 2002; Xu et al. 2013; Yin et al. 2014; Cao et al. 2015), biaxial (Bobet and Einstein 1998), and shear (Gehle and Kutter 2003) stress conditions. It was revealed that under load conditions, wing cracks first appear at the tips of pre-existing cracks (flaw) while shear cracks typically lead to coalescence and failure. The aforementioned studies also indicated that the process of coalescence was rather complex and depended on the rock material and geometry of pre-existing cracks.

While the mechanism of crack propagation is relatively well understood, the extent to which pre-existing cracks can affect the strength characteristics of rocks still remains unclear. Ramamurthy and Arora (1994), Yang et al. (1998) and Park and Bobet (2009) noted that the characteristics of joints such as their number and orientation can affect the strength of rock. Shen (1995) and Park and Bobet (2009) reported that the joint roughness and the friction of the filled material (Shen 1995; Park and Bobet 2009) can also influence the strength of rock and rock mass. These joint characteristics are considered in the joint strength parameter, which is commonly used in engineering practice (Ramamurthy and Arora 1994; Zhang 2010). Unfortunately, much less attention has been given to the length and width of joints, which are parameters that can also affect the strength of rock and rock mass. This study seeks to address this issue by investigating the effects of pre-existing cracks of different width and length on the unconfined compressive strength (UCS) of rock-like material of various strengths. This technical note presents and discusses the obtained results.

2 Experimental Programme

Three types of material (A, B, and C) were selected to provide a wide range of strengths of intact specimens. Type A was made of the commercially available Bastion concrete mix (a pre-made concrete mixture complied with the Australian Standard AS 3648-1993) to produce intact specimens with a relatively low UCS of about 10–11 MPa. The specimens of Type B were prepared from a mixture of water, cement, and coarse basalt aggregates of 10-mm size. The water/cement ratio of this mixture was 0.42, which resulted in the UCS of intact specimens to be about 45–46 MPa. Similar to Type B, specimens of Type C were made of a mixture of water, cement, and aggregates, but with a lower water/cement ratio of 0.29. The strength of

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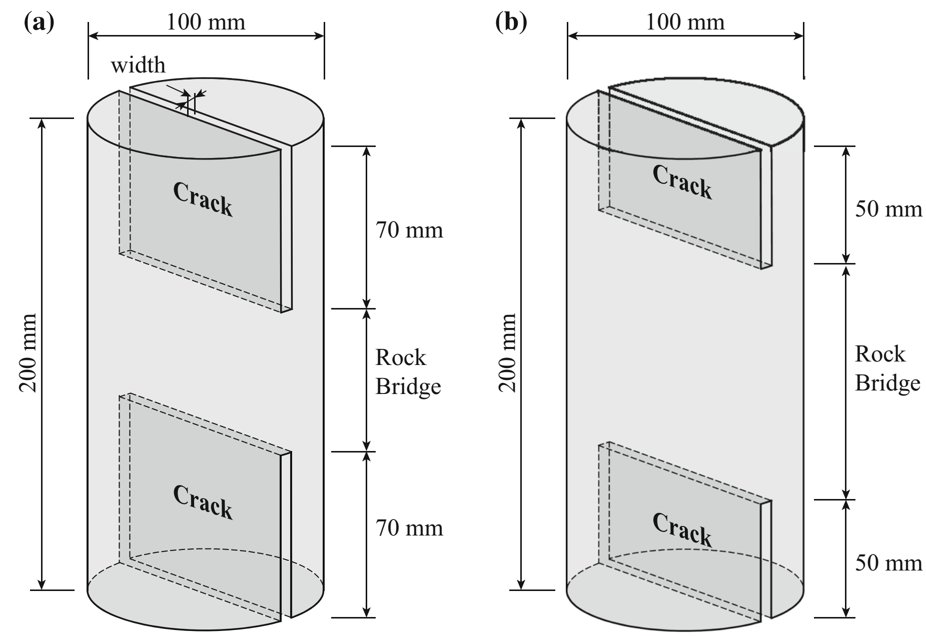

Fig. 1 Specimens with pre-existing cracks that form a short rock bridge (**a**), and a long rock bridge (**b**)

intact specimens of Type C was estimated to be 59–60 MPa.

