Shotcrete: Elements of a System – Bernard (ed)

Structural behaviour of shotcrete on irregular hard rock surfaces

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ABSTRACT: Tunnels and underground openings in hard rock are often constructed with arch-shaped ceilings and complicated 3D geometries arise at intersections with cross tunnels and other openings. This is further complicated due to the often irregular shape of the rock surface and the uneven shotcrete thickness, making it difficult to analyse the interaction between rock and support systems. A study of the interaction in 3D between an irregular, rough rock surface and supporting rock bolts and shotcrete has begun, through finite element modelling using non-linear material models and formulations capable of describing large deformations. Various cases that may cause failure are to be studied, such as falling blocks or heavily jointed rock, bolt failure and drumminess between rock and shotcrete. An important conclusion from the preliminary results is that rock bolts should be placed at points where the shotcreted surface is locally convex, i.e. at peaks.

1 INTRODUCTION

In underground construction and tunnelling, the need for more efficient use of materials and sustainable designs require an increased understanding of the interaction between the rock and rock reinforcement systems of shotcrete. Tunnels and underground openings in hard rock are often constructed with arch-shaped ceilings that carry the weight of the above rock. Complicated three dimensional (3D) geometries arise at intersections with cross tunnels and other openings making it difficult to analyse the interaction between rock, shotcrete and other support elements such as rock bolts. This is further complicated due to the often irregular shape of the rock walls and the uneven shotcrete thickness. The design of shotcrete based rock support systems for such geometries must therefore be done with advanced analysis tools, such as based on the finite element (FE) method.

The division of Concrete Structures at KTH have been involved in research on shotcrete as rock reinforcement since the middle of the 1970s, see e.g. Holmgren (1979, 1985, 1992). One of the doctoral projects studied the load carrying capacity of bolt anchored shotcrete on rock and it was demonstrated by Nilsson (2004) and Nilsson & Holmgren (1999, 2001) that a further, detailed study of the interaction in 3D between an irregular, rough rock surface supported by bolts and shotcrete with varying thickness is of great interest. The numerical investigation must be made using FE models with non-linear material formulations capable of describing large deformations as well as concrete cracking and crushing. Of special interest is the load carrying contribution from the bonding between rock and shotcrete. Various cases of local instability that may cause failure must be studied, such as falling blocks, heavily jointed rock, bolt failure and drumminess between rock and shotcrete. Time-dependent effects such as shotcrete creep and shrinkage, varying temperatures and humidity are also of interest. There is a need for geometric in situ data and experimentally obtained material data for structural shotcrete.

The aim of this recently initiated research project is to obtain an understanding of the performance of load carrying shotcrete systems for rock support. The main objective is to obtain an increased understanding of the behaviour of shotcrete as a construction material, with a focus on the entire life cycle from spraying until possible failure occurs. This paper summarizes the background to the project and the current knowledge, presents preliminary results and describes the ongoing work within the project.

Reliable and efficient analyses are needed since the construction of tunnels and other structures in rock are large investments for society and of great importance for infrastructure. As an example, there is today ongoing Swedish tunnelling and rock engineering projects for a cost of 1.5×10^9 EUR/year. The outcome of this project will lead to new guidelines and recommendations for practical use that will facilitate future construction of optimized, more efficient and economic tunnels and subspace structures. This will be of great importance in civil engineering underground work, tunnelling and also for the mining industry. An improved understanding of the interaction between the rock and rock reinforcement systems of shotcrete will be of great value when designing sustainable infrastructure systems and will also lead to a more efficient use of the building materials and result in constructions that can maintain a high degree of safety without unnecessary repairs and rehabilitation.

2 SHOTCRETE AS ROCK REINFORCEMENT

Rock reinforcement is necessary to create stable underground structures in rock, e.g. tunnels and other subspace openings. More than one material or element is often included in the support systems, such as shotcrete, cast in place concrete, rock bolts, arches and other pre-fabricated structural elements. The structural principle is to reinforce the rock so that it can carry its own weight, even when an opening has been created within the rock mass. The interaction between rock, shotcrete and other reinforcing elements is complex and factors such as geometry, shape and irregularities of surfaces, built-in stresses, systems of cracks in the rock and material strength affects the load carrying capacity and deformability.

