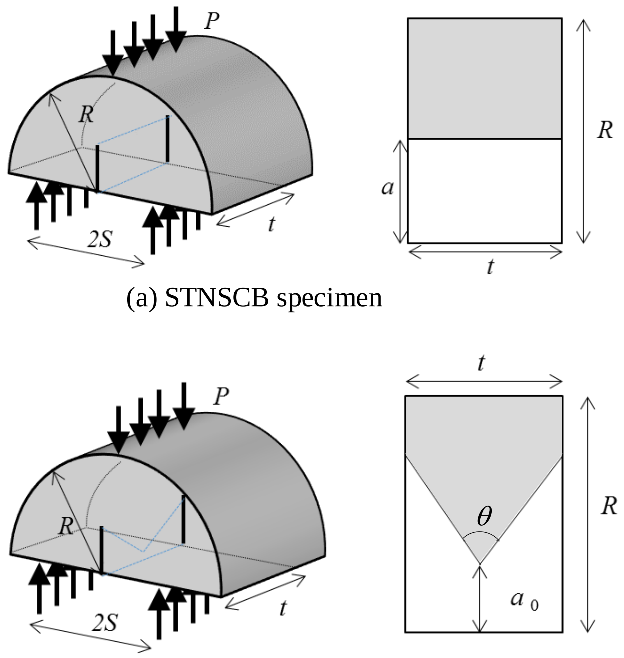
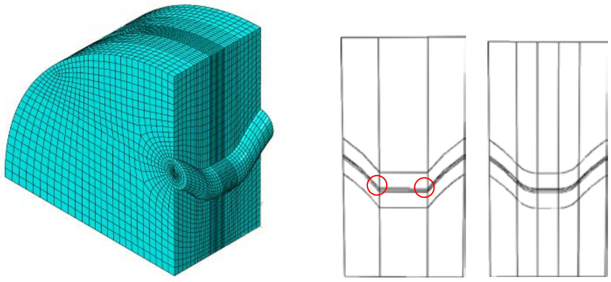


(a) STNSCB specimen

(b) CCNSCB specimen

Fig.1. Three points loading and geometry of artificial notch in cross section of specimen center; (a) STNSCB specimen, (b) CCNSCB specimen.



(a) (b) (c)

Fig.2 A finite element mesh and geometry of chevron notch: (a) 3D FEM model, (b) crack front with corners (Red circles), (c) modified crack front (Ayarollahi et al. 2016).

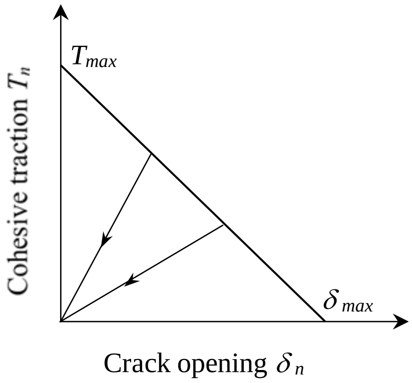


Fig.3 Typical linear traction-separation response.

