Parametrisation of Fractures - Direct Shear Tests on Calcite and Breccia infilled Rock Joints from Äspö HRL under Constant Normal Stiffness Condition

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April 2016
Updated 19.09.2016
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April 2016
Updated 20.06.2016

Working Reports contain information on work in progress or pending completion.
ABSTRACT

Normal loading and direct shear tests have been carried out on rock core specimens from the Åspö Hard Rock Laboratory, Sweden with opened calcite infilled joints with 2-4 mm thickness and on joints with breccia infill with a thickness of 40-50 mm. All samples originate from the same gently dipping fracture. The tests were conducted in four consecutive phases with two normal loading phases (first and last phase) up to 11 MPa and two direct shear phases, in between, with a normal stress of approximately 11 MPa. One shear phase was conducted with constant normal stiffness condition and the other with constant normal stress condition. The results of the calcite filled joints show no pronounced peak shear stress and small normal displacement. The small normal displacements implied that the effect on the normal stress was small when constant normal stiffness condition applied within the used range of normal stiffness, 1, 3 and 6 MPa/mm, during the shear tests. The joints with breccia infill crumbled during the tests and the material was squeezed out from the joint resulting in a large contractancy during the second shear phase. The friction angle was 22-34 degrees for the calcite infilled joints and 23-26 degrees for the breccia infilled joints assuming no cohesion.

The joint surface geometries of three calcite infilled joints were measured using photogrammetry before and after shear testing. The surface geometries before and after shearing were compared to evaluate how the contact areas were developed during the shearing and how much material that had been sheared off. The contact pressure distribution was measured on three other calcite infilled specimens using a pressure sensitive film prior to any mechanical tests. It was seen that the compressed contact area was about 30 to 60% of the total joint area, with maximum contact pressure up to 115-165 MPa at a normal load corresponding to an average normal stress of c 10 MPa. The accuracy of the measurements is not known at this point and should be regarded as indicative.

Keywords: Infilled rock joints, direct shear test, CNS-test, constant normal stiffness, contact pressure measurement, surface scanning, photogrammetry.
RAKOJEN PARAMETRISOINTI - ÄSPÖN KALSIITTI- JA BREKSIATÄYTYTTEISTEN RAKONÄYTTEIDEN SUORAT LEIKKAUSKOEET VAKIO NORMAALIJÄYKKYSREUNAEHDON ALAISENAT

TIIVISTELMÄ


Kalsiittitäytteisten rakonäytteiden leikkauskokeet eivät osoittaneet näytteiden korostunutta leikkauslujuutta tai normaalisirritymää kokeiden aikana. Mitatun pienen normaalisiirtymän vuoksi leikkauskokeiden aikana käytetyn normaalijännitysreunaehdon vaikutus jäi rajalliseksi kokeiden aikana käytetyillä 1, 3 ja 6 MPa/mm arvoilla. Breksiäätäytteiseillä näytteillä rakotäyte muren leikkauskokeiden aikana, ja täyte-materiaali puristui näyteistä ulos kokeiden aikana. Tästä johtuen leikkauskokeiden tuloksista on nähtävissä merkittävä näytteiden supistuma toisen leikkausvaiheen aikana. Leikkauskokeista määritetty kitkakulma kalsiittitäytteisille näytteille oli 22 - 34 astetta ja breksiäätäytteisille rakonäytteille 23 - 26 astetta kun koheesiota ei oletettu huomioon.


Avainsanat: Täytteinen rako, leikkauskoe, CNS - koe, vakio normaalijäykkyyys, pintapainemittaus, pintaavaintaminen, photogrammetria.
# TABLE OF CONTENTS

ABSTRACT

TIIVISTELMÄ

1 INTRODUCTION .................................................................................................... 3

2 TEST SPECIMENS ................................................................................................ 5

3 EQUIPMENT .............................................................................................................. 9

3.1 Specimen preparation ................................................................................... 9

3.2 Joint surface geometry measurements ......................................................... 9

3.3 Contact pressure measurement .................................................................... 9

3.4 Mechanical testing ........................................................................................ 9

3.5 Tilt test ......................................................................................................... 11

4 EXECUTION ......................................................................................................... 13

4.1 Specimen preparation ................................................................................. 13

4.2 Joint surface geometry measurements ....................................................... 14

4.3 Contact pressure measurements ................................................................ 15

4.4 Mechanical testing ...................................................................................... 15

4.5 Tilt test of steel reference specimen ........................................................... 16

4.6 Data handling .............................................................................................. 17

4.6.1 Joint surface geometry measurement ............................................. 17

4.6.2 Contact pressure test ...................................................................... 17

4.6.3 Normal loading and direct shear test .............................................. 17

4.7 Analyses and interpretation ......................................................................... 17

4.7.1 Normal loading test ......................................................................... 17

4.7.2 Shear test ................................................................................ 18

5 RESULTS ............................................................................................................... 19

5.1 Normal loading and direct shear test .......................................................... 19

5.2 Tilt test of steel reference specimen ........................................................... 21

5.3 Joint surface geometry measurement ......................................................... 21

5.4 Contact pressure test .................................................................................. 22

6 DISCUSSION ........................................................................................................ 25

7 REFERENCES ..................................................................................................... 27

APPENDICES ............................................................................................................... 29

APPENDIX 1: PICTURES OF SPECIMENS BEFORE GROUTING .................................... 31

APPENDIX 2: PICTURES OF SPECIMENS AFTER TESTING ........................................ 37

APPENDIX 3: RESULT DIAGRAMS FROM MECHANICAL TESTS .............................. 43

APPENDIX 4: RESULTS FROM JOINT SURFACE GEOMETRY MEASUREMENTS .......................................................... 61

APPENDIX 5: RESULTS FROM CONTACT PRESSURE MEASUREMENTS ............ 67
1 INTRODUCTION

The experiments described in this report are part of the Fracture Parametrisation for repository design and post-closure analysis project or in shorter form POST (Parametrisation of structures) project. The objective for the POST-project is to develop a strategy and guidelines for determining the parameters necessary for assessing fracture stability at the deposition tunnel scale for repository design and post closure analysis. A more complete description of the scope within the POST project can be found in Mattila et al. (2015). One of the parameters in the project that is of interest is the shear behaviour of joints under constant normal stiffness condition. This was planned to be investigated by large scale (tunnel-scale) in situ experiments at both Åspö and ONKALO. By these experiments increased knowledge will be obtain on how to scale shear properties of joints from laboratory scale to larger scale (tunnel scale). To complement the large shear experiments, experiments in smaller scale in laboratory were conducted (this report).