2.1 *Geometries in 3D*

Curved rock surfaces, such as tunnel roofs, will affect the load carrying capacity of rock-shotcrete systems. Sharp edges, peaks and depressions in the rock surface will provide anchorage between rock and shotcrete and lead to varying degrees of interaction and constraint as increasing load and stresses in the shotcrete approach the ultimate stress. The situation is further complicated by the often irregular shape of the rock walls and the varying shotcrete thickness which is a result of this. Shotcrete fills out holes and depressions in the rock resulting in a shotcrete surface that is smoother (harmonic-shaped) than the underlying rock, e.g. sine-shaped. This can lead to the formation of thin, critical shotcrete sections with lower load carrying capacity and an increased risk of crack formation. Rock bolts with washers (plates) give rise to stress concentrations in the shotcrete and it is therefore interesting to further study how the placement and properties of the bolts and washers affects the overall stress situation in the shotcrete.

Different cases of rock instability will define the design load cases for the rock support systems. A shotcrete lining sprayed onto an arch-shaped tunnel ceiling can be loaded by loose pyramid-shaped blocks of rock. Such blocks are the results of existing cracks in the rock mass and the pressure from the surrounding rock may push these against the shotcrete with possible punching failures as a result. Such a case is shown in Figure 1 where bending failure occurs in a bolt-supported shotcrete lining due to punching from a loose block. When a block or section of rock is severely fractured the tensile strength and bending stiffness are reduced to zero. This mass will act as a flexible surface load on a supporting shotcrete lining as it is deformable and therefore follows the displacements that occur in the shotcrete. The size of the load is given by the inner friction angle and the density of the material.

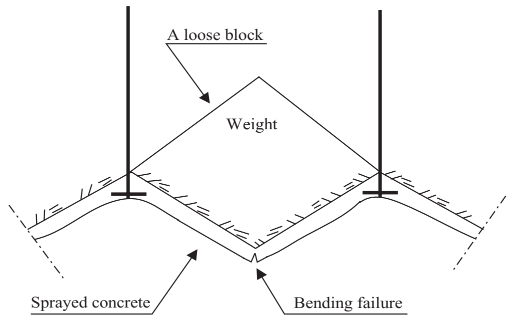

Figure 1. Failure in a bolt-supported shotcrete lining on rock (Chang 1994).

2.2 *Irregular rock surfaces*

The example shown in Figure 1 also demonstrates how the irregular shape of a rock surface can lead to bending and stress concentrations in shotcrete linings. The properties of irregular shotcrete surfaces have been investigated in laboratory tests by Chang (1994) who also used numerical modelling to evaluate the results. The tested shotcrete models were given sine-shaped surfaces. The importance of the shape of the shotcrete surface has also been a part of the work by Malmgren (2005). In numerical analyses with 2D models, that also included rock bolts, the shotcrete was given a saw-toothed variation and the importance of changes in shotcrete thickness was also studied to some extent. An example of a tunnel profile with irregular shape, based on in situ measurements, is shown in Figure 2. Another study on the topic has been presented by Fotieva & Bulychev (1996) who approached the problem with small scale analytical formulations. They concluded that variation in shotcrete thickness leads to stress concentrations and an increased risk of crack initiation. This has also been observed in situ by Ansell (2004) and Ansell & Slunga (2004) during failure mapping of shotcrete within the traffic tunnels of the Southern Link (Södra länken) in Stockholm. Shrinkage

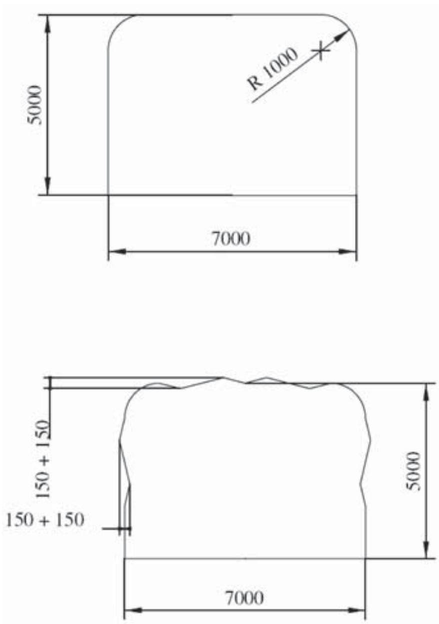

Figure 2. Tunnel with smooth rock surface and with a roughness of 150 mm (Malmgren 2005).

cracks often appeared at sections with thin shotcrete close to much thicker parts.

