

## **Forsmark site investigation**

### **Borehole KFM05A**

# **Normal stress test with direct and indirect deformation measurement together with shear tests on joints**

Lars Jacobsson, Mathias Flansbjer  
SP Swedish National Testing and Research Institute

May 2005

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*Keywords:* Rock mechanics, Joint test, Normal stiffness, Shear stiffness, Shear strength, Deformation, Direct measurement, AP PF 400-05-13.

This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

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## Abstract

Normal loading tests and shear tests on joints on 4 rock specimens from borehole KFM05A in Forsmark have been carried out. The main aim of the experimental study was to compare two test methods for determination of the normal deformation in the joint – one based on indirect deformation measurement and one based on direct deformation measurement over the joint. The specimens of medium-grained granite were taken from cores at two depth levels ranging between 329–336 m and 576 m.

For both normal loading test methods, two load cycles with a normal loading to 20 MPa were conducted on each specimen in order to investigate the joint stiffness in the normal direction. Moreover, three shear cycles were performed in the shear tests on each specimen, at 0.5 MPa, 5 MPa and 20 MPa constant normal stress level. 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 peak shear stress and the residual stress for all specimens were 0.99 MPa and 0.49 MPa respectively for the 0.5 MPa normal stress level, 4.75 MPa and 3.52 MPa respectively for the 5 MPa normal stress level, and 14.19 MPa and 13.22 MPa respectively for the 20 MPa stress level.

# Sammanfattning

Normalbelastnings- och skjuvförsök har genomförts på 4 stycken naturliga sprickor i bergprov från borrhål KFM05A i Forsmark. Proven har tagits från borrhämnor vid två djupnivåer, 329–336 m och 576 m av bergarten medelkornig granit.

För respektive försöksmetod för bestämning av normalstyvhet belastades sprickorna med två lastcykler i normalriktningen med en belastning upp till 20 MPa. Vidare genomfördes tre skjuvcykler på sprickorna under skjuvförsöken där en konstant normalspänning på respektive 0,5 MPa, 5 MPa och 20 MPa användes. Toppvärdet och residualvärdet på skjuvspänningen vid de olika normalspänningsnivåerna bestämdes ur dessa försök. Provobjekten fotograferades före och efter de mekaniska proven.

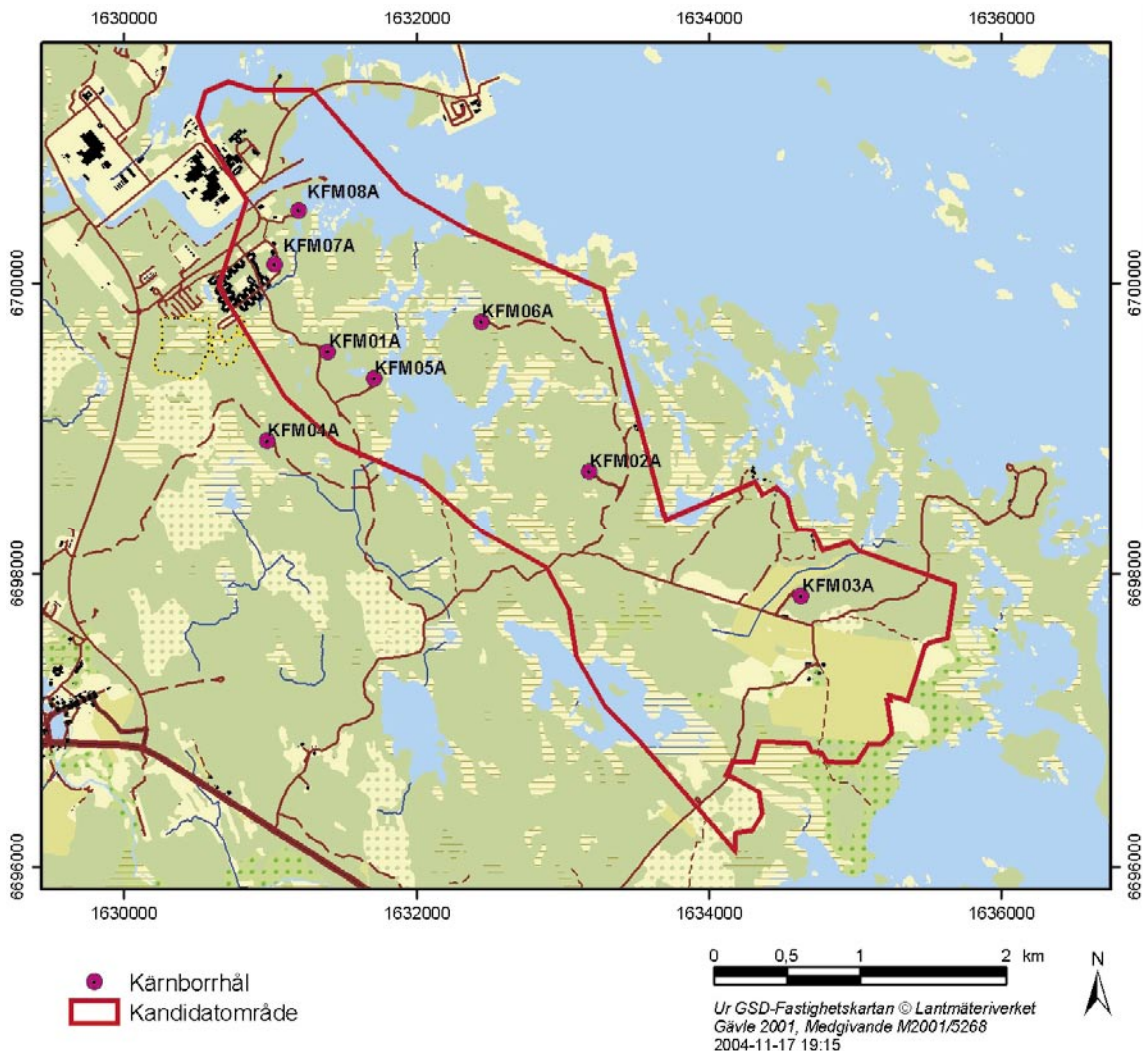
Medelvärdena för toppvärdet och residualvärdet hos skjuvspänningen för samtliga prov i de olika skjuvförsöken låg på respektive 0,99 MPa och 0,49 MPa med 0,5 MPa normalspänning, 4,75 MPa och 3,52 MPa med 5 MPa normalspänning och 14,19 MPa och 13,22 MPa med 20 MPa normalspänning.

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# 1 Introduction

Normal loading and shear tests on joints have been conducted on specimens sampled from borehole KFM05A in Forsmark, see map in Figure 1-1. In this investigation, two different test methods for determination of the normal deformation of the joint were compared. These tests belong to one of the activities performed as part of the site investigation in the Forsmark area managed by the Swedish Nuclear Fuel and Waste Management Co (SKB). The tests were carried out in the material and rock mechanics laboratories at the department of Building Technology and Mechanics at the Swedish National Testing and Research Institute (SP). All work is performed in accordance with the activity plan AP PF 400-05-13 (SKB internal controlling document) in conjunction with the ordinary test program defined by the activity plan AP PF 400-04-80 (SKB internal controlling document). Moreover, the work is controlled by SP-QD 13.1 (SP internal quality document).



*Figure 1-1. Location of the borehole KFM05A at the Forsmark site.*

SKB supplied SP with rock cores, which arrived at SP in September 2004 and were tested during January 2005. Specimens were cut from cores containing natural fractures and selected based on the preliminary core logging with the strategy to primarily investigate the mechanical properties of joints of the dominant rock types.

For both the normal loading test methods, two load cycles with a normal loading to 20 MPa were conducted on each specimen in order to investigate the joint stiffness in the normal direction. This was followed by three successive shear tests in which the normal stress was kept constant. The normal stress levels were 0.5 MPa, 5 MPa and 20 MPa. The shear deformation was controlled and given a constant deformation rate, and the shear stress and the normal deformation of the joint were recorded during the tests. The peak and residual shear stress at each shear cycle were determined from the shear tests. The specimens were photographed before and after the mechanical testing.

The method description SKB MD 190.005e, version 2.0, (SKB internal controlling document) was followed for the sampling and for the normal loading and shear tests. The method description is partly based on the ISRM suggested method /1/.

## 2 Objective and scope

The purpose of the tests in this report is to determine the mechanical properties of natural fractures in rock specimens. The behavior of the joints is investigated during normal loading and shear loading tests. The aim of the normal loading tests is to determine the relation between the normal stress and the normal deformation of the joints. The main aim of this investigation was to compare two test methods for determination of the normal deformation of the joint – one based on indirect deformation measurement and one based on direct deformation measurement over the joint. 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 shear tests. The results from the tests are going to be used in site descriptive model of rock mechanics, which will be established for the candidate area selected for site investigations at Forsmark

The specimens are collected from borehole KFM05A, which is a telescopic borehole inclined  $60^\circ$  from the horizontal plane and with a drilling length of c 1,000 m.



## **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.

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, with a specially designed fixture, the two halves of the holder were clamped 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 normal test with direct measurement, the specimens were cast in fast setting cement. The thickness of the cement layer was chosen to be as thin as possible to obtain a stiff support, at the same time as the stress was allowed to be evenly distributed to avoid cracking of the rock specimen.

For the normal test with indirect measurement and the subsequent shear test, a two-component epoxy glue mixed with quartz sand was used to cast the specimens. The sand increases the stiffness of the epoxy mix. The specimens were cured in a heat chamber in order to speed up the hardening process.

