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Comments on chevron bend specimen for determining fracture toughness of rock①

SUN Zong-qi(孙宗颀), CHEN Feng(陈 枫), XU Ji-cheng(徐纪成)
(Instrument Test and Analysis, Central South University, Changsha 410083, P. R. China)

[Abstract] Based on a number of tests on different rocks, Suggested Methods for Determining the Fracture Toughness of Rock (SMs) was reviewed. The advantages of SMs are obvious, but some problems are also discovered. A serious one is that the nonlinear corrected fracture toughness of chevron bend specimens, K^{C}_{CB}, is less than the uncorrected one, K_{CB}, for hard rock like granite, marble and others. The reason is discussed and the proposal is given.

[Key words] fracture toughness; nonlinear correction
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1 INTRODUCTION

It is well known that rock fracture toughness is important for geological and engineering purpose. The measured values of fracture toughness for a wide range of rocks have been published using a wide variety of specimen types and test methods. But the resulted values are generally not comparable[1]. Standardization of fracture toughness testing of rock had been required in order to obtain comparable and accurate values. To meet this demand, ISRM published Suggested Methods for Determining the Fracture Toughness of Rock in 1988, coordinated by Ouchterlony[2]. In the Suggested Methods two specimens, chevron bend (CB) and short rod (SR), were proposed. Later, ISRM published Suggested Methods for Determining Mode I Fracture Toughness Using Cracked Chevron Notched Brazilian Disk Specimens in 1995[3]. It can be seen that two Suggested Methods published by ISRM recommended three types of specimens with chevron notch. The advantages of specimen with chevron notch are obvious[4, 5].

To fully exam Suggested Methods of 1988, the international round robin testing group, including specialists from Germany, Sweden, Japan, USA, China and England, was organized and coordinated by Ouchterlony[2]. The rock types used in testing were Westerly granite (WG) from USA, Bohus granite (BG) from Sweden and Ogino tuff (OT) from Japan in form of core drilled from respective rock blocks. Each participant tested this rock of two specimen forms, CB and SR, in their own lab. After a series of tests on different rock types some problem arose. A serious one was that the corrected fracture toughness values, K^{C}_{CB}, for granite obtained from bending test was less than uncorrected, K^{CB}. Matsuki[1] also discovered that K^{C}_{CB} was much smaller than K_{CB} when bend specimens of Tohoku marble were tested. It looks to be unreasonable.

This paper first presents our tested results and then compares them with the results from Sweden. Based on analysis and discussion of the results the comments on chevron bend specimen are given.

2 TESTING TECHNIQUE

2.1 Mechanical properties of specimen and its preparation

Bohus and Westerly granite and Ogino tuff have following mechanical properties as shown in Table 1.

Table 1 Rock mechanical properties

Rock type	Elastic modulus / GPa	Poisson's ratio	Tensile strength / MPa
Bohus granite	40.5	0.23	8~ 10
Westerly granite	50~ 55	0.16, 0.23	13.7
Ogino tuff	11.9		5.6

To prepare chevron notched specimen, a special universal saw machine MRF-1 was designed and constructed based on plane machine[6].

The cores of Bohus and Westerly granite and Ogino tuff have diameters of 50, 48.7 and 68.5 mm respectively with various length. The bend specimens were slit into chevron notch only, the short rod specimens were prepared into configuration according to the SMs. All specimens were machined using clean water as coolant and then dried in oven at different temperatures: 62, 68 and 46 ℃ for Bohus, Westerly granite and Ogino tuff in various duration respectively.

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2.2 Fracture test and computer software ISRM-KIC

All fracture tests were conducted on INSTRON 1346 under computer control via ISRM-KIC[6] software at room temperature about 18 ℃ and humidity 80%.

The software ISRM-KIC consists of two parts, one for test procedure control and other for data-graphic processing.

3 TEST RESULTS

The test results of two specimens of above mentioned rock types are listed in Table 2, together with values given by Ouchterlony for comparison. In addition to fracture toughness values, K_{CB}, K_{SR} and K^C_{CB}, K^C_{SR}, the maximum load, F_{max}, the evaluated load, F_c, and plasticity index, p, in nonlinear correction, as well as Elastic Modulus, E, are also given in the Table 2. All data are given as mean ± standard deviation. Table 2 shows that test results from both labs agreed well with each other. The corrected fracture toughness of short rod tests, K^C_{SR} for all rocks were larger than uncorrected one. K^C_{SR} for OT, BG and WG are 0.86, 2.2 and 2.2 MPa·m$^{1/2}$ respectively.