3 FINITE ELEMENT MODELS

There is little published research on numerical studies of rock supported with shotcrete and bolts where non-linear material formulations for concrete and steel are used (Ansell 2009). It is today usually not possible to describe deformation of support systems up to crack initiation and failure. The focus is often set on the properties of the rock and the reinforcement is often given only elastic deformation properties, for example as in the recent studies by Karakus (2007) and Chen et al. (2009). There are some exceptions, e.g. from Golser (1999) and Liu et al. (2008), and in those cases a powerful, general FE program with built-in advanced material formulations such as Abaqus/Standard (Simulia 2009) have been used.

3.1 *Irregular 2D slabs*

Models in 3D are needed for detailed studies of the interaction between rock, shotcrete and other support. One simple model is a horizontal slab of shotcrete that carries a severely cracked rock mass, as described in section 2.1. Such a model will only include the shotcrete, and possibly also rock bolts, but the rock will be present as a uniformly distributed load applied on top of the slab. The easiest way to approximate irregularities such as those shown in Figure 2 is to apply harmonic (sine-shaped) variations in two orthogonal directions to the surface of this otherwise plane and horizontal slab. The result is shown in Figure 3 and can be seen as a model of a part of a shotcreted horizontal tunnel ceiling. These types of shell structure were modelled by Nilsson (2004) who studied slabs with freely supported and fixed edges. The effect of one or many rock bolts was also included by restricting the vertical movements for a small number of nodes before the load was applied. Sharp irregularities can in this way thus be approximated with harmonically varying surfaces. It should be noted that this shape is a better approximation of the outer surface of the shotcrete than of the rock surface. However, different upper and lower surfaces require varying shotcrete thickness which is not included in this simplified approximation.

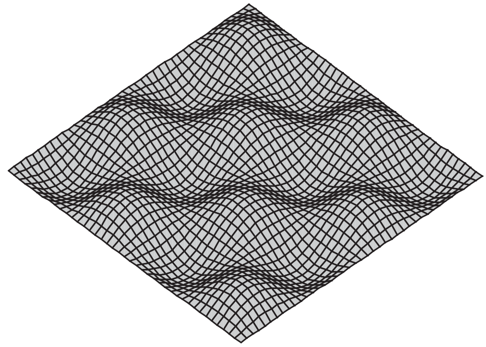

Figure 3. Finite element model of a plane shotcrete slab with harmonic irregularities.

3.2 *Shotcrete models in 3D*

A further development of the modelled plane slab is a curved shotcrete shell with a semi-circular cross-section. In its most simple form it will have a constant thickness and harmonic irregularities, such as shown in Figure 4. These types of shells can also be suspended using rock bolts but will also carry load through the arch effect. A more sophisticated version is shown in Figure 5. The outer surface of the curved shell is here given a highly irregular, randomly distributed shape which is more similar to profiles such as in Figure 2. The inner surface of the shell is completely smooth, thus approximating the outer surface of shotcrete that fills out depressions in the rock. Such a shotcrete shell will

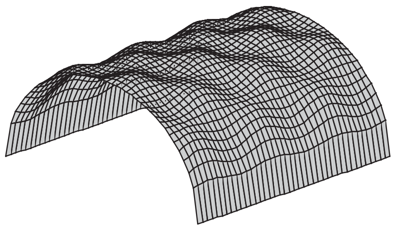

Figure 4. Finite element model of a shotcrete shell with harmonic irregularities.

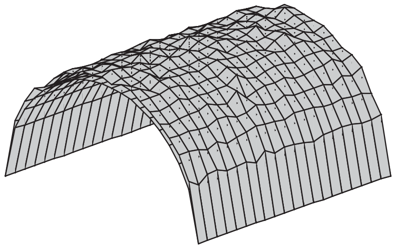

Figure 5. Finite element model of a shotcrete shell with a highly irregular outside and a smooth inside.

thus have a varying thickness and is a reasonable approximation of what can be observed in situ.