Normal loading and direct shear tests on infilled joints have been conducted on specimens sampled from the TASQ-tunnel at Åspö HRL. The aim of this investigation is to provide knowledge of the mechanical behaviour of infilled rock joints under different normal loading conditions. We will investigate the difference between the behaviour when constant normal stiffness (CNS) respective constant normal stress (CS) condition is used. The importance of taking into account the changed normal stress caused by dilatancy (or contractancy) of joints were observed and brought up in the 1970’s by e.g. Goodman (1976) and Obert et al. (1976). Obert et al. (1976) also conducted direct shear tests under CNS conditions on rock joints from cores where tensile fractures had been manufactured by splitting. Other investigations on the shear behaviour of clean rock joints under CNS conditions is for example Jiang (2004).

Not until the 1990’s, studies of direct shear of infilled joints under CNS conditions were reported (e.g. Cheng et al. (1996) on rock joints, Indraratna et al. (1998, 1999) on artificial joints made from gypsum plaster). Indraratna et al. (1998, 1999) did a systematic investigation with a number of tests where the thickness of the bentonite infill layer was varied for different idealized saw tooth shaped joints. It was found that the mechanical response depends on the thickness of the infill to asperity height ratio. Indraratna et al. (2005) reported additional test results on infilled joints of gypsum plaster joins. Boulon et al. (2002) reported results direct shear tests under CNS condition on calcite healed joins of granodiorite with a thickness up to 2 mm.

The samples in the present investigation were obtained from 102 mm drill cores. The cores had been drilled along joints with the joint centred along the diameter of the core. This yielded joints with a width of around 100 mm which extended along the core axis.

---

1 We are using the notation CS to distinguish from the constant normal load (CNL) condition that is normally used in the literature, where the change of actual joint area is not taken into account.
The joints were of two types:

- calcite infill with a thickness of 2-5 mm and
- breccia infill with a thickness of 40-50 mm.

Some of the calcite infilled joints were open when the cores arrived to the laboratory. The selection of specimens was carried out in agreement with SKB and six specimens with calcite infill joints and two specimens with Breccia infill were selected. The program for the mechanical tests was developed within the POST project.

The mechanical tests were carried out in four phases:

- phase A: two normal loading cycles on matched joints,
- phase B: direct shear test under constant normal stiffness (CNS) condition,
- phase C: direct shear test under constant normal stress (CS), and
- phase D: two normal loading cycles on unmatched joints.

The test sequence was designed to provide the normal stiffness on matched and unmatched joints and shear response on shear cycles using both CNS and a corresponding CS condition. The test on one specimen was carried out with the phase 2 and 3 carried out in reversed order to check if any dependence of the phase order could be observed. The direct shear tests were carried out according to the ISRM Suggested method (Muralha et al. 2013). Ideally, in the case of multi-stage testing, the shear cycles should be carried out with increasing normal stress to minimize the effect of degradation of the shear surfaces on subsequent shear cycles. This was not possible in the present investigation.

The actual normal stress was obtained by using the true area and force in the normal stress calculation. The true area was calculated based on initial area the actual shear displacement throughout the test. The shear displacement 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. In addition, the joint surface geometry were scanned before and after testing on three specimens and a contact pressure measurement was carried out during the normal loading cycles on the matched joints on three specimens.

The cores from Äspö HRL were sent to SP in December 2014 and were tested during January and February 2015. The tests were carried out in the rock mechanics laboratory at the department of Structural and Solid Mechanics at SP Technical Research Institute of Sweden.

The work has been conducted with a quality control in accordance with SPs internal quality system which follows ISO/IEC 17025:2005. The environmental management at SP is in accordance with ISO 14001.
2 TEST SPECIMENS

The test material in form of drill cores originates from the TASQ-tunnel at the Äspö HRL in Sweden. The cores with diameter of 102 mm had been drilled along joint planes such that the joints were approximately centred along the cores, yielding a maximum joint area. The joints were secured by duct tape prior to shipping.

All cores were sampled from a long, gently dipping fracture. The fracture is visible in the corner of the main tunnel (A-tunnel) and the K-tunnel. The location is shown in Figure 2-1. The cores KI0011A01 and KI0011A02 had a Breccia infill with a thickness of 40-50 mm. The other cores KA3495A01, KA3501A01 and KA3501A02 had calcite infilled joints with a thickness of 2-5 mm. The calcite infill was rather weak and joints of KA3501A01 and KA3501A02 were open.

![Figure 2-1. Location of the samples from the gently dipping fracture in the junction A and K tunnels shown in the 3D model (top). A-tunnel is here drilled with TBM. The fracture has been polished for better visibility at the location of borehole KA3495.](image)

A list of the sent core material and the possible number of specimen possible to extract from respective core are shown in Table 2-1. Based on this, the location of specimens with a length of 100 mm was marked on the cores. The location of the specimens on the cores is shown in Figures 2-1 to 2-6. This yielded specimens with a joint area of approximately 100 x 100 mm².
Table 2-1. List of cores and possible specimen sampling.