K^C_{CB} of OT was equal to 0.8～0.9 MPa·m$^{1/2}$ and equivalent to K^C_{SR}. But the corrected fracture toughness of two granites from bending test, K^C_{CB}, were less than uncorrected, K_{CB}, in both labs. As mentioned before it is unreasonable.

4 DISCUSSION

4.1 On short rod specimen

From short rod tests the values of K_{SR} for Ogino tuff and Westerly granite obtained from two labs were identical and the nonlinear corrected values, K^C_{SR}, of these rocks were always larger than K_{SR}, of corresponding rock. For Bohus granite the difference of mean value of K_{SR} from two labs was 7.8%, after nonlinear correction the difference increased up to 13%.

In general, the fracture toughness values of rock, as its other mechanical properties, are scattered. Usually the scatter increases after nonlinear correction and it is more pronounced for granite. But no matter what the scatter of the fracture toughness was obtained, its values from two labs should be considered in good correspondence.

4.2 On chevron bend specimen

The K_{CB} values obtained from two labs had difference in range from 7%～8%, occasionally up to 11% for Bohus granite. The difference increased after nonlinear correction. But the most serious question was that the K^C_{CB} of granite was less than K_{CB}.

For chevron notched specimen, it is well known that F_C is always the peak load in real linear elastic fracture mechanics tests. It may not be the peak load in elastic-plastic specimen[4]. In this case the evaluated point, F_C, can be obtained using slope ratio of unloading line, s_c, at a_c (critical crack length) and initial load line, s_i, of load-displacement curve[7]. The slope ratio, s_c/s_i, equal to 0.822 was recommended by Suggest Methods and was corrected to 0.836 by Matsuki[1].

Fig. 1 shows load versus load-point displacement curves of OT and BG. The arrows indicated the evaluated points, F_C, calculated according to SMs. The linear portion of initial load line of tuff was relatively long, or in other words, load line deviated from linearity at relatively high load level, at about 50% of F_{max} for tuff. Thus F_C is close to F_{max}, it led to K^C_{CB} being larger than K_{CB} as expected. The picture for BG was different. The initial load line deviated at

Table 2 Test results from two specimens: SR & CB

Rock type	Specimen type	Name of lab*	E / GPa	F_{max} / kN	K_{CB}, or K_{SR} / (MPa·m$^{1/2}$)	F_C / kN	p	K^C_{CB}, or K^C_{SR} / (MPa·m$^{1/2}$)
Ogino tuff	SR d68 mm	Sun	12.3 ±.52	0.557	0.738 ±.015	0.549	0.163 ±0.057	0.857 ±0.051
		Finn	12.2 ±.05	0.549	0.724 ±.03	0.545	0.183 ±0.036	0.864 ±0.04
	CB d68 mm	Sun	14.3 ±1.3	1.24	0.782 ±0.013	1.23	0.15 ±0.086	0.907 ±0.067
		Finn	12.5 ±0.6	1.30	0.73 ±0.04	1.27	0.113 ±0.04	0.793 ±0.05
Bohus granite	SR d50 mm	Sun	42.8 ±6.3	0.867	1.83 ±0.141	0.838	0.18 ±0.067	2.14 ±0.026
		Finn	52.8 ±1.3	0.886	1.97 ±0.015	0.866	0.225 ±0.028	2.42 ±0.18
	CB d50 mm	Sun	59.5 ±4.8	1.65	1.61 ±0.075	1.31	0.215 ±0.058	1.59 ±0.386
		Finn	57.2 ±2.3	1.88	1.79 ±0.07	1.13	0.23 ±0.07	1.37 ±0.46
Westerly granite	SR d48.7 mm	Sun	55.7 ±5.8	0.91	2.04 ±0.067	0.819	0.164 ±0.051	2.17 ±0.194
		Finn	53.8 ±1.6	0.941	2.05 ±0.06	0.877	0.165 ±0.016	2.28 ±0.08
	CB d48.7 mm	Sun	60.4 ±6.5	1.874	1.804 ±0.07	1.17	0.203 ±0.041	1.38 ±0.398
		Finn	58.0 ±1.9	2.063	1.96 ±0.08	1.57	0.107 ±0.04	1.65 ±0.25

* Sun represents lab tests in China, Finn represents lab tests in Sweden.