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 normal loading and 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 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 used for guidance of the lower box in order to have a controlled linear movement. The maximum stroke is 100 mm in the vertical direction and  $\pm 50$  mm in the shear direction.

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%.



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

In the normal loading test with direct deformation measurement, the normal displacement over the joint is measured by the use of two crack opening displacement gauges (COD) that are attached at two opposite sides of the rock specimen. Each of the CODs has a measurement range of 4 mm and a relative error less than 1%. The average value of these two CODs is used to represent the normal deformation over the rock joint presented in the results section.

The maximum vertical (normal) load that can be applied is 300 kN and the maximum load in the horizontal (shear) direction is  $\pm 300$  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.

## 4 Execution

The normal loading and shear tests were carried out according to the method description SKB 190.005e, version 2.0, (SKB internal controlling document). The test method follows ISRM suggested methods for determining shear strength /1/.

### 4.1 Description of the samples

The rock type characterisation was made according to Strähle /2/ 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.

**Table 4-1. Specimen identification, sampling depth and rock type for all specimens.**

Identification	Secup (m)	Seclow (m)	Rock type
KFM05A-117-2	329.30	329.43	Medium-grained granite
KFM05A-117-5	335.96	336.09	Medium-grained granite
KFM05A-117-7	575.83	575.99	Medium-grained granite
KFM05A-117-8	576.34	576.50	Medium-grained granite

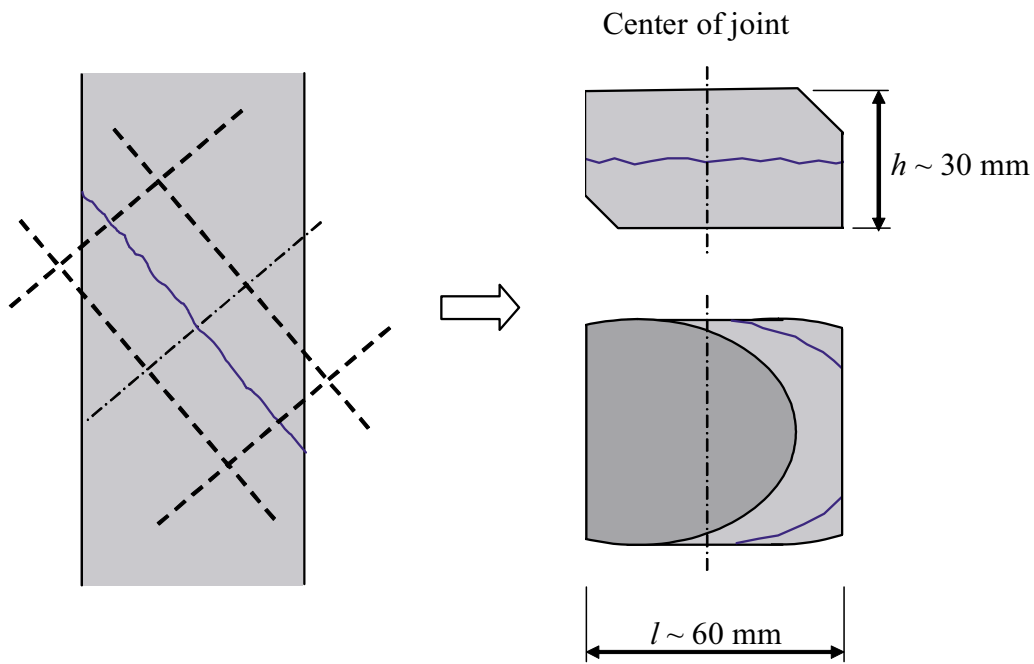
### 4.2 Specimen preparation

The specimens are cut out from rock cores. The pieces are shaped and trimmed to obtain a total thickness  $h$  of approximately 30 mm and a maximum length  $l$  of 60 mm, cf Figure 4-1. The specimens will therefore have similar shape and joint area size.

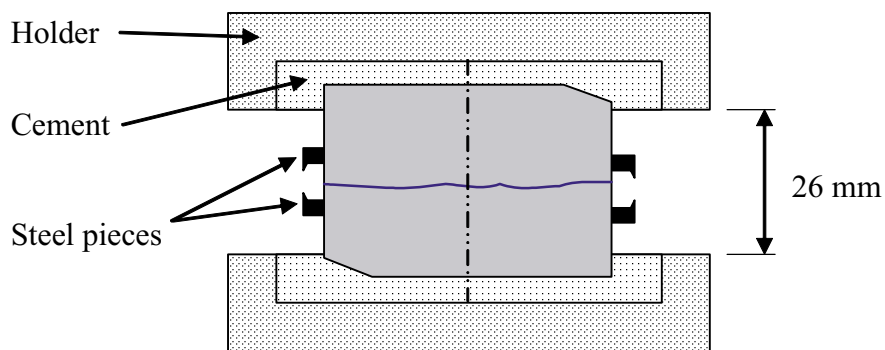
#### 4.2.1 Normal loading test with direct deformation measurement

The specimens are grouted in steel holders, which consist of one upper and one lower half, using fast setting cement, see Figure 4-2. A direct measurement of the joint displacement is obtained by use of crack opening displacement gauges (COD) attached between two small metal pieces glued to the opposite sides of the rock joint.

First, the two pairs of small metal pieces, to be used as holders for the COD gauges, are glued onto two opposite sides of the rock specimen. One half of the specimen is cast by pouring the cement into the holder with the specimen held in correct position. The cement is hard enough after one hour to fixate the specimen. The second half of the specimen is positioned relative to the first one such that the two specimen pieces best fit together, implying that the joint is optimally closed. The second half of the holder is then mounted on top of the first one with a 26 mm gap between the two halves and turned upside down. The second half is cast by pouring cement into the holder. The cement is fully hardened after one day in room temperature.



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



**Figure 4-2.** Specimen cast with cement in the specimen holder.

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

**Table 4-2. Activities during the specimen preparation.**

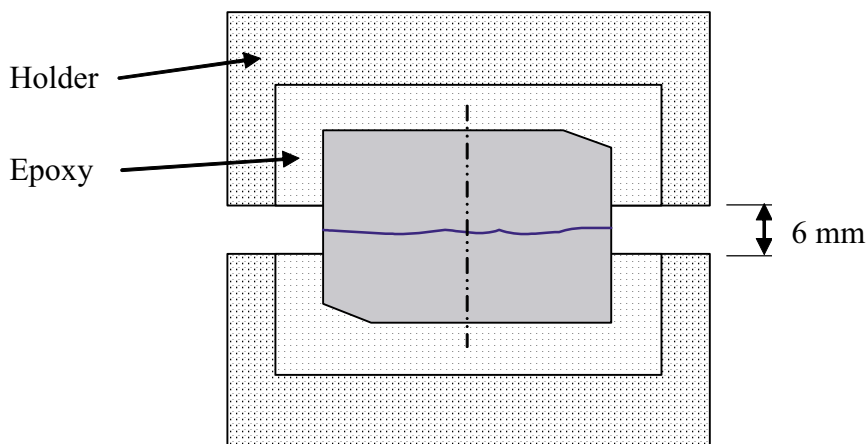
Step	Activity
1	Mark the drill cores at the position of the joints selected for testing.
2	Cut out the specimens from the cores and trim them to the specified dimensions.
3	Measure the specimen dimensions and calculate the joint surface area.
4	Take digital photos on each specimen.
5	Glue the metal pieces onto the specimen.
6	Cast the specimens into the specimen holders.

## 4.2.2 Normal loading test with indirect deformation measurement and shear test

The specimens are cast in steel holders using an epoxy that is reinforced with fine quartz sand in order to increase the stiffness, see Figure 4-3. The specimen halves are positioned relative to each other such that the two specimen pieces best fit together, implying that the fracture or joint is optimally closed. This will be termed the zero or the initial position for the shear displacement in conjunction with the shear tests.

One half is cast first by pouring the epoxy into the holder with the specimen held in correct position. The epoxy is hard enough after one day 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 epoxy into the holder. After one half to one day, the holders with the cast specimen are put in a heat chamber with 40°C. The epoxy is fully hardened after three days in the heat chamber and the holders with the specimens are taken out to cool down to room temperature.

An overview of the activities during the specimen preparation is shown in the step-by-step description in Table 4-3.



*Figure 4-3. Specimen cast with epoxy in the specimen holder.*

**Table 4-3. 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 on each specimen.
5	Cast the specimens into the specimen holders.

## 4.3 Mechanical testing

### 4.3.1 Normal loading test with direct deformation measurement

Two load cycles, with a normal loading between 0.5 MPa and 20 MPa, were conducted in the normal loading tests on each specimen. The test was performed with a loading/unloading rate of 10 MPa/min. In these tests, the normal deformation over the joint measured by the COD gauges was recorded. After the test was completed, the specimen was removed from the grout and the metal pieces were removed from the specimen.

A form was filled in for each specimen containing specimen dimensions and date of casting. Further, the form also contains comments and observations during the different test steps. Moreover, a check list was filled in during the work in order to confirm that the different specified steps had been carried out.

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

**Table 4-4. Activities during the normal loading test with direct deformation measurement.**

Step	Activity
1	Mount the specimen holders in the shear testing machine.
2	Attach the two COD gauges.
3	Perform the normal loading tests with two load cycles. Zero the channels for the normal deformation measurement before the test at 0.5 MPa normal stress. The specified loading/unloading rate is 10 MPa/min.
4	Take out the specimens from the shear boxes.
5	Remove the metal pieces and holders from the specimen.
6	Store the test results on the computer network.

