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# Calibration of an advanced material model for a shotcrete lining

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**Abstract.** Proper choice of a constitutive model is an essential part of any successful application of numerical methods in geotechnical engineering. In most cases, attention is paid to the soil constitutive model. For structural elements, such as tunnel linings, retaining structures etc. elastic constitutive models are often used. These material models however do not involve many aspects of a real structural behavior such as limited tensile and compressive strength, strain softening and time dependent behavior during service life of a construction. In the proposed paper, an application of the novel constitutive model for shotcrete (Schädlich, Schweiger, 2014) is presented. The paper is focused at the process of determination of input parameters values of this model based on performed laboratory test. Section of the primary collector network in Brno was chosen for the purpose of obtaining shotcrete lining samples.

## 1. Tested material and laboratory tests

For described calibration of the material model sprayed concrete from lining of collector network in Brno was selected. The particular section of primary collector is situated under Leitnerova street (near the shaft Š 13 A) and which was constructed in 1980's. Sensors of geotechnical monitoring has been installed there so the sampling was easier and desirable right there. A drill core with diameter of 23 cm through whole thickness of the lining was obtained at first. Smaller samples for laboratory testing were made afterwards from the first core.

Amount of the material for testing was limited. Also, a lot of steel bar reinforcement was involved in the big drilled core. Thus, smaller diameter for core drilling of laboratory test samples was selected. Three types of test procedures were done:

- Splitting tensile strength
- Uniaxial compressive strength
- Triaxial compressive strength

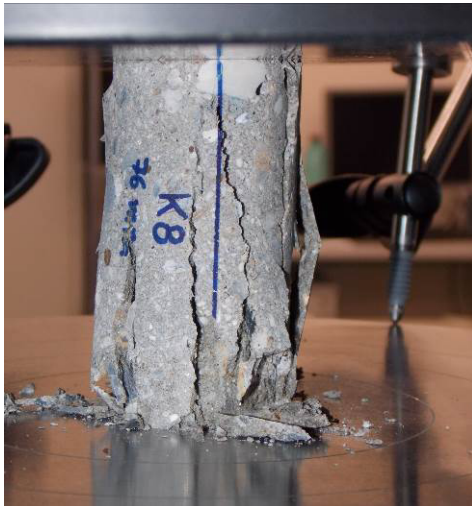
### 1.1. Splitting tensile strength

Parameter of tensile strength is required in the shotcrete material model. Tensile strength was determined by three point bending test in other calibration of the material model [1]. Lack of the testing material lead us to decision to obtain this parameter by splitting tensile test. Cylindrical samples with diameter 55 mm were prepared. Requirement of the standard [4] to height-to-diameter



ratio at least 1.0 was satisfied with 55 mm height of the sample. The test was driven by rate of loading at 190 N/s. A sample after test is shown in Figure 3.

As the result of splitting test was obtained 3.4 MPa in tensile strength for the sprayed concrete. This value is an average of three individual tests with standard deviation 0.12 MPa, hence the result can be considered as reliable.



**Figure 1.** Sample after failure in uniaxial compressive test.



**Figure 2.** Hoek cell during triaxial test.

### 1.2. Uniaxial compressive strength

Due to considerable amount of reinforcement bars in the concrete, as it was mentioned before, was selected diameter of 38 mm for core drilling of laboratory samples. The diameter of the aggregate used in the concrete was estimated to fraction less than 8 mm. Ratio of aggregate diameter to cored diameter was less than maximally allowed 1:3 according standard [5] so the selection of the drill core diameter was appropriate. To satisfy criterion of height-to-diameter ratio 2.0 was given requirement on samples height equal to approximately 76 mm.



**Figure 3.** Sample after splitting tensile test.



**Figure 4.** Sample after uniaxial compression test.



**Figure 5.** Sample after triaxial test at  $\sigma_1 = -8$  MPa with diagonal shear crack.

The compression test was governed by deformation with rate 0.5  $\mu\text{m/s}$ . For illustration see Figure 1. Higher deformation rates were also tested, but behavior of the concrete was more brittle in

other cases. Smaller increments of deformation caused more ductile response of samples. Thus, it was considered as suitable for obtaining calibration parameters of the shotcrete material model.

Results from one uniaxial compressive test were selected as representative with further relations to triaxial tests. Peak stress level was reached -44.1 MPa as peak strength.

