Spalling prediction by distortion strain energy

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Abstract. Spalling can be a serious threat to underground excavation works in hard, good quality rock masses at great depth. Spalling endangers drill & blast advance or TBM drives with severe damage of tunnel walls or the face. In mining the concern is about spalling at pillars and at the face. Research on spalling is mainly associated with the definition of Crack Initiation (CI) and Crack Damage (CD) stresses and the definition of the S-shaped spalling strength envelope. Particularly CI stress at low confining stress ($\sigma_C/\sigma_3 < 0.05$ and $\sigma_1/\sigma_3 < 10$) is important for defining spalling around an underground excavation in hard rock. We summarize 59 UCS tests and 197 triaxial tests ($\sigma_3 < 2.5$ MPa) with sedimentary, magmatic, and metamorphic rocks, respectively, and defined robust CI and CD stresses. In this paper, we focus on the distortional strain energy at CI and CD stresses. From a rock mechanical point of view, crack initiation and crack damage are associated with stress (or strain) deviation. Analyses of the very well instrumented tests shows that for any rock type (saturated and dry) crack initiation (CI) occurs at 20% and crack damage (CD) at 75% of the distortion strain energy at failure. This approach was tested at the well-known case of spalling at the test tunnel in the AECL Underground Research Laboratory. Mechanical properties for the Lac du Bonnet granite were used to estimate distortional energy at CI and to model breakout depth and shape.

1. Introduction
Spalling is becoming a recognized problem when excavating underground openings in a competent rock mass under high in-situ stresses. It is agreed that rock masses with RMR > 75, GSI > 70 or Q > 40 qualify for competent rock mass prone to stress driven failure [1, 2]. Spalling may endanger pillars [3] or tunnel faces [4]. Recently, [5] reported about TBM problems in Mixed-Face-Conditions due to spalling.

Spalling is known to occur in hard rock under minor principal stress in the range of $\sigma_3 < 0.05 \div 0.1$ UCS and below $\sigma_1/\sigma_3 \approx 20$. The latter comes from research about stable tensile fracture propagation in glass and may not necessarily be applicable to brittle rocks. This area around an underground opening is referred to as the inner shell where stress rupture dominates. In the outer shell shear failure dominates [1]. This leads to the well-known S-shaped strength criterion for brittle rocks (figure 1a). Figure 1b shows the minor principal stresses around a 8 m dia. circular tunnel at approximate 750 m of overburden for different $k (= \sigma_H/\sigma_V)$. 

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Clearly triaxial tests with low confining pressures should be performed to evaluate crack initiation CI and crack damage CD stresses employing monitoring techniques as discussed [7]. Unfortunately, the need for and the value of well instrumented low-confinement triaxial tests is often neither appreciated nor understood. [8] conducted 95 uniaxial and 196 triaxial tests ($\sigma_3 < 2.5$ MPa) on sedimentary, metamorphic and igneous rocks and confirmed the following criteria for crack initiation (CI) and crack damage (CD) stresses:

\[
CI = 0.45 \pm 0.04 \times (\sigma_1 - \sigma_3) \quad (1)
\]

\[
\frac{CI}{CD} = 0.51 \pm 0.04 \quad (2)
\]

Details about the tested rocks and applied techniques can be found in [9, 10, 11]. Numerical modeling is used to delineate the spalling potential around an underground opening. Transfer of the S-shaped strength criterion into numerical models using Hoek–Brown criterion is often somewhat laborious and quite difficult (see [6] eq. 3-5; [12]; [13] Table 2). We propose a different approach to the prediction of spalling by employing the concept of strain energy.

2. Strain energy at CI, CD and peak strength

The elastic strain energy per unit volume is given by:

\[
E = \frac{1}{2} (\sigma_1 \varepsilon_1 + \sigma_2 \varepsilon_2 + \sigma_3 \varepsilon_3) \quad (3)
\]

One part of the strain energy is associated with volume change and one part with deviatoric stresses (or strains). The latter are responsible for failure processes in a rock, i.e., for crack initiation, crack damage or macroscopic failure. The distortional strain energy $E_d$ can be calculated from compressive tests with:

\[
E_d = \frac{1}{4G} [(\sigma_1 - \sigma_{\text{mean}})^2 + (\sigma_2 - \sigma_{\text{mean}})^2 + (\sigma_3 - \sigma_{\text{mean}})^2] \quad (4)
\]
where $\sigma_{1,2,3}$ are principal stresses, $\sigma_{\text{mean}}$ is the mean stress and $G$ is the bulk modulus. We analyzed the triaxial tests at low confining pressures for Ruhr-Sandstone (RS), Gneiss (GN) and Granite (GR) for $E_d$. The basic properties of the rocks are given in table 1.