### 4.3.2 Normal loading test with indirect deformation measurement and shear test

Two load cycles, with a normal loading between 0.5 MPa and 20 MPa, were conducted in the normal loading tests on each specimen. The normal deformation of the joint was recorded in these tests. Three successive shear tests were carried out directly after the normal loading tests, starting from the same initial position in the shear direction as when the normal loading tests were made (zero shear displacement). The shear tests were performed 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, respectively. 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 of the joint were recorded in the shear tests.

The program controlling the tests is divided in four parts: one part for the two normal loading cycles and one program each for the three shear tests resulting in four separate data files for each specimen.

A form was filled in for each specimen containing specimen dimensions and date of casting. Further, the form also contains comments and observations during the different test steps. Moreover, a check list was filled in during the work in order to confirm that the different specified steps had been carried out.

An overview of the activities during the mechanical testing is shown in the step-by-step description in Table 4-5.

**Table 4-5. Activities during the normal loading test with indirect deformation measurement and shear test.**

Step	Activity
1	Mount the specimen holders in the shear testing machine.
2	Perform the normal loading tests with two load cycles. Zero the channels for the normal deformation measurement before the test at 0.5 MPa normal stress. The specified loading/unloading rate is 10 MPa/min.
3	Perform the shear tests at the three constant normal stress levels, 0.5 MPa, 5 MPa and 20 MPa: <ul style="list-style-type: none"> <li>• Apply a normal stress of 0.5 MPa and zero the deformation channels.</li> <li>• Increase the normal stress to the prescribed value for the actual test.</li> <li>• 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.</li> <li>• Unload the shear stress to zero.</li> <li>• Unload the normal stress to 0.2 MPa and restore the shear deformation to zero (initial position). Repeat this for the three shear cycles.</li> </ul>
4	Take out the specimens from the shear boxes.
5	Take digital photos on each specimen.
6	Store the test results on the computer network.

## 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 /3/. Moreover, MATLAB was used to produce the diagrams shown in section 5.1 and in Appendix A. 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.

## 4.5 Analyses and interpretation

### 4.5.1 Normal loading test with direct deformation measurement

The results of the normal loading tests with direct deformation measurement are represented by normal stress-normal deformation relations. The normal stress  $\sigma_N$  is defined as

$$\sigma_N = \frac{F_N}{A}$$

where  $F_N$  is the normal force acting on the joint and  $A$  is the area of the joint. The joint deformation in the normal direction,  $\delta_{N, \text{joint}}$  is defined as

$$\delta_{N, \text{joint}} = \frac{\delta_{\text{COD1}} + \delta_{\text{COD2}}}{2}$$

where  $\delta_{\text{COD1}}$  and  $\delta_{\text{COD2}}$  are the measured displacements recorded by the two COD gauges during the tests.

#### 4.5.2 Normal loading test with indirect deformation measurement and shear test

As to the definition of the different result parameters for the normal loading test with indirect deformation measurement and shear test we begin with the normal  $\sigma_N$  and shear stresses  $\sigma_S$ , which are defined as

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

where  $F_N$  is the normal force,  $F_S$  is the shear force acting on the joint, and  $A$  is the area of the joint. The peak value  $\sigma_{\text{SP}}$  and the residual value  $\sigma_{\text{SR}}$  of the shear stress  $\sigma_S$  on each of the three shear cycles 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. The actual shear force is fluctuating up and down caused by a stick-slip response obtained during the shear process due to the uneven surfaces of the joints. The shear stress used when the residual value is evaluated, is defined as the envelope achieved that is by interconnecting the sub-peaks observed during the 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 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 normal and shear displacements are denoted as  $\delta_N$  and  $\delta_S$ , respectively.

A part of the measured normal deformation in the normal loading tests and a part of the measured shear deformations 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. The deformation measured during the normal loading test not belonging to the deformation in the joints is denoted the system deformation  $\delta_{N, \text{system}}$ . By knowing the system deformation, the joint deformation can be obtained as

$$\delta_{N, \text{joint}} = \delta_{N, \text{total}} - \delta_{N, \text{system}} \quad (1)$$

where  $\delta_{N, \text{total}}$  is the normal displacement registered during the normal loading tests containing the joint displacement  $\delta_{N, \text{joint}}$ . The system deformation in the normal loading test has significance on the obtained results and will be thoroughly discussed below. The system deformations during the shear tests are of less significance for the results and no correction is made.



One normal loading test consisting of two load cycles with a normal stress varying between 0.5 and 20 MPa, with a steel specimen instead of a rock specimen, was carried out as a reference test in order to determine the magnitude of the system deformation (epoxy and contact areas). The steel specimen had a quadratic cross section of 50×50 mm and 30 mm height. This yields a total epoxy layer of 20 mm thickness between steel specimen and the top and bottom surfaces of the holders. The dimensions of the steel specimen were chosen such that the cross sectional area is similar to the area of the joints in the rock specimens. Furthermore, the height of the steel specimen was chosen in the same order as the height of the rock specimens. This was done to obtain a similar thickness of the epoxy layers in the normal loading direction in both cases, in order to get values of the system deformation with the same magnitude. The system deformations in the reference test can be estimated as

$$\delta_{N, \text{system}} = \delta_{N, \text{total}} - \delta_{N, \text{steel}} \quad (2)$$

where

$$\delta_{N, \text{steel}} = \frac{\sigma_N}{E} \cdot t_{\text{steel}}$$

using  $E = 210 \text{ GPa}$  and  $t_{\text{steel}} = 30 \text{ mm}$ . The result from the reference test in which the system deformation is computed according to (2) is shown in Figure 4-4.

It is seen that the response during loading and unloading displays a non-linear behaviour. Moreover, a large part of the permanent deformation is developed during the first load cycle. This can be seen both in the reference test and in the tests on joints. The epoxy layers deform and cause residual deformations after unloading. The different contact areas deform as well. The first load cycle can thus be considered as a conditioning load cycle. The residual deformation is only slightly increasing during the second load cycle. The results from the second load cycle are the most suitable for finding an appropriate correction of the results. The results will be corrected according to (1). Further, the results from the second load cycle are probably most suitable for evaluating the behaviour of the joints as well. We will use the data from the second load cycle in the reference test to account for the system deformations in the joint tests.

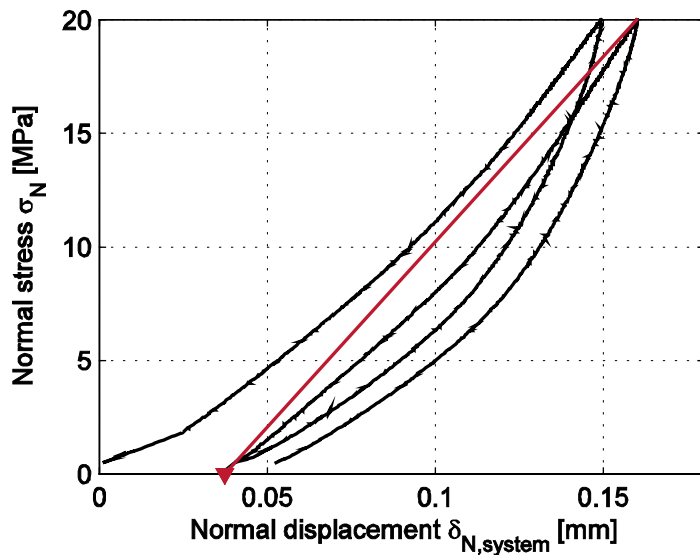
The test results will be arranged such that a supposed starting point of the second load cycle corresponds zero normal displacement at complete unloading, i.e.  $\sigma_N = 0$ . In order to do so we first make an assumption that the point at complete unloading before the loading at the second load cycle is obtained as the linear extension of a secant line drawn between the starting and end points of the loading curve for the second cycle. The normal deformation in the point when  $\sigma_N = 0$  is denoted  $\delta_{N,0}$ . This is shown in Figure 4-4.

Hence, the data can be shifted by subtracting the value  $\delta_{N,0}$  from normal displacement results. The maximum normal displacement during the second load cycle, when both the loading and the deformation start from zero, is denoted  $\delta_{N, \text{max}}$ .

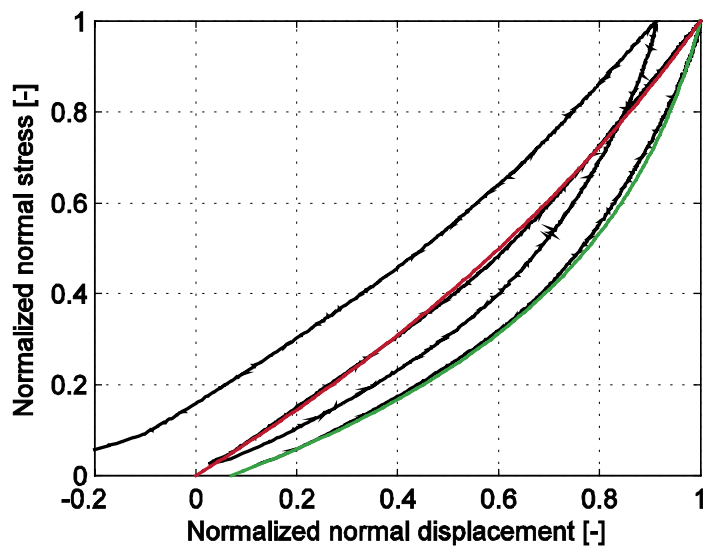
Normalized normal stress and normal deformation are introduced as

$$\bar{\delta}_N = \frac{\delta_N}{\delta_{N, \text{max}}} \quad \text{and} \quad \bar{\sigma}_N = \frac{\sigma_N}{\sigma_{N, \text{max}}} \quad (3)$$

where  $\sigma_{N, \text{max}} = 20 \text{ MPa}$  is given in the normal loading tests and  $\delta_{N, \text{max}}$  was defined above. The results from the reference tests using the normalized normal stress and normal deformation are shown in Figure 4-5.



