Thin shotcrete layers subjected to punch loads.

by

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1. INTRODUCTION

The investigation presented in this paper is the first step in a joint project between the Royal Swedish Fortifications Administration (FortF) and the Swedish Rock Mechanics Research Foundation (BeFo).

Its aim is better knowledge of shotcrete as a means of rock strengthening. If this aim is reached considerable economic savings could be made since the thicknesses of shotcrete used in practice probably are overestimated because of this lack of knowledge and the psychology of safety.

The problem complex is a large one and it has to be examined step-wise. To start with a rather simple case is studied which is defined in chapter 3.

2. EARLIER INVESTIGATION

The interaction between shotcrete and hard rocks has not been investigated previously in Scandinavia to the knowledge of the author, Östlund (3/), Sällström (4/) and Poijärvi (5/) investigated the properties of the shotcrete itself. Barbo (6/) has published results from some adhesion tests on shotcrete applied to different minerals. The number of tests is rather limited and of course the structural behaviour of the shotcrete has not been determined in his investigation.

In Austria several investigators have studied the use of shotcrete as tunnel lining. The investigated rock materials were weak, however, so the problem studied is principally the one of a concrete pipe surrounded by soil. (Ref /7/, /8/, /9/, /10/). See also chapter 3.

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This investigation is concerned with high strength jointed rocks.

3. **LOADING CASE**

A rather simple loading case, the punching of a large rock fragment through a shotcrete layer, was chosen for this investigation.

This case was studied by Rotter (11) who assumed a shear failure in the shotcrete layer. This led to the conclusion that a 3 cm shotcrete layer could carry 13 times the weight of a rock pyramide having a base area of one m². The consequence of this model was that the carrying capacity of the shotcrete layer was proportional to the layer thickness and the shear strength of the shotcrete.

![Diagram of loading case](image)

**Fig 3** a Loading case in this investigation

4. **TEST RIG AND TEST SPECIMENS**

4.1 **MAIN TESTS**

The main tests were made in the 3.7 m x 1.2 m test rig shown in Fig 4 a. Rock slabs of fine-grained grey granite were tested. The middle slab was pressed upwards during a test for practical reasons. The rig was fixed to the ground with a hinge parallel to the test specimen and was tilted to make the rock surface vertical during the application and curing of the shotcrete.
The different parts of the rig were balanced against each other with respect to the deformations in order to avoid bending of the shotcrete layer. The fulfilment of this was checked with a strain gauge during one of the tests. The load was applied with two parallell-connected handpumped hydraulic jacks.

![Diagram of test rig for plane test](image1)

Fig 4 a Test rig for plane test.

5. TEST DESCRIPTIONS AND TEST RESULTS

5.1 A BASIC DESCRIPTION OF THE PLANE TESTS. TERMINOLOGY

![Diagram of principal view of main test specimen for plane tests](image2)

Fig 5 a Principal view of main test specimen for plane tests.

The middle rock slab was pressed upwards by the load $P$ during a test. The outer rocks slabs were restrained by the loads $P/2$. The applied load was distributed from the middle slab to the outer slabs by the shotcrete layer.
The applied load, $P$, and the vertical displacement, $w$, of the middle slab were measured during the test.

At a certain load level, the primary failure load, an adhesion crack formed between the shotcrete and the surface of the outer rock slabs near the slit between the rock slabs. This happened in all tests. The load suddenly dropped to one third or less when the adhesion crack formed. This load was called the adhesion crack propagation load and it remained nearly constant during the crack propagation until a flexural failure took place in the shotcrete layer.

For the reinforced test specimens it was possible to increase the applied load after the adhesion crack propagation in some cases. For these tests a final failure load or secondary failure load existed.

5.2 TESTS WITH UNREINFORCED SHOTCRETE

Ten tests under normal adhesion conditions and three tests under special
conditions were made. The layer thickness and concrete age were varied.

The adhesion crack spread along the rock-shotcrete interface at a load of about one third the failure load until the concrete cover failed by bending. See Fig 5 c.

The failure load was not affected by the layer thickness except in the 2-cm tests probably because of the rather large slit (≈5 mm) between the rock slabs.

Fig 5 c Plane unreinforced shotcrete layers after failure.
The dependence of the adhesion strength was obvious:

\[ \delta = \frac{\delta_F}{\gamma_{ad}} \]  
(see Fig 5 d)

was nearly a constant with a value of about 30 mm. This indicated that only a narrow band of shotcrete at a crack carried the load.

Fig 5 d Nominal adhesion stress block.

5.3 REINFORCED SHOTCRETE COMBINED WITH ROCK BOLTS

5.3.1 Description of reinforced test specimens

Five tests were made with 8 cm reinforced shotcrete combined with rock bolts. The test specimens are shown in Fig 5 f.

