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Oskarshamn site investigation

Borehole KLX07A

Shear tests on sealed joints

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October 2006

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Abstract

Shear tests on sealed joints on 3 rock specimens from borehole KLX07A in Oskarshamn, Sweden, have been carried out. The specimens were taken from cores of Ävrö granite at a depth level ranging between 364–436 m borehole length.

Direct shear tests on rock specimens with a sealed joint subjected to a constant normal stress of 5 MPa were initially conducted. This test was followed by three shear cycles, at the normal stress levels 0.5 MPa, 5 MPa and 20 MPa, on the open joint which was created after breaking the sealed joint. The peak and residual shear stresses were deduced from the tests. The specimens were photographed before and after the mechanical tests.

The mean value for the shear strength of sealed joints was 11.02 MPa. The mean value for the peak shear stress and the residual stress were 0.66 MPa respectively 0.58 MPa for the 0.5 MPa normal stress level, 4.87 MPa respectively 4.48 MPa for the 5 MPa normal stress level and 16.64 MPa respectively 13.79 MPa for the 20 MPa stress level.

Sammanfattning

Skjuvförsök har genomförts på 3 stycken bergprov med läkta sprickor från borrhål KLX07A i Oskarshamn. Proven har tagits från borrkärnor vid en djupnivå mellan 364–436 m borrhålslängd. Proven bestod av bergarten Ävrö granit.

Först genomfördes direkta skjuvförsök på bergprover med läkt spricka vid en konstant normalspänning på 5 MPa. Efter att brott uppstått i de läkta sprickorna genomfördes tre skjuvcykler på de öppna sprickorna med en konstant normalspänning på respektive 0,5 MPa, 5 MPa och 20 MPa. Toppvärdet och residualvärdet på skjuvspänningen vid de olika normalspänningsnivåerna bestämdes ur dessa försök. Provobjekten fotograferades såväl före som efter de mekaniska proven.

Medelvärdet på skjuvhållfastheten för de läkta sprickorna var 11,02 MPa. Medelvärdena för toppvärdet och residualvärdet hos skjuvspänningen i de olika skjuvförsöken låg på respektive 0,66 MPa och 0,58 MPa med 0,5 MPa normalspänning, 4,87 MPa och 4,48 MPa med 5 MPa normalspänning respektive 16,64 MPa och 13,79 MPa med 20 MPa normalspänning.

Contents

1 Introduction

Direct shear tests on sealed joints have been conducted on specimens sampled from borehole KLX07A in Oskarshamn, Sweden, see map in Figure 1-1. These tests belong to one of the activities performed as part of the site investigation in the Oskarshamn area managed by the Swedish Nuclear Fuel and Waste Management Co (SKB) /1/. The tests were carried out in the material and rock mechanics laboratories at the department of Building Technology and Mechanics at Swedish National Testing and Research Institute (SP).

The borehole KLX07A is a so called "long hole" with a planned total length of c 1,000 m. However, the drilling was stopped after c 845 m as the hole had passed and confirmed the deformation zone EW007, which was the main aim with this borehole.

Figure 1-1. *Location of all telescopic boreholes drilled up to December 2005 within or close to the Oskarshamn candidate area. The projection of each borehole on the horizontal plane at top of casing is also shown in the figure.*

The controlling documents for the activity are listed in Table 1-1. Both Activity Plan and Method Description are SKB's internal controlling documents, whereas the Quality Plan referred to in the table is an SP (The Swedish National Testing and Research Institute) internal controlling document. The method description 190.005e is partly based on the ISRM suggested method /2/.

SKB supplied SP with rock cores, which arrived at SP in October 2005 and were tested during February and April 2006. Specimens were cut from cores containing natural joints and selected based on the preliminary core logging with the strategy to primarily investigate the mechanical properties in joints of the dominant rock types.

Direct shear tests on rock specimens with a sealed joint subjected to a normal stress of 5 MPa were initially conducted. This test was followed by three shear cycles, at the normal stress levels 0.5 MPa, 5 MPa and 20 MPa, on the open joint that was created after breaking the sealed joint. The shear deformation was controlled and given a constant deformation rate and the shear stress and the normal deformation in the joint were recorded during the test. The peak and residual shear stress at each shear cycle were determined from the shear test. The specimens were photographed before as well as after the mechanical testing.

The shear strength on the specimens containing a sealed joint was expected to be higher than for similar specimens having an open joint. The increased shear force yield a higher stress on the fixation of the specimen in the specimen holders. A high strength concrete material was used for grouting in order to prevent a failure in the fixation of the specimens. The shear force causes a rotation of the specimen due to deformation in the grouting material and deformations in the mechanical loading system. Strain gauges were mounted across the joint at the rear end front sides of the specimens in order to monitor the normal deformation in the joint during loading and to see if the rotations cause a bending of the specimen.

Direct shear tests on intact rock specimens were conducted in addition to investigate the above mentioned effects of a high shear resistance. Intact rock specimens, located nearby the joints, were chosen as they are assumed to represent an upper limit of the shear resistance. The results from the direct shear tests on the intact rock specimens are found in Appendix 1.

Finite element simulations on the complete mechanical system containing the machine characteristics, the grouting and the specimens themselves were carried out in order to investigate the normal and shear stress distributions during shearing. A non-uniform stress distribution was expected in accordance with a similar investigation reported by Afridi, Kwon and Wilson /3/ on direct shear tests on intact lime stone specimens. The results from the finite element simulations are shown in Appendix 2.

Table 1-1. Controlling documents for performance of the activity.

Activity Plan	**Number**	**Version**
KLX07A. Bergmekaniska och termiska laboratoriebestämningar	AP PS 400-05-061	1.0
Method Description	**Number**	**Version**
Normal stress and shear tests on joints	SKB MD 195.005e	2.0
Quality Plan		
SP-QD 13.1		

2 Objective and scope

The purpose of the tests in this report is to determine the mechanical properties of sealed natural joints in rock specimens from borehole KLX07A at Oskarshamn. The behaviour of the sealed joints is investigated during shear loading tests at a constant normal stress level of 5 MPa. The aim is to determine the peak shear stress when the sealed joint fails. Further, the joint friction represented by the peak and residual shear stresses together with the dilatancy of the joints during shearing at different constant normal stress levels were obtained from the subsequent shear tests conducted on the open joints. The results from the tests are going to be used in the site descriptive rock mechanics model, which will be established for the candidate area selected for site investigations at Oskarshamn.

3 Equipment

3.1 Specimen preparation

A circular saw with a diamond blade was used to cut out and trim the specimens to the final shape. The specimen dimensions were measured by means of a sliding calliper.

Before each of the shear test, the specimens were cast in special holders (one upper and one lower). A device for holding the specimens in a fixed position was used during casting. Further, a specially designed fixture was used to clamp the two halves of the holder in the exact position relative to each other. This is of great importance in order to obtain the correct initial conditions for the tests.

For the shear test, the high strength concrete material Ducorit D4, was used to cast the specimens. The suitability of using this material as grout was evaluated by the shear tests on intact rock specimen presented in Appendix B.

A digital camera with 4 Mega pixels has been used to photograph the specimens.

3.2 Mechanical testing

A servo hydraulic testing machine, designed for direct shear tests, has been used for the shear tests, see Figure 3-1. The machine is supplied with two shear boxes, one upper and one lower. The upper box can be moved vertically and the lower box horizontally. Two actuators, one acting vertically and one acting horizontally, are used to apply the forces in the two directions (degrees of freedoms). Two linear bearings are guiding the lower box in order to obtain a controlled linear movement. The maximum stroke is 100 mm in the vertical direction and +/- 50 mm in the shear direction.

In the shear test the normal and shear displacements are measured by means of LVDTs. The vertical displacement between the shear boxes is measured by four LVDTs, positioned in a square pattern around the specimen, one in each corner. Each of the LVDTs has a measurement range of 5 mm and a relative error less than 1%. The average value of these four LVDTs is used to represent the vertical (normal) displacement presented in the results section. The relative displacement between the shear boxes in the horizontal (shear) direction is measured by one LVDT, which has a 10 mm range and a relative error less than 1%.

The maximum vertical (normal) load that can be applied is 300 kN and the maximum load in the horizontal (shear) direction is +/- 300 kN. Load cells are used to measure the forces in both directions. The accuracy of the load measurement is within 1%. The machine is connected to a digital controller with a computer interface for setting up and running tests.

Figure 3-1. *Equipment for direct shear tests and digital controller unit.*

4 Execution

The mechanical tests were carried out according to activity plan and the method description SKB 190.005e (SKB internal controlling document). The test method follows ISRM suggested methods for determining shear strength /2/.

For each specimen, a form containing specimen dimensions is filled in. Further, the form also contains comments and observations during the different test steps. Moreover, a check list is filled in during the work in order to confirm that the different specified steps have been carried out. The specimens are photographed before and after the mechanical tests.

4.1 Description of the samples

The rock type characterisation was made according to Stråhle /4/ using the SKB mapping (Boremap). The identification marks, upper and lower sampling depth (Secup and Seclow) and the rock type are shown in Table 4-1.

4.2 Specimen preparation

The specimens are cut out from rock cores. The pieces are shaped and trimmed to obtain a total thickness *h* of approximately 40 mm and a maximum length *l* of 60 mm, cf Figure 4-1. The specimens will therefore have similar shape and joint area size.

An overview of the activities during the specimen preparation is shown in the step-by-step description in Table 4-2.

Table 4-1. Specimen identification, sampling depth and rock type for all specimens (based on the Boremap overview).

Identification	Adj secup [m]	Adj seclow [m]	Rock type
KLX07A-117-1	364.52	364.68	Ävrö granite
KLX07A-117-2	421.59	421.72	Ävrö granite
KLX07A-117-4	435.22	435.36	Ävrö granite

Table 4-2. Activities during the specimen preparation.

Step	Activity
1	Mark the drill cores at the position of the joints selected for testing.
2	Cut out the specimens from the cores and trim them to the specified dimensions.
3	Measure the specimen dimensions and calculate the joint surface area.
4	Take digital photos of each specimen.

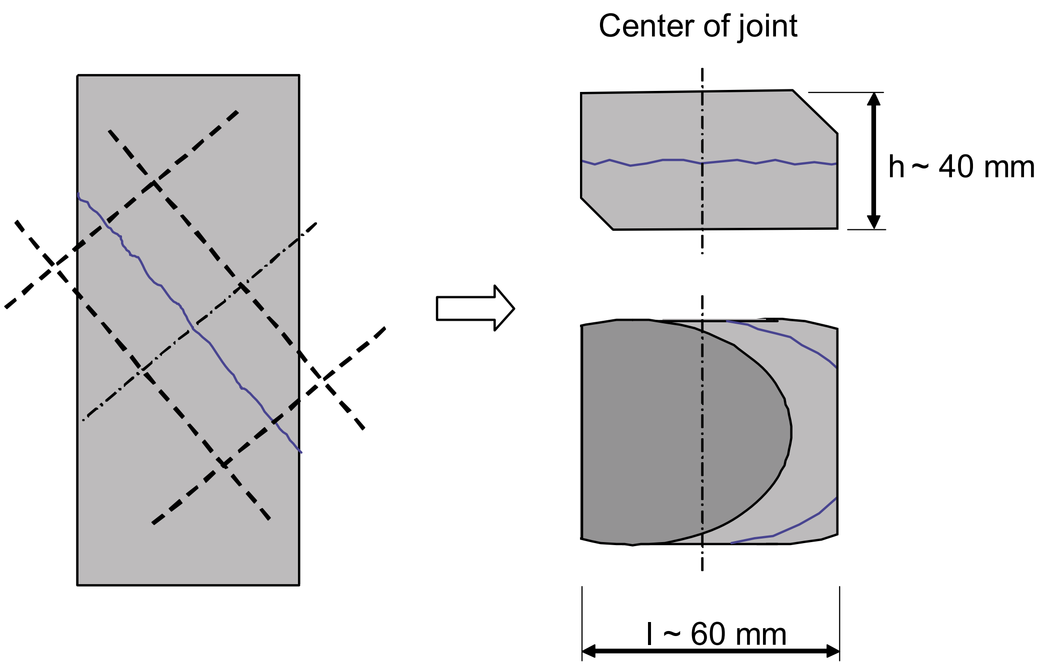


__Figure 4-1.__ Principle of specimen processing. Left: Cylindrical core containing a sealed joint. The dashed lines show the cutting lines; Right: Specimen after processing.