<table>
<thead>
<tr>
<th>Core ID</th>
<th>Position (cm)</th>
<th>Max no of Specimens</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>KA3495A01</td>
<td>c. 36–73</td>
<td>3</td>
<td>Good sample, sealed fracture. 3 samples are possible</td>
</tr>
<tr>
<td>KA3501A02</td>
<td>13–45</td>
<td>2 or 3</td>
<td>Fracture filling minerals partly washed out during drilling. At least one sample is possible (open joint)</td>
</tr>
<tr>
<td>KA3501A01</td>
<td>c. 60–90</td>
<td>4</td>
<td>Likely also washed out fracture infilling material. At least one sample is possible (open joint)</td>
</tr>
<tr>
<td>KA3501A01</td>
<td>24–45</td>
<td>0</td>
<td>The core has opened up along the fracture. The sample might be able for calibration of the test rig.</td>
</tr>
<tr>
<td>KI0011A02</td>
<td>60–80</td>
<td>1</td>
<td>Partly breccia. One sample probable</td>
</tr>
<tr>
<td>KI0011A02</td>
<td>80–108</td>
<td>2</td>
<td>Partly breccia. At least one sample is possible</td>
</tr>
<tr>
<td>KI0011A01</td>
<td>0–14</td>
<td>1</td>
<td>One sample is possible</td>
</tr>
<tr>
<td>KI0011A01</td>
<td>30–c. 60</td>
<td>0</td>
<td>Partly breccia. 2 samples might be possible</td>
</tr>
<tr>
<td>KI0011A01</td>
<td>62–80</td>
<td>0</td>
<td>Partly breccia. One sample probable</td>
</tr>
</tbody>
</table>

Figure 2-2. Location of specimen SH-01 on core KA3501A01, 60-90 cm.

Figure 2-3. Location of specimen SH-02, SH-03 and SH-04, on core KA3501A02, 13-45 cm. Specimen SH-02 was not tested.
Figure 2-4. Location of specimen SH-11 on core KI0011A01, 0-14 cm.

Figure 2-5. Location of specimen SH-12 and SH-13 on core KA3495A01, 36-73 cm.

Figure 2-6. Location of specimen SH-31 on core KI0011A02, 60-80 cm.
Figure 2-7. Location of specimen SH-32 and SH-33 on core KI0011A02, 80-102 cm. Specimen SH-33 was not tested.
3 EQUIPMENT

3.1 Specimen preparation

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

The specimens were cast in specimen 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. A high strength concrete was used to cast the specimens.

A digital camera with high resolution has been used to photograph the specimens.

3.2 Joint surface geometry measurements

The surface geometry was measured on specimen SH-01, SH-03 and SH-04 before and after testing. The surface geometry was measured by photogrammetry using the system ATOS Core MV 320 (GOM 2015). The spatial resolution of the images was 0.115 mm before testing and 0.055 mm after testing. The measurements were carried out at the company Cascade AB.

3.3 Contact pressure measurement

A pressure measurement film from Fujifilm was used to measure the contact pressure distribution between the joint surfaces (Fujifilm 2015). Films with three different pressure ranges were used: low pressure, which can measure pressures in the range 2.5-10 MPa, medium pressure (MS), with the measurement range 10-50 MPa, and high pressure (HS), with the measurement range 50-130 MPa. The film becomes red coloured at the locations where the pressure is applied. The actual colour intensity corresponds to a given pressure value. The thickness of the film is less than 200 µm according to the technical specifications.

3.4 Mechanical testing

The normal loading and direct shear tests were made in a servo hydraulic testing machine aimed for 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.

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 25 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. Electrical 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.

The area correction and CNS condition were accomplished in the control software.

Figure 3-1. Equipment for direct shear tests and digital controller unit.
3.5 Tilt test

A tilt test device was constructed using a laminated wooden board as the tilt table with a stop block in the lower end. The tilting was done by manually lifting the tilt table slowly in one end. The tilt angle was measured using a digital level. The digital level was aligned to the tilt table and was measuring the actual inclination. Two persons were needed to conduct the tilt test, one catching the sliding part and one lifting the end of the tilt table. The angular value was read by both persons and the angle at the onset of sliding was read instantly from the digital display. The tilt angle was estimated to be determined within 0.5 degrees. The tilt test set-up is shown in Figure 3-2.

Figure 3-2. Set-up for the tilt tests of the steel reference specimen.
4 EXECUTION

This section describes the different activities regarding specimen preparation, tests, data handling and data processing.

A form containing specimen identification and dimensions were filled in. Further, the form also contains comments and observations during the different test steps. The specimens were photographed before and after the mechanical tests.

4.1 Specimen preparation

Eight direct shear specimens were extracted by cutting 100 mm long sections from the cores at the locations on the cores shown in Figures 2-1 to 2-6. The list of specimens is shown in Table 4-1. The joints of specimen SH01, SH-02 and SH-04 were open. The joints of the other specimens were sealed. Pictures of the specimens with sealed joints after cutting are shown in Appendix 1.

Table 4-1. List of specimens, dimensions, tests and joint area after preparation. The phase order and extra tests are defined below in this section.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Core Position on core (cm)</th>
<th>Width (mm)</th>
<th>Length (mm)</th>
<th>Phase order</th>
<th>Extra test</th>
<th>Joint type</th>
<th>Initial joint area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH-01</td>
<td>KA3501A01 60-90</td>
<td>102</td>
<td>104</td>
<td>A-B-C-D</td>
<td>S</td>
<td>C</td>
<td>108.1</td>
</tr>
<tr>
<td>SH-03</td>
<td>KA3501A02, 13-45</td>
<td>102</td>
<td>101</td>
<td>A-B-C-D</td>
<td>S</td>
<td>C</td>
<td>100.7</td>
</tr>
<tr>
<td>SH-04</td>
<td>KA3501A02 13-45</td>
<td>102</td>
<td>100</td>
<td>A-B-C-D</td>
<td>S</td>
<td>C</td>
<td>99.6</td>
</tr>
<tr>
<td>SH-11</td>
<td>KI0011A01 0-14</td>
<td>101</td>
<td>101</td>
<td>A-B-C-D</td>
<td>P</td>
<td>C</td>
<td>101.7</td>
</tr>
<tr>
<td>SH-12</td>
<td>KA3495A01 36-73</td>
<td>100</td>
<td>100</td>
<td>A-B-C-D</td>
<td>P</td>
<td>C</td>
<td>100.5</td>
</tr>
<tr>
<td>SH-13</td>
<td>KA3495A01 36-73</td>
<td>98</td>
<td>101</td>
<td>A-B-C-D</td>
<td>P</td>
<td>C</td>
<td>98.8</td>
</tr>
<tr>
<td>SH-31</td>
<td>KI0011A02 60-80</td>
<td>100</td>
<td>100</td>
<td>A-B-C-D</td>
<td>-</td>
<td>B</td>
<td>100.1</td>
</tr>
<tr>
<td>SH-32</td>
<td>KI0011A02 80-102</td>
<td>101</td>
<td>101</td>
<td>A-C-B-D</td>
<td>-</td>
<td>B</td>
<td>102.3</td>
</tr>
</tbody>
</table>

Explanations to values in the table

S = Surface scanning, P = Contact stress measurement
C = Calcite, B = Breccia.