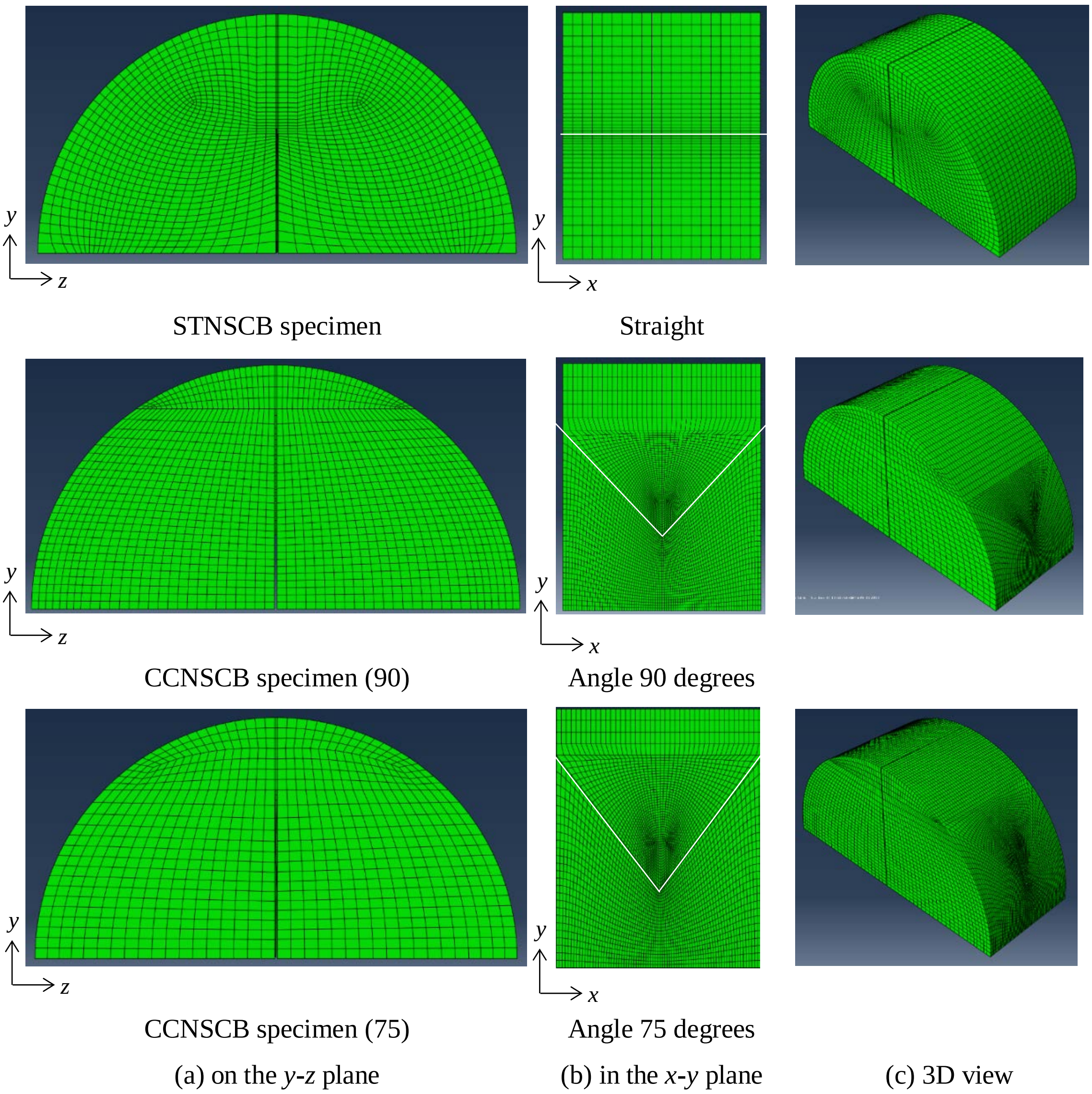


Fig.4 XFEM model: (a) cross section on the *y*-*z* plane, (b) perspective view of the crack front geometry in the *x*-*y* plane, (c) three dimensional view.

Table 1. Geometric and mechanical parameters.

Geometric parameter	value	
Radius of specimen R	37.5mm	
Thickness of specimen t	30.0mm	t/R = 0.8
Support distance $2s$	60.0mm	s/R = 0.8
Initial crack length a_0	11.25, 18.75mm	a_0/R= 0.3, 0.5
Chevron angle θ	Straight, 90, 75 degrees	

Mechanical parameter	value
Young's modulus E	7.7GPa
Poisson's ratio ν	0.22

Table 2. Number of node and element of each model.

	STNSCB	CCNSCB(90)	CCNSCB(75)
Number of node	787469	125045	125045
Number of element	114209	111080	111080

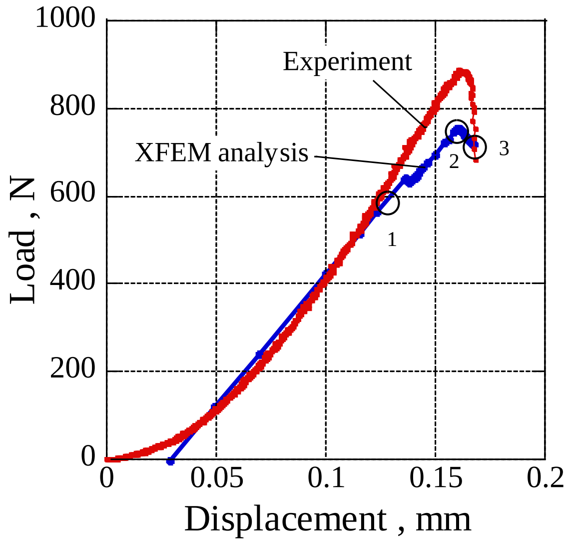


Fig.5 Comparison of load-displacement curve obtained from STNSCB test for sandstone with that by the XFEM analysis using model of STNSCB.

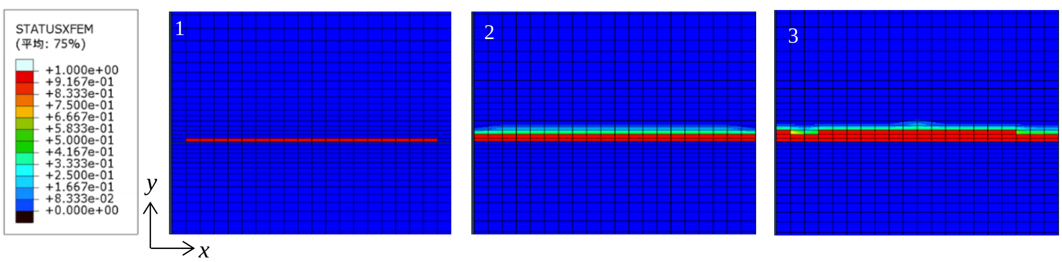


Fig.6 State of crack propagation at a moment of the numbers in Fig.5.