### Table 1. Properties of the rocks. Value ± standard deviation. Value in brackets are numbers of tests.

|       | Dry density $\rho$ (g/cm$^3$) | Porosity $n$ (%) | UCS (MPa) | Young’s Modulus $E$ (GPa) | Poisson’s ratio $\nu$ | Tensile strength (MPa) | Average grain size (mm) |
|-------|-------------------------------|------------------|-----------|---------------------------|-----------------------|------------------------|-------------------------|
| RS    | 2.57±0.02 (45)                | 5.3              | 177.7±34.5 (11) | 24.7±1.0 (11) | 0.12±0.03 (11) | 12.2±2.5 (19) | 0.4                     |
| GN    | 2.73±0.01 (34)                | 0.6              | 138.9±38.6 (8)  | 30.4±1.8 (8)   | 0.19±0.13 (8)  | 8.7±3.7 (17)  | 0.9                     |
| GR    | 2.66±0.01 (28)                | 0.8              | 169.4±18.0 (4)  | 32.2±2.7 (4)   | 0.14±0.05 (4)  | 9.8±1.5 (11)  | 1.2                     |

We show exemplarily individual results for Ruhr-Sandstone (RS). For each test, the distortional strain energy $E_d$ was calculated at CI, CD and at peak strength, respectively. The ratios of $E_d$ at crack initiation stress (CI) and at crack damage stress (CD) to $E_d$ at peak strength are shown in figure 2. Note that dry as well as saturated samples were tested. The distortional strain energy $E_d$ at CI is $\approx 20\%$ of $E_{d(\text{max})}$ at peak strength for dry and saturated samples. $E_d$ at CD is more scattered in the very low range of confining pressure but typically at $\approx 75\%$ of $E_{d(\text{max})}$.

All the $E_d$-ratios for all rocks (dry and saturated) are given in figure 3. It is evident that $E_{d(CI)} = 0.213 E_{d(\text{max})}$ is a robust estimate of CI for a wide range of dry or saturated rocks. For crack damage $E_{d(CD)} = 0.774 E_{d(\text{max})}$ is also a good estimate. Further analyses showed that CD appears to be positively correlated with the grain size.

![Figure 2](image.png)

**Figure 2.** Ratios of distortional energy $E_d$ at CI and at CD to maximum distortional energy at peak strength for dry and saturated Ruhrsandstone (RS).

### 3. Use of distortion energy for estimating spalling potential by numerical modeling

The classic example of a well-documented spalling phenomenon is the AECL URL test tunnel at the 420 level [14]. The mechanical excavated 3.5 m dia. tunnel showed progressive failure and developed
over time a notch in $\sigma_3$ direction. [15] reported detailed compressive tests on granite samples from the 420 level. We analysed the data as summarized in table 2.

![Figure 3. Boxplot of distortional energy ratios for all rock types (SD = standard deviation).](image)

**Table 2.** Properties of the granite at the URL 420 level used for numerical modeling.

| Property   | Value               |
|------------|---------------------|
| UCS        | 170 MPa             |
| $E$        | 51.9 GPa            |
| $\nu$      | 0.21                |
| $E_d(\text{max})$ | 0.27 kJ/m$^3$   |
| $E_d(\text{CI})$  | 0.0755 kJ/m$^3$  |
| $s$        | 1                   |
| $m$        | 30                  |

We use RS3 (RocScience, 2020) for 3D elastic modelling with in-situ stresses $\sigma_1 = 55$ MPa, $\sigma_2 = 48$ MPa (parallel to tunnel) and $\sigma_3 = 14$ MPa [12]. Figure 4 shows an isometric view of the zone where the distortional strain energy $E_d$ exceeds its CI-limit. Figure 4 clearly shows that the spalling zone widens and gets deeper with distance from the face. The maximum width is 1.1 m and smaller than the 1.92 m reported by [14]. The modelled notch depth is 0.25 m and smaller than the observed 0.53 m. Figure 5 shows the comparison of the modelled with the observed notch and it may be concluded that the extend of the first modelled notch matches quite good the observation. The distortional strain energy is always below CD and suggests spalling will continue – as observed in-situ – for some time. With multi-stage modelling, i.e., removal of the rock with more than 21.3 % of $E_{d,\text{max}}$ will lead to further stress redistribution and finally to a deeper and wider notch.