3.3 *Models with rock and shotcrete*

It is possible to describe the interaction between punching loads from loose blocks with the shell models described above. The bonding between rock and shotcrete can also be included by fixing all the nodes in the direction orthogonal to the shell surface. The rock will, however, give no contribution to the load carrying capacity of the system. For detailed studies and more complicated load cases the rock must therefore be directly included in the models. Models in 3D including rock and rock support are often done in a large scale with a focus on the deformation of the rock mass directly around a tunnel or other opening. One such example is presented by Brandshaug & Rosengren (2008) who studied the effect of blasting in rock tunnels. The rock support included consists of bolts and shotcrete described with only linear material models, also with a smooth rock surface and a constant shotcrete thickness. A detailed study of the non-linear deformation of bolts and shotcrete would be too computationally expensive with such a large model. Results from large-scale modelling of tunnels in large volumes of rock can, however, be used as boundary conditions for smaller models, in local scale. Such 3D models can be used for detailed studies of the shotcrete-rock interface, also including rock bolts and other reinforcement.

4 MATERIAL PROPERTIES

Modern concrete technology makes it possible to adapt the composition of shotcrete to the performance needed. Changes in material properties will have a great impact on the load carrying capacity of shotcrete-based reinforcement systems. The effects of steel and synthetic fibre reinforcement can also be included in the models and if needed also bar- and mesh-reinforcement. For concrete (shotcrete) and steel the stress-strain relations must be described with non-linear material formulations that account for plastic deformation in steel and cracking in concrete materials. Research on non-linear material models for shotcrete has been published by e.g. Meschke et al. (1996). That particular model describes the strain in the shotcrete as a sum of elastic strain, shrinkage, temperature dependent strain, visco-plastic strain and strain due to aging.

4.1 *Non-linear behaviour of shotcrete*

The analyses within this project have been carried out using the general finite element program Abaqus/Standard (Simulia 2009) which contains linear and non-linear material formulations suitable for concrete, also in combination with other materials. The non-linear model chosen for the analysis is based on the “smeared crack approach” which means that no individual cracks are initiated in a structure but there will locally be areas with decreased stiffness.

The material properties for one type of fibre reinforced shotcrete used in the analyses are given in Table 1. The uniaxial stress-strain relationship in compression and tension is governed by the piece-wise linear curve shown in Figure 6. On the compressive side (negative σ) the first line represents elastic deformations up to the elastic limit f_{cy}. The inelastic part is described by three lines before the ultimate compressive strength f_c followed by another five lines until the maximum compressive strain is reached. The tensile stresses (positive σ) follow the linear, elastic relation until crack failure at f_t. The response after cracking in Abaqus/Standard (Simulia 2009) is governed by a relation based on fracture mechanics. A stress-displacement relation approximated with a linear function is used, for the analyzed shotcrete shown in Figure 7. The area under the curve represents the fracture energy $G_F = 0.5u_0 f_t$ where u_0 is the crack opening displacement. Typical values for G_F representing concrete is within 50–200 N/m and in this case was a value

Table 1. Material properties for the analyzed fibre reinforced shotcrete.

Modulus of elasticity	E	34 GPa
Poisson's ratio	ν	0.2
Compressive strength	f_c	50 MPa
Elastic limit	f_{cy}	30 MPa
Tensile strength	f_t	4.5 MPa
Fracture energy	G_F	135 N/m
Crack opening displacement	u_0	0.06 mm

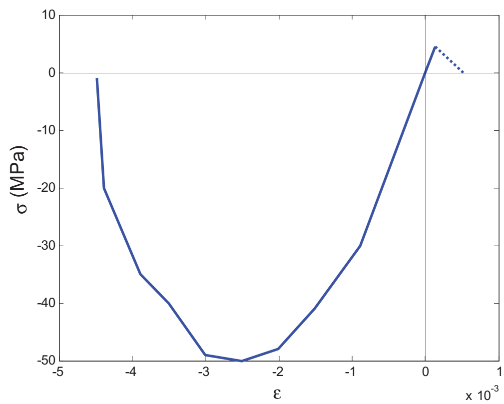

Figure 6. Uniaxial stress-strain relationship for the analyzed fibre reinforced shotcrete.