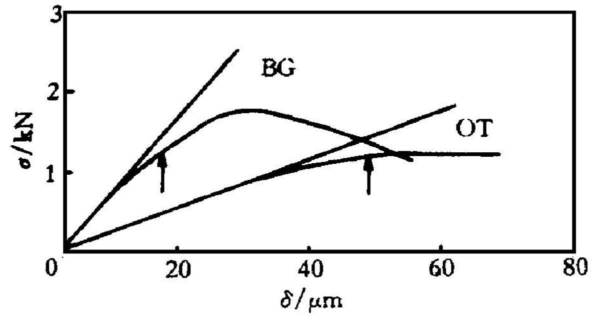

Fig. 1 Load-displacement curves of OT and BG

relatively lower load level, at about 18% of F_{max}. It resulted in F_C much lower than F_{max}, in consequence K_{CB}^{C} was less than K_{CB}.

4.3 Comparison of two specimens

Note, because the test results always show scatter for material like rock, to compare tested data from two specimen configurations, it is better to show all data from CB and SR in figure to see weather they overlap each other in larger portion or not. If it is so then it should be aware that they agree well with each other. The load versus load-point displacement curves and fracture toughness of OT obtained from two labs are shown in Fig. 2. As shown in Fig. 2(a) the curves were quite different for CB and SR specimens. The curve of SR test shows plateau, while curve of CB exhibits peak. The K_{CB} (mean values) was about 6% larger than K_{SR}. K_{CB}^{C} was 6% larger than K_{SR}^{C} from Sun's lab, while K_{CB}^{C} was 9% less than K_{SR}^{C} in Finn's lab. The overlap of K_{CB}^{C} and K_{SR}^{C} in Fig. 2(b) in two labs indicated that they agreed well with each other. Regarding granite of BG and WG, K_{CB} were 10% ~ 13% less than K_{SR}. Thus they were comparable. But here K_{CB}^{C} less than K_{CB}, as mentioned above, were considered invalid and were not shown in Fig. 3, in consequence were incomparable with K_{SR}^{C}.

The reason of $K_{CB}^{C} < K_{CB}$ and $K_{SR}^{C} > K_{SR}$ could be explained partly by their geometry, partly by grain size of rock. Regarding specimen geometry Suggested Methods give: $a_c - a_o = 0.15D$ for CB, while $a_c - a_o = 0.34D$ for SR, where a_o is initial crack length, a_c is a critical crack length at which the fracture toughness is evaluated. D is a diameter of specimen.

Note, the crack front was tortuous with deviation about ±3 mm around the mean value for crystal rock like granite[8]. Thus for bend specimen the initial crack 'pop-in'[7] at the apex of V-notch for granite will approach or even across the critical point a_c, where $a_c - a_o$ is only 7.5 mm when $D = 50$ mm. It yields a lower F_{max} and more pronounced nonlinear behavior of load-displacement curve during bending tests. For short rod specimen since $a_c - a_o$ is sufficient long, for example, it equals 17 mm when $D = 50$ mm, the initial crack 'pop-in' will never approach a_c, no matter what rock will be tested. It results in steady crack extension after crack 'pop-in' up to a_c and reasonable F_{max} during short rod test. In addition, two specimens cause different load versus load-point displacement curves as shown in Fig. 2 (a). The plateau on load displacement curve and $s_c/s_i = 0.5$ for SR test makes evaluated load, F_C, insensitive to nonlinear behavior of initial load line. For example, the linear portion of initial load line of SR test was also small as shown in Table 3, but evaluated load in nonlinear correction of SR, F_C, was close to F_{max}, shown in Table 2.

Considering grain size of rock the grain size of

Table 3 Linear portion of initial load line of CB and SR test

Rock type	Chevron bend specimen (CB)			Short rod specimen (SR)		
	OT	BG	WG	OT	BG	WG
Linear portion of initial load line	(46.65 ±18.5)%	(18.34 ±5.4)%	(19.7 ±3.58)%	(30.82 ±4.36)%	(23.02 ±3.77)%	(23.39 ±4.7)%
Number of tested specimens	6	7	4	6	9	7