### 1.3. Triaxial compressive strength

The same dimensions and axial loading conditions were used for triaxial compressive tests as for the uniaxial testing. Hoek cell was used for applying lateral (radial) pressure (see Figure 2) and LVDT sensors were used for deformation control. Convention of “-” for compression and “+” for tension stresses is used in this paper. Thus,  $\sigma_1$  represents the highest stress level and  $\sigma_3$  represents the lowest stress level with taking into account the signs.

Three different lateral pressures were applied gradually. Reached peak strength values are shown in Table 1 below. Post-peak softening of the material was observed in all three cases. The sample 3 after test is shown in Figure 5.

**Table 1.** Peak axial stress  $\sigma_3$  reached in triaxial tests at corresponding lateral pressure  $\sigma_1$ .

Sample	$\sigma_1$ (MPa)	$\sigma_3$ peak (MPa)
1	- 2.0	- 56.0
2	- 4.0	- 63.5
3	- 8.0	- 84.2

## 2. Model calibration

Process of determination of input parameters values for the Shotcrete model (SC) developed by [1,2] is presented in the following section.

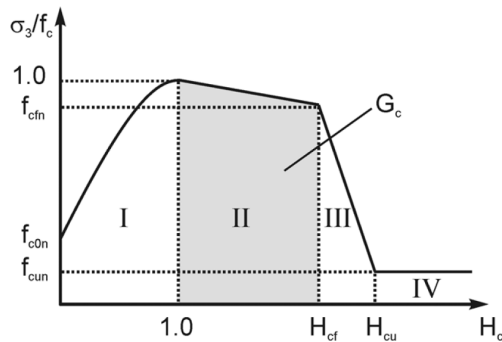
### 2.1. Brief description of the Shotcrete model

The SC model belongs to a group of elasto-plastic constitutive models involving strain hardening and softening. The following main features are involved in the SC model:

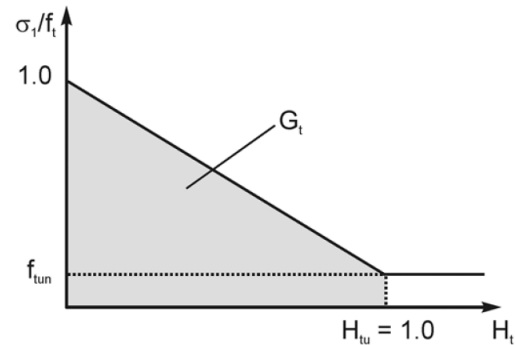
- Mohr-Coulomb yield surface for a deviatoric loading and Rankine yield surface for a tensile loading regime
- Strain hardening and softening in tension and compression
- Regularization during the softening regimes in order to avoid mesh dependency
- Increase of the shotcrete stiffness and strength with time
- Decrease of the shotcrete ductility with time
- Creep and shrinkage strains

Determination of input parameters related to the hardening during loading is presented in the paper. The stress – strain curves for loading in compression and tension are shown in Figures 4 and 5.

$H_c = \varepsilon_3^p / \varepsilon_{cp}^p$  and  $H_t = \varepsilon_1^p / \varepsilon_{tu}^p$  are normalized hardening – softening parameters in compression and tension,  $\varepsilon_3^p$  is a minor plastic strain,  $\varepsilon_{cp}^p$  is a plastic peak strain in uniaxial compression,  $\varepsilon_1^p$  is a major principal plastic strain and  $\varepsilon_{tu}^p$  is a plastic ultimate strain in uniaxial tension. Further details about the material model can be found in [1,2]. The list of relevant input parameters is stated in the Table 2.