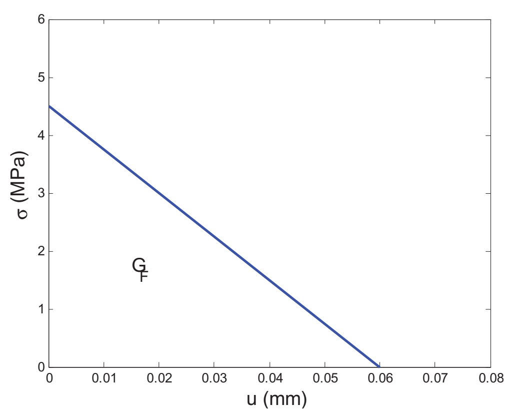

Figure 7. Tensile stress-displacement relationship for the analyzed fibre reinforced shotcrete.

representative for (sprayable) concrete containing steel fibres chosen, see Nilsson (2004).

4.2 *Steel*

The steel material in rock bolts, bars and mesh reinforcement can be described using linear or non-linear stress-strain models, depending on the expected stress levels in the steel. For rock bolts, the non-linear model is justified for cases with weak bolts and concentrated, large deformations around single bolts. This usually requires a ductile shotcrete, reinforced with e.g. large amounts of steel fibres or steel mesh. The use of stiff steel washers, quadrilateral or circular steel discs, is necessary for the transformation of load from rock to bolts, via the shotcrete lining. In a case with strong rock bolts failure will occur in the shotcrete, without plastic deformations in the bolts which thus can be defined as only linearly elastic. This is demonstrated in the preliminary results presented in the following sections.

The reinforcing effect from evenly distributed steel fibres can be included by increasing the ductility of the shotcrete, i.e. changing G_F and u_0, as pointed out in the previous section. Steel mesh and discrete reinforcing steel bars can be included as embedded elements in the shotcrete and it is also possible in Abaqus/Standard (Simulia 2009) to define the degree of coupling between the two materials. The stress-strain relationships can be either linear or non-linear, the choice should be based on the levels of strain expected. An elastically linear model for the reinforcement may give an over-stiff behaviour for cases with large deformations.

4.3 *Rock*

In the presented preliminary examples the rock only acts as a load and does not contribute to the supporting system. This case is relevant for a severely fractured rock with a zero modulus of elasticity, giving an evenly distributed surface load on the supporting shotcrete lining. In later more detailed modelling examples, the properties of the rock mass will be described based on realistic material data including system of cracks, the possible geometry of loose blocks, properties of cracks and the arch shape of the analyzed tunnel or opening. A jointed rock mass will be described as built up by blocks that are loose or connected to "solid rock". The deformation of each block will be elastic while the rock joints will be described using elasto-plastic laws based on rock mechanic theories. In the studied models at a "local" scale the rock will be solid and elastic but with one or more loose blocks held in place by shotcrete, rock bolts and possibly also other reinforcing elements. Displacement of blocks can be described based on experience or results from large-scale rock mechanic models.

5 PRELIMINARY RESULTS

As a first part of the project preliminary results from the work by Nilsson (2004) are included.

An important part of that investigation was a study of the importance of placement of rock bolts with respect to the load carrying capacity and risk of early shotcrete failure. The examples studied include a horizontal, quadrilateral section of shotcrete suspended with single or multiple rock bolts. The thickness of the shotcrete was set to 40 or 80 mm and the irregular surfaces were as described in Figure 3. The shotcrete lining was modelled with 3D shell elements with four nodes and nine integration points through the thickness, referred to as S4R5 in Abaqus/Standard (Simulia 2009). The uniformly distributed load from the weight of the rock was applied as vertical point-loads at every node of the model. The load-deformation behaviour and the ultimate load were calculated by step-wise increasing the load.

5.1 *Irregular slab with one rock bolt*

The first studied section of shotcrete is a quadrilateral 4×4 m^2 slab with a bolt placed at the centre. The finite element model with 40×40 shell elements is shown in Figure 8. The irregular surface is sine-shaped with a “wave length” of 1.6 m. No displacements or rotations are allowed at the edges of the slab, thereby accounting for the influence from adjacent sections of a large, continuous shotcrete slab. The rock bolt with a quadrilateral washer is represented by 9 nodes that are fixed in the vertical direction. Two cases were studied, with the bolt placed either at a peak or at a depression in the slab, as shown in Figure 9.