The specimens were cast in steel holders using a high strength concrete as shown in Figure 4-1. The specimen halves for the open joints were positioned relative to each other such that the two specimen pieces best fit together implying that the fracture or joint is optimally closed (matching joints). This is termed the zero or the initial position for the shear displacement in conjunction with the shear tests. The specimens were grouted in two steps. The first specimen half were grouted in one of the holders and then after curing, the second half was grouted in the other holder. The specimen was oriented such that the joint surface was aligned in the prescribed shear plane, i.e. parallel to the shear movement, centred in the holders and at the right height position.
This yields a closed matched joint with a gap between the specimen holders of 10 mm, see Figure 4-1.

After the grouting it was later decided to carefully open the sealed joint of specimen SH-11, SH-12 and SH-13 to obtain more results on open calcite joints since there was an error in the tests of specimen SH-01, SH-03 and SH-04, see section 5.1.

A list of activities during the specimen preparation is shown in Table 4-2.

![Figure 4-1. Principal picture showing the specimen in two side views cast in the specimen holder for the normal loading and shear tests.](Image)

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mark the drill cores at the position of the joints selected for testing.</td>
</tr>
<tr>
<td>2</td>
<td>Cut out the specimens from the cores each with a length of 100 mm.</td>
</tr>
<tr>
<td>3</td>
<td>Remove the duct tape that secure the joins.</td>
</tr>
<tr>
<td>4</td>
<td>Measure the specimen dimensions and calculate the joint surface area.</td>
</tr>
<tr>
<td>5</td>
<td>Take digital photos of each specimen.</td>
</tr>
<tr>
<td>6</td>
<td>Cast the specimens into the specimen holders.</td>
</tr>
</tbody>
</table>

**4.2 Joint surface geometry measurements**

The geometry of the joint surfaces of specimen SH-01, SH-03 and SH-04 were measured before and after the mechanical tests. A number of adhesive markers were put on the rings to provide reference positions on the specimens. The reference positions were used to match the geometry of the scanned surfaces before and after testing such that the surface geometry change could be obtained. Furthermore, a matching of the two joint surfaces was made before and after the testing using the ATOS software. The relative geometry change could be calculated that shows extension and magnitude of the mechanical wear in the joint.
4.3 Contact pressure measurements

The contact pressure was made by cutting sheets of the pressure sensitive film that were slightly larger than the joint surface and placed on the lower half of the specimen that was already inserted in position in the lower shear box. Two sheets of different measurement range were placed on top of each other. In one case, three sheets were placed on top of each other. The other specimen half were carefully put on top of the lower half such that the joints match to each other. The lower shear box with the two specimen halves in the correct position and the pressure sensitive film in between were then slid in position under the upper shear box. The upper shear box was carefully lowered such that the upper specimen half slid inside the upper shear box until contact was reached. The specimens were manually loaded up to 100 kN (specimens SH-11 and SH-12) respective 99 kN (specimen SH-13) and unloaded whereby the test was finished. The upper shearbox were lifted and the pressure sensitive film could be taken out.

4.4 Mechanical testing

The mechanical testing was divided in four phases. The following scheme was used in all tests except for one specimen:

- phase A normal loading test on matched joints (3 load cycles),
- phase B direct shear test using constant normal stiffness condition, CNS,
- phase C direct shear test using constant normal stress, and
- phase D normal loading test on non-matched joints (2 load cycles).

The phase B and C was conducted in reverse order on specimen SH-32.

An overview of the activities during the normal loading and direct shear test is shown in the step-by-step description in Table 4-3. A detailed description of the four phases, A to D, is shown in Table 4-4. The complete test scheme was tested prior using a steel specimen having an inclined flat joint and milled surfaces. The specimen was intentionally made to verify that the CNS condition worked properly during the shear cycle at phase B.

Table 4-3. Activities during the normal loading and shear test of natural fractures.

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mount the specimen holders in the shear testing machine.</td>
</tr>
<tr>
<td>2</td>
<td>Conduct all four phases of the normal loading test and shear test.</td>
</tr>
<tr>
<td>3</td>
<td>Take out the specimens from the shear boxes.</td>
</tr>
<tr>
<td>4</td>
<td>Take digital photos of each specimen.</td>
</tr>
<tr>
<td>5</td>
<td>Store the test results on the computer network.</td>
</tr>
</tbody>
</table>
Table 4-4. Activities during the normal loading and direct shear tests. The order of phase B and C was reversed for specimen SH-32.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
</table>
| A     | Normal stress cycles (matched joints)  
Normal loading 3 x 11 MPa (3 cycles). Loading/unloading rate 10 MPa/min. |
| B     | Direct shear test (Constant normal stiffness)  
B1 Normal loading to 11 MPa with a loading rate of 5 MPa/min  
B2 Shear test (CNS condition) with a shear displacement rate of 2 mm/min up to 15 mm shear displacement.  
Normal stiffness $k_n = 1$ MPa/mm. Specimen SH-01, SH-11, Steel  
Normal stiffness $k_n = 3$ MPa/mm. Specimen SH-03, SH-12  
Normal stiffness $k_n = 6$ MPa/mm. Specimen SH-04, SH-13, SH-31, SH-32 |
| B3    | Unload the shear stress with 5 MPa/min. |
| B4    | Unload the normal stress manually to 0.1 MPa. |
| B5    | The shear position was restored to its initial position with mated joints (zero shear displacement) before the next shear phase. |
| C     | Direct shear test (Constant normal stress)  
C1 Normal loading with 5 MPa/min to max normal stress encountered in phase B2.  
C2 Shear test under constant normal stress (area corrected) with a shear displacement rate of 2 mm/min up to 15 mm shear displacement.  
C3 Unload the shear stress at 5 MPa/min.  
C4 Unload the normal stress manually to 0.5 MPa. |
| D     | Normal stress cycles (unmatched joints i.e. at 15 mm shear displacement)  
Normal loading 2 x 11 MPa (2 cycles). Loading/unloading rate 10 MPa/min. |

4.5 Tilt test of steel reference specimen

A tilt test was conducted on the steel reference specimen. The steel specimen was placed on the tilt table and the small inclination of the joint surface was oriented as shown in Figure 4-2. The test was carried out by two persons, one catching the upper sliding part and one lifting the end of the tilt table. The angle of the tilt table was read from the digital display on the level by both persons and the angle at the onset of sliding was noted in a protocol. The tilt test was repeated more than 10 times.
Data handling

Joint surface geometry measurement

The raw data of surface geometries were stored in files with stl-format. The data were processed using the software ATOS Professional V8 to achieve the final results. The raw data were sent to SP and stored in a file server on the SP computer network.