*Figure 4-4. Results from a normal loading test with a steel specimen cast in epoxy. The black curve is showing the results from the tests where the steel deformation has been subtracted from the results. The red line is representing the secant of the loading curve during the second load cycle intersecting the points at full unloading and full loading. The extension of the line is intersecting the zero stress level at the displacement  $\delta_{N,0}$ . This point is regarded as a theoretical starting point of the second load cycle and is marked with a filled triangle in the figure.*



*Figure 4-5. Results from normal loading test on a steel specimen with normalized result parameters. The black curve is showing the results from the tests where the steel deformation has been subtracted from the results. The red and the green curves illustrate the fitted approximating functions for the loading and unloading responses during the second load cycle.*

The results from the reference test with the two load cycles are divided into four segments: loading 1, unloading 1, loading 2 and unloading 2. The normalized values of the loading and the unloading response at the second load cycle can be approximated with an exponential expression according to

$$\bar{\delta}_N = A[1 - \exp(-B \cdot \bar{\sigma}_N)] \quad (4)$$

where  $A$  and  $B$  are constants determined from the experiments. It is found that  $A = 1.63$  and  $B = 0.95$  are suitable for the loading curve and  $A = 1.08$  and  $B = 2.00$  are suitable for the unloading part of the second load cycle. The approximating curves together with the experimental results are shown in Figure 4-5.

The thickness of the rock specimens with joints is different from specimen to specimen. This means that the thickness of the epoxy layer is shifting as well. It is fair to expect that the system stiffness is dependent on the thickness of the epoxy layer. In order to account for that, we assume a linear dependence of the maximum deformation according to

$$\delta_{N, \max} = \frac{t_{\text{epoxy}}}{t_{\text{epoxy ref}}} \cdot \delta_{N, \max \text{ ref}} \quad (5)$$

where  $t_{\text{epoxy ref}}$  and  $\delta_{N, \max \text{ ref}}$  are the values obtained from the reference test. Finally, the system deformation in (1) is obtained by rewriting (4) as

$$\delta_{N, \text{system}} = A[1 - \exp(-B \cdot \bar{\sigma}_N)] \cdot \delta_{N, \max} \quad (6)$$

The results presented in section 5 are processed segment-by-segment according to the methodology outlined above using (1), (3), (5) and (6), in order to get the true joint deformations.

## 4.6 Nonconformities

The testing was conducted according to the method description and the activity plan with no departures.

## 5 Results

The 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 stored on a CD and handed over to SKB. The handling of the results follows SDP-508 (SKB internal controlling document) in general.

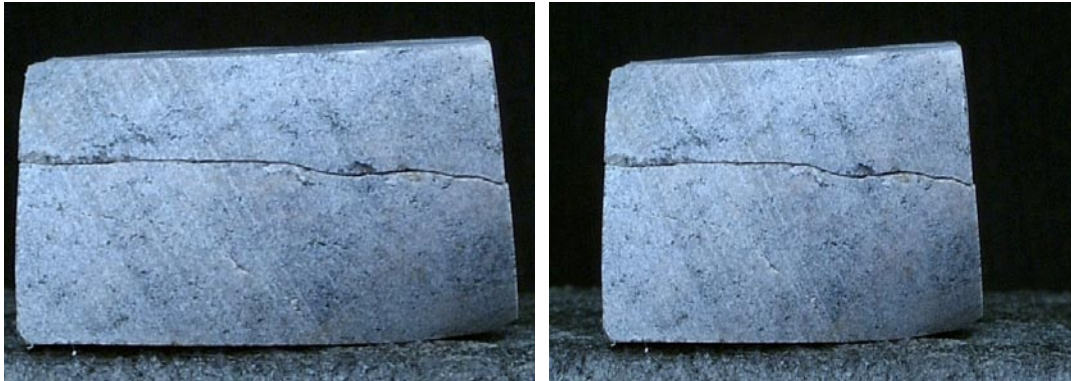
### 5.1 Description and presentation of the specimen

The specimens and joints before casting and after testing are shown on pictures. Comments on observations made during the testing are reported. The results from the normal loading tests with direct deformation measurement are marked "Direct measurement". On the following page the results from the normal loading tests with indirect measurement are shown in the upper diagram, together with the results from the shear tests shown in the middle and the lower diagrams. The results from the shear tests for the three normal stress levels are displayed in black (0.5 MPa), green (5 MPa) and blue (20 MPa). Furthermore, the red triangle markers show the peak shear stresses and the red square markers the residual stresses.

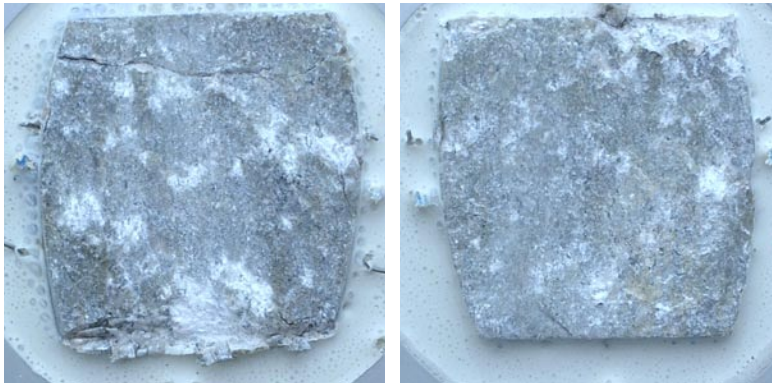
It should be remarked that the normal deformations pertinent to the normal loading tests with indirect measurement displayed in the upper diagrams have been adjusted by subtracting the system deformations, cf section 4.5. The original results, i.e. the actually measured data, from these normal loading tests, are shown in Appendix A.

**Specimen ID:** KFM05A-117-2

Before mechanical test



After mechanical test



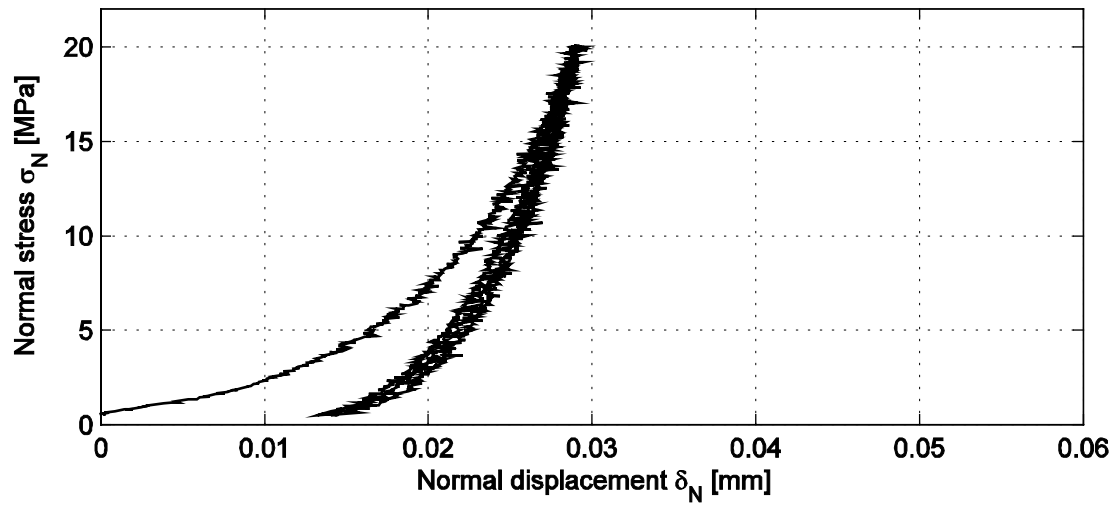
**Comments**

Upper half: At the rear end of the specimen, small pieces have spalled off. One crack across the joint surface was observed.

Lower half: At the rear end of the specimen, small pieces have spalled off. Click sounds were heard after approximately 1.0 mm and 1.7 mm shearing at the 5 MPa and 20 MPa normal stress level, respectively.