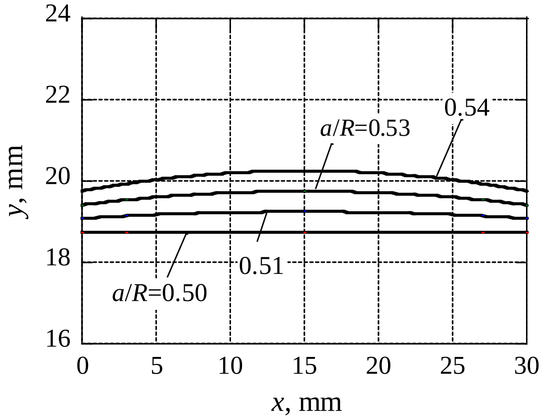


Fig.7 Cross sectional geometry of crack front during crack propagation of STNSCB test.

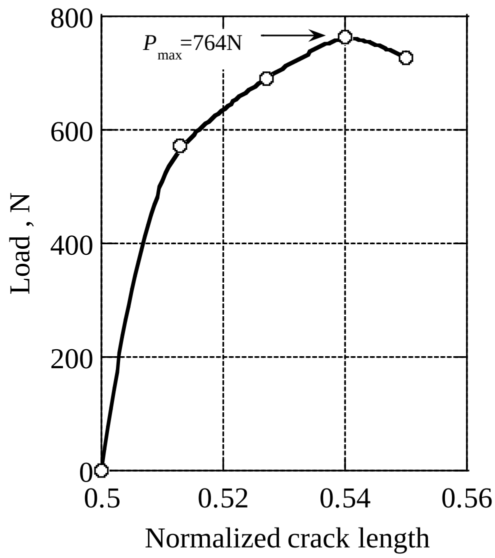


Fig.8 Load-crack length curve of STNSCB test.

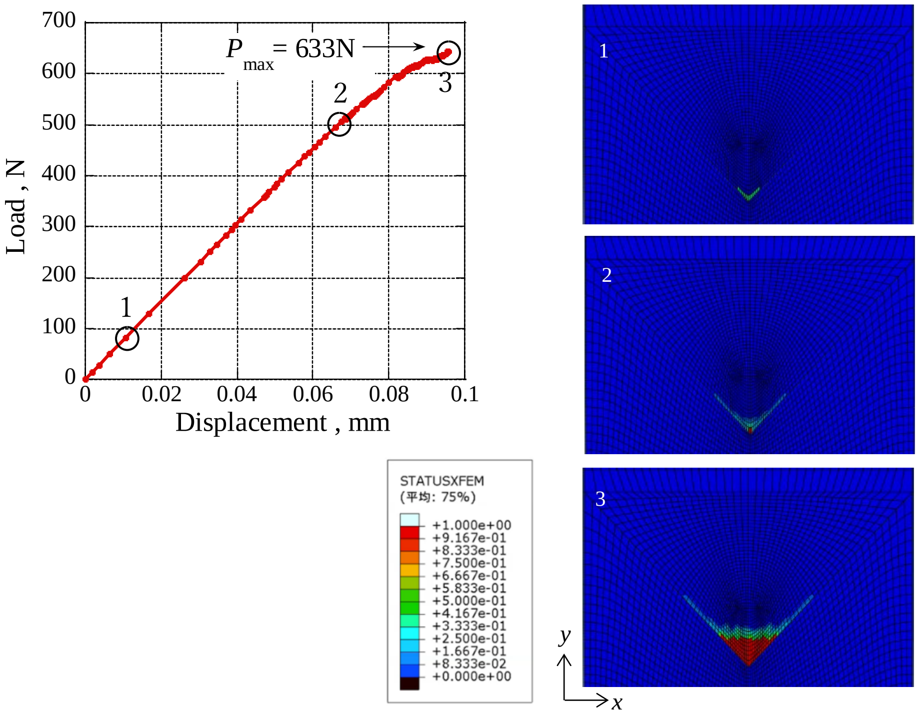


Fig.9 Load-displacement curve and states of crack propagation of CCNSCB specimen with a chevron angle of 90 degrees. Right figures represent the state of crack propagation at a moment of 1: P_{max}= 90kN, 2: 500kN and 3: 633kN.