**4. Conclusions and recommended workflow**

Deviatoric stresses and strains lead to crack initiation, crack damage and finally to macroscopic rock failure. Distortional strain energy per unit rock volume has been defined for CI, CD and peak strength from numerous uniaxial and triaxial compression tests at low confining pressures. The proposed CI-criterion is valid for the $\sigma_3$-range below 5 MPa. The estimation of the spalling zone around an underground excavation in hard rock under high stresses follows the workflow shown in figure 6. The proposed procure was tested at several deep alpine tunnels, the modelled and observed spalling zones were in good agreement. Further research about the triaxial strength and strain energy in the confining pressure range from 5 - 15 MPa would be beneficial for the confidence about the S-shaped strength.
Figure 4. Modelled extend of the spalling zone as evaluated by the distortional strain energy $E_d > 21.3 \% E_{d(max)}$.

Figure 5. Comparison of modelled (blue colors) and observed notch [14].

Figure 6. Suggested workflow for delineating spalling zones.
References

[1] Kaiser P K 2020 From common to best practices in underground rock engineering Proc. ISRM Congress 2019 Rock Mechanics for Natural Resources and Infrastructure Development ed S A B de Fontoura et al (London: Taylor & Francis Group) pp 141–79

[2] Diederichs M S 2007 Mechanistic interpretation and practical application of damage and spalling prediction criteria for deep tunneling Can. Geotech. J. 44(9) pp 1082–116

[3] Kaiser P K, Kim B, Bewick R P and Valley B 2010 Rock mass strength at depth and implications for pillar design Proc. of the 5th Int. Seminar on Deep and High Stress Mining, Australian Centre for Geomechanics, Perth ed M Van Sint Jan and Y Potvin (Crawley: Australian Centre for Geomechanics) pp 463–476

[4] Diederichs M S, Kaiser P K and Eberhardt E 2004 Damage initiation and propagation in hard rock during tunneling and influence of near-face stress rotation IJR MMS 41(5) pp 785–812

[5] Alber M, Plinninger R and Düllmann J 2018 Mixed face conditions (MFC) in hard rock tbm drives – causes, effects and solutions Proc. Eurock 2018 Geomechanics and Geodynamics of Rock Masses ed V Litvinenko (London: Taylor & Francis Group) pp 1093–98

[6] Kaiser P K and Kim B-H 2015 Characterization of strength of intact brittle rock considering confinement-dependent failure processes Rock Mech. Rock Eng. 48 pp 107–119

[7] Nicksiar M and Martin C D 2013 Crack initiation stress in low porosity crystalline and sedimentary rocks Eng. Geo. 154 pp 64–76

[8] Bartmann K 2019 Untersuchungen zum Sprödbruchversagen von Gesteinen unter triaxialen Druckbedingungen mit geringen Seitendrücken PhD Thesis, Ruhr-University Bochum, p 241

[9] Bartmann K and Alber M 2016 Experimental determination of crack initiation and crack damage in sedimentary rocks under low confinement Proc. Eurock 2016 Rock Mechanics and Rock Engineering: From the Past to the Future ed R Ulusay et al (London: Taylor & Francis Group) pp 177–180

[10] Bartmann K and Alber M 2017 Experimental determination of crack initiation and crack damage of two granites Proc. Eurock 2017 Procedia Engineering vol 191 pp 119–126

[11] Bartmann K and Alber M 2018 Analysis of crack initiation and crack damage of metamorphic rocks with emphasis on acoustic emission measurements Proc. Eurock 2018 Geomechanics and Geodynamics of Rock Masses ed V Litvinenko (London: Taylor & Francis Group) pp 205–210

[12] Diederichs M S, Carter T and Martin C D 2010 Practical rock spall prediction in tunnels ITA-Meeting World Tunnel Congress p 8

[13] Carter T G, Diederichs M S and Carvalho J L 2008 Application of modified Hoek-Brown transition relationships for assessing strength and post yield behaviour at both ends of the rock competence scale J. South. Afr. Inst. Min. Metall vol 108 pp 37–60

[14] Martin C D 1993 The strength of Massive Lac du Bonnet granite around underground openings PhD Thesis, University of Manitoba, p 303

[15] Everitt R A 2001 The influence of rock fabric on excavation damage in the Lac du Bonnet Granite PhD Thesis, University of Manitoba, p 42