Specimen ID: KFM05A-117-02 (Direct measurement)

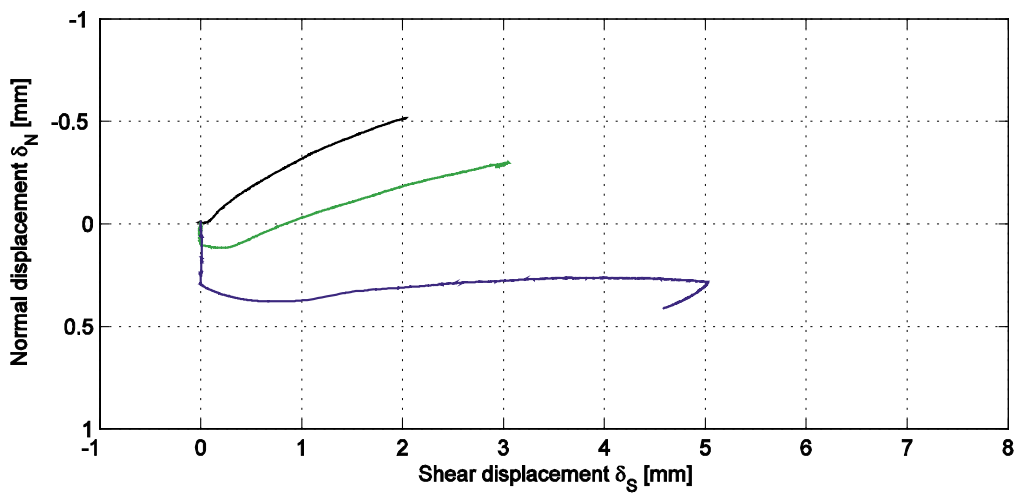
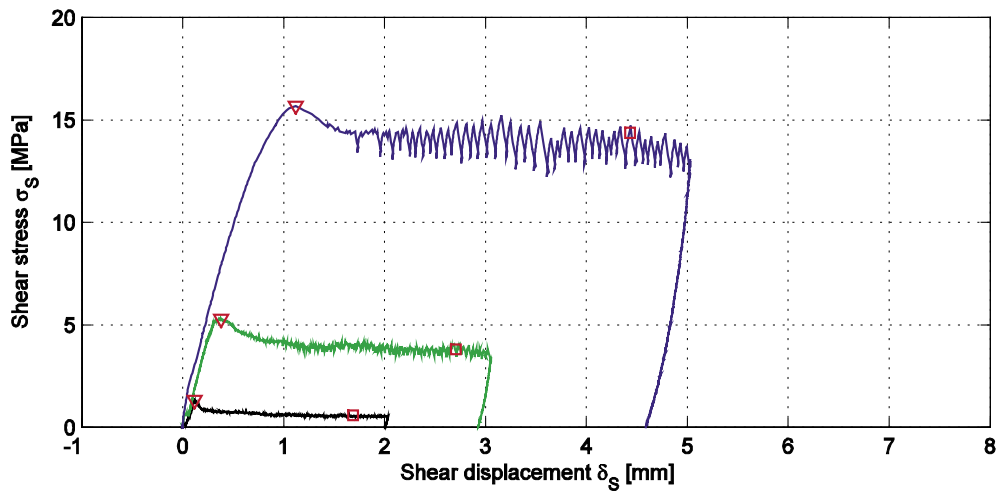
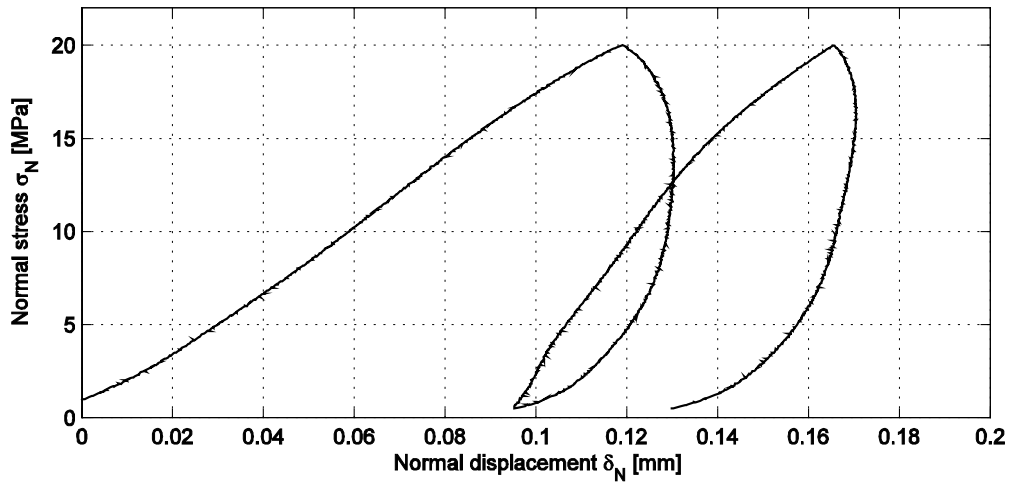
Joint area : 24.4 cm<sup>2</sup>



Specimen ID: KFM05A-117-02

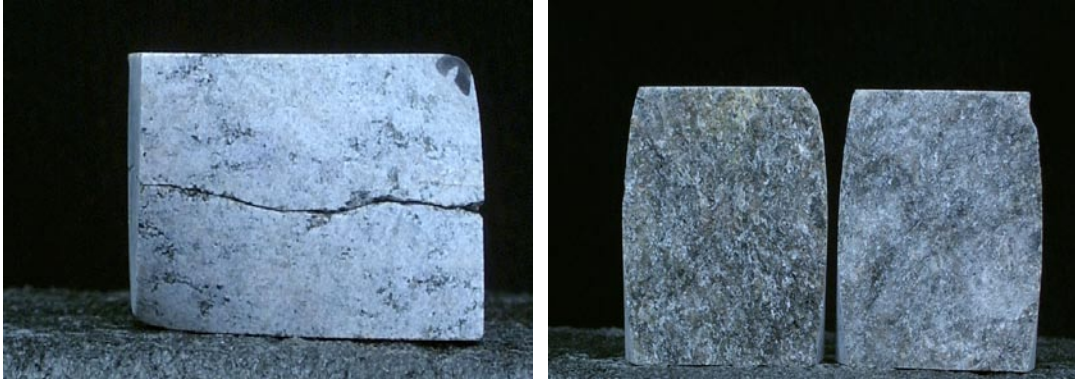
Joint area : 24.4 cm<sup>2</sup>

Specimen height : 30.5 mm

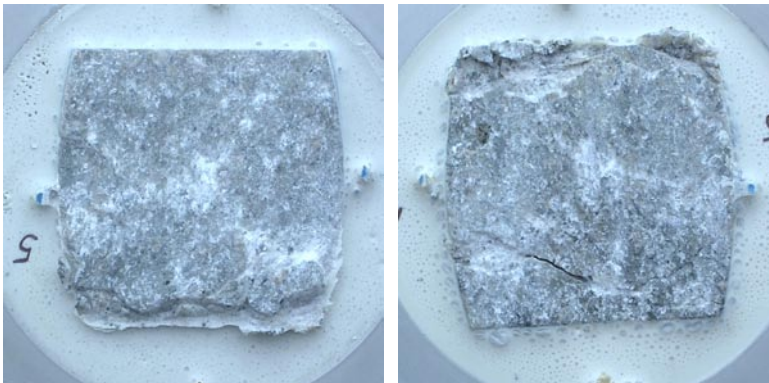


**Specimen ID:** KFM05A-117-5

Before mechanical test



After mechanical test



**Comments**

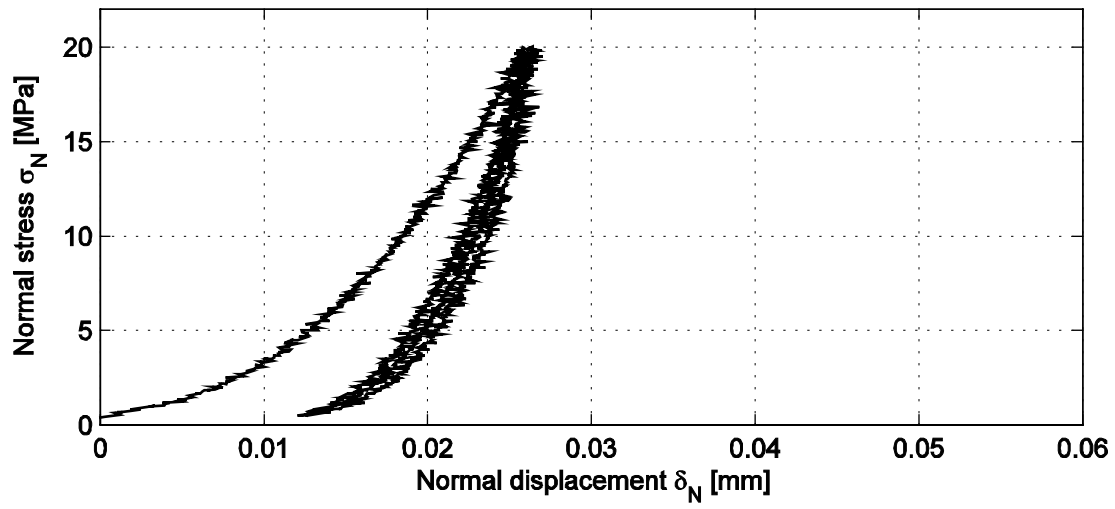
Upper half: At the rear end of the specimen, small pieces have spalled off. One crack across the joint surface was observed.

Lower half: At the rear end of the specimen, small pieces have spalled off. Click sounds were heard after approximately 0.8 mm and 1.6 mm shearing at the 5 MPa and 20 MPa normal stress level, respectively.