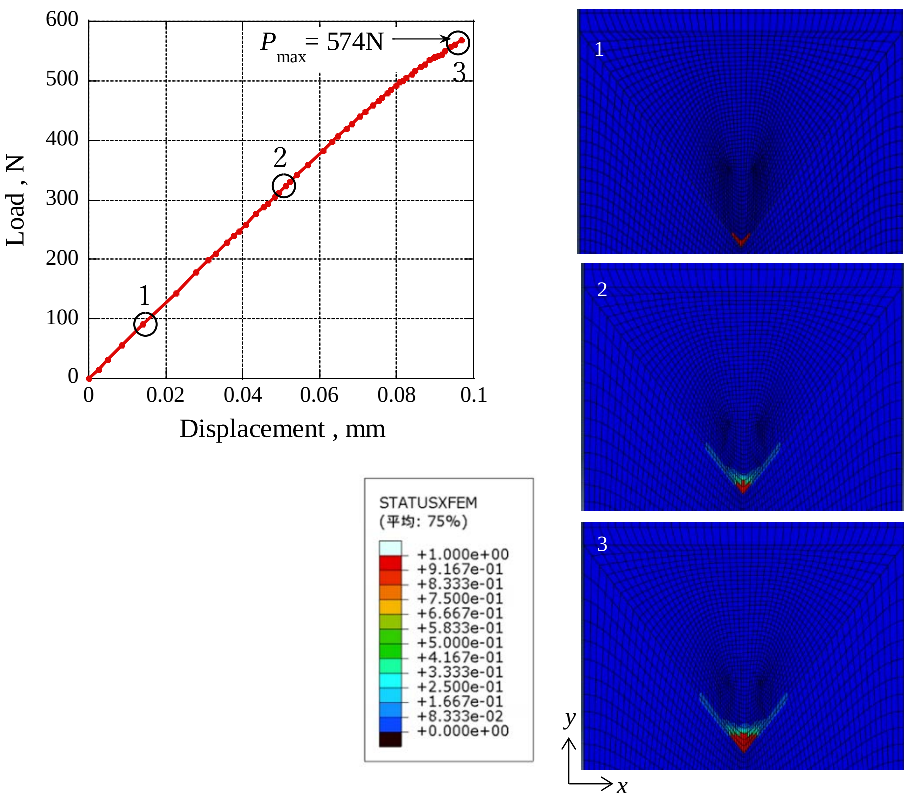
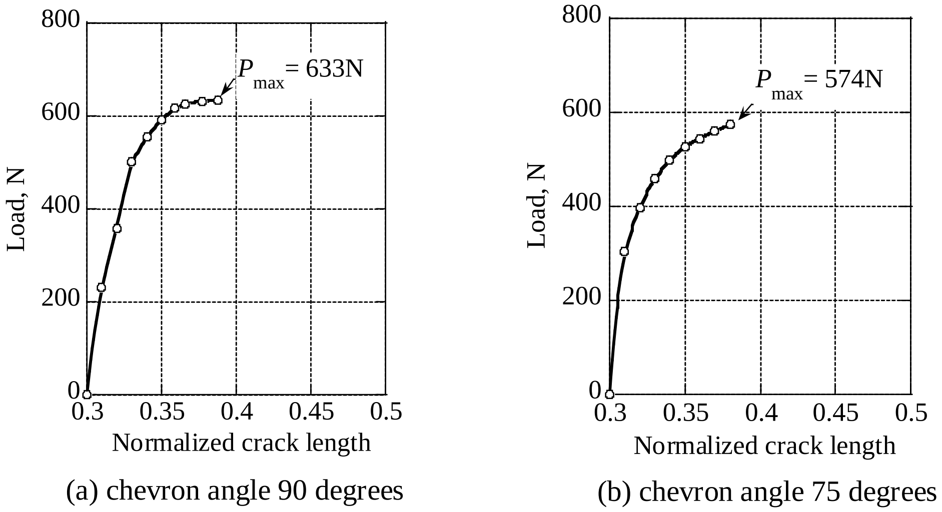


Fig.10 Load-displacement curve and states of crack propagation of CCNSCB specimen with a

chevron angle of 75 degrees. Right figures represent the state of crack propagation at a moment of 1: P_{max}= 90kN, 2: 310kN and 3: 574kN.



Fug. 11 Relationship between load and normalized crack length a/R of CCNSCB models in the XFEM analysis.

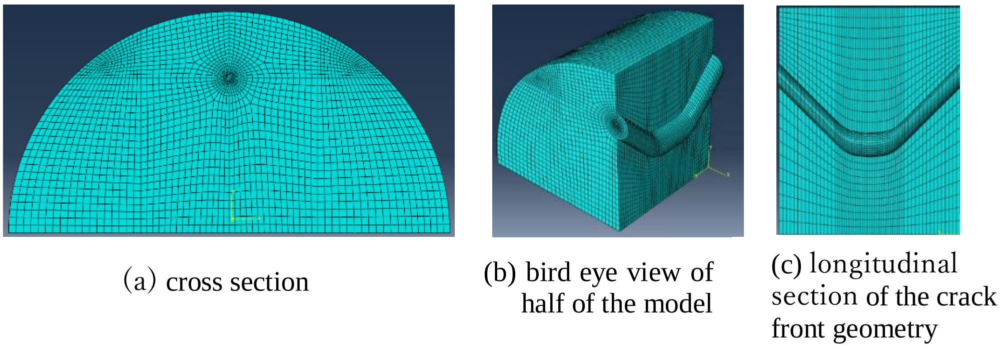


Fig.12 An example of FEM model of CCNSCB specimen with a crack length of a/R=0.38 of chevron angle of 90 degrees.

