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Ductile shotcrete linings: A potential solution for mining in overstressed weak rocks?

Helmut Wannenmacher [a], Manuel Entfellner [a,*], Kathy Kalenchuk [b], Jeffrey Oke [b], Thomas Fiest [a], Matthew A Perras [c]

[a] *Implenia AG, Austria*

[b] *RockEng Inc., Canada*

[c] *York University, Canada*

Abstract

Mining and tunnelling in overstressed weak rocks can result in substantial and long-lasting deformations, often referred to as 'squeezing ground conditions'. The magnitude of deformations is closely tied to the rock mass competency and stress conditions, as well as the applied excavation and support concept and can reach tens or even hundreds of centimetres in very weak rock conditions.

The direct relation between rock pressure and deformation, represented by the ground reaction curve, suggests applying the yielding principle. The yielding principle states that the support capacity requirement decreases as deformation increases. To enable controlled deformation and safe working conditions, yielding elements as a part of the shotcrete lining are implemented. These elements avoid overstressing the shotcrete lining even at large and long-lasting creep displacements. During the deformation process, the support pressure of the yielding elements and liner increases, thus stabilising the rock mass. This economic support technique represents the state-of-the-art infrastructure tunnelling practice in overstressed weak rocks. A novel yielding element of high-strength expanded polystyrene has been invented, which overcomes existing systems' drawbacks. Recent experiences from applications in Alpine base tunnels are presented. This deformation-based support system may be an economical solution in mining for permanent structures with large deformations and required long-term stability.

Keywords: *deep mining, tunnelling, ground support, ductile lining, shotcrete, squeezing ground, overstressed weak rock, yielding elements, NATM, HS-EPS*

1 Introduction

Mining and tunnelling in overstressed weak rocks can experience significant and long-term deformations. In the literature, the deformation of low-competency rock masses under high in situ stress is often referred to as 'squeezing ground conditions' (Warren et al. 2019; Hadjigeorgiou & Potvin 2023; Mercier-Langevin & Wilson 2013); the more specific term 'overstressed weak rock', defined by Entfellner (2024), is used in this paper to describe the phenomenon at hand. The magnitude of deformation depends on rock mass competency and induced stress conditions around a tunnel periphery as well as the applied excavation and support concept (Radončić 2011). Magnitudes can typically be several tens of centimetres (Schubert 2008).

The direct relation between rock pressure and deformation is described by the ground reaction curve of the convergence-confinement method (Fenner 1938; Pacher 1964). Figure 1 shows a typical ground reaction curve (red line) for an overstressed weak rock mass with initial elastic deformations and final plastic deformations. Two design principles are available to reach deformation-equilibrium between the excavated space and applied support in overstressed weak rocks: (a) the resistance principle and (b) the yielding principle. The resistance

[*] Corresponding author. Email address: manuel.entfellner@implenia.com

principle relies on a rigid support system (e.g. thick shotcrete lining or stiff steel supports) that can withstand the rock pressure at minimised deformation. Figure 1 schematically illustrates this concept, with a stiff lining immediately installed after excavation (shown as the blue solid/dashed line). An excessively high support resistance may be necessary to achieve equilibrium with the rock mass and prevent lining failure where the support reaction curve intersects the ground reaction curve (Cantieni & Anagnostou 2008; Oke et al. 2018). However, this support principle can lead to uneconomical increases in support requirements. As such, the practicality of the resistance principle is generally limited to minor stressed, weak rock conditions. On the other hand, the yielding principle allows for a tolerated magnitude of liner deformation. This generally requires yielding elements within a shotcrete/concrete liner or steel sets equipped with sliding connections. The support capacity requirement can be reduced by allowing some ductility in the lining's response. The yieldable support reaction curve in Figure 1 clearly illustrates the benefit of this principle. In practice, the yielding principle enables efficient mining and tunnelling in overstressed, weak rock conditions while maintaining reasonable support requirements. Anagnostou & Cantieni (2007) have demonstrated that it is the most suitable construction method in such rock conditions.