Specimen ID: KFM05A-117-05 (Direct measurement)

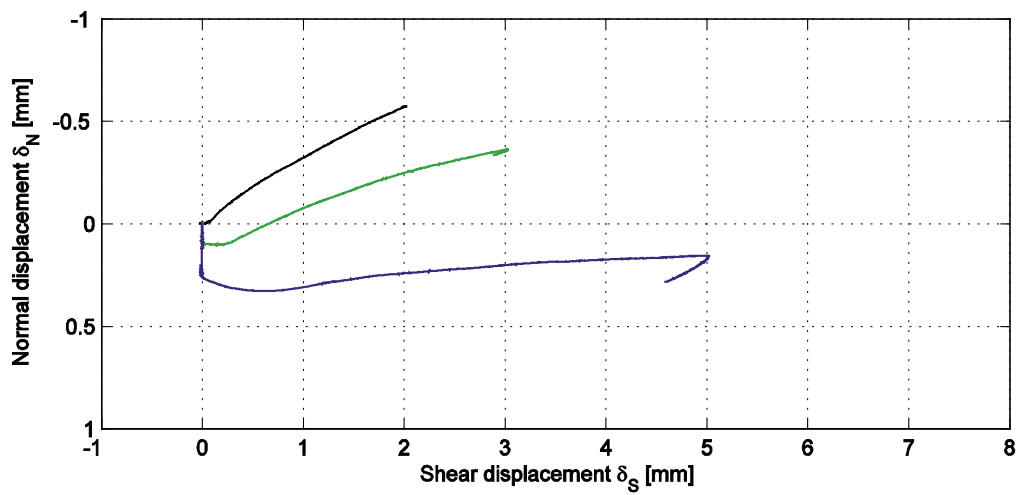
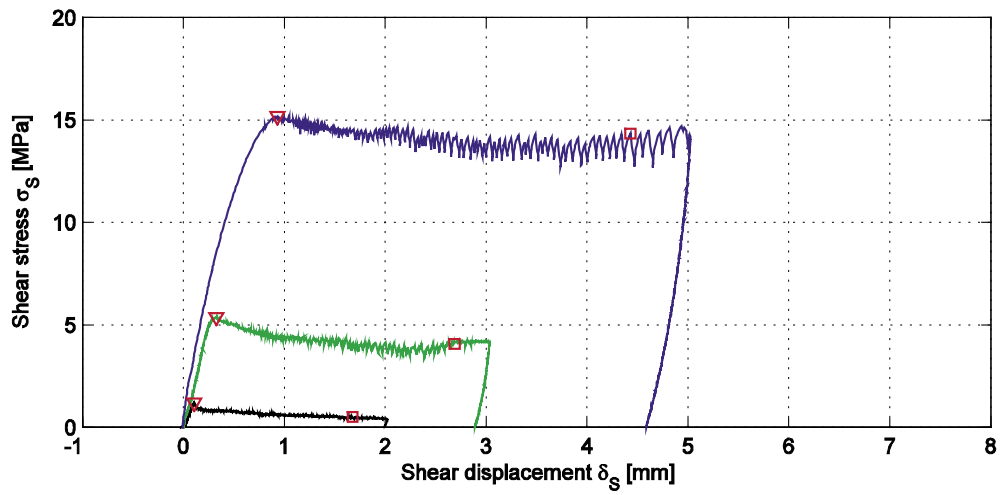
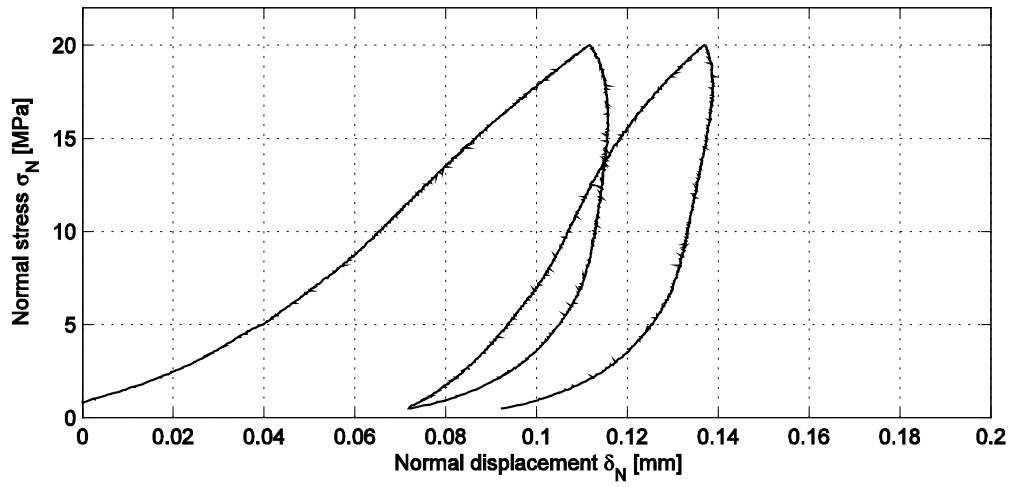
Joint area : 23.6 cm<sup>2</sup>



Specimen ID: KFM05A-117-05

Joint area : 23.6 cm<sup>2</sup>

Specimen height : 30.5 mm

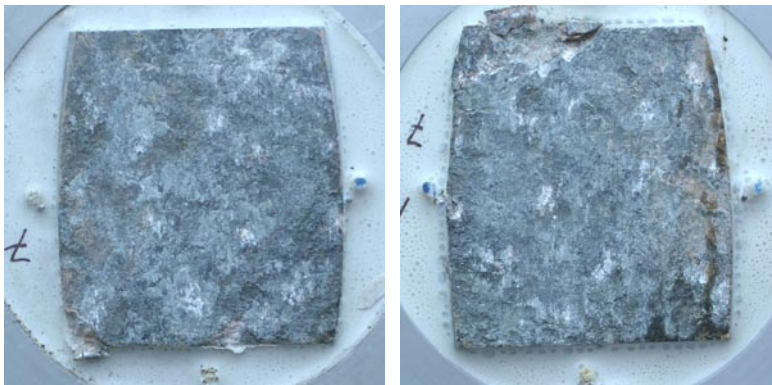


**Specimen ID:** KFM05A-117-7

Before mechanical test



After mechanical test



**Comments**

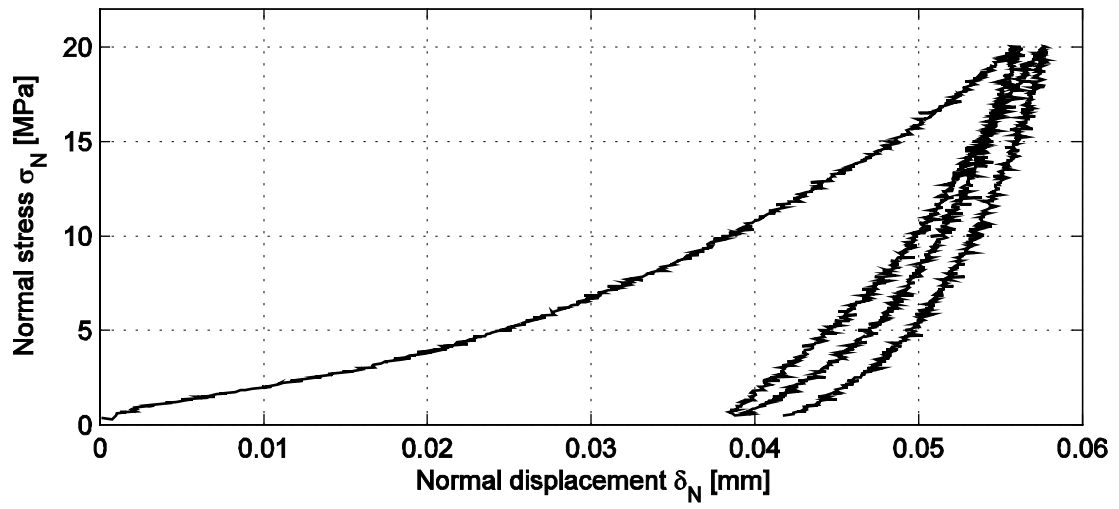
Upper half: At the rear end of the specimen, small pieces have spalled off.

Lower half: At the rear end of the specimen, small pieces have spalled off.

Distinct click sounds were heard after approximately 1.0 mm and 1.4 mm shearing at the 5 MPa and 20 MPa normal stress level, respectively.

Specimen ID: KFM05A-117-07 (Direct measurement)