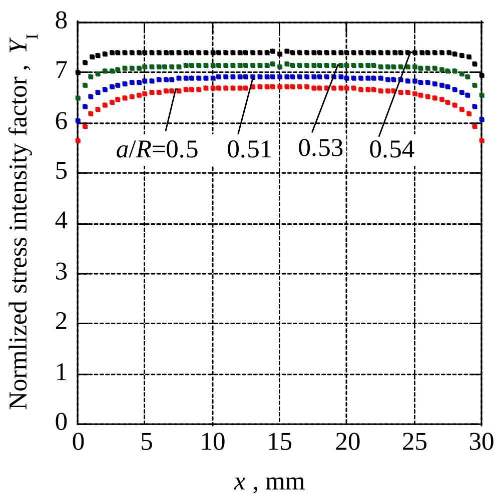


Fig.13 Distribution of normalized stress intensity factor along crack front shown in Fig.7 with increasing crack length in the STNSCB test.

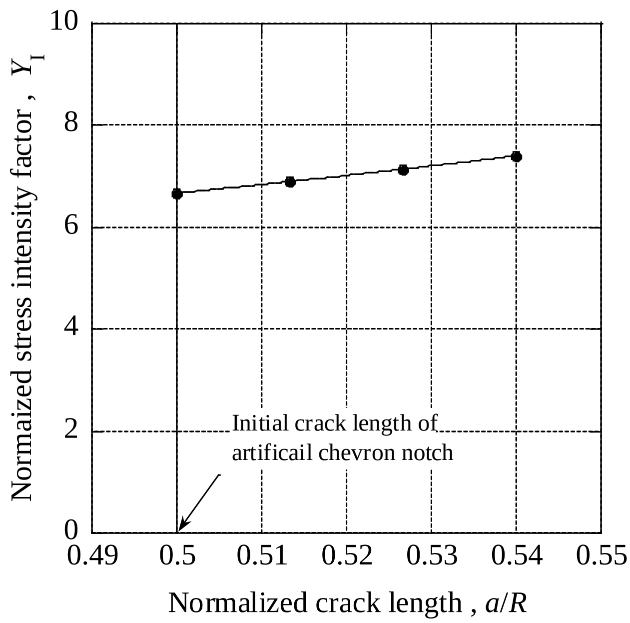


Fig.14 Relation between normalized stress intensity factor and normalized crack length in STNSCB test.

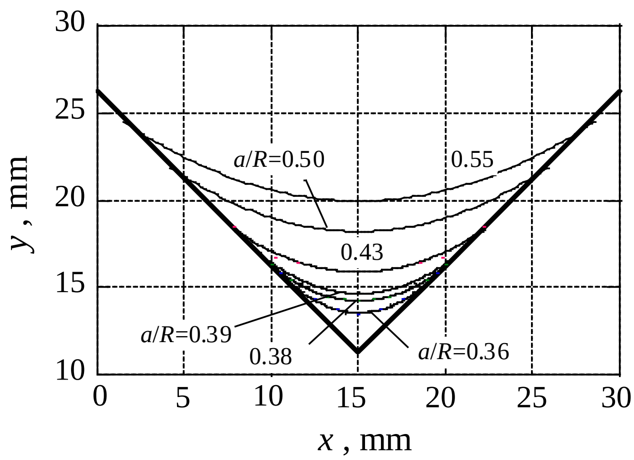


Fig.15 Cross-sectional geometry of the crack front for each crack length of the CCNSCB specimen with a chevron angle of 90 degrees obtained from the XFEM analysis.

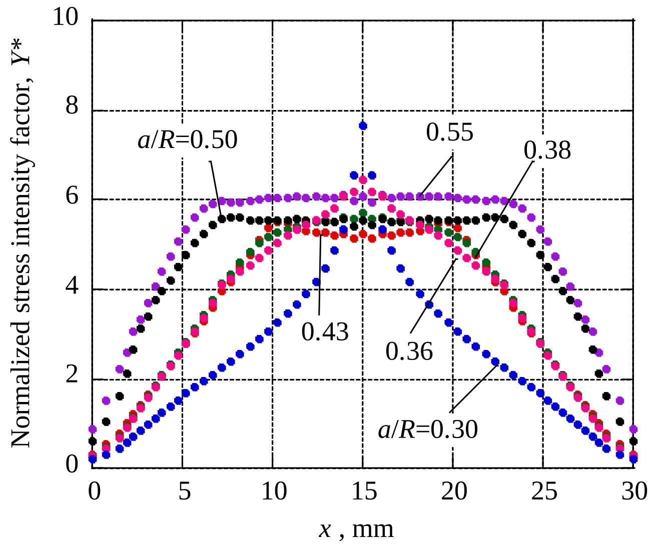


Fig. 16 Distributions of stress intensity factor in the range of 0.3 to 0.55.