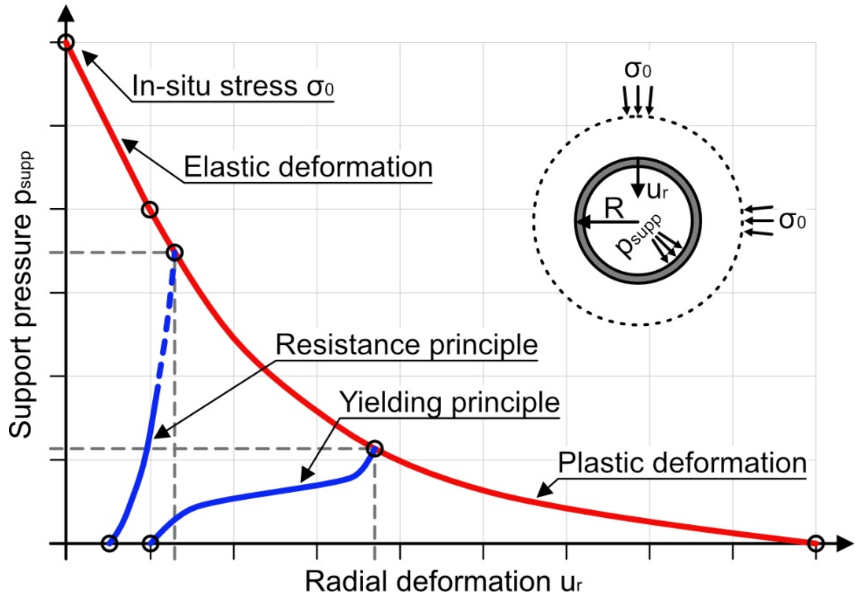

Figure 1 Ground reaction curve and support reaction curves representing the (a) resistance principle and (b) yielding principle (Entfellner 2024)

2 Ductile shotcrete lining with yielding elements

Shotcrete (sprayed concrete) is a commonly used rock support technique in mining and civil tunnelling. It involves spraying concrete onto the rock surface, stabilising an excavation and preventing loosening or disintegration of the rock mass. Shotcrete also plays a crucial role in enhancing safety. In addition to shotcrete, rockbolts are systematically installed, for example, to increase the wedge stability, increase the shear strength of the rock mass, and harmonise deformation behaviour (Rabcewicz & Pacher 1975; Schubert 1996). In civil tunnelling infrastructures, ductile shotcrete liners (shotcrete and yieldable elements) are always combined with dense, systematic, fully grouted bolting. This approach can be an economical solution for special mining applications, such as permanent structures, where large deformations must be managed for long-term excavation stability (Morgenroth et al. 2020; Bharadwaj et al. 2024).

2.1 Historical development

Large deformations in combination with (stiff) shotcrete linings are prone to cracks and damage (Figure 2a). These cracks cause at least a partial loss of support resistance, triggering further displacements or even a collapse of the excavated space. The consequences include costly, hazardous and time-consuming repair work. As a pragmatic solution, historically, mining and tunnelling projects in overstressed weak rocks have integrated open slots or timber elements into the stiff liners (Lenk 1930; Rabcewicz 1950; Pöchhacker 1974). While this reduced the need for repairs, it adversely impacts utilisation of the shotcrete lining due to a reduced transfer of hoop stresses.

In the 1990s, a tunnel collapse in the Alps, described by Harer et al. (1996), led to the development of a ductile shotcrete lining with integrated yielding elements (Schubert et al. 1996). This innovative approach demonstrated that displacements could be better controlled and reduced when applying yielding elements compared to open slots (Figure 2b). The ductile shotcrete lining system has successfully facilitated tunnelling in numerous geotechnically challenging projects worldwide (Schubert 1996; Wittke et al. 2005; Kovári 2009; Barla et al. 2011). In modern tunnelling applications, this support technique is state-of-the-art in overstressed weak rocks. Table 1 provides an overview of major tunnel projects applying yielding elements.