4.3 Shear test

The program controlling the shear tests is divided into four parts, one part for the shear test on the sealed joint and one program each for the three subsequent shear tests, resulting in four separate data files for each specimen.

The specimens are cast in steel holders using a high strength concrete material, see Figure 4-2.

One half is cast first by pouring the grout into the holder with the specimen held in correct position. The grout is hard enough after three days to fixate the specimen. The second half of the holder is then mounted on top of the first one with a 6 mm gap between the two halves and turned upside down. The second half is cast by pouring grout into the holder. The grout is fully hardened after approximately two weeks in room temperature.

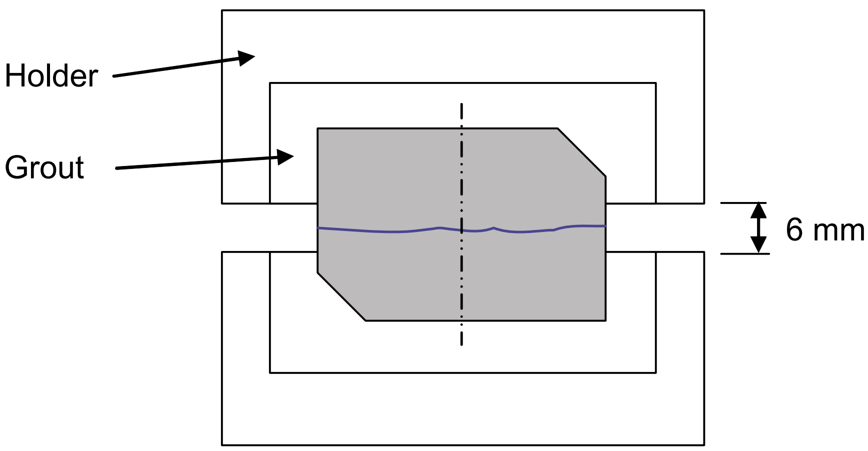


__Figure 4-2.__ Specimen cast in the specimen holder for the shear tests.

The behaviour of the sealed joints is investigated during shear loading tests at a constant normal stress level of 5 MPa. The aim is to determine the peak shear stress when the sealed joint fails.

Subsequently, three successive shear tests were conducted with a constant normal stress, at 0.5, 5 and 20 MPa, respectively. Each joint was sheared with a constant displacement rate to a final displacement value slightly exceeding 2, 3 and 5 mm for the 0.5, 5 and 20 MPa normal stress levels. The shear tests were finished by unloading the shear stress to zero. The normal stress was lowered to 0.2 MPa before the shear position was restored to its starting point (zero shear displacement) for the following shear test. Both the normal and the shear displacements in the joint were recorded in the shear tests.

An overview of the activities during the shear test is shown in the step-by-step description in Table 4-4.

4.4 Data handling

The test results were exported as text files from the test software and stored in a file server on the SP computer network after each completed test. The main data processing, in which the peak and residual shear stresses were determined, has been carried out in the program MATLAB /5/. Moreover, MATLAB was used to produce the diagrams shown in Section 5.1. The summary of results in Section 5.2 with tables containing mean value and standard deviation of the different parameters and diagrams were produced using MS Excel. MS Excel was also used for reporting data to the SICADA database. Data are traceable in SICADA by the activity plan number.

Table 4-4. Activities during the shear test.

Step	Activity
1	Cast the specimens into the specimen holders.
2	Mount the specimen holders in the shear testing machine.
3	Perform the shear test on the sealed joint at a constant normal stress level of 5 MPa.
	• Apply a normal stress of 0.5 MPa and zero the deformation channels.
	• Increase the normal stress to 5 MPa.
	• Apply a shear deformation with a rate of 0.5 mm/min and shear until the sealed joint fails.
	• Unload the shear stress to zero.
	• Unload the normal stress to 0.2 MPa and restore the shear deformation to zero (initial position).
4	Perform the shear tests on the open joint at the three constant normal stress levels, 0.5 MPa, 5 MPa and 20 MPa:
	• Apply a normal stress of 0.5 MPa and zero the deformation channels.
	• Increase the normal stress to the prescribed value for the actual test.
	• Apply a shear deformation with a rate of 0.5 mm/min and shear until the shear displacement reaches 2, 3 or 5 mm respectively for the 0.5 MPa, 5 MPa and 20 MPa stress levels.
	• Unload the shear stress to zero.
	• Unload the normal stress to 0.2 MPa and restore the shear deformation to zero (initial position).
	Repeat this for the three shear cycles.
5	Take out the specimens from the shear boxes.
6	Take digital photos of each specimen.
7	Store the test results on the computer network.

4.5 Analyses and interpretation

In the shear tests, the normal stress σ_N and shear stress σ_S are defined as

$$\sigma_N = \frac{F_N}{A} \text{ and } \sigma_S = \frac{F_S}{A}$$

where F_N is the normal force and F_S is the shear force acting on the joint and A is the joint area. The shear strength σ_{SS}, of the sealed joint, the peak value σ_{SP} and the residual value σ_{SR} of the shear stress σ_S on each of the three shear cycles on the broken joint are determined. The peak value is defined as the maximum value during the whole shear cycle. The residual value is defined as the mean value of the shear stress of the last 0.5 mm of the shear cycle before the unloading of the shear stress for the 0.5 and 5 MPa normal stress levels and the last 1 mm for the 20 MPa normal stress level. In some cases the actual shear force is fluctuating up and down caused by a stick-slip response that is achieved during the shear process due to the uneven surfaces in the joints. The shear stress used when the residual value is evaluated, is defined as the envelope obtained by interconnecting the sub-peaks obtained during shearing. The distance between the sampled sub-peak points during the tests is quite coarse which makes the mean value calculation less accurate. New data points are therefore added in the interval for the mean value calculation with a linear interpolation, if the distance in the shear direction between the sampled sub-peaks is less than 0.01 mm. The new points are equidistantly distributed and the number of new points that are created are determined with the criterion that the distance of the added points should be just less or equal to 0.01 mm.

The shear deformation δ_S is represented by the relative displacement between the shear boxes in the horizontal (shear) direction measured by one LVDT. The normal deformation δ_N is defined as the average value of four LVDTs used to measure the vertical (normal) displacement between the two shear boxes.

A part of the normal deformations and shear deformations measured in the shear tests belong to the deformations in the epoxy, in the holders and shear boxes and in the contact surfaces between the specimen holders and the shear boxes. However, the system deformations during the shear tests are of less significance for the results and no correction is made.

4.6 Nonconformities

The testing was conducted according to the method description with no departures. Specimen KLX07A-117-3 failed during the preparation and was replaced with KLX07A-117-4. This is a departure of the activity plan.

5 Results

The test results of the individual specimens are presented in Section 5.1, and a summary of the results is given in Section 5.2. The reported parameters are based both on unprocessed raw data obtained from the testing and processed data and were reported to the SICADA database. These data together with the digital photographs of the individual specimens were handed over to SKB. The handling of the results follows SDP-508 (SKB internal controlling document) in general.

5.1 Description and presentation of the specimens

The specimens and joints before casting and after testing are shown on photos. Comments on observations appeared during the testing are reported. The results from the four shear tests are shown in the upper and the middle diagrams. The results from the shear test on the sealed joint are displayed in magenta and the results from the shear tests on the open joint for the three normal stress levels are displayed in black (0.5 MPa), green (5 MPa) and blue (20 MPa), respectively. Furthermore, the red triangle markers show the peak shear stresses and the red square markers indicate the residual stresses. Moreover, the dilatancy in the joints is derived from the shearing part of the four shear tests. The results from the strain gauge measurements during the shear test on the sealed joint are shown in the lower diagrams.

Specimen ID: KLX07A-117-1

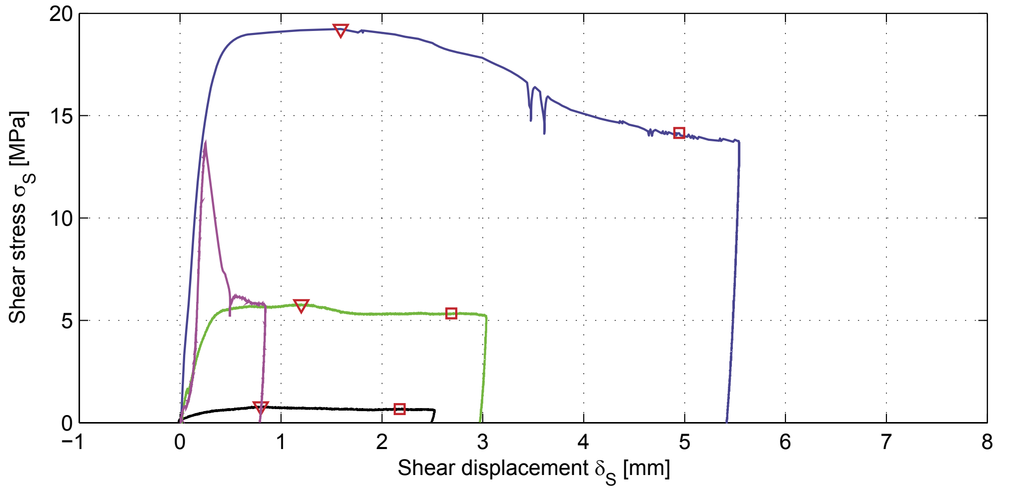
Before mechanical test

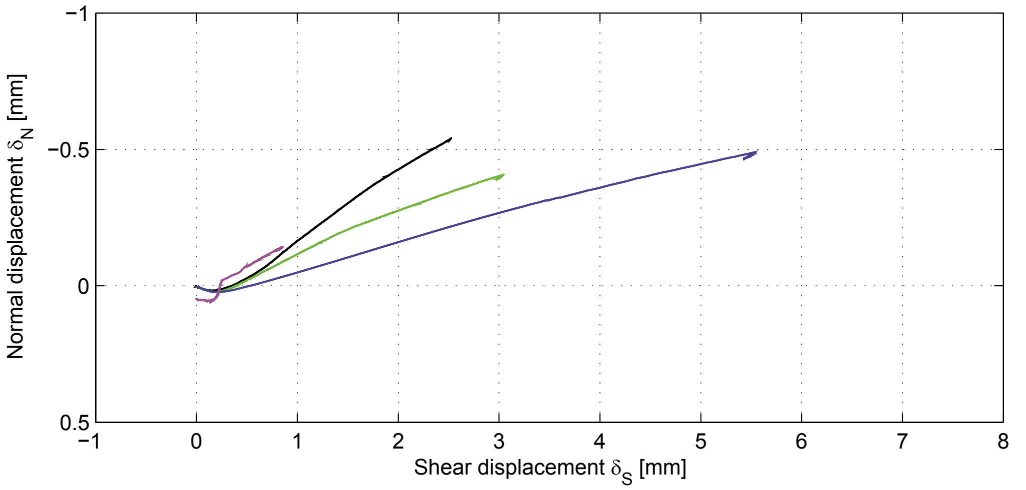
After mechanical test

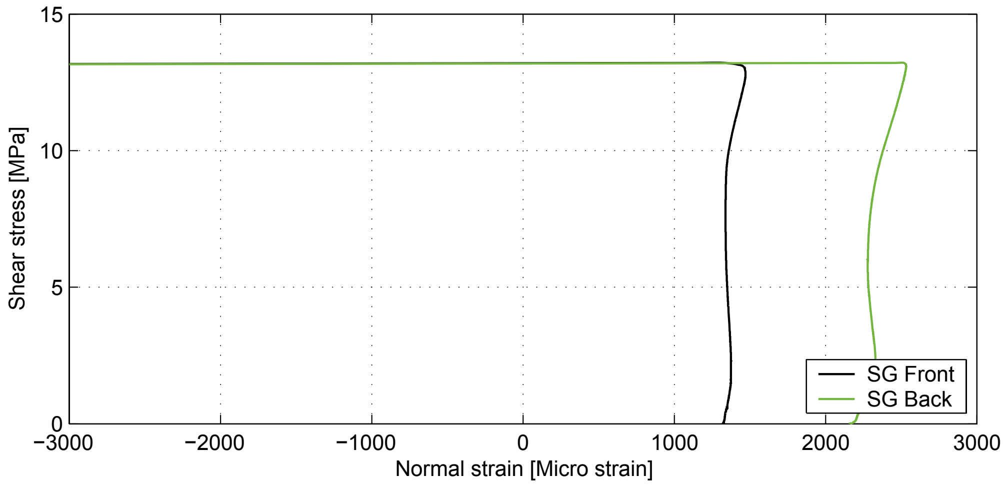
Comments The shear failure occurred in the sealed joint.