The relative stiffness of the shotcrete slab is here defined as the ratio between the ultimate deflection of a similar but plane slab δ_0 and the analyzed irregular slab δ_i. For the presented case the results are given in Figure 10, for 40 and 80 mm shotcrete and heights of the irregularities up to 400 mm. The

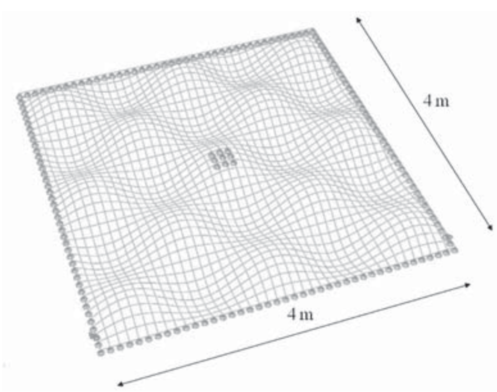

Figure 8. Finite element model of shotcrete and one rock bolt (Nilsson 2004).

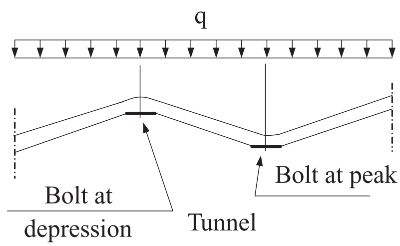

Figure 9. Placement of rock bolts at peaks or in depressions (Nilsson 2004).

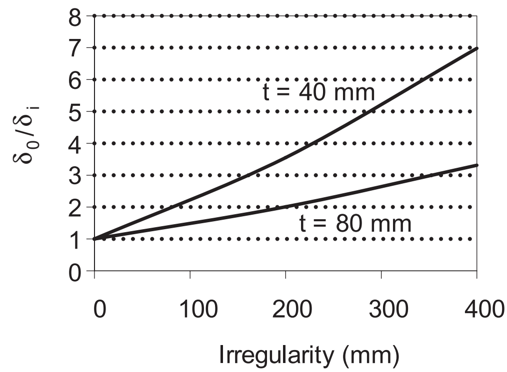

Figure 10. Relative stiffness as a function of irregularity and shotcrete thickness (Nilsson 2004).

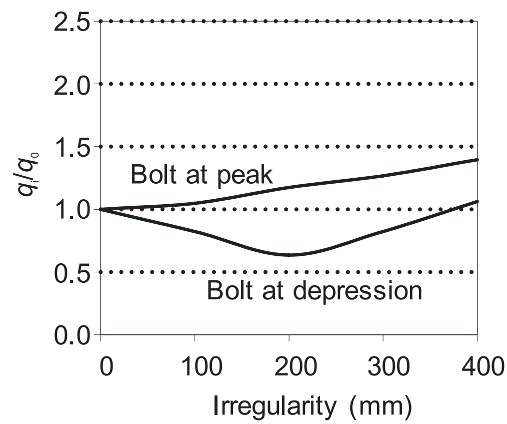

Figure 11. Failure load for a 80 mm thick shotcrete slab as function of irregularity and placement of rock bolt (Nilsson 2004).

relative load carrying capacity can in the same way be defined as the ratio between the corresponding maximum distributed loads q_0 and q_i, respectively, at which failure occurred. The results are shown in Figure 11, for the cases of the bolts being placed at a peak and in a depression of the slab. The stress

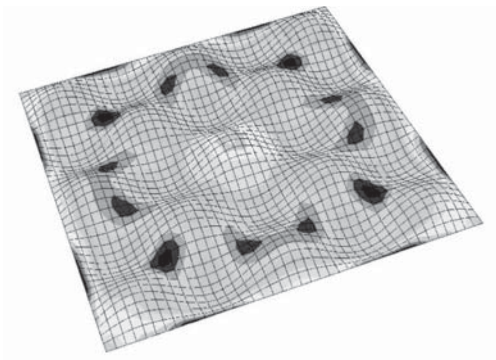

Figure 12. Principal stress distribution on the upper surface of a 80 mm thick shotcrete slab. High tensile stresses around the bolt placed in a depression within the slab (Nilsson 2004).