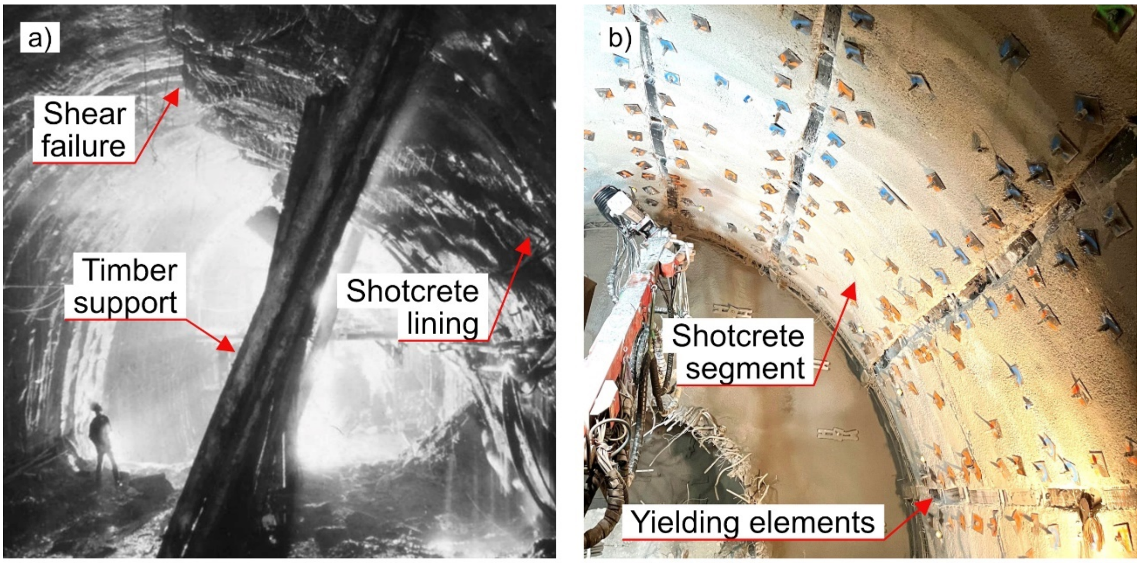

Figure 2 Tunnelling in overstressed weak rocks with large deformations, showing (a) shear failure of a stiff shotcrete lining with provisory timber support to avoid a collapse of the tunnel (modified after Golser 2012) and (b) solution with a ductile shotcrete lining with yielding elements (Entfellner 2024)

Table 1 Selective tunnel projects applying yielding elements

Tunnel	Country	Reference
Galgenberg Tunnel	Austria	Schubert (1996)
Semmering Road and Pilot Tunnel	Austria	Moritz (1999)
Strenger Tunnel	Austria	Pöttler et al. (2005)
Lötschberg Base Tunnel	Switzerland	Thut et al. (2006)
Bolu Tunnel	Türkiye	Dalgic (2002)
Lyon-Turin Base Tunnel	Italy–France	Barla (2009)
Tauern Tunnel (2nd tube)	Austria	Weidinger (2012)
Gotthard Base Tunnel	Switzerland	Röthlisberger et al. (2016)
Ceneri Base Tunnel	Switzerland	Merlini et al. (2018)
Koralm Tunnel	Austria	Wagner et al. (2009)
Semmering Base Tunnel	Austria	Daller et al. (2011)
Brenner Base Tunnel	Austria–Italy	Entfellner et al. (2023)

2.2 Structural aspects

A 'standard shotcrete lining' can withstand approximately 0.6 to 0.8% tangential strain before cracks develop (Schubert & Brunnegger 2017). However, when higher deformations or strains are anticipated, yielding elements must be integrated into the shotcrete lining. The (radial) displacements caused by the rock pressure are transformed into a circumferential closure of the ductile lining and absorbed by the yielding elements. This prevents the overstressing of the shotcrete by simultaneously allowing a specific amount of deformation and decreasing the support capacity requirement. Figure 3 illustrates a top-heading advance with ductile shotcrete lining featuring these yielding elements.