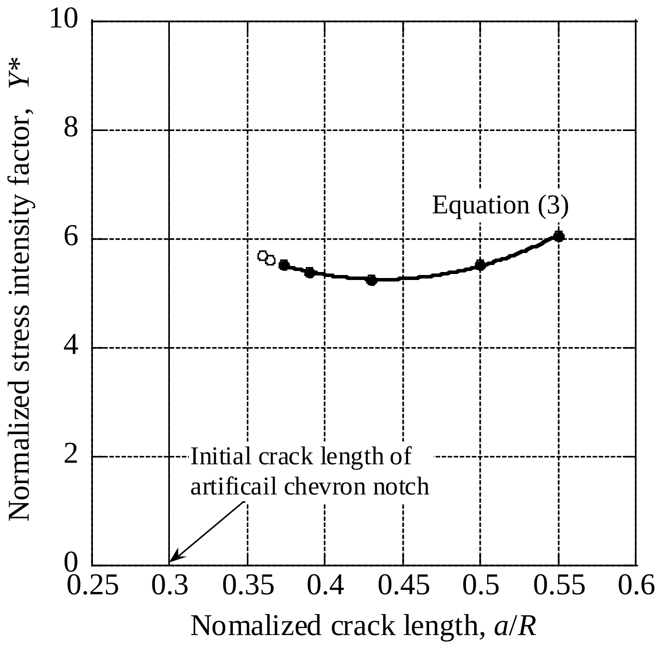


Fig.17 Relationship between normalized stress intensity factor with respect to *a*/*R* in the CCNSCB

specimen with a chevron angle of 90 degrees.

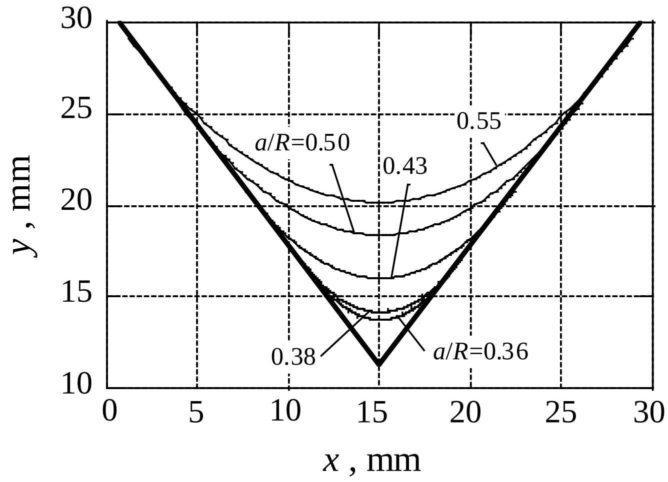


Fig.18 Cross-sectional geometry of the crack front for each crack length of the CCNSCB specimen with a chevron angle of 75 degrees obtained from the XFEM analysis.

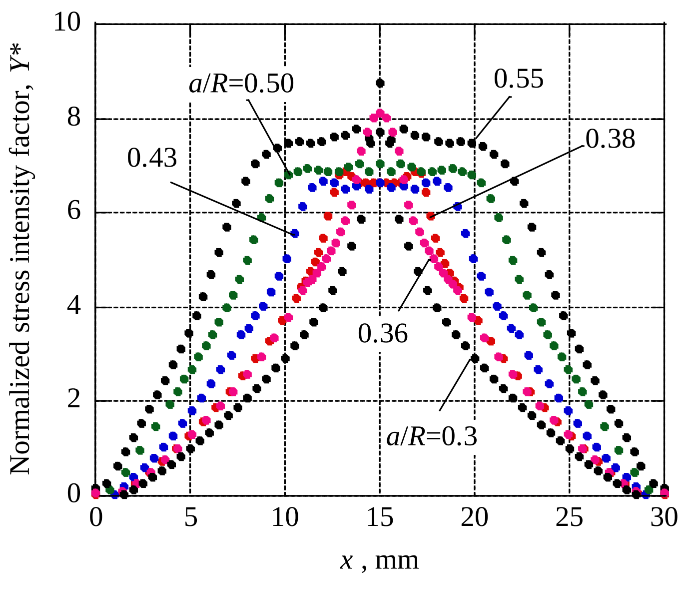


Fig. 19 Distributions of stress intensity factor in the range of 0.3 to 0.55.