Contact pressure test

The films were given to Caltech AB after testing. The colour patterns were digitized by scanning the films. The colour codes were interpreted using special software from Fujifilm, where also the results were post-processed into the final form by Caltech AB.

Normal loading and direct shear test

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 all parameters were determined, has been carried out in the program MATLAB (2014). MATLAB was also used to produce the results diagrams.

Analyses and interpretation

Normal loading test

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. In the normal loading tests the joint deformation in the normal direction, $\delta_N$, is defined as mean value of the four LVDTs that measure the vertical (normal) relative displacement between the shear boxes at the corners of the two shear boxes.
A part of the normal deformations measured in the normal loading tests belong to the deformations in the concrete in the holders, in the shear boxes and in the contact surfaces between the specimen holders and the shear boxes. These additional deformations are not accounted for. A correction may be made, see further discussion in section 6.

The secant normal stiffness $K_N$ is determined as the secant evaluated between the unloaded state and full loading belonging to the loading path during the second load cycle.

### 4.7.2 Shear test

In the shear tests, the normal stress $\sigma_N$ and shear stress $\sigma_S$ are defined as:

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

where $F_N$ is the normal force and $F_S$ is the shear force acting on the joint and $A$ is the actual joint area for a given shear displacement. The actual area is computed as:

$$A(\delta_S) = W \cdot L - W \cdot \delta_S$$

where $W$ is the width of the joint and $L$ is the length of the joint (in the shear direction). The peak value $\sigma_{S,p}$ of the shear stress $\sigma_S$ on both shear cycles are determined. The peak value is defined as the maximum value during the whole shear cycle.

The shear deformation $\delta_S$ is represented by the relative displacement between the shear boxes in the horizontal (shear) direction measured by one LVDT. The normal deformation $\delta_N$, is defined as mean value of the four LVDTs that measure the vertical (normal) relative displacement between the shear boxes at the corners of the two shear boxes.

A part of the normal deformations and shear deformations measured in the shear tests belong to the deformations in the concrete, 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 small and negligible for the results and no correction should be necessary.

The secant shear stiffness $K_S$ is determined as the secant evaluated between 30% and 50% of the peak shear stress $\sigma_{S,p}$. The secant dilatancy angle $\Psi$ is determined between 2 and 10 mm shear deformation.
5 RESULTS

5.1 Normal loading and direct shear test

All results from the normal loading and direct shear tests are summarised in Table 5-1. Pictures of all specimens after testing are found in Appendix 2. Diagrams showing the stresses and displacements are found in Appendix 3.

The actual joint area during shearing was computed incorrectly during the three first shear tests, which were the tests of specimens, SH-01, SH-03 and SH-04. The area was computed as (cf. section 4.7)

\[ A(\delta_s) = W \cdot L - 2 \cdot W \cdot \delta_s \]

This error has an implication on the results on all phases except for phase A in the tests on the aforementioned specimens. The effect is that the normal stress becomes successively lower than the correct value during shearing. For, example, in a constant stress condition, the normal stress will be decreasing linearly with a constant slope. The results for all phases are shown in Appendix 3. The effect of the error of the area calculation can clearly be seen in the diagrams showing the normal stress versus shear displacement. The effect of the decreasing normal stress can be noticed in the diagrams showing shear stress versus shear displacement.

Table 5-1. Summary of results from the mechanical tests. \( K_{N1} \) belongs to phase A, \( K_{S1} \), \( \sigma_{S,p1} \) and \( \psi_1 \) belongs to phase B, \( K_{S2} \), \( \sigma_{S,p2} \) and \( \psi_2 \) belongs to phase C and \( K_{N2} \) belongs to phase D. \( \sigma_N \) is the normal stress used at the constant normal stress shear phase.

<table>
<thead>
<tr>
<th>Spec ID</th>
<th>( K_{N1} ) (MPa/mm)</th>
<th>( K_{S1} ) (MPa/mm)</th>
<th>( \sigma_{S,p1} ) (MPa)</th>
<th>( \psi_1 ) (deg)</th>
<th>( K_{N2} ) (MPa/mm)</th>
<th>( K_{S2} ) (MPa/mm)</th>
<th>( \sigma_{S,p2} ) (MPa)</th>
<th>( \psi_2 ) (deg)</th>
<th>CNS (MPa/mm)</th>
<th>( \sigma_N ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH-01*</td>
<td>30.8</td>
<td>45.8</td>
<td>5.82</td>
<td>0.53</td>
<td>22.7</td>
<td>11.0</td>
<td>5.71</td>
<td>0.15</td>
<td>1</td>
<td>10.93</td>
</tr>
<tr>
<td>SH-03*</td>
<td>38.7</td>
<td>44.3</td>
<td>7.02</td>
<td>1.16</td>
<td>32.9</td>
<td>21.7</td>
<td>7.43</td>
<td>0.54</td>
<td>3</td>
<td>11.58</td>
</tr>
<tr>
<td>SH-04*</td>
<td>41.4</td>
<td>55.4</td>
<td>6.49</td>
<td>0.63</td>
<td>35.8</td>
<td>19.9</td>
<td>6.44</td>
<td>0.32</td>
<td>3</td>
<td>12.04</td>
</tr>
<tr>
<td>SH-11</td>
<td>49.6</td>
<td>32.5</td>
<td>7.78</td>
<td>-0.10</td>
<td>42.1</td>
<td>22.5</td>
<td>8.07</td>
<td>-0.75</td>
<td>1</td>
<td>10.91</td>
</tr>
<tr>
<td>SH-12</td>
<td>49.1</td>
<td>23.8</td>
<td>7.82</td>
<td>1.92</td>
<td>33.3</td>
<td>24.8</td>
<td>8.23</td>
<td>0.62</td>
<td>3</td>
<td>12.13</td>
</tr>
<tr>
<td>SH-13</td>
<td>33.6</td>
<td>15.8</td>
<td>6.36</td>
<td>0.73</td>
<td>27.8</td>
<td>13.3</td>
<td>6.75</td>
<td>0.78</td>
<td>6</td>
<td>11.80</td>
</tr>
<tr>
<td>SH-31</td>
<td>48.2</td>
<td>12.5</td>
<td>5.46</td>
<td>-0.59</td>
<td>28.0</td>
<td>0.8</td>
<td>3.37</td>
<td>-2.65</td>
<td>6</td>
<td>11.00</td>
</tr>
<tr>
<td>SH-32†</td>
<td>35.0</td>
<td>21.9</td>
<td>4.78</td>
<td>-0.55</td>
<td>40.0</td>
<td>6.0</td>
<td>3.78</td>
<td>-1.90</td>
<td>6</td>
<td>11.00</td>
</tr>
<tr>
<td>Steel</td>
<td>59.8</td>
<td>12.0</td>
<td>3.29</td>
<td>1.38</td>
<td>65.2</td>
<td>15.6</td>
<td>3.90</td>
<td>1.34</td>
<td>1</td>
<td>11.36</td>
</tr>
</tbody>
</table>