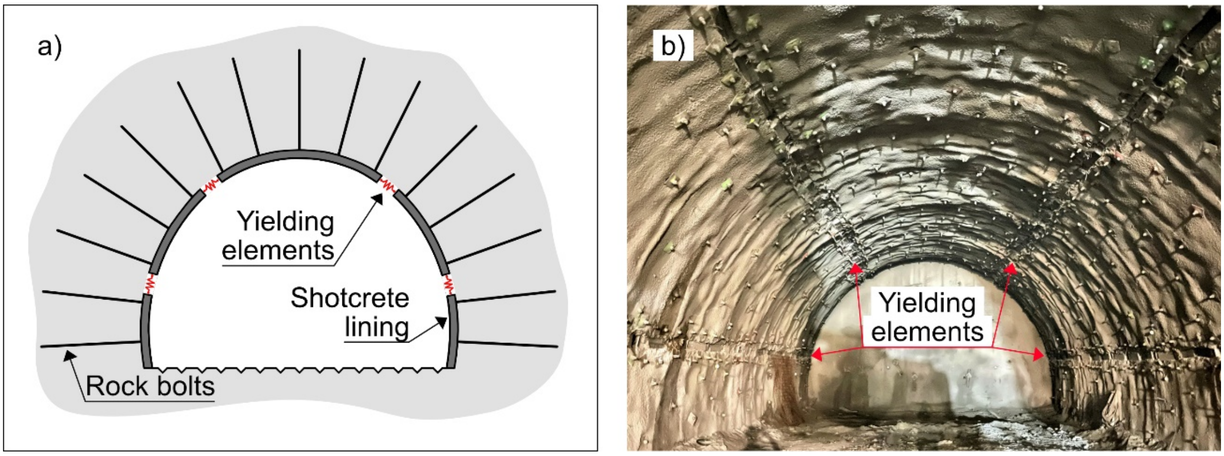

Figure 3 (a) A schematic illustration of a ductile shotcrete lining with yielding elements; (b) An example of a tunnel with four rows of yielding elements in the top-heading (Entfellner 2024)

A ductile shotcrete lining with yielding elements provides adequate radial support resistance and additional benefits compared to steel sets (e.g. TH-sets) with sliding connections. The innovative yielding element approach ensures safe working conditions and stable long-term system behaviour. Additionally, it enhances resistance against buckling during asymmetrical deformations.

2.3 Yielding elements

Modern yielding elements, which emerged in the 1990s (Schubert et al. 1996), revolutionised tunnelling in overstressed weak rock. These elements allow the benefits of shotcrete to be applied even in geotechnical conditions with significant deformations. In Figure 4, the mechanism of a yielding element is presented: (a) and (b) before deformation, and (c) and (d) after deformation. The radial displacements caused by rock pressure are converted into circumferential closure of the ductile lining, effectively absorbed by the yielding elements. Over the last three decades, there have been advancements in different types of yielding elements consisting of steel, porous concrete material, or a combination of both (Moritz 2011). Entfellner (2024) developed a new, lightweight yielding element of High-Strength Expanded Polystyrene (HS-EPS), which is presented in Section 3.