Specimen ID: KLX07A−117−01

Joint area : 25 cm^2







Specimen ID: KLX07A-117-2

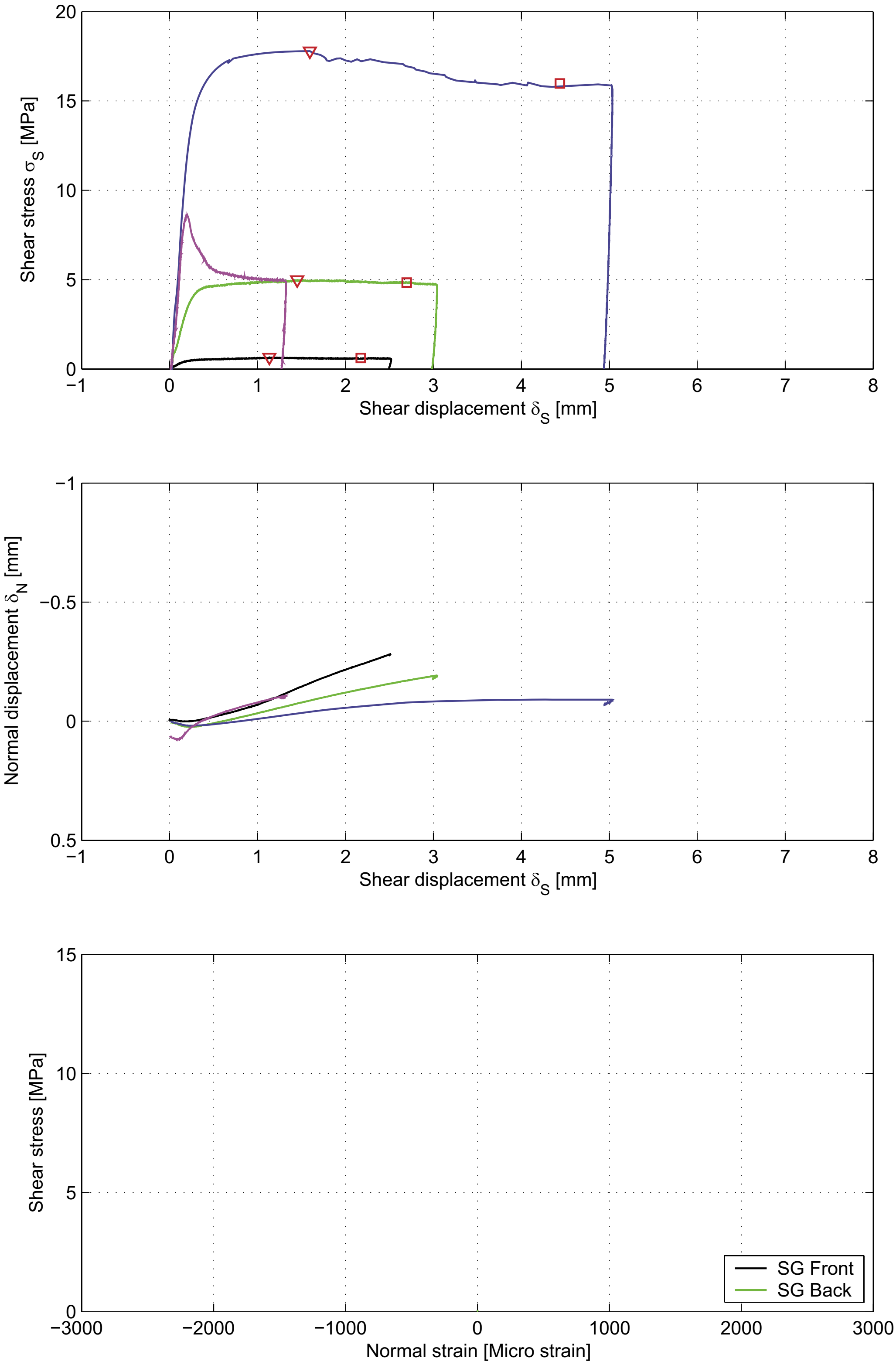
Before mechanical test


After mechanical test


Comments	The shear failure occurred in the sealed joint.
	Diagrams: No results were obtained for the strain gauges during the shear test of the sealed joint.

Specimen ID: KLX07A−117−02

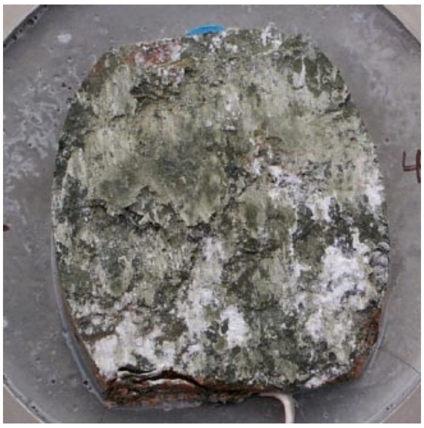
Joint area : 25.2 cm^2

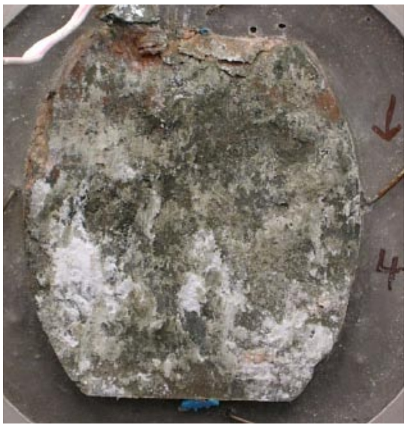


Specimen ID: KLX07A-117-4

Before mechanical test

After mechanical test

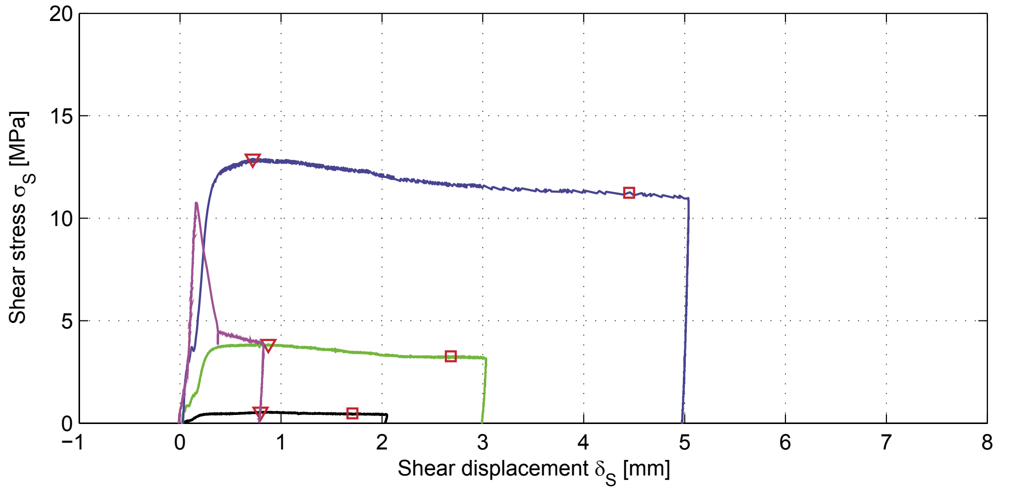


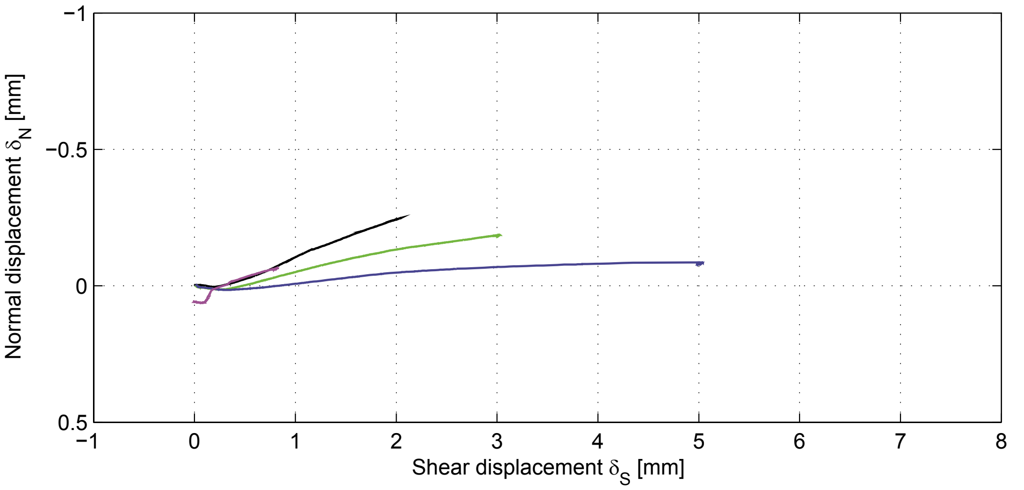


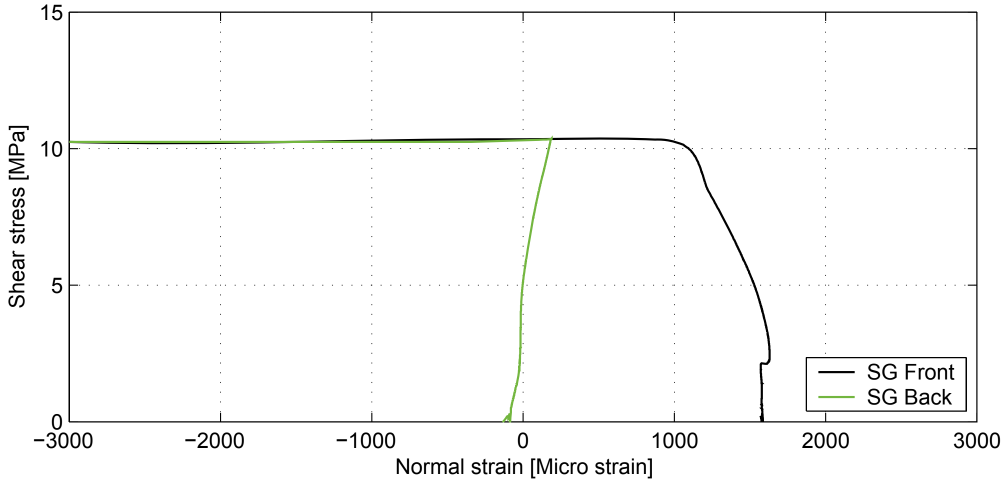
Comments The shear failure occurred in the sealed joint.

Specimen ID: KLX07A−117−04

Joint area : 23.4 cm^2







5.2 Results for the entire test series

A summary of the test results is shown in Tables 5-1 and 5-2.

Table 5-1. Summary of results.