Test A1 was made mainly to demonstrate that a plane reinforcement is not effective under the loading conditions chosen if it is not fixed properly to the rock due to the character of the adhesion failure.

Test A2 corresponded to the common case when the reinforcement nets are attached to rock bolts only with thin steel wires.
Fig 5f Test specimens in series A. Notations for reinforcement according to Swedish design specifications.
The common arrangement of reinforcement nets and commercially available, shallow clasps was investigated in Test A3.

In Test A4 the reinforcement was combined with a new, high clasp. This clasp was designed by H. Sundquist, FortF, (Fig 5 g). This FortF clasp supports the shotcrete plate in the compressed zone nearly as a column does. It is also rather simple to shotcrete it.

In Test A5 the amount of reinforcement was increased considerably in order to test the capacity of the FortF clasp. The reinforcement was arranged as usually for normal concrete structures: close to the rock at the bolts and away from the rock surface between the bolts.

5.32 Observed failure modes

The primary failure was adhesion failure between rock and shotcrete at a very small deformation for all the tests (A1 to A5).

The behaviour after the primary failure differed between the tests.

The failure process never stopped or stabilized in Test A1. It was very similar to the unreinforced tests.

In Test A2 the load dropped almost to zero after the primary failure but the rock bolts made it possible to increase the load somewhat. The final failure was caused by bond failure between the rock bolts and the concrete, as in a pull-out test. The corresponding uniformly distributed "anchorage" stress was 4.8 MPa in each rock bolt.

The load decreased considerably after the adhesion failure in Test A3. It was, however, possible to increase the load to about 30 % of the maximum load. Only two wide cracks developed on each side of the loading block because of the arrangement of the reinforcement. Any bending of the shotcrete layer could not be observed between the cracks. The final failure was by punching. The failure load corresponded to a nominal shear stress

\[ \tau_{nom} = \frac{2P}{\pi h^2 \left( \frac{B}{h} + 1 \right)} = 1.2 \text{ MPa} \]
Fig 5 g Clasp used together with rock bolts in Tests A4 and A5.

using a modified formula by Nylander and Kinnunen (/11/).

B is a nominal width of the clasp and h is the effective depth of the shotcrete layer. In this case P in the original formula is replaced by 2 P because the rock bolt is subjected to load on one side only.

The theoretical failure stress according to Nylander and Kinnunen (/11/) is 1.4 MPa. Thus the measured failure load was 80% of the theoretically calculated load. This result indicates that the clasps did not transfer the load quite properly from the concrete to the bolts since the punching theory mentioned above normally underestimates the failure load.

A considerable drop of the load occurred after the adhesion failure in Test A4. It was, however, possible to increase the load up to 36% of the primary failure load. The crack pattern was the same as for Test A3.

The failure was caused by punching. The nominal shear stress at failure
\[ \tau_{\text{nom}} = 1.3 \text{ MPa}, \] which is equal to the theoretical value. This indicates that the FortF clasps transferred the load more properly from the concrete to the bolts and that the failure load corresponded to the amount of reinforcement in agreement with the punching theory mentioned above.

In Test A5 the decrease of the load was smaller than for the other test. It was possible to increase the load up to 94% of the primary failure load (only 75% of the primary failure load for Test A3, though). During the reloading several fine flexural cracks developed and a considerable curvature was noticed. The failure was by punching at one side of the test specimen and more like a beam shear failure at the other side. The nominal shear stress at failure was 3.0 MPa, which corresponds 110% of the theoretical value.

5.33 Deformations

In Fig 5 h the relative displacement of the middle slab is plotted against the applied load. Test specimen A5 is of special interest. A properly designed reinforcement in combination with an effective clasp gave a very strong and ductile shotcrete cover. The plastic energy in Test A5 at failure was six times the energy in Test A3. The energy ratios for Tests A5, A4, A3 were 6:1.6:1.0.
Fig 5 h Load-deformation curves for Tests A2-A5.

1 \( M_p = 10 \) kN, 1 kp/cm = 1 kN/m. Arrows show the primary failure loads for the different tests.

6. PLATE AND MEMBRANE ACTION OF PLANE SHOTCRETE LAYERS AFTER THE ADHESION FAILURE

6.1 GENERAL REMARKS

The performed tests were one-dimensional, since strips of constant width were tested. In reality the plane case nearly always is two-dimensional. An adhesion crack around a single rock piece spreads more or less like a ring on a water surface. Since the periphery of the failure zone grows larger and larger the bearing capacity has to increase since the failure load has been found to be proportional to the length of the failure zone. The adhesion crack has to stabilize somewhere. It is of interest to study a circular concrete plate and examine which load it can carry.
In the following an attempt will be made to get an idea of what might happen after the primary adhesion failure.