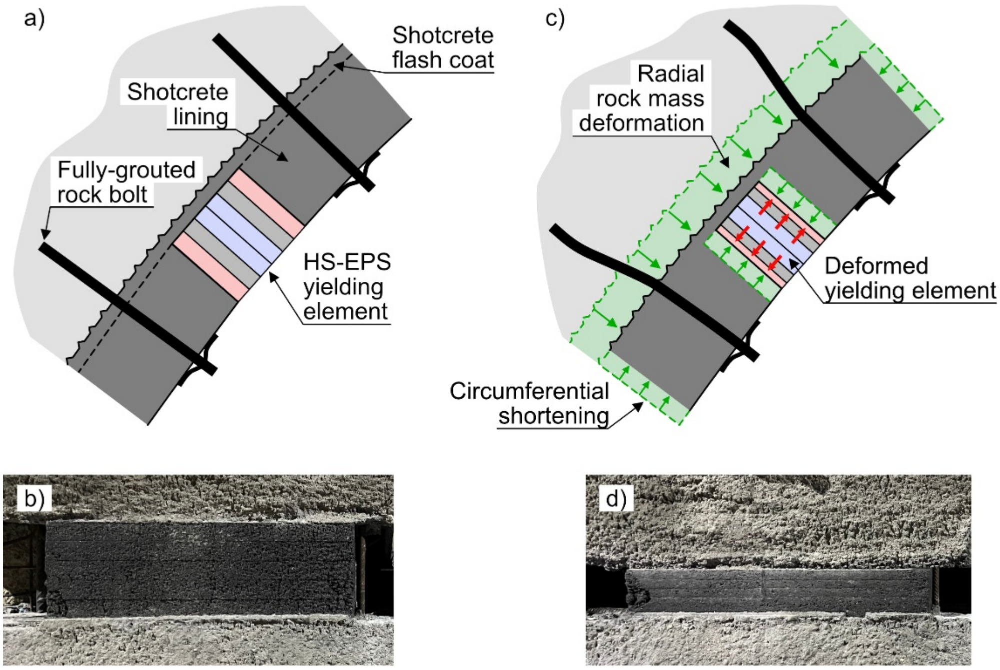

Figure 4 Detail of the deformation process of shotcrete lining with yielding elements, showing (a) and (b) initial state after installation, and (c) and (d) deformed state with displacements (modified after Entfellner 2024)

3 High-strength expanded polystyrene yielding elements

The HS-EPS yielding element was developed with two primary goals: (1) to reduce the weight for rapid, simple and safe installation, and (2) to enhance the flexibility of the stress–strain behaviour. This innovative element comprises layered panels, each with a fixed height of 50 mm. When assembled and glued together, these panels form a cuboid shape with a customisable base area (Figure 5). This design allows efficient stress transfer between the shotcrete and the yielding element. Based on experience, optimal total element heights range from 150 mm to a maximum of 300 mm (achieved by stacking up three to six panels).

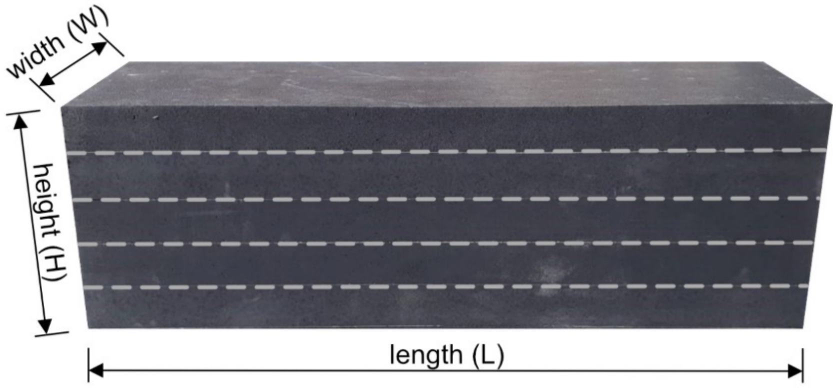

Figure 5 Layout of a typical HS-EPS yielding element with the dimension 800 × 250 × 250 mm (L × W × H) and a total weight of 7-20 kg, depending on the configuration (Implenia Austria GmbH 2020)

The HS-EPS material possesses inherent mechanical properties that make it ideal for mining and tunnelling applications. The closed-foam cellular structure results in a rigid material with a high strength-to-weight ratio. The resilient material is non-biodegradable. The strength and stiffness of EPS directly correlate with the specific weight of the material, which ranges from approximately 100 up to 410 kg/m³ for tunnel applications. This density range refers to a HS-EPS. Depending on the height and panel configuration, the total weight of the element is 7–20 kg (Figure 5). In terms of fire safety, HS-EPS is classified as 'E' (an acceptable contribution to fire) according to the European standard EN 13501-1 (European Standards Organisations 2020). To prevent ignition, polymeric flame-retardant additives are incorporated.