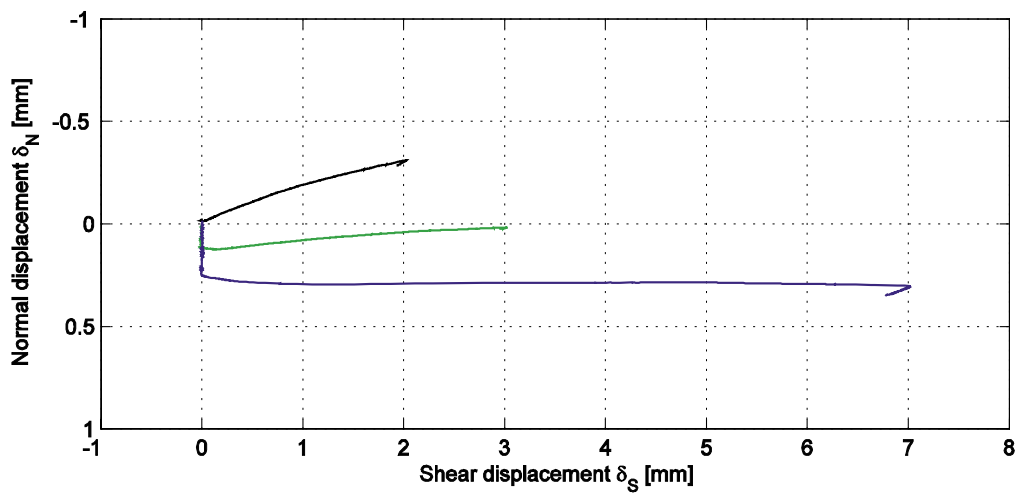
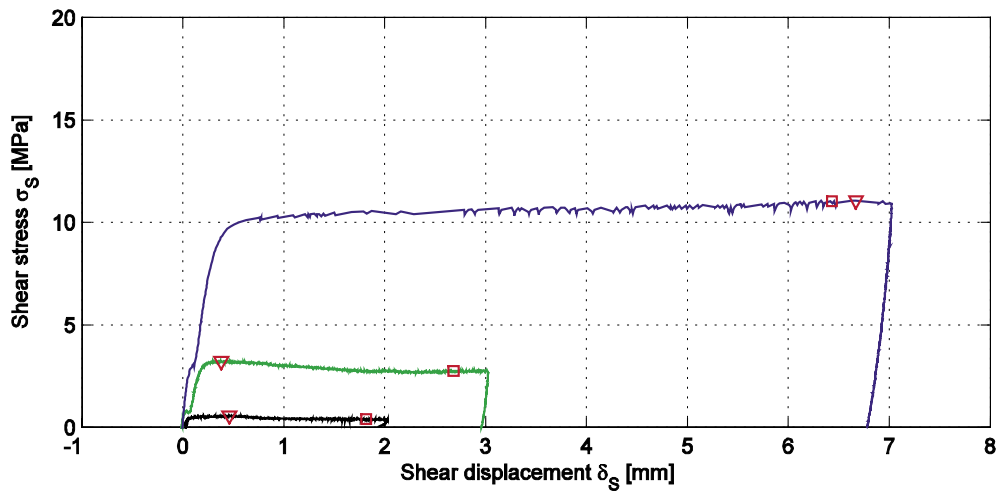
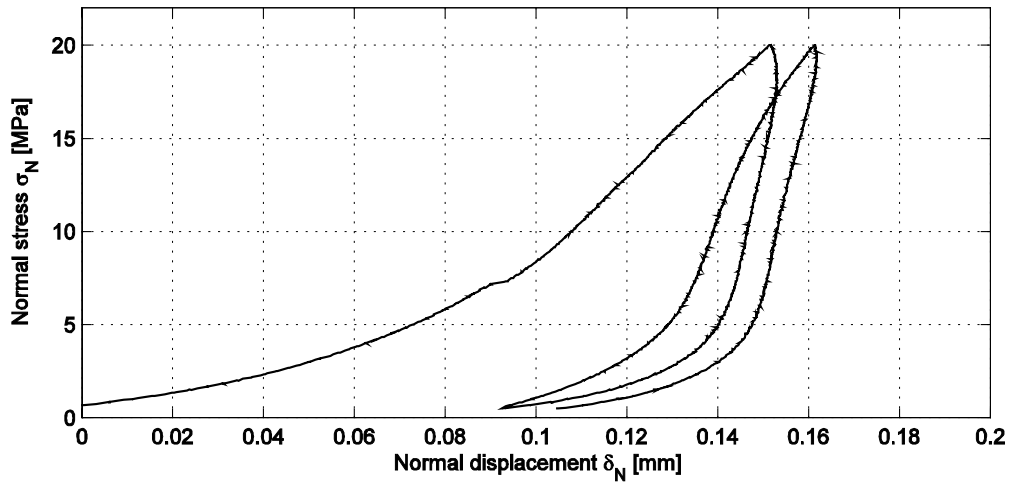
Joint area : 27.6 cm<sup>2</sup>



Specimen ID: KFM05A-117-07

Joint area : 27.6 cm<sup>2</sup>

Specimen height : 30.2 mm

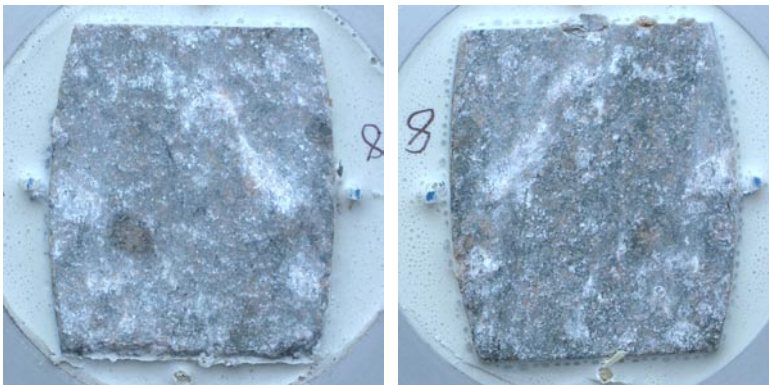


**Specimen ID:** KFM05A-117-8

Before mechanical test



After mechanical test



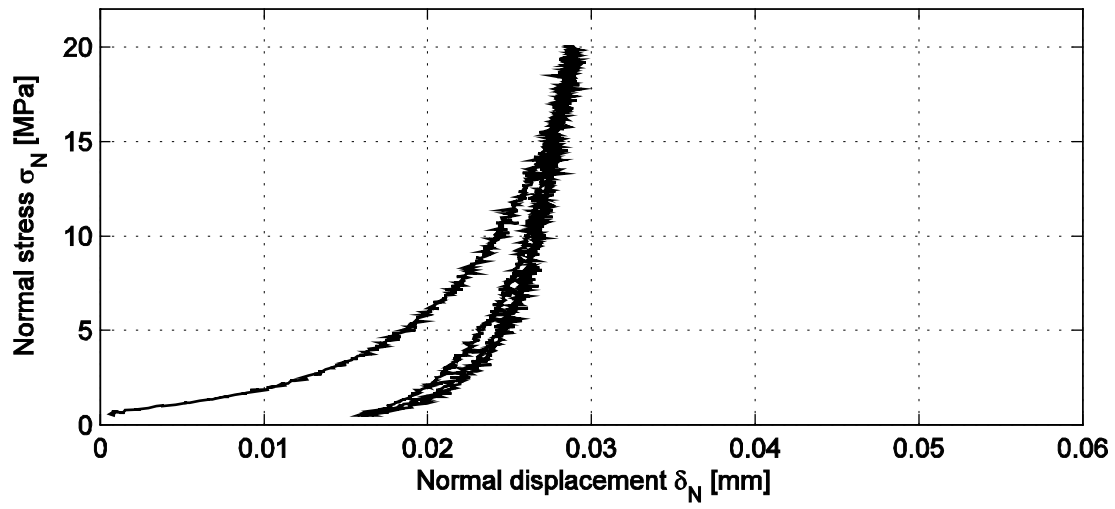
**Comments**

Upper half: At the rear end of the specimen, small pieces have spalled off.

Lower half: At the rear end of the specimen, small pieces have spalled off.

Specimen ID: KFM05A-117-08 (Direct measurement)

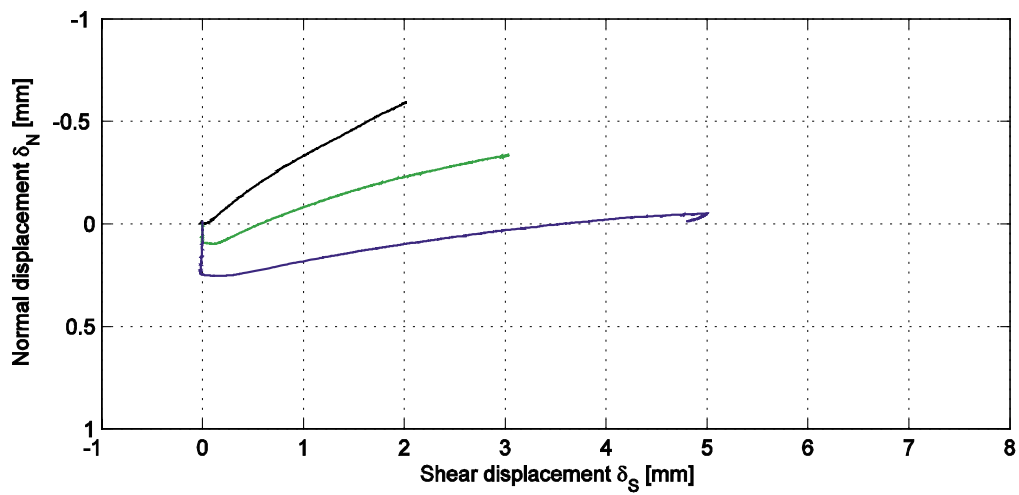
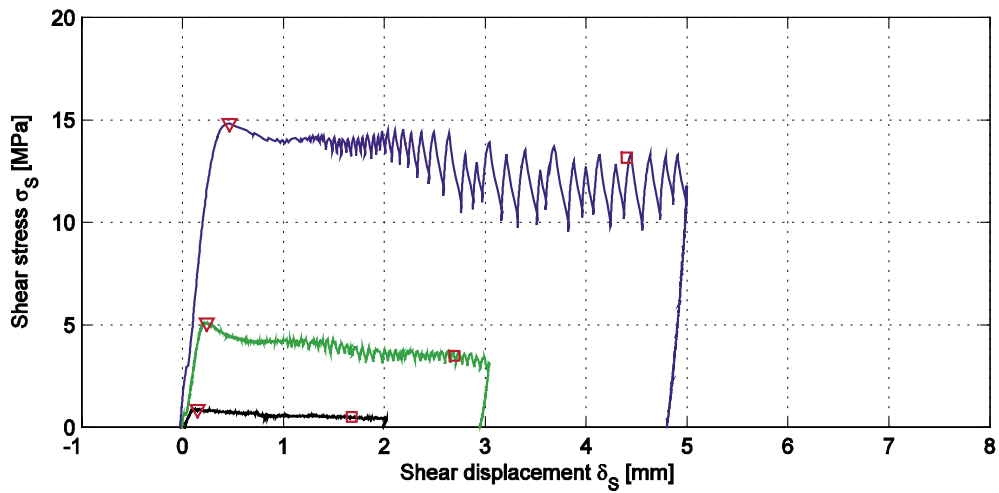
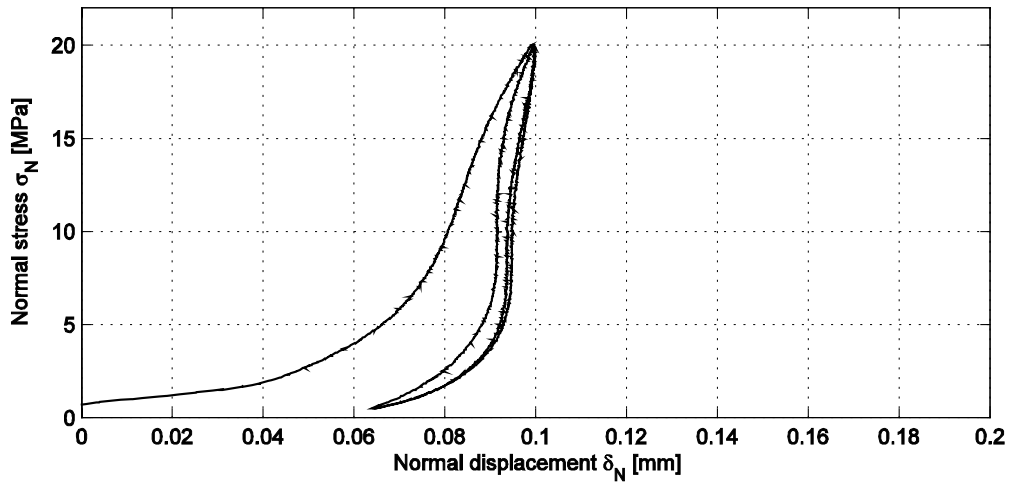
Joint area : 28.6 cm<sup>2</sup>