Identification	Area [cm^2]	Shear strength [MPa]	Peak 05 [MPa]	Resid 05 [MPa]	Peak 5 [MPa]	Resid 5 [MPa]	Peak 20 [MPa]	Resid 20 [MPa]	Comments
KLX07A-117-1	25.0	13.68	0.79	0.67	5.78	5.34	19.23	14.15	
KLX07A-117-2	25.2	8.58	0.65	0.61	4.98	4.83	17.79	15.98	
KLX07A-117-4	23.4	10.79	0.55	0.47	3.86	3.26	12.90	11.24	

Table 5-2. Calculated mean values and standard deviation (Std dev).

	Shear strength [MPa]	Peak 05 [MPa]	Resid 05 [MPa]	Peak 5 [MPa]	Resid 5 [MPa]	Peak 20 [MPa]	Resid 20 [MPa]
Mean value (all specimens)	11.02	0.66	0.58	4.87	4.48	16.64	13.79
Std dev (all specimens)	2.55	0.12	0.10	0.96	1.09	3.32	2.39

References

/1/ **SKB, 2001.** Site investigations. Investigation methods and general execution programme. SKB TR-01-29, Svensk Kärnbränslehantering AB.

/2/ **ISRM, 1974.** Suggested methods for determining shear strength. Part 2: Suggested method for laboratory determination of direct shear strength. Final draft 1974.

/3/ **Afridi AJ, Kwon S, Wilson JW, 2001.** Investigation of rock failure in a direct shear machine. Trans Instn Metall (sect A: Min Technol), 110(3), pp 158-162, 2001.

/4/ **Stråhle A, 2001.** Definition och beskrivning av parametrar för geologisk, geofysisk och bergmekanisk kartering av berg, SKB-01-19. In Swedish. Svensk Kärnbränslehantering AB.

/5/ **MATLAB, 2002.** The Language of Technical computing, Version 6.5, MathWorks Inc.

/6/ **ABAQUS, 2004.** Version 6.5, ABAQUS Inc.

Appendix A

Shear test on intact rock specimens

A.1 General

Direct shear tests on intact rock specimens were conducted. The aim of the tests was to:

- Check if the grouting with the new high strength concrete was able to sustain the forces during the direct shear tests without breaking.
- Check how the shear machine responds to an expected higher shear force compared to the forces acting during shear tests on open joints.
- Obtain reference data of the shear strength for the intact rock.

The tests were carried out according to the method description given in Section 4.3.

A.2 Specimen

The specimens were taken out from rock cores close to the locations of the sealed joints. The pieces were cut to obtain a total height h of approximately 40 mm. The identification marks, upper and lower sampling depth (Secup and Seclow) and the rock type are shown in Table A-1.

A.3 Grout specification

The grout used to cast the specimens was a modification of the high strength concrete material Ducorit D4 delivered by Densit AS in Denmark. To ensure good pourability and backfilling, fractions larger then 2.0 mm were sifted away from the original ready dry mix. The grout was mixed in the proportions of 100 g water per 1,000 g of dry mix. Three material cylinders (∅50×125 mm), to be tested in uniaxial compression, were cast at the same occasion as the shear specimens of the intact rock. The cylinders were stored in water until testing, approximately two weeks after casting. The mean value of the uniaxial compressive strength and Young's modulus for the three specimens were 200 MPa and 50 GPa, respectively.

Table A-1. Specimen identification, sampling depth and rock type for all specimens.

Identification	Adj secup [m]	Adj seclow [m]	Rock type
KLX07A-117-R1	421.83	421.87	Ävrö granite
KLX07A-117-R2	421.87	421.91	Ävrö granite
KLX07A-117-R3	421.91	421.95	Ävrö granite
KLX07A-117-R4	347.82	347.86	Ävrö granite

A.4 Mechanical testing

The intact rock specimens were cast in steel holders using the high strength concrete material described earlier, see Figure A-1. The tests were conducted approximately 2 weeks after the grouting. In the shear test the specimens were subjected to a constant normal stress of 5 MPa and sheared with a constant displacement rate until final break.

Both the normal and the shear displacements between the upper and lower shear boxes were recorded in the shear tests. Moreover, vertical strains were measured on the rock specimen, by two strain gauges placed at the opposite side of each other in the shear direction, see Figure A-1.

A.5 Test results

The specimens before casting and after testing are shown on photos. Comments on observations appeared during the testing are reported. The results from the shear tests are represented by shear stress versus shear displacement, normal displacement versus shear displacement and shear stress versus normal strain.

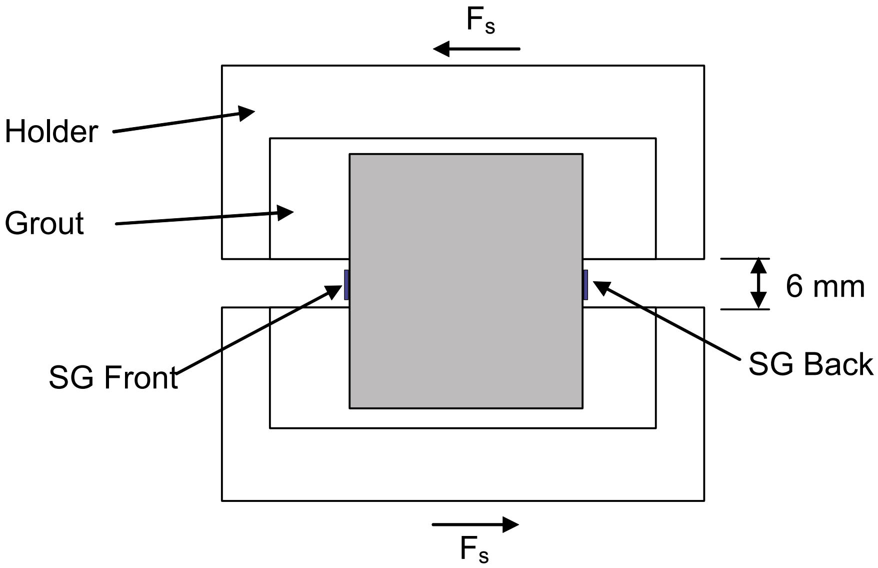
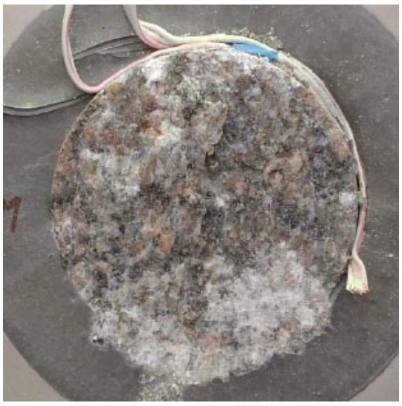


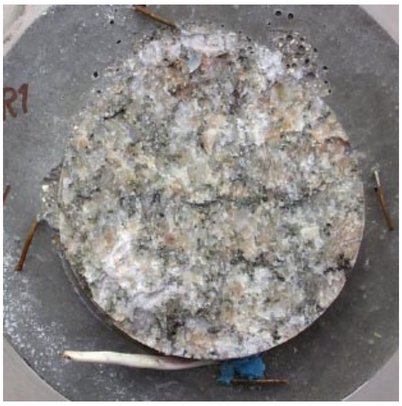
Figure A-1. *Intact rock specimen cast in the specimen holder for the shear tests.*