Explanations to values in the table

CNS = Constant normal stiffness, CS = constant normal stress

(*) Incorrect area correction during the shear phases
(†) CS was conducted prior to CNS
From the diagrams of the shear stress versus shear displacement for the specimens with the calcite infilled joints (Appendix 3) it can be seen that the shear stress at the onset of sliding was between 4.5 and 7.5 MPa at a normal stress of 11 MPa, which yields friction angles between 22 to 34 degrees. Moreover, there was no pronounced initial peak shear stress. The results show a similar response and are in the same magnitude as was reported by Boulon et al. (2002). They found that there was no pronounced peak stress and that the friction angle was in the order of 30-32 degrees when 0.3-2 mm thick calcite infilled joints were sheared.

A peak of the shear stress could be seen on the results from the tests on the specimens with Breccia infilled joints with a drop when the intact Breccia was broken. The peak was more pronounced on specimen SH-31. The peak shear strength was 5.5 MPa respectively 4.8 MPa at a normal stress of 11 MPa. This corresponds to friction angles of 26 and 23 degrees if no cohesion is assumed.

The normal deformation of the joints during shearing was in general small. This means that the effect of a normal stiffness condition is small and is close to a constant normal stress condition. Looking at the first shear cycle at all tests, we see that the normal displacement was not more than 0.4 mm for any specimen. The tests on specimens with calcite infilled joints show a slight dilation of the joint, between 0.18 mm to 0.38 mm, except for specimen SH-11 that show a small compaction of 0.08 mm. The results of the two specimens, with the thick Breccia infill, SH-31 and SH-32, show almost identical response with a compaction of 0.17 mm. All specimens show an initial compaction at the beginning of the second shear cycle in the order of 0.07-0.46 mm as compared with the initial condition at the first shear cycle.

Looking at the joint surfaces after testing (Appendix 2), it can be seen that that the calcite infill material acts like a soft layer providing small or no dilatancy. The existing roughnesses were sheared off and smoothen. Moreover the calcite layer acted like soft layer yielding rather low friction. The samples with the Breccia infill show that the material in the joint has crumbled and squeezed out, see Figure A2-7 to A2-10. As a result, the joint obviously collapse with a large contraction during the second shear cycle. The shear stress versus shear displacement at the second shear cycle (Figure A3-13 and A3-15) shows a slow increase of the shear stress with low shear stiffness, like a loose compacted granular material.

The normal stiffness obtained in phase A was 30.8-49.6 MPa/mm, which can be compared with the results by Boulon et al. (2002) which reported a stiffness of 37.7±2.3 MPa/mm on thick joints for a normal loading between 1-20 MPa. The normal stiffness was in general lower at the last phase except for specimen SH-32. The same was seen on the shear stiffness. The shear stiffness was in general lower during the second shear phase except for specimen SH-12. The shear stiffness during the first shear cycle on the tests on the calcite specimens, show a large variation with a stiffness of 15.8-55.4 MPa/mm. Again the results can be compared with the results reported by Boulon et al. (2002). They reported a shear stiffness of 227 MPa/mm for the thick joints and 16.9 MPa/mm on the thin joints at 10 MPa normal stress.
5.2 Tilt test of steel reference specimen

A number of repeated tilt tests were carried out on the steel specimen after the shear test was conducted. The basic tilt angle was estimated to be around 12.5-13.2 degrees. In a few cases, the two halves stuck to each other, since the surfaces were locally damaged after the shear tests. The angle could go up to 15-19 degrees in those cases. The inclination of the joint surfaces (dilatancy angle) of the steel specimen was 1.3-1.4 degrees determined from the shear tests presented in the previous section. The different angles are defined in Figure 4-2.

5.3 Joint surface geometry measurement

All results of the joint surface geometry measurements are found in Appendix 4. It can be seen at which positions that the joint asperities has been worn down during the shearing and how much material that is locally missing. The maximum depth of material that was sheared off is around 1.5-1.6 mm on all three joints that were tested (SH-01, SH-02, SH-04). In one case it was locally up to a little bit than 2 mm material missing (SH-02). In one case it can be seen that material had been locally deposited in the joints (SH-02). It shall be noted that the joints were not touched after the testing before the second scanning in order to get the final surface geometries as it was in the shear box. Loose debris was not protected from falling off.

No analysis was made to see how the individual surface profile or roughness was changed, for example, to see if the surfaces were smoothened by shearing off asperities. This could be done by comparing the surface roughness on the scanned surfaces before and after testing. In the results shown here, only the relative changes are evaluated.

As an example, the geometry change of the mated joint between the measurement before and after testing for specimen SH-02 is shown in Figure 5-1.