All specimens were prepared according to the Australian Standard AS 1012-1994 and then poured into a cylindrical (100 mm in diameter and 200 mm in height) mould. Foam sheets with the length of either 50 or 70 mm were fitted in the top and bottom parts of the mould to produce pre-existing cracks in the specimens (Fig. 1). Two pre-existing cracks with a length of 70 mm each formed a "short" rock bridge (Fig. 1a) while the 50-mm-long cracks created a "long" rock bridge (Fig. 1b). To produce cracks of different width, sheets of different thickness of either 1, 3, or 5 mm were used.

The concrete mixture was stored in the mould for 24 h before de-moulding and then placed in a curing tank for 7 days at a temperature of 24°. After 7 days, the specimens were removed from the curing tank, fan-dried for 3 h, and tested in unconfined compression. A compression load was applied with an increment of 2.6 kN/s until the specimen failed (AS 1141-1996). A high-speed camera was used to record the behaviour of the specimen throughout the test. In total, 78 specimens were tested; each test with pre-existing cracks was repeated 4 times, and the average value was used. The test conditions are summarized in Table 1.

3 Results and Discussion

3.1 Unconfined Compression Tests

Results from unconfined compression tests on the specimens of Type B with and without pre-existing cracks are plotted in Fig. 2 to demonstrate a typical stress–stain behaviour observed in this study. As can be seen in this figure, the intact specimen exhibits a higher stress at failure (46.6 MPa) compared to the specimens with the pre-existing cracks. It is interesting that the specimen with pre-existing cracks of 1-mm width reached almost the same value of stress (44.6 MPa) as the intact specimen. However, the specimens with wider cracks (3 and 5 mm) were observed to have much lower strength of 35.6 and 31.9 MPa, respectively.

To better understand the effect of the crack properties, all data from unconfined compression tests on specimens of Type A (a), Type B (b), and Type C (c) are plotted in Fig. 3 in the form of the stress at failure against the width of pre-existing cracks. It is evident from this figure that regardless of the type of material, the specimens with a longer rock bridge have a higher strength. However, for the specimens of Types A and B, when the width of the pre-existing cracks was only 1 mm, the effect of the bridge length on the strength of specimens was found to be insignificant. These results suggest that the effect of the bridge length may also be material dependent, and it can become more pronounced as the strength of intact specimens (Type C) increases.

The results in Fig. 3 also indicate that an increase in the crack's width decreases the strength of specimens. To estimate the influence of a crack's width on different types of specimens, the laboratory data are re-plotted in Fig. 4 in terms of the strength reduction (which is defined as the ratio between the strength of the specimen with pre-existing cracks and the strength of the intact specimen) against the width of pre-existing cracks. This figure suggests that

Table 1 Summary of test conditions and laboratory data

Test no.	Type of bridge	Crack width (mm)	Stress at failure (MPa)
Type A			
1	Intact specimen		11.6
2			11.4
3	Short	1	10.5
4			11.2
5			10.6
6			10.9
7	Long	1	10.4
8			11.7
9			11.7
10			10.3
11	Short	3	2.9
12			2.8
13			3.0
14			2.7
15	Long	3	4.3
16			4.8
17			5.1
18			5.1
19	Short	5	1.4
20			1.5
21			1.5
22			1.6
23	Long	5	1.9
24			1.6
25			1.1
26			1.6
Type B			
27	Intact specimen		45.5
28			46.6
29	Short	1	43.9
30			44.6
31			46.9
32			45.6
33	Long	1	44.6
34			46.6
35			44.6
36			45.6
37	Short	3	37.5
38			37.8
39			36.0
40			35.6
41	Long	3	40.9
42			40.6
43			41.6
44			42.6
45	Short	5	30.5
46			31.8
47			29.8
48			31.5

Table 1 continued

Test no.	Type of bridge	Crack width (mm)	Stress at failure (MPa)
49	Long	5	35.4
50			35.5
51			36.5
52			35.9
Type C			
53	Intact specimen		59.1
54			59.9
55	Short	1	52.4
56			52.4
57			51.2
58			51.3
59	Long	1	55.5
60			55.9
61			54.6
62			54.5
63	Short	3	44.3
64			43.1
65			44.4
66			43.9
67	Long	3	48.6
68			48.4
69			50.1
70			51.3
71	Short	5	43.2
72			42.2
73			43.1
74			43.2
75	Long	5	47.5
76			46.6
77			47.3
78			48.4