**Figure 4.** Normalized stress strain curve in compression (taken from [2]).



**Figure 5.** Normalized stress strain curve in tension (taken from [2]).

**Table 2.** Input parameters related governing strain hardening

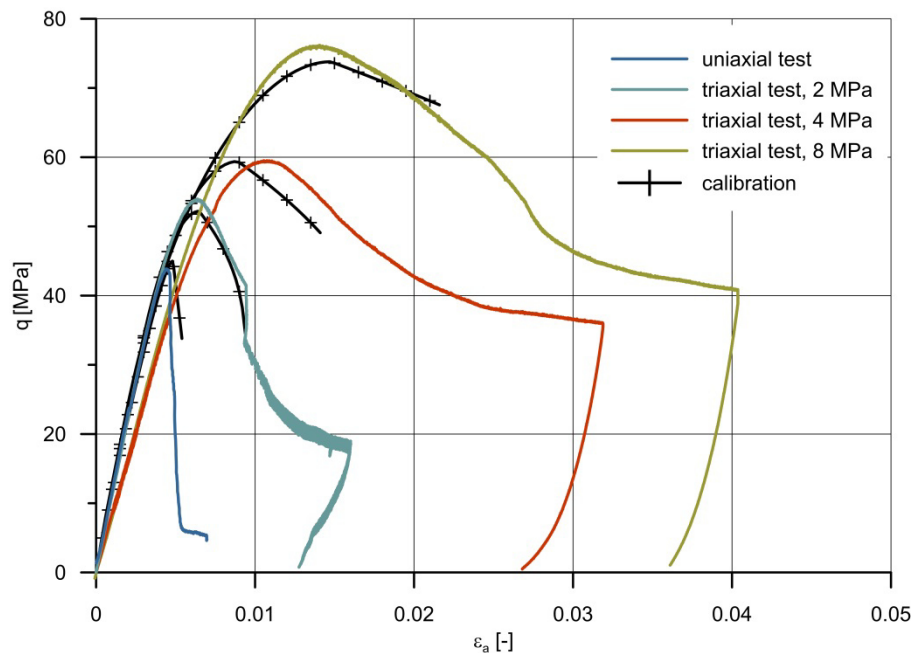
Parameter	Unit	Description
$E_{28}$	MPa	Young's modulus of cured shotcrete
$\nu$	-	Poisson's ratio
$f_{c,28}$	MPa	Uniaxial compressive strength of cured shotcrete
$f_{t,28}$	MPa	Uniaxial tensile strength of cured shotcrete
$f_{c0n}$	MPa	Normalized initially mobilized strength
$\epsilon_{cp}^p$	-	Uniaxial plastic failure strain
$a$	-	Parameter governing increase of $\epsilon_{cp}^p$ with $p'$
$\varphi_{max}$	°	Maximum friction angle

## 2.2. Model calibration

The uniaxial tensile strength  $f_{t,28} = 3.4$  MPa was derived from the performed splitting tests. The parameter  $a$  governing the shotcrete ductility and the maximum friction angle  $\varphi_{max}$  were derived from series of three triaxial tests described in the previous section. For determination of the remaining parameters it is possible to use the uniaxial test. Measured and calibrated stress strain curves are shown in Figure 6. Calibration was performed on a stress point level using the Plaxis 2D 2016 software package. Care must be taken when comparing post-peak behavior with experimental data due to inhomogeneity such as shear bands and transverse cracks occurring in the sample during post-peak strain softening. This requires a complete 3D FE model of a laboratory test. The final model parameters are listed in Table 3.

**Table 3.** Final set of input parameters

$E_{28}$ [MPa]	$\nu$ [-]	$f_{c,28}$ [MPa]	$f_{t,28}$ [MPa]	$f_{c0n}$ [MPa]	$\epsilon_{cp}^p$ [-]	$a$ [-]	$\varphi_{max}$ [°]
13500	0.2	45	3.4	0	0.0015	18	40



**Figure 6.** Stress – strain curves: measurements and calibration uniaxial test, triaxial tests with confining pressures -2, -4 and -8 MPa.

### 3. Results evaluation

#### 3.1. Performed laboratory tests

The compressive strength and shotcrete ductility is increasing and the rate of strain softening is decreasing for higher confining pressures. Differences between the peak and residual stresses are lower for higher confining pressures. All these aspects are in accordance with other experimental results (f. e. [3]). The initial stiffness for the triaxial tests with confining pressures -4 and -8 MPa is slightly lower in comparison with the remaining test which is in contrast with theoretical assumptions. This discrepancy might be caused by an initial sample disturbance or a slightly different original position of the sample in the lining.

#### 3.2. Calibration of the SC model

SH model correctly predicts the following features of shotcrete behaviour:

- Nonlinear stiffness decrease during strain hardening
- The compressive strength and ductility increase with increasing confining pressure
- The decrease of the rate of strain softening with increasing confining pressure. This aspect is however possible to analyse only from a qualitative point of view. A quantitative prediction would require a complete 3D model.

### 4. Conclusions

The computed stress – strain curves are in reasonable match with the laboratory tests. The discrepancy described in the previous section is not taken into account in the calibration. Slightly lower compressive strength was reached for the test simulation with the confining pressure -8 MPa. A linear Mohr-Coulomb yield surface is implemented in the model. The failure surface for rocks and concrete is however not linear which might cause differences especially for higher ranges of confining pressures ranges. From an engineering point of view the level of compliance is however satisfactory.

### Acknowledgements

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