![Figure 5-1. Specimen SH-02. Total geometry change for matched joint before and after shear test.](image-url)
5.4 Contact pressure test

The measurement of the contact pressure was carried out on specimen SH-11, SH-12 and SH-13. The pressure sensitive films that have been coloured after the test of SH-11 are shown in Figure 5-2 and 5-3. The pressure values were converted from the intensity of the red colour into a pressure scale, see Figure 5-4 and 5-5. Figure 5-4 and 5-5 also show examples of the possibility to visualize the pressure variation along

![Figure 5-2. Specimen SH-11 after contact pressure measurement. The high scale (HS) film is below the medium scale (MS) film.](image)

![Figure 5-3. Pressure sensitive films after the test of specimen SH-11. Left: medium scale (MS) film; Right: high scale (HS) film.](image)
two different selected lines. The results of all measurements are shown in Appendix 5. A summary of results are found in Table 5-2. The table show values for the size of the contact areas, maximum and average pressure and the calculated total load acting on the surface. The calculated load is obtained as the integrated of the pressure values over the surface. There was a contribution to the calculated load from the pen cross mark that was subtracted in values shown in the table for SH-11 and SH-12.

Figure 5-4. Contact pressure variation for specimen SH-11 (HS) along a horizontal line. The legend to the left show the contact pressure in MPa. The vertical axis in the diagram to the right show the contact pressure in MPa and the horizontal axis show the position along the line in mm.

Figure 5-5. Contact pressure variation for specimen SH-11 (HS) along a vertical line. The legend to the left show the contact pressure in MPa. The vertical axis in the diagram to the right show the contact pressure in MPa and the horizontal axis show the position along the line in mm.
Table 5-2. Summary of results from contact pressure measurements.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Pressure film</th>
<th>Compressed area (mm²)</th>
<th>Max pressure (MPa)</th>
<th>Average pressure (MPa)</th>
<th>Calculated load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH-11</td>
<td>MS</td>
<td>6262</td>
<td>63.8(††)</td>
<td>13.3</td>
<td>82.1(†)</td>
</tr>
<tr>
<td>SH-11</td>
<td>HS</td>
<td>2191</td>
<td>115(†)</td>
<td>54.6</td>
<td>116(†)</td>
</tr>
<tr>
<td>SH-12</td>
<td>MS</td>
<td>2884</td>
<td>63.8(††)</td>
<td>16.0</td>
<td>45.3(†)</td>
</tr>
<tr>
<td>SH-12</td>
<td>HS</td>
<td>895</td>
<td>165.8(††)</td>
<td>70.8</td>
<td>60.9(†)</td>
</tr>
<tr>
<td>SH-13</td>
<td>LS</td>
<td>5226(*)</td>
<td>12.8(*,††)</td>
<td>6.90(*)</td>
<td>36.1(*)</td>
</tr>
<tr>
<td>SH-13</td>
<td>MS</td>
<td>(*,**</td>
<td>45.5(*)</td>
<td>17.3(*)</td>
<td>(*,**)</td>
</tr>
</tbody>
</table>

(*) The contact pressure distribution was disturbed since one of the two MS films did not cover the whole joint area.

(**) The evaluation was done on the two MS films together and does not yield representative results.

(†) Estimated value from colour plots. The automatically obtained maximum value was obscured by the pen cross mark.

(††) Probably the maximum detectable value for the actual type of pressure sensitive film.

(‡) The estimated contribution from the pen cross mark was subtracted from the integrated value by 0.9 kN (SH-11 MS), 3.8 kN (SH 11 HS), 0.8 kN (SH-12 MS) and 2.5 kN (SH-12 HS).

The results on specimen SH-13 have to be considered as indicative since one of the films did not cover the whole joint surface. This has affected the pressure measurements. The contribution on the total load from the pen writing was not considered in this case.

It can be seen that the calculated load for SH-11 is in the correct range as compared with the applied load of 100 kN. The MS film slightly underestimates the value and the HS film overestimates the value. There can be several reasons behind the differences such as inaccuracy of pressure determination, inaccuracy of pressure integration, small sliding of the specimen surfaces when the surfaces are mated. The measurement with the MS film shows that the pressure probably exceeds the upper range and therefore contributes to the underestimation of the load.

The calculated loads for SH-12 were significantly lower than the applied load of 100 kN. In this case, the contacts were localised to smaller area than for SH-11 leading to higher local pressure. As a result the pressure exceeded the upper range for both types of films and thus yield an error in the calculated load.
6 DISCUSSION

The results of the tests on the specimens with the calcite infilled joints show only small or no dilation. The effect of a CNS condition will thus have no or small effect with the range of normal stiffnesses that were used in comparison with a constant normal stress condition. Moreover, there is no clear peak shear strength at the onset of sliding. Similar behaviour was observed in the tests on thick calcite infilled joints reported by Boulon et al. (2002). Indraratna et al. (1998) studied bentonite infilled artificial joints with different thickness to asperity height ratios. Their results show that the behaviour of joints with a thickness to asperity height ratio more than around 0.8 to 1 yields no or small dilation or compaction. Moreover, the shear stress is rather constant during shearing. This behaviour was seen on the results from specimen SH-01, SH03, SH-04, SH-11 and SH-13. The results of SH-12 show a little increase of the shear stress and dilation. Comparing, again, with the results in Indrata et al. (1998) this could indicate that the thickness to asperity height ratio slightly smaller in specimen SH-12. A small dilatancy was also found by Boulon et al. (2002) in their results. The effect of a large infill is that the properties of the infill material such as compressibility and shear behaviour become decisive for the results. A possibility for future measurements on similar samples would be to determine the thickness to asperity height ratio. The effect of the incorrect, too progressive, area correction on specimen SH-01, SH-03 and SH-04, is found to be small due to the small dilatancy in the calcilte infilled joints. The principal behaviour is judged to be correct.

It was noticed that the thick breccia layer in specimen SH-31 and SH-32 collapsed during shearing and loose material at the lateral boundaries of the joint squeezed out. Larger joints should be used to obtain more representative results with decreased boundary effects. This effect was also discussed by Boulon et al. (2002) for thick calcite infilled joints. Moreover, The breccia infill was rather thick. In order to determine the effective strength more accurately of such a joint would require much larger samples and that the gap between the shear boxes to be larger as well.