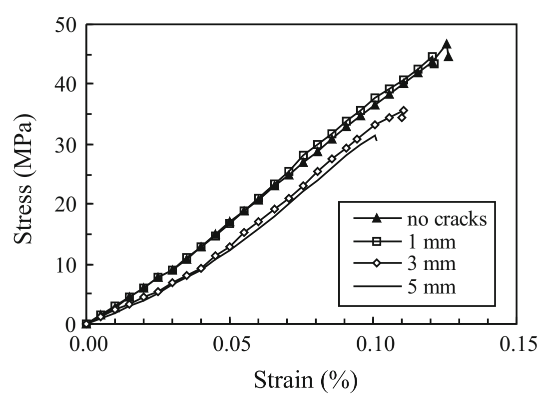

Fig. 2 Stress–strain curves of the specimens of Type B including the intact specimen and specimens with pre-existing cracks of 1, 3, and 5 mm width

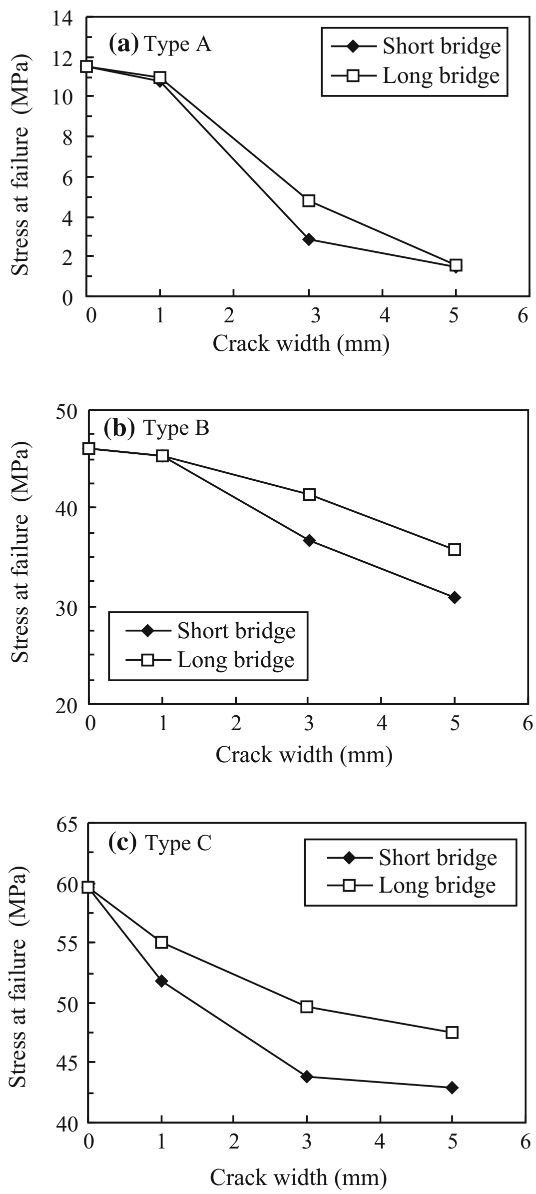

Fig. 3 Results from unconfined compression tests on specimens with short and long rock bridges: **a** Type A, **b** Type B, and **c** Type C

the extent to which the width of pre-existing cracks can influence the behaviour of specimens in unconfined compression depends on the strength of intact specimens. For example, for the specimens with a higher strength (Type C), a relatively small reduction in the strength (about 30 %) was observed as the width of crack increased from 1 to 5 mm. In contrast, there was a significant drop in the strength of specimens of Type A (almost 90 %) as the width of pre-existing cracks increased from 1 to 5 mm. It is noted that such a large decrease in the strength occurred in specimens of Type A with both long and short rock bridges (Fig. 4).