Specimen ID: KLX07A-117-R1

Before mechanical test

After mechanical test

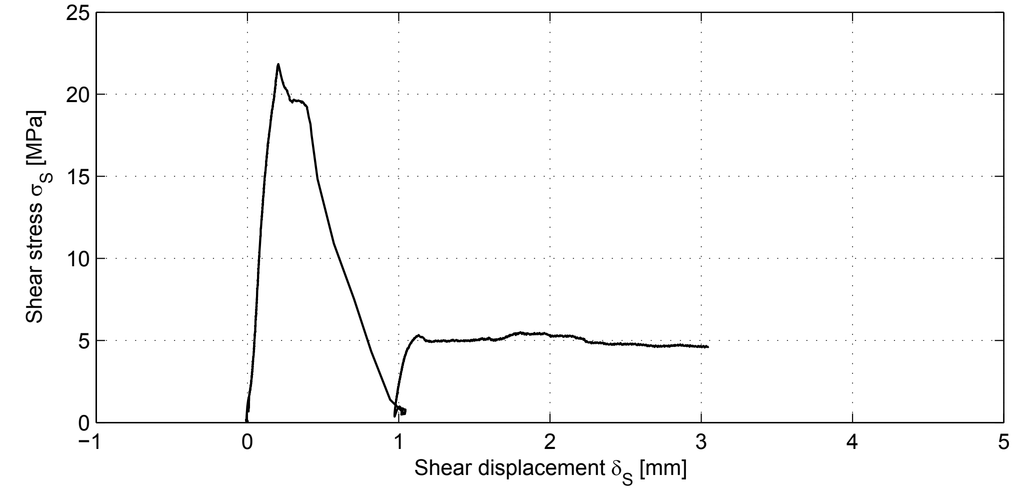


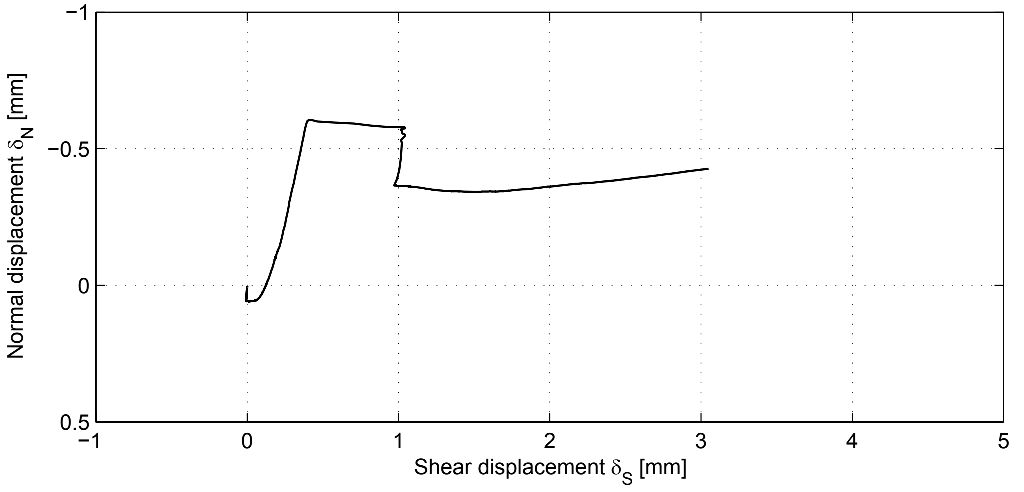


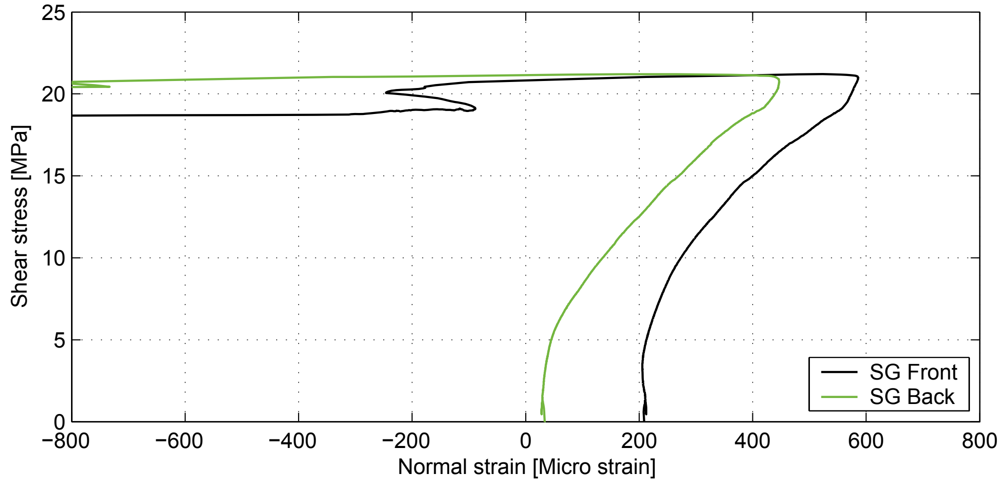
Comments

Specimen ID: KLX07A−117−R1

Joint area : 19.7 cm^2



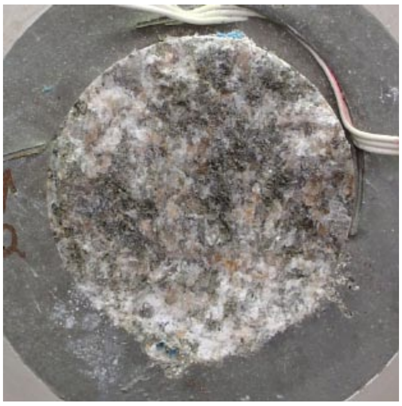


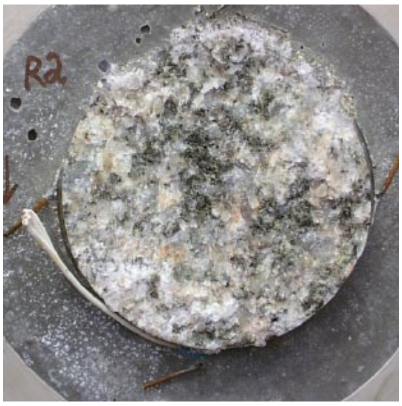


Specimen ID: KLX07A-117-R2

Before mechanical test

After mechanical test

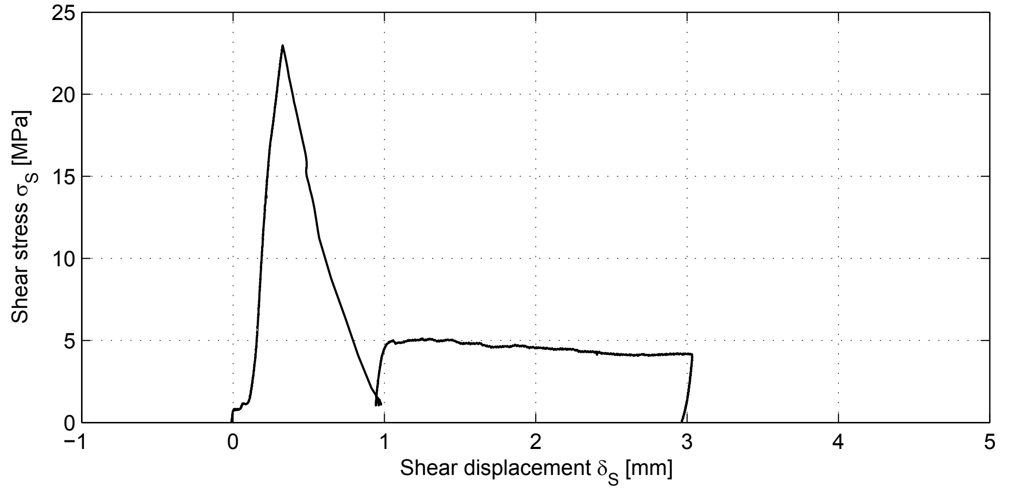


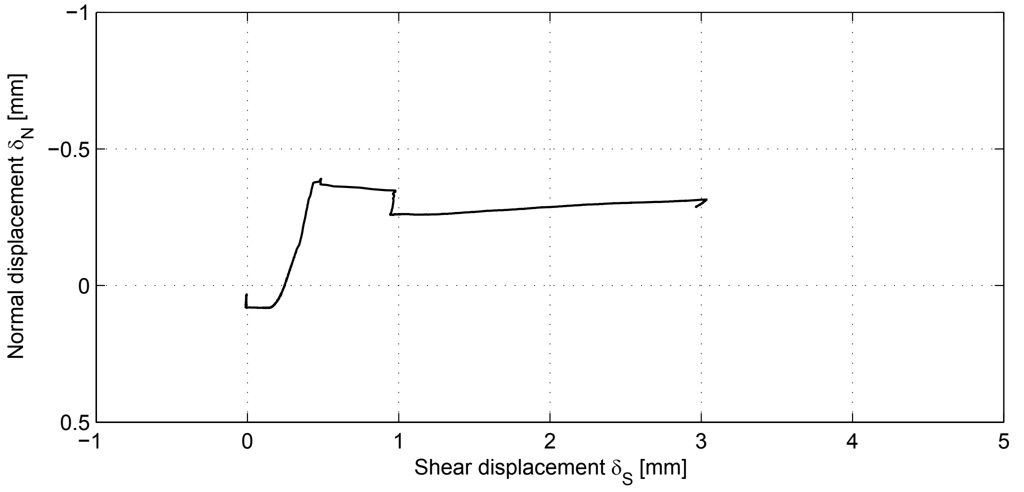


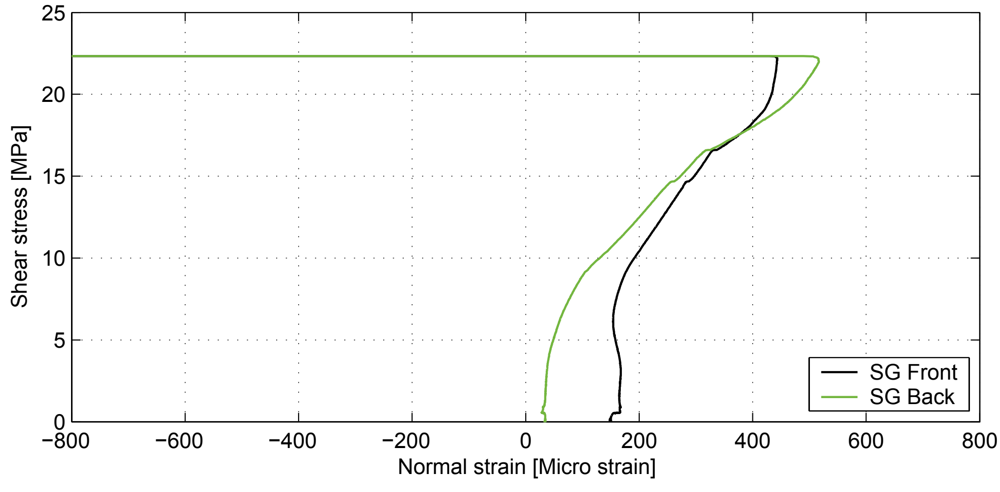
Comments

Specimen ID: KLX07A−117−R2

Joint area : 19.7 cm^2



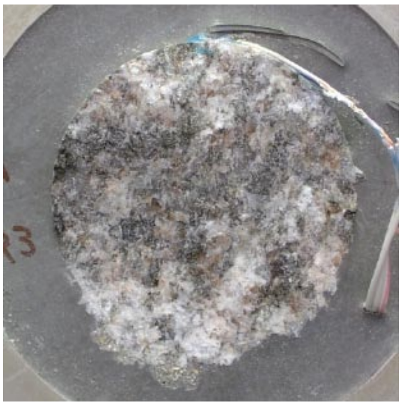




Specimen ID: KLX07A-117-R3

Before mechanical test

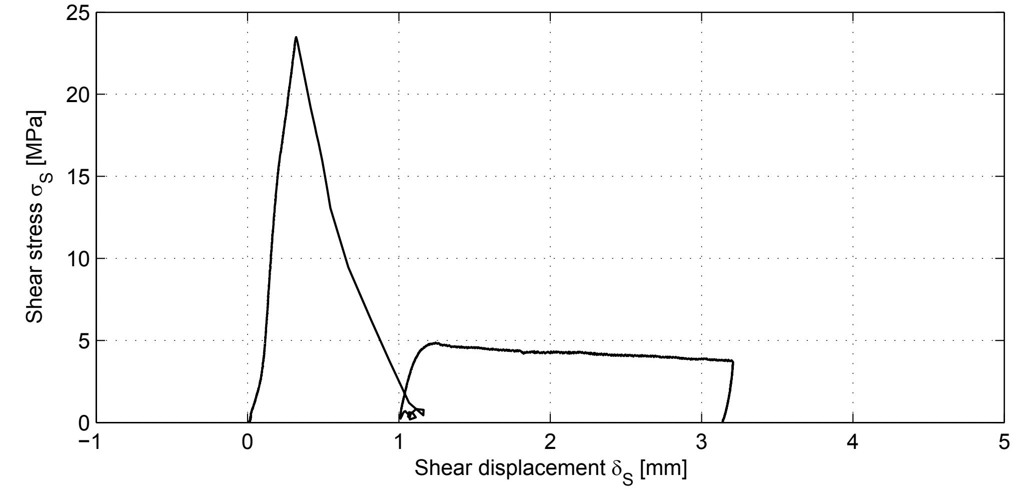
After mechanical test

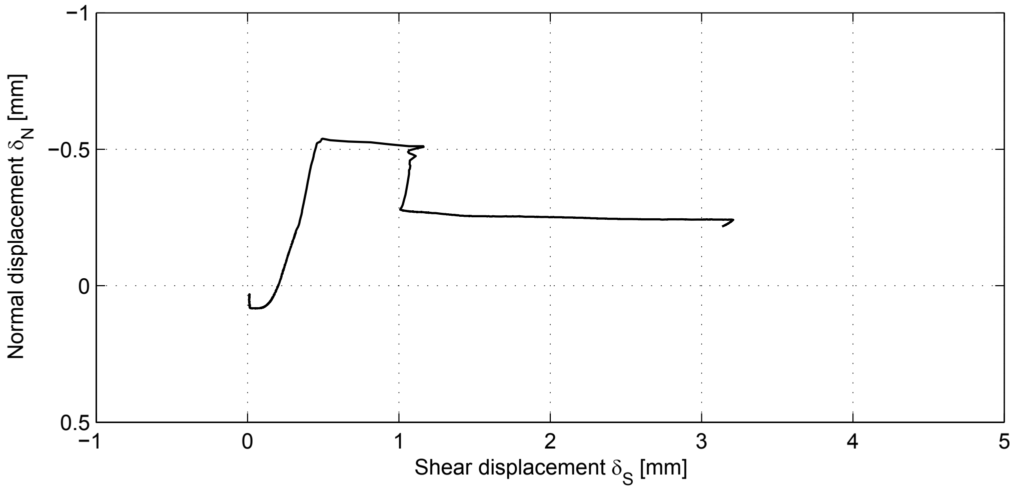


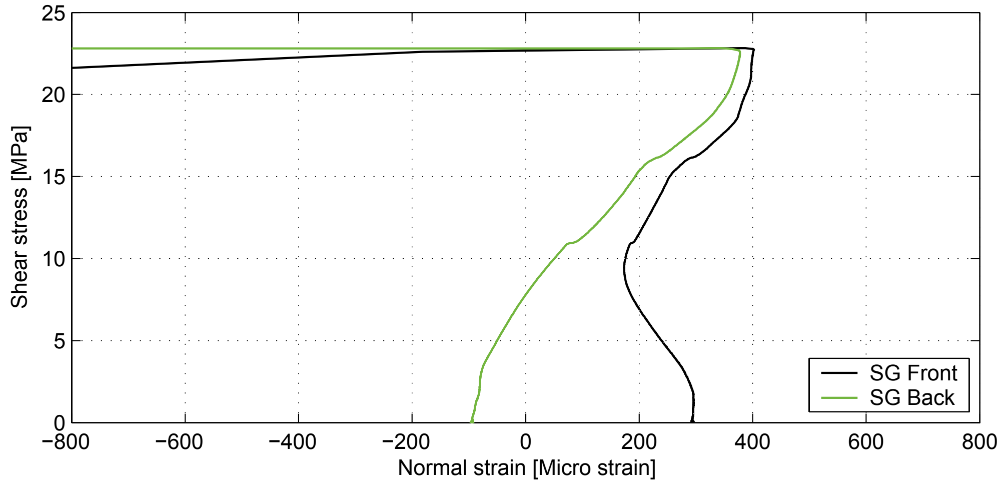
Comments

Specimen ID: KLX07A−117−R3

Joint area : 19.7 cm^2



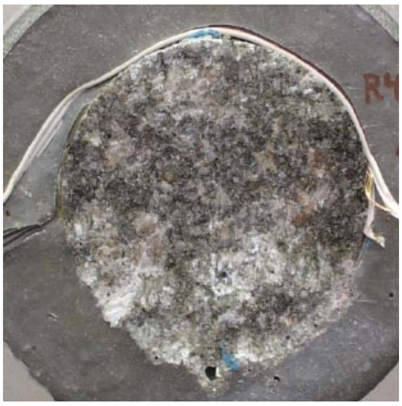




Specimen ID: KLX07A-117-R4

Before mechanical test

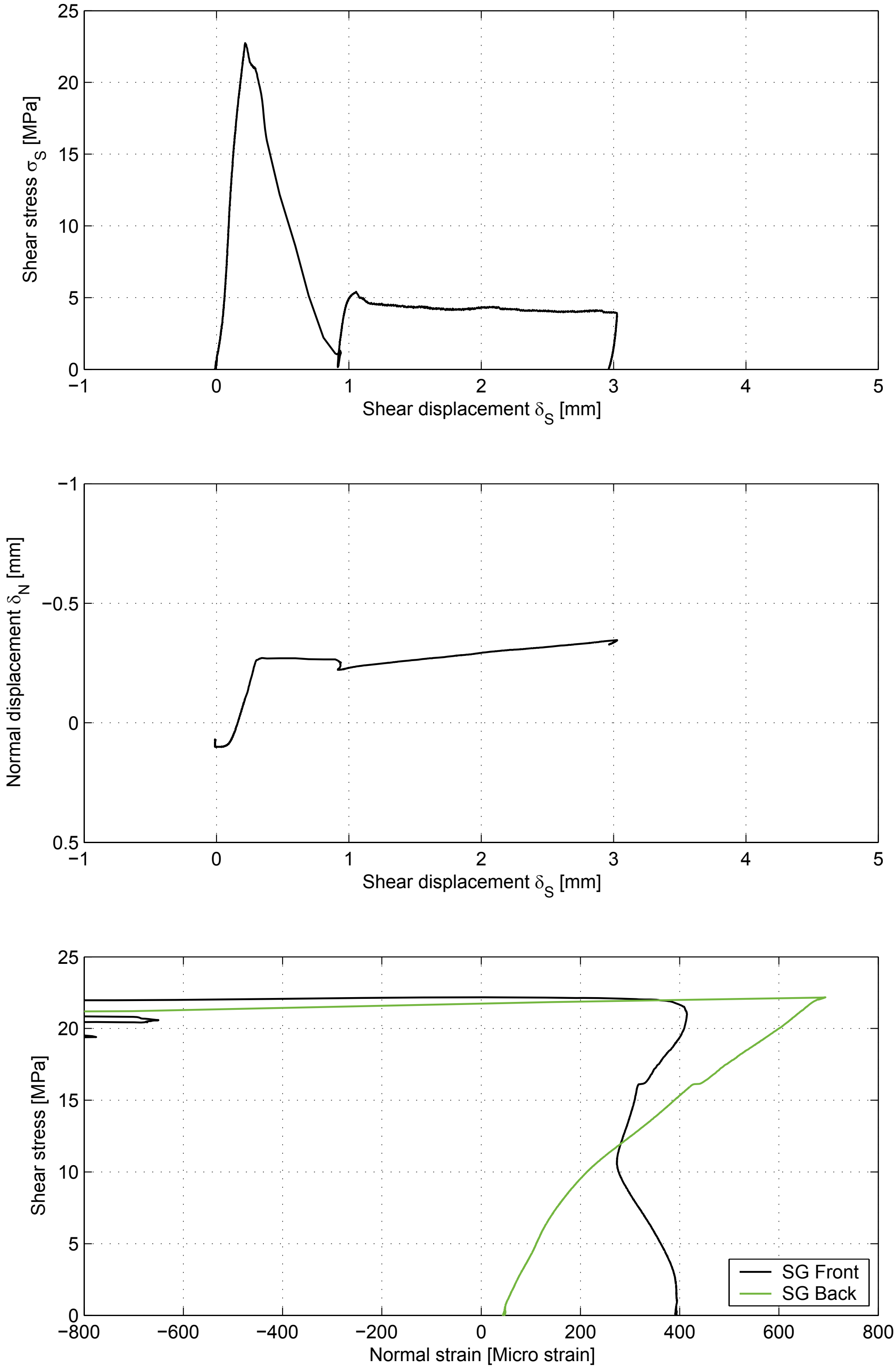
After mechanical test



Comments

Specimen ID: KLX07A−117−R4

Joint area : 19.7 cm^2



A summary of the test results is shown in Tables A-2.

Table A-2. Summary of results.

Identification	Area [cm²]	Shear strength [MPa]	Comments
KLX07A-117-R1	19.7	21.84	
KLX07A-117-R2	19.7	22.98	
KLX07A-117-R2	19.7	23.49	
KLX07A-117-R4	19.7	22.75	
Mean value		22.77	
Std dev		0.69	

Appendix B

Finite element analyses

B.1 General

Finite element analyses of the direct shear tests on intact rock specimens were conducted. The aim of the analyses was to:

- Study the mechanical behaviour of the rock specimen during the initial loading.
- Study the normal and the shear stress distribution in the rock specimen, especially at the expected location of the shear failure plane.

B.2 Finite element model