The normal stiffness that was measured during phase A and D has to be considered as a lower bound. The true normal stiffness is probably higher. The reason is that the deformations measured by the LVDTs also include deformations outside the joint such as in the concrete and in the contact interfaces between the specimen holder and the shear box. A direct measurement of the joint stiffness such as in Jacobsson & Flansbjer (2005) is recommended in order to obtain more precise stiffness values. An estimate of the system deformation, i.e. deformations outside the joint, may be done based on the results from the steel specimen with the method used by Chryssanthakis (2004) and Jacobsson (2005). However, this correction may be uncertain.

The joint surface geometries were determined by photogrammetry. The data was used to determine the relative geometry changes before and after testing of the individual surfaces and the total geometry change when the two surfaces were matched together. The surface roughness was not determined, which is a possibility to give an idea on how the asperities or local elevations were worn down. Another addition would be to scan the surfaces directly after shearing and then again after removing material that has been sheared off
and still is inside the joint. The total influence area and depth caused by the shearing could then be determined.

The results from the pressure sensitive film show that the contact pressure distribution varies significantly over the joint surface. It was seen that the compressed contact area was about 30 to 60% of the total joint area. The peak contact stress was seen to be up to 115 MPa to more than 165 MPa in the extreme points. And this was for a load corresponding to an average normal stress of c 10 MPa. The accuracy of the measurements is not known at this point and should be regarded as indicative. The effect on the contact pressure distribution of inserting a thin film may be investigated by simulating the contact area with a film in between using a computational model. These types of measurements can be useful input if a contact model for the joints is going to be developed.
7 REFERENCES


## APPENDICES

1. Photographs of the specimens before grouting
2. Photographs of the specimens after testing
3. Result diagrams from the mechanical tests
4. Results from surface scanning
5. Results from contact pressure measurements
APPENDIX 1: PICTURES OF SPECIMENS BEFORE GROUTING

Figure A1-1. Pictures of specimen SH-11 before grouting.
Figure A1-2. Pictures of specimen SH-12 before grouting.
Figure A1-3. Pictures of specimen SH-13 before grouting.
Figure A1-4. Pictures of specimen SH-31 before grouting. The black lines show the alignment of the specimen in the shear box.
Figure A1-5. Pictures of specimen SH-32 before grouting. The black lines show the alignment of the specimen in the shear box.
APPENDIX 2: PICTURES OF SPECIMENS AFTER TESTING

Figure A2-1. Pictures of the two specimen halves belonging to SH-01 after testing.

Figure A2-2. Pictures of the two specimen halves belonging to SH-03 after testing.
Figure A2-3. Pictures of the two specimen halves belonging to SH-04 after testing.

Figure A2-4. Pictures of the two specimen halves belonging to SH-11 after testing.
Figure A2-5. Pictures of the two specimen halves belonging to SH-12 after testing.

Figure A2-6. Pictures of the two specimen halves belonging to SH-13 after testing.
**Figure A2-7.** Pictures of the two specimen halves belonging to SH-31 after testing.

**Figure A2-8.** Picture of one specimen half belonging to SH-31 after testing.
Figure A2-9. Pictures of the two specimen halves belonging to SH-32 after testing.

Figure A2-10. Picture of one specimen half belonging to SH-33 after testing.
Figure A3-1. Results from specimen SH-01. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-2. Results from specimen SH-01. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-3. Results from specimen SH-03. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 3 MPa/mm).
Figure A3-4. Results from specimen SH-03. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 3 MPa/mm).
Figure A3-5. Results from specimen SH-04. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 6 MPa/mm).
**Figure A3-6.** Results from specimen SH-04. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 6 MPa/mm).
Figure A3-7. Results from specimen SH-11. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-8. Results from specimen SH-11. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-9. Results from specimen SH-12. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 3 MPa/mm).
Figure A3-10. Results from specimen SH-12. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 3 MPa/mm).
Figure A3-11. Results from specimen SH-13. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-12. Results from specimen SH-13. Upper: Normal versus shear displacement; Lower: Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-13. Results from specimen SH-31. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-14. Results from specimen SH-31. Upper: Normal versus shear displacement; Lower: Normal stress versus shear displacement (CNS = 6 MPa/mm).
Figure A3-15. Results from specimen SH-32. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 6 MPa/mm).
Figure A3-16. Results from specimen SH-32. Upper: Normal versus shear displacement; Lower: Normal stress versus shear displacement (CNS = 6 MPa/mm).
Figure A3-17. Results from steel specimen. Upper: Normal loading cycles; Lower Shear stress versus shear displacement (CNS = 1 MPa/mm).
Figure A3-18. Results from steel specimen. Upper: Normal versus shear displacement; Lower: Normal stress versus shear displacement (CNS = 1 MPa/mm).
APPENDIX 4: RESULTS FROM JOINT SURFACE GEOMETRY MEASUREMENTS

Figure A4-1. Specimen SH-01, side 1. Surface topology change before and after shear test.

Figure A4-2. Specimen SH-01, side 2. Surface topology change before and after shear test.
Figure A4-3. Specimen SH-01. Total geometry change for matched joints before and after shear test.

Figure A4-4. Specimen SH-02, side 1. Surface topology change before and after shear test.
Figure A4-5. Specimen SH-02, side 2. Surface topology change before and after shear test.

Figure A4-6. Specimen SH-02. Total geometry change for matched joints before and after shear test.
Figure A4-7. Specimen SH-04, side 1. Surface topology change before and after shear test.

Figure A4-8. Specimen SH-04, side 2. Surface topology change before and after shear test.
Figure A4-9. Specimen SH-04. Total geometry change for matched joints before and after shear test.
APPENDIX 5: RESULTS FROM CONTACT PRESSURE MEASUREMENTS
Figure A5-1. Contact pressure distribution for specimen SH 11. Upper figure: Measurements using medium scale (MS) film; Lower figure: Measurements using high scale (HS) film. The unit of the scales are MPa.
Figure A5-2. Contact pressure distribution for specimen SH 12. Upper figure: Measurements using medium scale (MS) film; Lower figure: Measurements using high scale (HS) film. The unit of the scales are MPa.
Figure A5-3. Contact pressure distribution for specimen SH 13. Upper figure: Measurements using low scale (LS) film; Lower figure: Measurements using medium scale (MS) film. The unit of the scales are MPa. The lower pressure in the bottom part was caused.