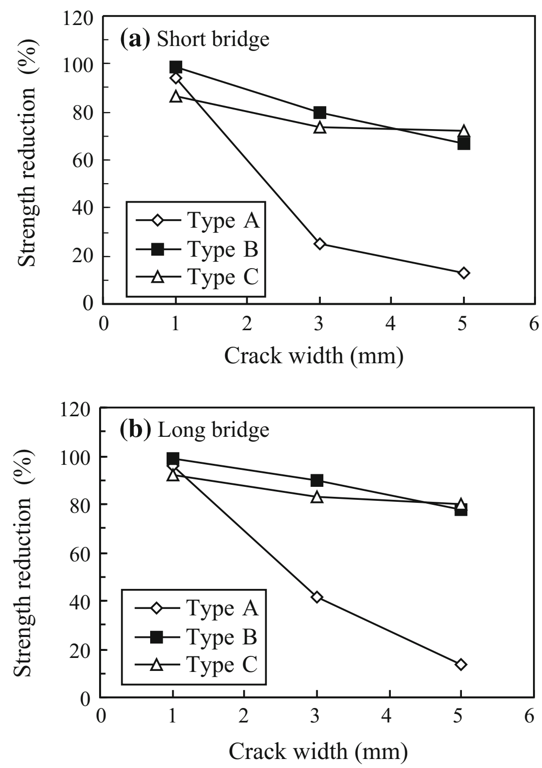

Fig. 4 Strength reduction versus the width of pre-existing cracks obtained for specimens with a short rock bridge (**a**), and a long rock bridge (**b**)

3.2 Failure Patterns

Visual observations during testing revealed some similarities in the failure pattern of specimens with different characteristics of pre-existing cracks. For most of the specimens, it was a shear crack that appeared at the tip of the top pre-existing crack as shown in Fig. 5b. This shear crack then propagated in a stable manner through the rock bridge (Fig. 5c), causing the failure of the specimen. There were a few cases recorded when the coalescence of the top and bottom pre-existing cracks (Fig. 5d) occurred during loading.

Figure 6 summarizes the most common failure patterns, which were observed for all three types of specimens. The failure pattern shown in Fig. 6a, b involved the coalescence of pre-existing cracks, and it was primarily found in the specimens with the short bridge. In contrast, the failure patterns shown in Fig. 6c, d were mostly observed in the specimens with the long rock bridge. This failure mode was characterized by the shear failure that occurred without the coalescence of the pre-existing cracks. As can be seen in Fig. 6c, d, the shear crack propagated through the rock bridge at an angle, resulting in failure.