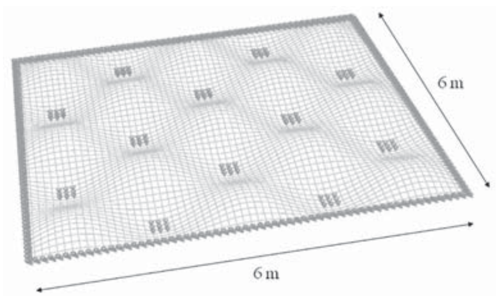

Figure 13. Finite element model of shotcrete and twelve rock bolts (Nilsson 2004).

distribution in a slab is represented by Figure 12 which shows the principal stresses over the upper surface of a 80 mm thick shotcrete slab with fixed edges and the rock bolt placed at a depression in the slab. The highest tensile stresses occur at the edges and around the bolt where tensile failure occurs.

5.2 *Irregular slab with systematic bolting*

This second example demonstrates the behaviour of a slab with multiple bolts placed systematically over the surface. The model of this slab shown in Figure 13 is 6×6 m^2, with 60×60 shell elements and with twelve sets of fixed nodes, but otherwise identical to the slab in Figure 8. The height of the irregularities was set to 400 mm and the "wave length" was here 2.4 m. The load-deflection relations up to failure are shown in Figure 14, for 40 and 80 mm thick shotcrete slabs, respectively. The results also demonstrate the differences due to bolt placement, i.e. the entire set of bolts placed at peaks or in depressions. The stress distributions in the loaded slabs are here shown in Figures 15–16.

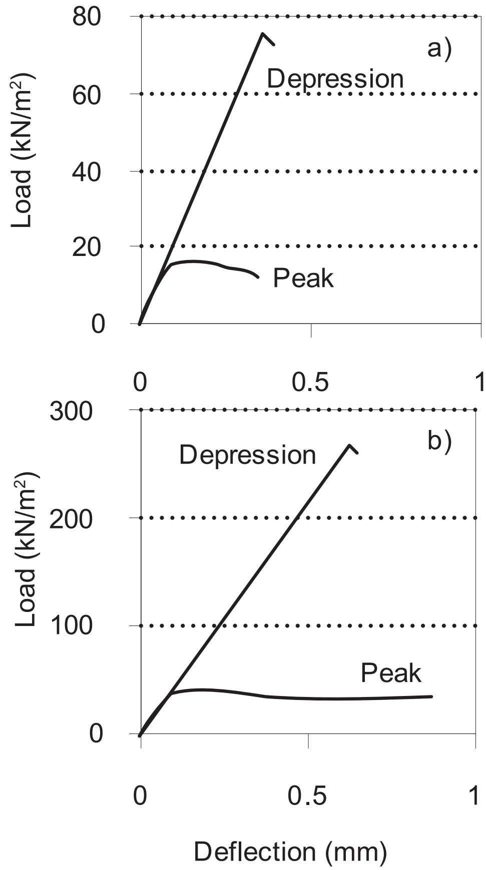

Figure 14. Load-deflection for shotcrete slab with multiple bolts and a thickness of a) 40 mm and b) 80 mm (Nilsson 2004).

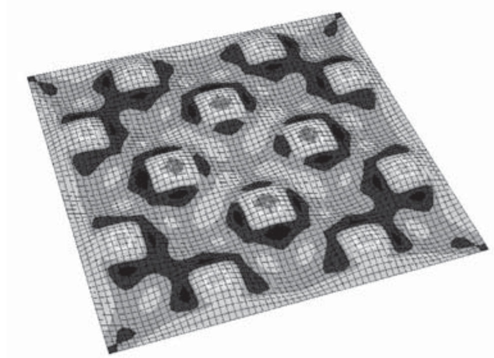

Figure 15. Principal stress distribution on the upper surface of a shotcrete slab suspended using twelve rock bolts. High tensile stresses around the bolts placed in depressions of the slab (Nilsson 2004).

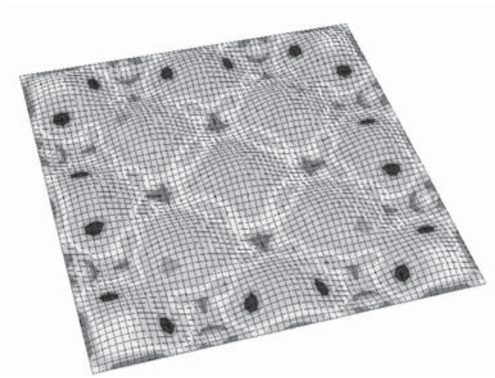

Figure 16. Principal stress distribution on the upper surface of a shotcrete slab suspended using twelve rock bolts. Low tensile stresses around the bolts placed at peaks on the slab (Nilsson 2004).