To analyse the direct shear tests on the intact cylindrical rock specimens, the finite element program ABAQUS /6/ has been used. Furthermore, an intact rock specimen with a geometry similar to the specimens containing a joint was also analysed. Parts of the test setup belonging to the test equipment, i e specimen holders, upper and lower shear boxes and the vertical loading piston and the cement grout were beside to the rock specimen itself included in the model. All parts included in the finite element model were based on 8-node linear brick elements, see Figure B-1. However, in the model for the sealed crack specimen, the grout was instead modelled with 4-node linear tetrahedron elements, see Figure B-2.

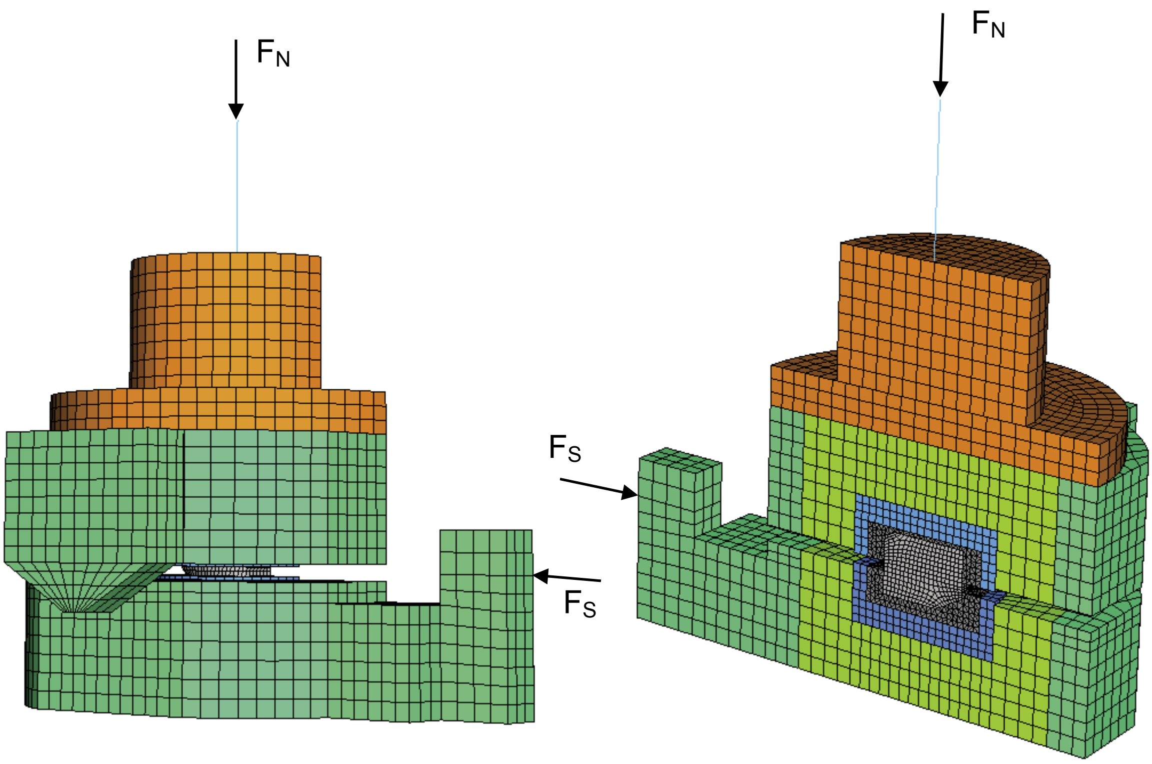


Figure B-1. *Finite element model of the direct shear test setup.*

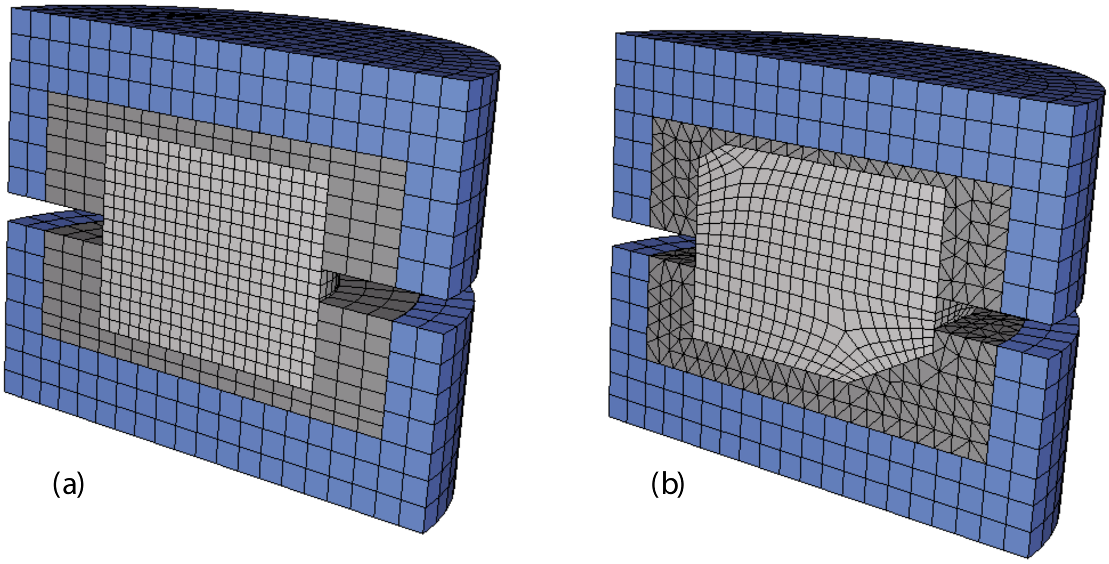


Figure B-2. *Detail of the FE-model showing the specimen, grout and holders for (a) intact rock specimen and (b) specimen with a geometry similar to sealed crack specimen.*

The interaction between different parts was simulated with a surface-based interaction model using a hard contact pressure-overclosure formulation in the normal direction and a Coulomb friction model in the transversal direction, cf /6/. Thereby, the surfaces of the different parts can separate and slide relative each other, as well as, transmitting contact pressure and shear stresses. The normal actuator was modelled with 2-node cubic beam elements, with the assumption that all translations were restrained at the top. The shear actuator was not modelled; instead the shear load was applied directly at the lower shear box. The vertical translations were restrained at the bottom surface of the lower shear box. The upper shear box was restrained in the shear direction at the location of the shear leg connection. Furthermore, one plane of symmetry in the vertical direction was used to reduce the size of the model.

Small geometrical imperfections and plays between parts existing in the test setup were included in the model in order obtain a realistic model. The upper shear box was assumed to have an initial inclination of 0.025˚ relative the lower shear box. Furthermore, the radial play between the holders and the shear boxes was assumed to be 0.05 mm.