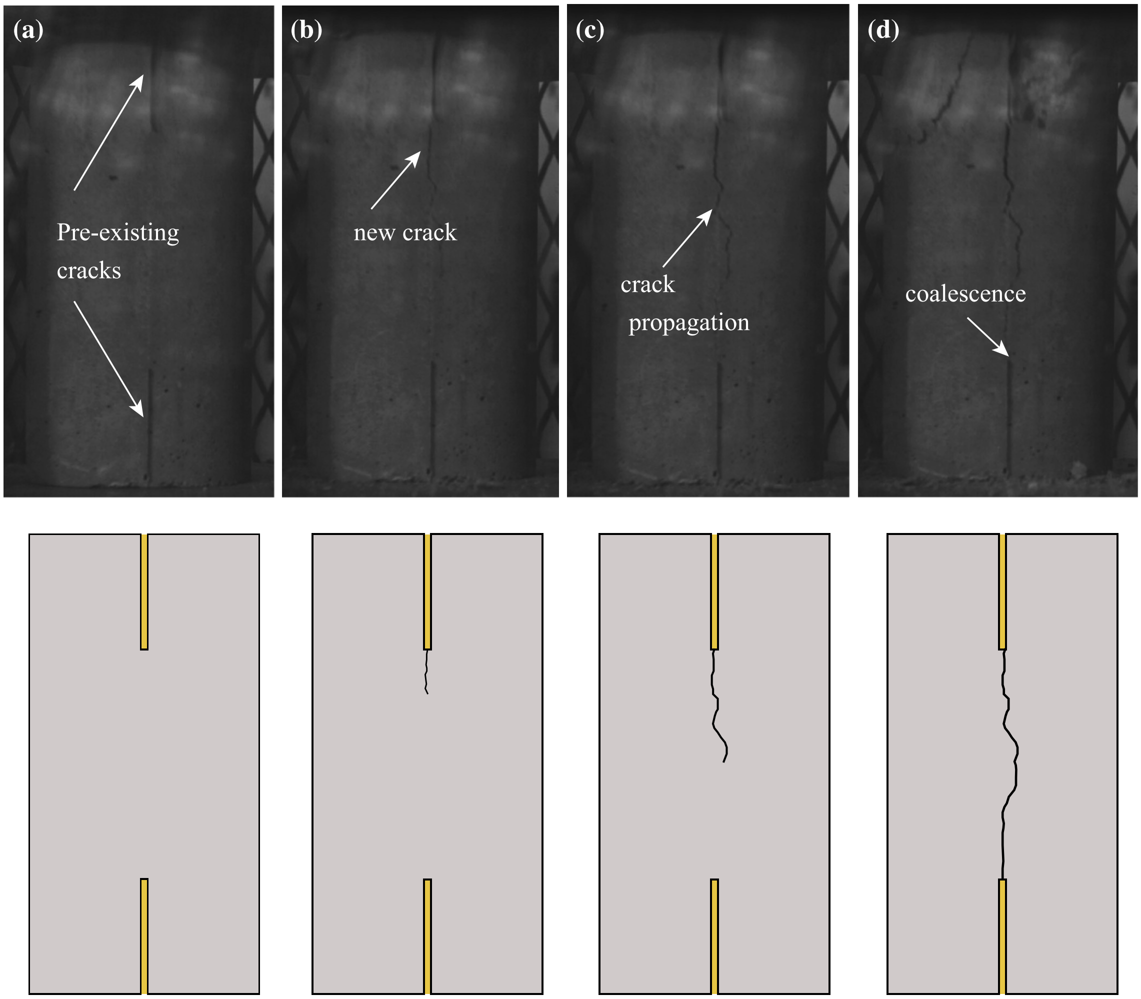

Fig. 5 Initiation and propagation of cracks in the specimen under unconfined compression

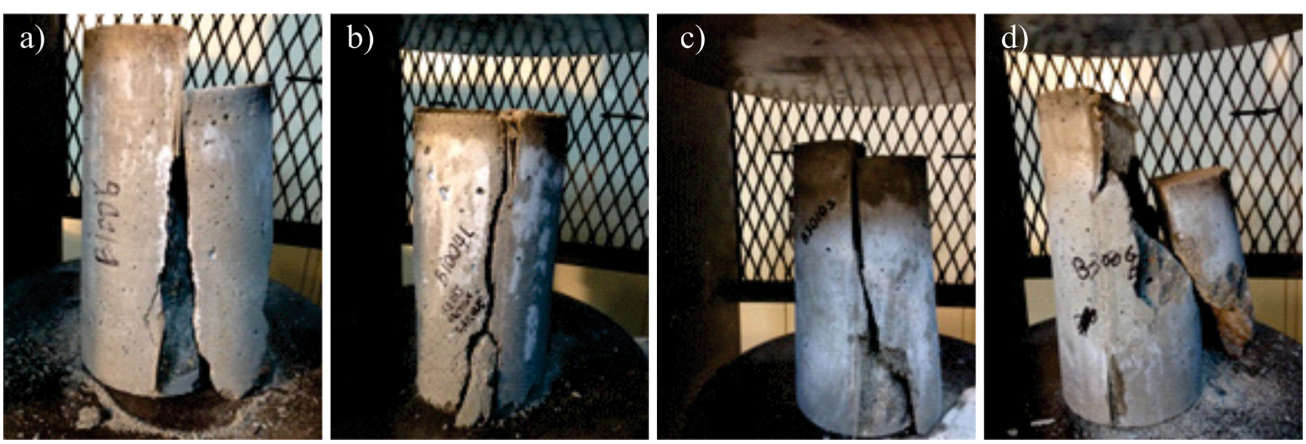

Fig. 6 Failure patterns observed in specimens

4 Conclusions

In this work, the effect of pre-existing cracks of different length and width on the strength of rocks was studied using three types (Types A, B, and C) of specimens. The following conclusions can be drawn:

- Regardless of the type of specimens, the longer rock bridge was associated with a higher stress at failure. However, for specimens of Types A and B with a crack width of 1 mm, the influence of rock bridge length was found to be insignificant.
- The width of pre-existing cracks had a significant effect on the strength of specimens. The strength of specimens of all three types decreased as the crack's width increased from 1 to 5 mm; however, this effect was more pronounced in the specimens with a relatively low strength of the intact specimens (Type A).
- For most of the specimens, failure was caused by a shear crack while the coalescence of the pre-existing cracks was mostly observed in the specimens with the short rock bridge.

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