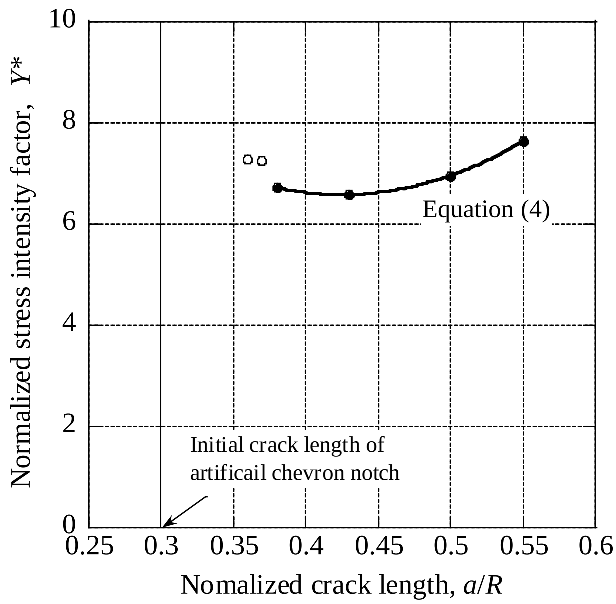


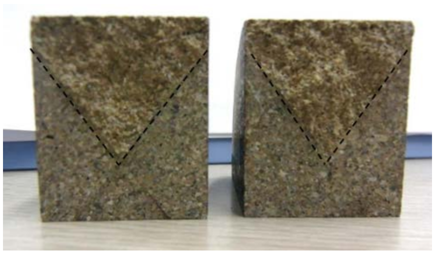
Fig.20 Relationship between normalized stress intensity factor with respect to *a*/*R* in the CCNSCB specimen with a chevron angle of 75 degrees.

Table 3 Material properties of Kimachi sandstone.

Material property	Values
Uniaxial compressive strength	59.3 MPa
Young’s modulus	7.7 GPa
Poisson’s ratio	0.22
Tensile strength	6.17 MPa
Elastic wave velocity	2.6–2.9 km/s

(a)

(b)



(c)

(d)

Fig.21 Examples of fractured surface of STNSCB and CCNSCB specimens after test: (a) CSNSCB specimen, (b) CCNSCB specimen with a chevron angle of 90 degrees, (c) 75 degrees, (d) photo from an oblique direction.

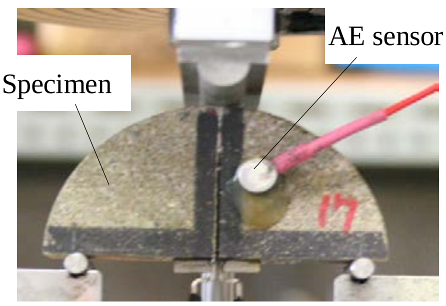
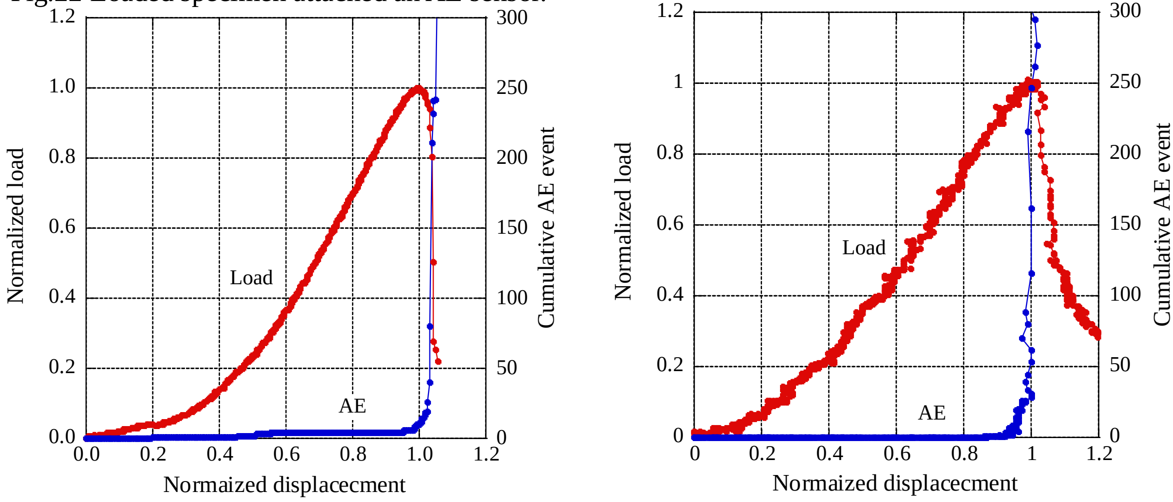
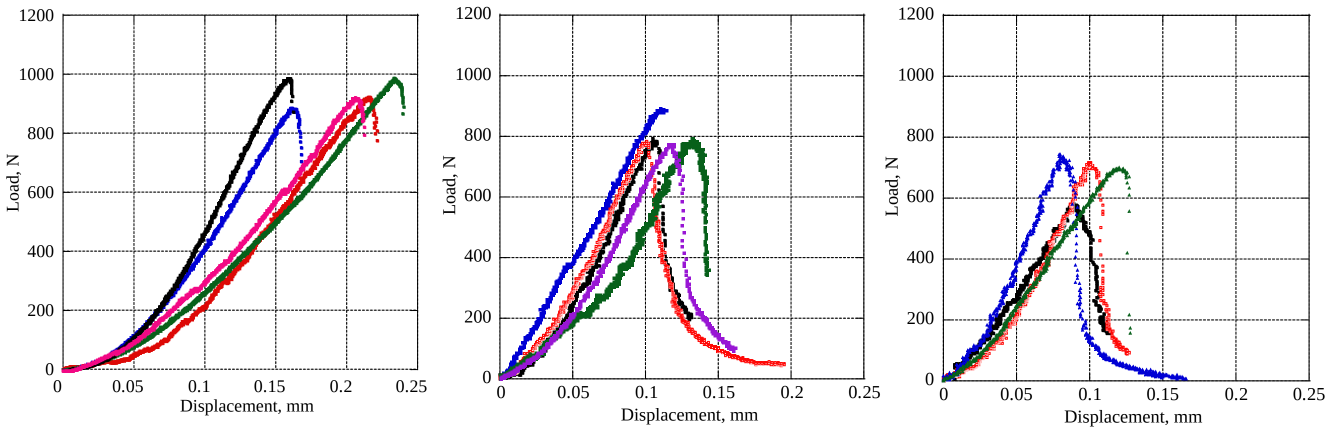