Linear elastic behaviour was assumed for all materials contained in the model. The Young's modulus and Poisson ratio were 200 GPa and 0.3 respectively for all steel parts, 50 GPa and 0.2 for the grout and 70 GPa and 0.27 for the rock specimen.

As in the tests, the loads in the FE-analyses were applied in two steps. In the first step the specimen was loaded in the normal direction with a load, F_N, corresponding to an average normal stress of 5 MPa. In the second step the normal load was kept constant and the shear load, F_S, was successively increased up to 25 kN.

B.3 Results

In Figure B-3 to B-6, results from the FE-analysis are compared with results obtained from the tests on the intact rock specimens presented in Appendix A.

From the FE-analysis it can be seen that the shear stress distribution in the intact rock specimen is non-uniform during the shear loading, see Figures B-7 and B-8. Similar results were also found by /3/. The non-uniform stress distribution is even more pronounced for the specimen with geometry similar to the sealed cracked specimen; see Figures B-9 to B-11.

Moreover, it was observed that the maximum compressive principal stress in the grout was 182 MPa during the shear loading. Even though this value is relatively high, it is below the uniaxial compressive strength of the grout material.

B.4 Concluding remarks

The agreement between computed results and results from tests are in general good and the principal behaviours are captured. The model assumes a linear material behaviour which restricts the model to the initial loading part. A more realistic behaviour when the load is approaching the failure load would be obtained if the rock specimen if a model for the joint breakage would be included in the analyses. Moreover, the model should be able to serve as a tool to estimate the magnitude of the fictitious shear deformations appearing from the deformations in the components outside the specimen. By knowing the fictitious shear deformations, they could be subtracted from the measured total shear deformations in order to yield a better estimate of the actual shear deformation in the joint.

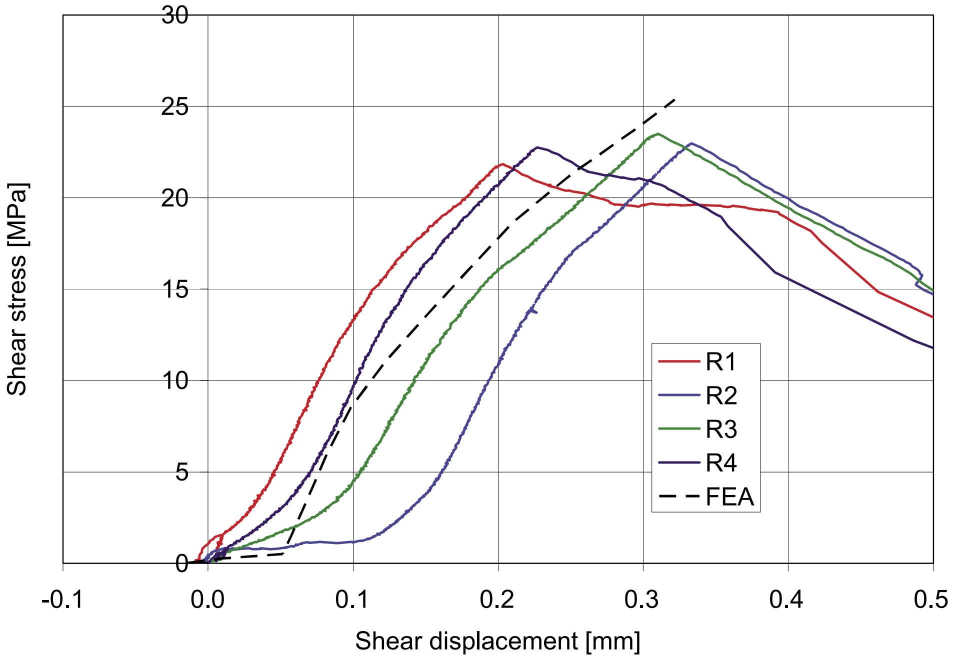


Figure B-3. Comparison of shear stress versus shear displacement relations obtained from tests and FEA.

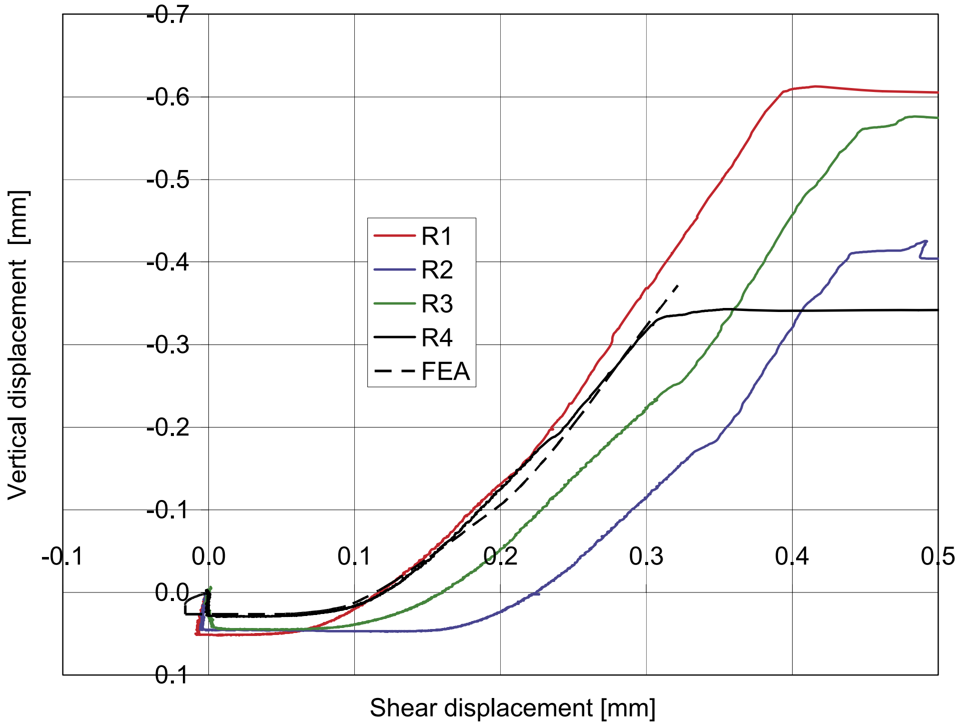


Figure B-4. *Comparison of normal displacement versus shear displacement relations obtained from tests and FEA.*

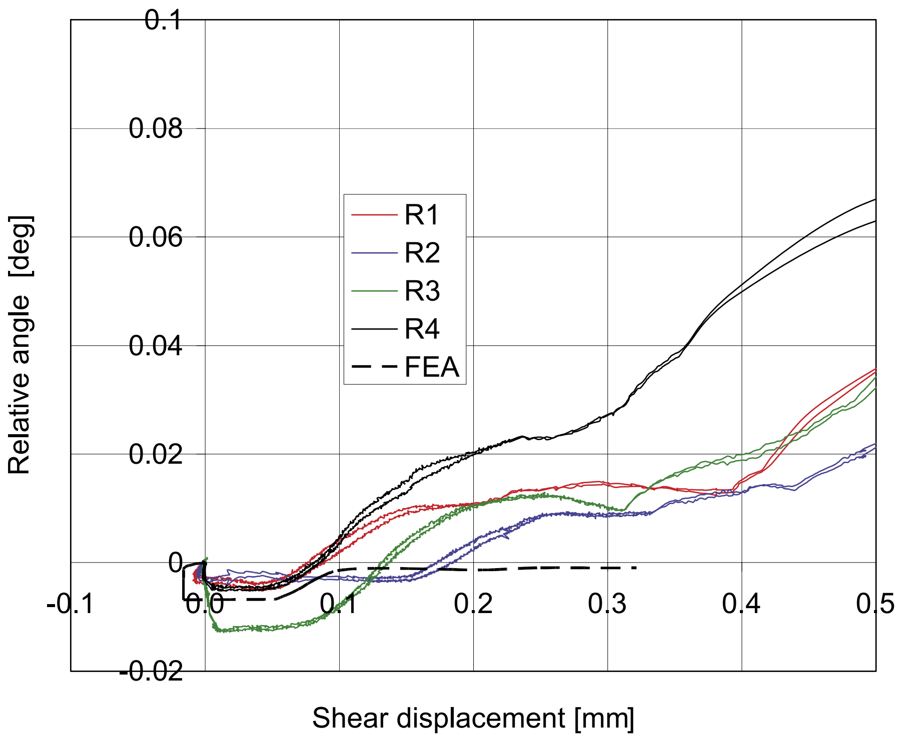


Figure B-5. *Comparison of the change in relative angle between the two shear boxes during the shear loading, obtained from tests and FEA.*

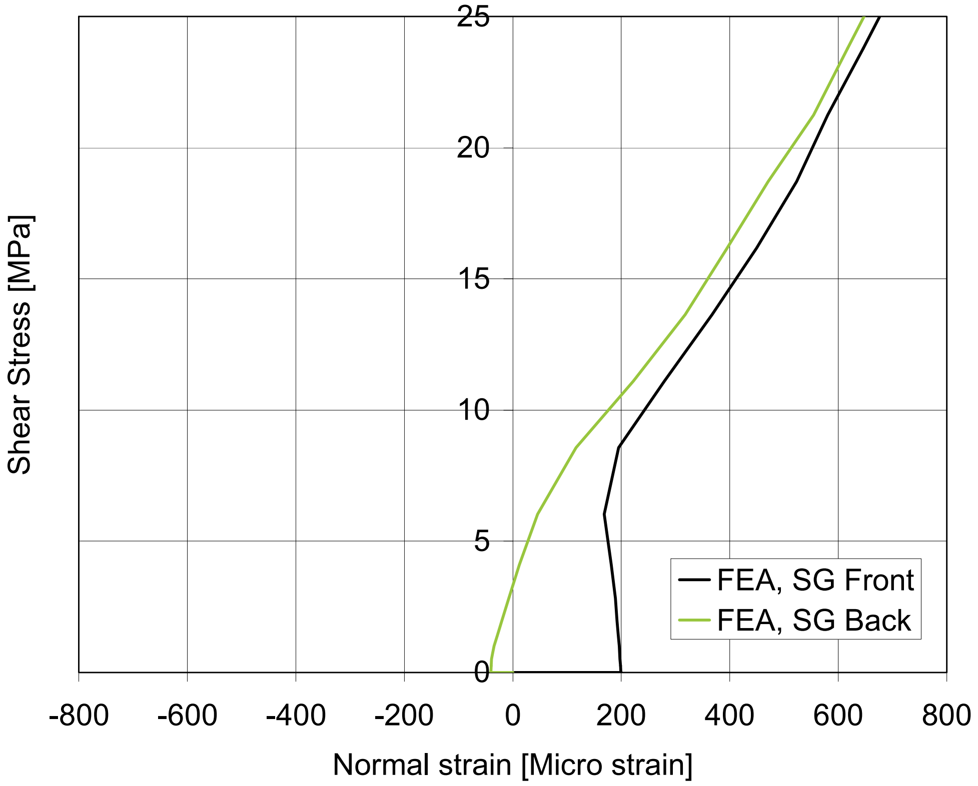


Figure B-6. *Shear stress versus normal strain for obtained from FEA at the location of the strain gauges on the intact rock specimens.*