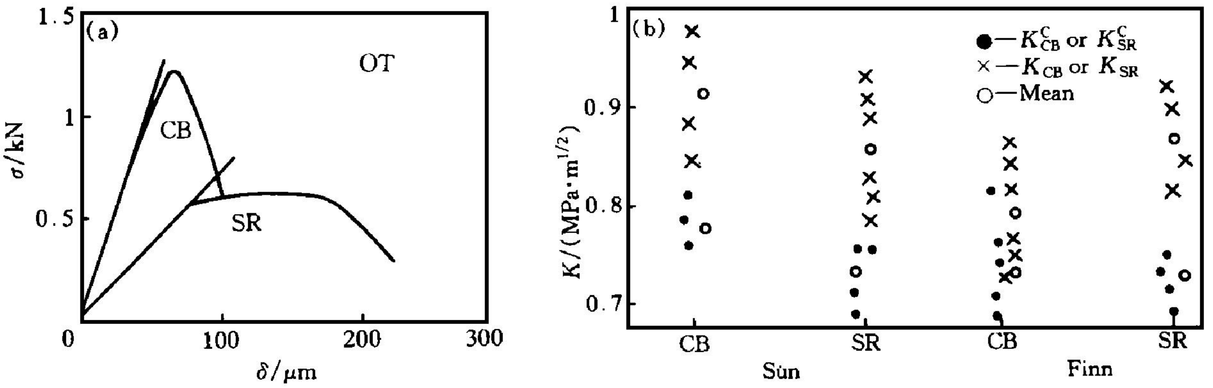

Fig. 2 Load versus load-displacement curves (a), and test results of CB and SR from two labs specimens of OT (b)

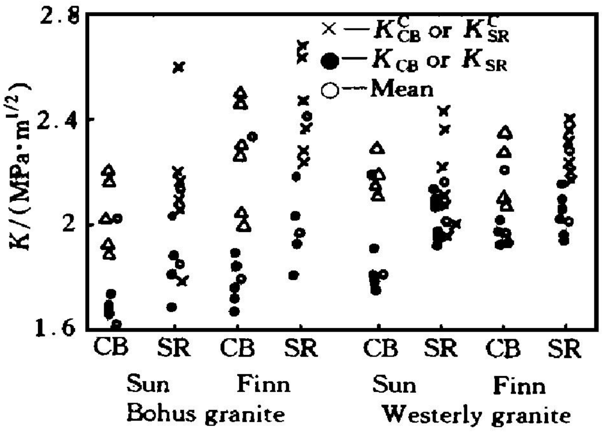

Fig. 3 Tested results of BG and WG

tuff being less than 1 mm was much less than that of granite BG and WG. It caused the crack front of tuff during test more or less like straight line. It could be justified by more smooth fracture surface than granite' s one. Thus the actual crack ' pop-in' at the apex of V-notch arrested before crack reaches a_c, subsequent crack growth was stable up to a_c, and it gave the expected F_{max}.

4. 4 Proposal to suggested methods

To solve the discrepancy of $K^C_{CB} < K_{CB}$ in CB test Ouchterlony[9] suggested to shift the evaluation point in CB test to the crack length equal to that in SR test and a new slope ratio equation was proposed as

$$s_c = 0.66[1 - 1.86(a_o/D) + 0.65(a_o + D)]\, s_i$$

For standard specimen configuration s_c is equal to 0.49 s_i. Figures in Fig. 3. 24[9] showed that K^C_{CB} agreed well with K^C_{SR}.

But the proposal contradicts the numerical[1] and experimental calibration[10] for chevron bend specimen, which indicated that $s_c/s_i = 0.82$. In addition, the application of new slope ratio equation to rock like tuff leads to underestimate K^C_{CB}, which was valid according to Suggested Methods.

Based on consideration that obtained F_C in bending test for crystal rock is always less than expected, it will be more reasonable to choose F_{max} instead of F_C as evaluated load for nonlinear correction. The results are shown in Fig. 3 with triangle symbol. Now K^C_{CB} agrees well with K^C_{SR}.

5 CONCLUSIONS

1) The short rod specimen is an acceptable geometry for fracture toughness test of rock material. The results obtained from two labs are in good agreement.

2) The fracture toughness values of OT from CB test corresponds well with that from SR test for both uncorrected and corrected fracture toughness values.

3) The corrected fracture toughness, K^C_{CB} of granite being less than K_{CB}, is mainly caused by unexpected low evaluated load, F_C, which is yielded by earlier deviation of initial load line from linearity during test.

4) Maximum load obtained from CB test for crystal rock like granite is always lower than expected. Thus F_{max} instead of F_C is proposed to use in nonlinear correction calculation. The obtained K^C_{CB} is in good correspondence with K^C_{SR}.

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