Four cases can be distinguished:

a) An uncracked circular concrete plate carries the load after the adhesion crack has stabilized.

b) A cracked reinforced circular concrete plate carries the load.

c) A circular membrane carries the load.

d) The reinforcement bars are torn off and the slab collapses.

In the following analysis two fundamental assumptions are made:

1) An adhesion crack forms when the distributed shear force, \( p \), is 40 kN/m. The crack stabilizes when \( p = 13.3 \) kN/m. This assumption has been empirically confirmed by the test, but is probably not valid for all rock materials.

2) The load follows the movements of the concrete plate. This assumption is probably not realistic for all rock loads, especially at large deformations.

6.2 THE UNCRACKED SHOTCRETE LAYER ACTING AS AN ISOTROPIC CIRCULAR PLATE

The loading case is indicated in Fig 6 a below.

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Fig 6 a Loading case for circular plate.
Fig 6 b Theoretically calculated primary (P₁) and secondary (P₂) failure loads for plane circular shotcrete layers. Bending tensile strength 6 MPa and adhesion failure load 40 kN/m.

In Fig 6 b P₁ and P₂ as functions of the block area $A = \pi r^2$ are given for two usual thicknesses of the shotcrete layer, 4 and 8 cm. It can be easily seen that P₂ always is much smaller than P₁, which means that there is no redundancy in an unreinforced plane shotcrete lining.
6.3 THE CRACKED REINFORCED SHOTCRETE LAYER STUDIED WITH YIELD LINE THEORY

The loading case is the same as in Fig 6 a. The assumed yield line pattern is shown in Fig 6 c below.

![Yield line pattern and sector element used in the yield line analysis.](image)

At for example $r_0/R = 1/3$, $p = 40 \text{kN/m}$, $h = 8 \text{ cm}$, $f_{sy} = 400 \text{ MPa}$ the following reinforcement will be required for a circular block.

<table>
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<tr>
<th>Area of moving block $m^2$</th>
<th>Required reinforcement area %</th>
<th>Center distance for bar $\varnothing 6$ mm</th>
<th>$\varnothing 8$ mm</th>
<th>$\varnothing 10$ mm</th>
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<td>0.5</td>
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</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>44</td>
<td>80</td>
<td>125</td>
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<tr>
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<td>1.3</td>
<td>31</td>
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<td>56</td>
</tr>
</tbody>
</table>

Table 1. Required two-way reinforcement to maintain plate effect of an 8 cm plane shotcrete layer.
The table shows that it is possible to reinforce against downfall of small blocks and that normally used reinforcement is insufficient under the assumed circumstances.

6.4 THE CRACKED REINFORCED SHOTCRETE LAYER ACTING AS A CIRCULAR MEMBRANE

The effect of the two-way reinforcement is taken into account by assuming that it acts as radial reinforcement with equal spacing when \( r = r_0 \). It has also been assumed that it reaches some characteristic tension \( E_B \) over the distance \( r_0 \) to \( R \) at a failure stress \( f_B \).

Some calculations give that the failure tension of the bars must be at least 8 % to get a higher carrying capacity of the membrane than of the adhesion action in the uncracked state.

It is possible to reach this level by using ordinary deformed bars but not by using welded reinforcement nets of cold deformed steel.

7. TESTS ON CURVED SHOTCRETE LAYERS

7.1 GENERAL REMARKS

In the second part of this shotcrete investigation 16 tests according to figs 7 a and 7 b were performed. The tests have not been finally published so there will only be given a very brief description here.

Fig 7 a Test specimens in Tests 1–9.

Fig 7 b Test specimens in Tests 10–16.
By changing the position of the horizontal rods the ratio horizontal force, $H$, to vertical force, $V$, could be changed.

The primary failure mechanism was always spalling of the shotcrete layer from the rock surface.

In tests 10–16 where supports for the shotcrete arch were introduced, the load could be increased after the adhesion failure until concrete failure occurred. Because of the dimensions and geometry this failure was mostly a shear failure but sometimes buckling of the horizontal part of the shotcrete layer caused the failure. The tests showed that the carried vertical load is strongly dependent on the horizontal force acting at the joint.

The tests also showed that a shotcrete arch which is loaded might loosen totally from the rock without any visible failure in the shotcrete, i.e., if the arch has sufficient supports for its legs.

8. **SUMMARY**

This paper can be shortly summarized as follows:

a) Shotcrete structures often fail primarily by high adhesion stresses between the shotcrete and the rock. The adhesion failure may lead to the final failure unless special precautions are taken.

b) Only a narrow band of shotcrete carries the load at a joint.

c) Reinforcement in a plane, or nearly plane shotcrete structure is (probably) of no use unless it is combined with rock bolts and clasps.

d) A proper design of these clasps and reinforcement gives a very strong and ductile structure.

e) A shotcrete arch shall always have supports. In that case its loading capacity will be very high even if the arch loosens from the rock.