The highest tensile stresses occur for the case with the bolts placed within depressions (Fig. 15) while placement at a peak results in low tensile stresses around the bolts (Fig. 16). In the latter case there is high, concentrated compressive stresses on the lower side of the slab, at each bolt, i.e. a stress distribution as in Figure 15 but with opposite stress sign (+/–).

6 SUMMARY

The presented project has recently started and currently the preliminary results from a pilot-study are available. These results do, however, give a representative description of some of the features that are studied in detail within the ongoing project. The finite element models of rock and shotcrete surfaces will be based on realistic data, from measurements in situ and a side-project with in situ measurements is therefore being prepared. The data must capture the structure of the rock surface with holes, depressions and peaks clearly defined. It is also important to have accurate measurements of the outer shotcrete surface since the variation in shotcrete thickness is the difference between these two sets of geometric data. Geometric data can possibly be obtained with laser-scanning, but a review of previous measurements from large civil engineering projects is also done.

6.1 *Preliminary results*

The results from modelling of the shotcrete slab with one rock bolt presented in section 5.1 shows that the irregularities have a greater effect on the slab stiffness than on the load bearing capacity. The structural response of the slab is affected by the thickness in relation to the irregularities so that a thin slab becomes relatively much stiffer with increased irregularity compared to a thicker slab. The reason for this is the relatively large change in bending stiffness as a function of irregularity for the thinner slab (Nilsson 2004). The placement of the bolt in a depression within the shotcrete resulted in tension across the entire shotcrete thickness around the bolt. This reduced the load bearing capacity compared to a case with the bolt placed at a peak. It was also observed by Nilsson (2004) that the maximum load capacity of an irregular slab was reached at a smaller deflection compared with a plane slab of identical dimensions, especially when the bolt was placed at a depression.

The examples in section 5.2 show that the load bearing capacity increases if bolts are located at peaks instead of depressions. It should be noted that these results demonstrate this for sets of evenly distributed bolts, with all bolts placed either at peaks or at depressions in the shotcrete. The distribution of the principal stresses given in Figures 15–16 show that large concentrated tensile stresses develop when the bolts are located at the depressions and lower stresses develop when placed at peaks. A change in bolt placement resulted in completely different structural behaviour, as demonstrated in Figure 14. The 40 mm thick slab with bolts at the peaks show an almost linear response up to the maximum load whereas the slab with bolts at depressions begins to soften at a considerably lower load. For the 80 mm slab the behaviour is similar but the load level is much higher. It should be noted that the load bearing capacity of the 40 mm slab with bolts at the peaks is twice that of the 80 mm slab with bolts at depressions.

It is commented by Nilsson (2004) that when the bolts are placed at the peaks the load is basically carried by compressed domes between the bolts, thereby increasing the load bearing capacity. It is also pointed out that these high values increase the risk of tensile failures in the bolts and punching failures of the bearing plates. The most economical way to avoid this problem must be to increase the dimensions of bolts and washers instead of the thickness of the shotcrete.

6.2 *Ongoing research*

The ongoing work focuses on the behaviour of irregular shotcrete slabs and shells and the effect of varying shotcrete thickness (Beijer-Lundberg 2009). The following parts of the project will deal with the interaction between rock and reinforcement consisting of shotcrete and rock bolts, studied through detailed modelling in 3D including variations in rock geometries, shotcrete thickness, material descriptions, etc. The models of the rock-shotcrete system describe sections with 3D geometry, based on the principles outlined here in section 3, but with increased complexity. The models will include local instabilities in the rock, such as loose rock blocks, seriously cracked rock masses, rock bolt failure, and partial debonding between shotcrete and rock. The behaviour of rock-shotcrete systems are simulated all the way until failure occurs and the tested constitutive material models must therefore be able to account for large deformations in 3D. Reinforcing steel and other reinforcement will be included in some models which will facilitate a detailed representation of stresses, deformations, damage and cracks within the shotcrete and at the interface between shotcrete and rock. The applied loads, the geometries of tunnels and underground openings, etc will be chosen on basis of conditions that are common in tunnelling and civil engineering.

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