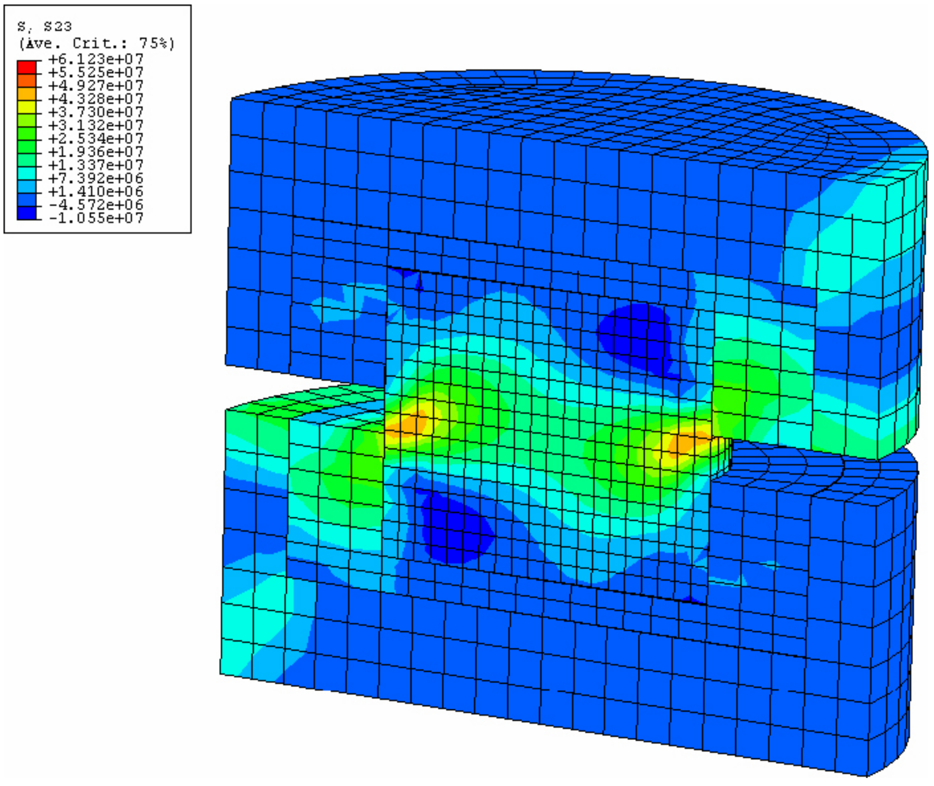


Figure B-7. *Shear stress distribution in the intact rock specimen at maximum shear load.*

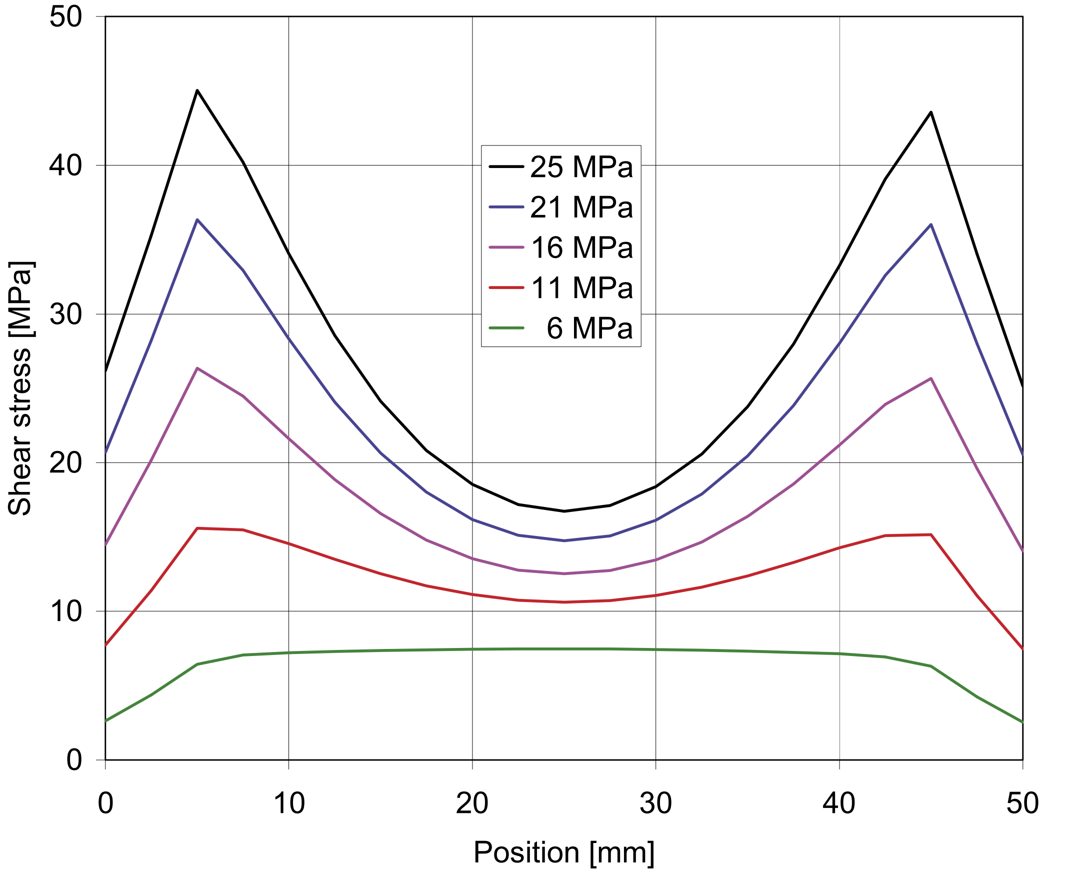


Figure B-8. *Shear stress distribution along the center line of the intact rock specimen at different levels of mean shear stress* σ_S.

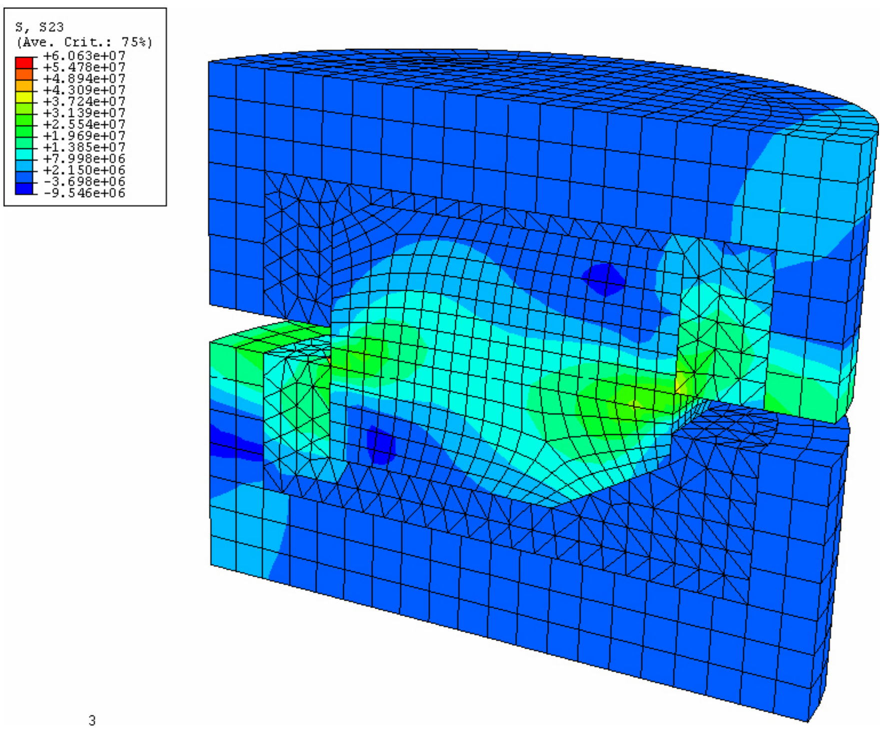


Figure B-9. *Shear stress distribution in the sealed crack specimen at maximum shear load.*

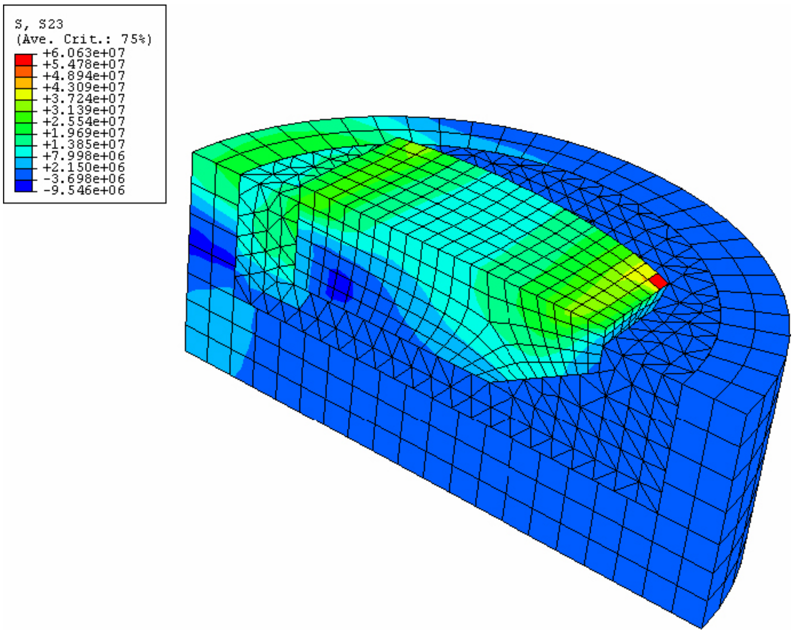


Figure B-10. *Shear stress distribution in the centre plane of the sealed crack specimen at maximum shear load.*

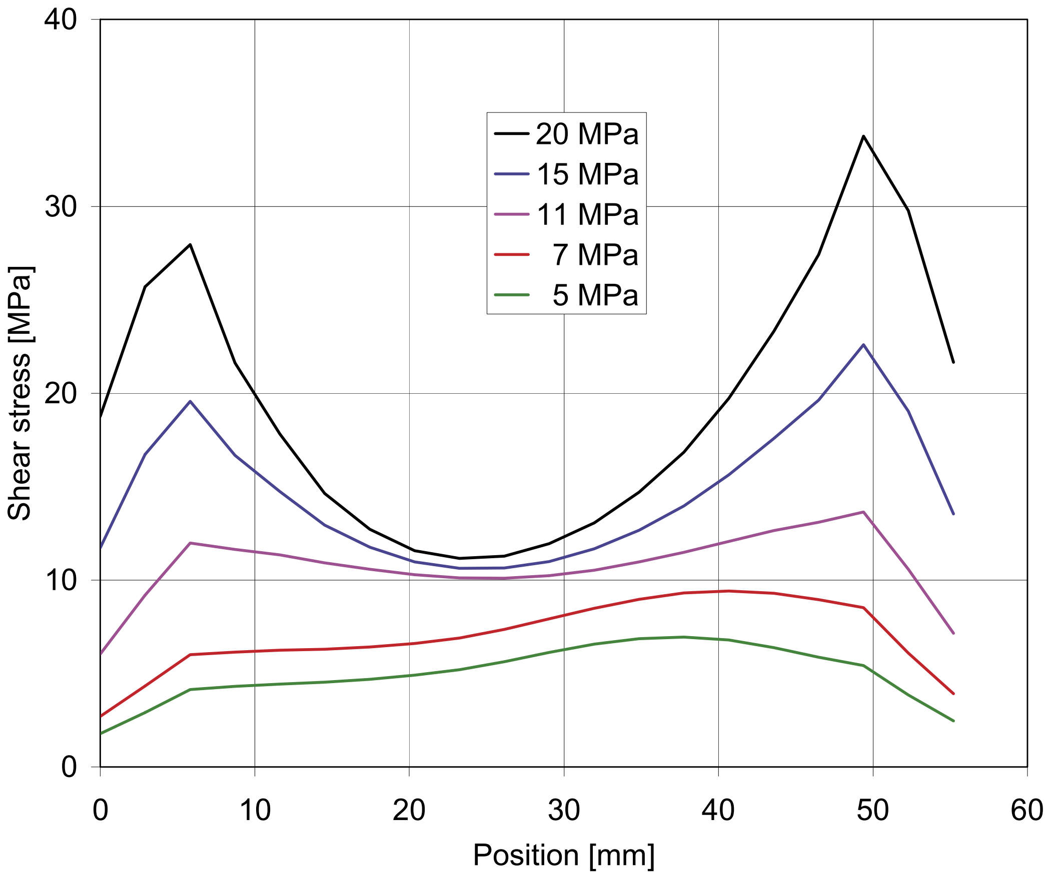


Figure B-11. *Shear stress distribution along the center line of the sealed crack specimen at different levels of mean shear stress* σ_S*.*