Specimen ID: KFM05A-117-08

Joint area : 28.6 cm<sup>2</sup>

Specimen height : 29.3 mm





## 5.2 Results of the entire test series

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

**Table 5-1. Summary of results.**

Identification	Area (cm <sup>2</sup> )	Peak 05 (MPa)	Resid 05 (MPa)	Peak 5 (MPa)	Resid 5 (MPa)	Peak 20 (MPa)	Resid 20 (MPa)	Comments
KFM05A-117-2	24.4	1.33	0.57	5.29	3.79	15.69	14.37	
KFM05A-117-5	23.6	1.19	0.51	5.38	4.07	15.17	14.33	
KFM05A-117-7	27.6	0.57	0.40	3.22	2.75	11.06	11.03	
KFM05A-117-8	28.6	0.88	0.50	5.10	3.47	14.84	13.16	

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

	Peak 05 (MPa)	Resid 05 (MPa)	Peak 5 (MPa)	Resid 5 (MPa)	Peak 20 (MPa)	Resid 20 (MPa)
Mean value (all specimens)	0.99	0.49	4.75	3.52	14.19	13.22
Mean value (329–336 m)	1.26	0.54	5.34	3.93	15.43	14.35
Mean value (576–577 m)	0.72	0.45	4.16	3.11	12.95	12.09
Std dev (all specimens)	0.34	0.07	1.03	0.57	2.11	1.56

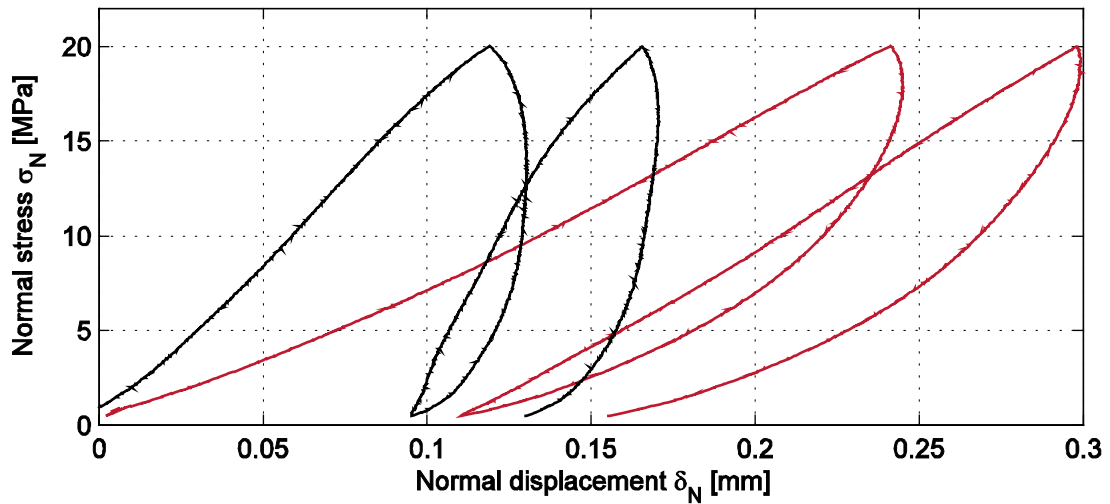
## References

- /1/ **ISRM**. Suggested methods for determining shear strength. Part 2: Suggested method for laboratory determination of direct shear strength. Final draft 1974.
- /2/ **Stråhle A, 2001**. Definition och beskrivning av parametrar för geologisk, geofysisk och bergmekanisk kartering av berg, SKB-01-19, In Swedish. Svensk Kärnbränslehantering AB.
- /3/ **MATLAB**. The Language of Technical computing, Version 6.5, MathWorks Inc, 2002.

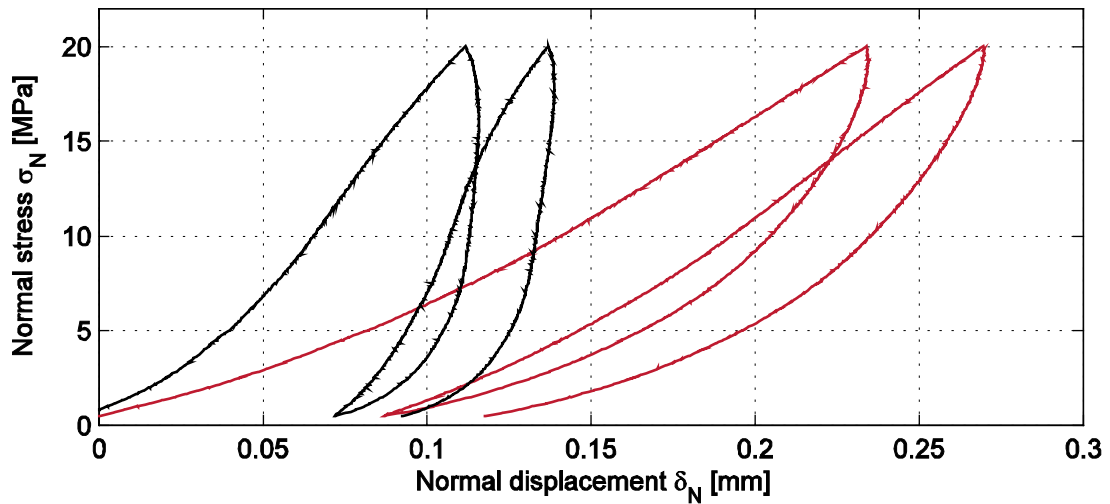
## Appendix A

Results from the normal loading tests are shown below. The original unprocessed results (red) and results where the normal deformation from the system have been subtracted from the measured total normal deformation (black) are displayed in the diagrams.

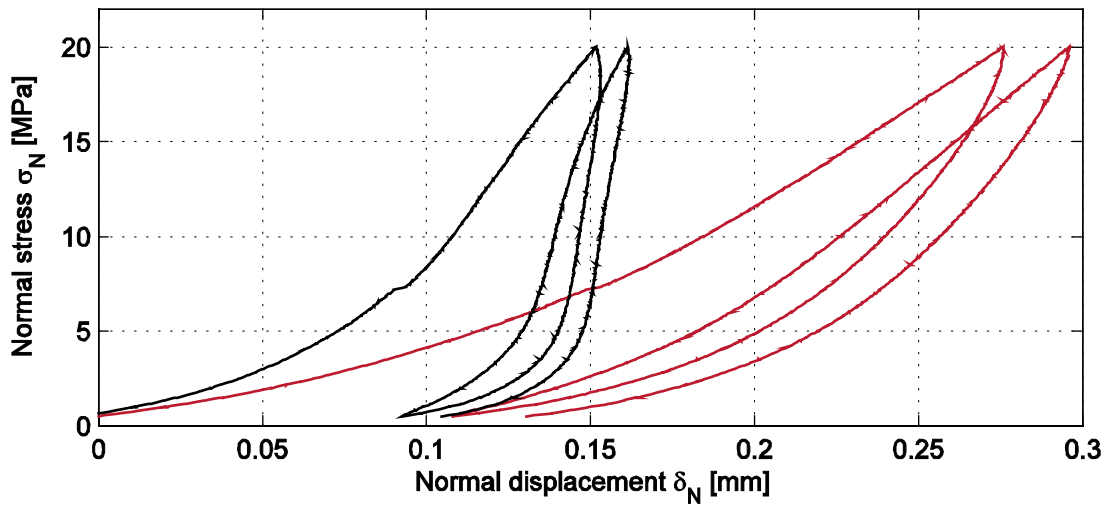
**Specimen ID: KFM05A-117-02**



**Specimen ID: KFM05A-117-05**



Specimen ID: KFM05A-117-07



Specimen ID: KFM05A-117-08