Fig.22 Loaded specimen attached an AE sensor.



(a) (b)

Fig.23 Load and AE event rate – displacement curves: (a) STNSCB test (b) CCNSCB test with a chevron angle of 90 degrees during the test.



(a) (b) (c)

Fig.24 Load-displacements curves obtained SCB test: (a) STNSCB specimen, (b) CCNSCB specimen with a chevron angle of 90 degrees and (c) 75 degrees.

Table 4 Results of STNSCB test.

No.	Radius R, mm	Thickness t, mm	Crack length a_0, mm	a_0/R	$2S/R$	Y_I	Max. load P_{max}, kN	Fracture toughness K_{IC}, MN/m$^{3/2}$
1	37.5	30.4	19.8	0.53	0.8	7.09	0.93	0.72
2	37.5	30.4	19.8	0.53	0.8	7.09	0.92	0.71
3	37.5	30.9	19.7	0.53	0.8	7.04	0.89	0.67
4	37.5	30.9	19.6	0.52	0.8	7.00	0.99	0.74
5	37.5	31.5	19.7	0.53	0.8	7.04	0.98	0.73

Remarks: Y_I was calculated by the original formulation of ISRM (Kuruppu, Obara *et al*. 2014).

Table 5 Results of CCNSCB(90) test.

No.	Radius R, mm	Thickness t, mm	Crack length a_0, mm	a_0/R	$2S/R$	Y_I	Max. load P_{max}, kN	Fracture toughness K_{IC}, MN/m$^{3/2}$
1	36.4	30.6	10.7	0.29	0.8	5.26	0.77	0.69
2	36.3	31.6	10.0	0.28	0.8	5.26	0.79	0.69
3	36.6	31.2	11.1	0.30	0.8	5.26	0.89	0.78
4	36.2	30.9	10.1	0.28	0.8	5.26	0.78	0.70
5	37.1	30.0	11.1	0.30	0.8	5.26	0.79	0.72

Table 6 Results of CCNSCB(75) test.

No.	Radius R, mm	Thickness t, mm	Crack length a_0, mm	a_0/R	$2S/R$	Y_I	Max. load P_{max}, kN	Fracture toughness K_{IC}, MN/m$^{3/2}$
1	35.7	30.1	10.7	0.30	0.8	6.58	0.58	0.67
2	36.0	30.4	10.8	0.30	0.8	6.58	0.72	0.82
3	36.8	30.4	11.4	0.31	0.8	6.58	0.74	0.83
4	36.3	30.9	11.3	0.31	0.8	6.58	0.70	0.78

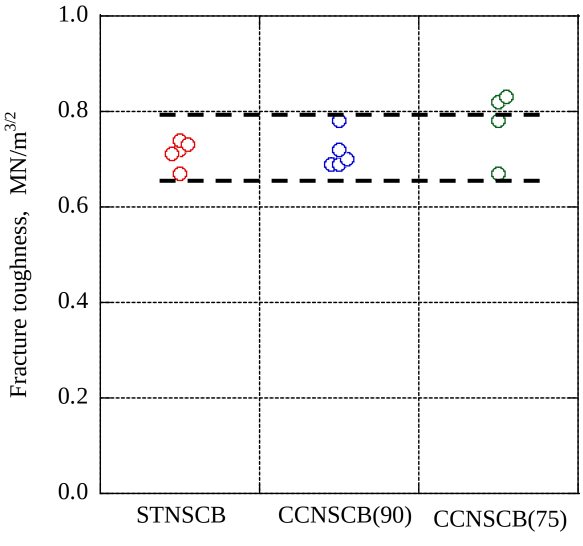


Fig 25 Fracture toughness of Kimachi sandstone estimated by the specimen with different artificial notch shape.