The modular sandwich construction of HS-EPS allows for customised dimensioning based on specific project requirements. The combination of panels significantly influences the mechanical properties of the element, making it a crucial technical advantage. This design flexibility enables achieving various stress–strain configurations to accommodate practically all geotechnical conditions.

3.1 Modelling of high-strength expanded polystyrene yielding elements

HS-EPS exhibits a non-linear, hyper-elasto-plastic stress–strain behaviour under uniaxial compressive stress. The stress–strain response can be categorised into three phases (Chen et al. 2015), as shown in Figure 6:

1. linear-elastic phase
2. yielding phase
3. densification phase.

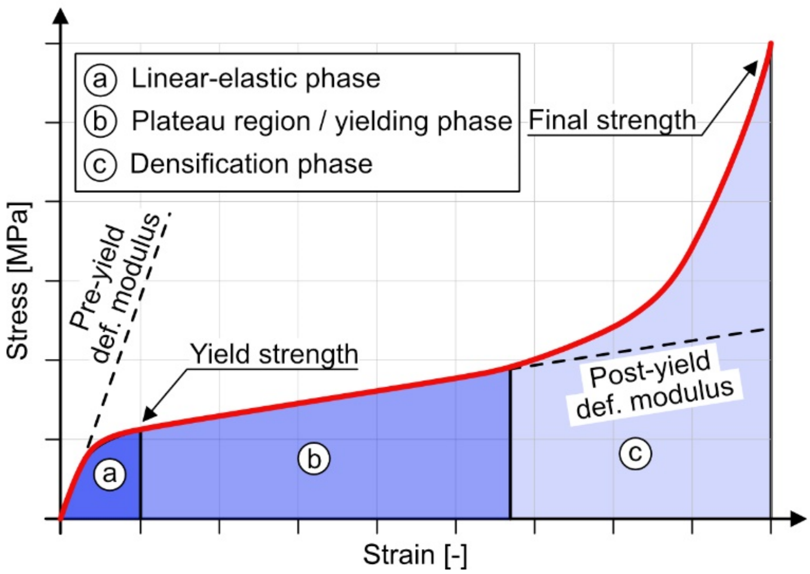

Figure 6 Typical stress–strain response of standard HS-EPS showing linear-elastic, yielding and densification phase (Entfellner 2024)

Extensive small-scale and large-scale laboratory tests have been conducted to characterise the specific material behaviour of novel HS-EPS (Implenia Austria GmbH 2020; Entfellner et al. 2023; Entfellner 2024). The material constitutive behaviour can be described using the strain-energy function for hyper-elastic foams (Hill 1979; Storåkers 1986). For 2D numerical modelling of the HS-EPS yielding elements, the software *Abaqus/CAE* (Dassault Systèmes Simulia Corp. 2022) was used. Entfellner (2024) performed the model calibration for the mechanical material parameters. This was achieved using load–displacement data from uniaxial compressive strength tests combined with strain profiles extracted from digital image correlation. This approach facilitated a strong correlation between the model and laboratory tests. Observations from the multilayer sample include gradual compressive deformation due to vertical strains, with the lowest-density panels experiencing the highest strain (Figure 7). As stiffness becomes equal, subsequent panels begin to deform. Similar behaviour was observed in in situ installed HS-EPS yielding elements. Due to stiffness contrasts between the different density panels, horizontal stresses/strains accumulate. The vertical stresses, on the other hand, exhibit an almost constant distribution along the sample height.

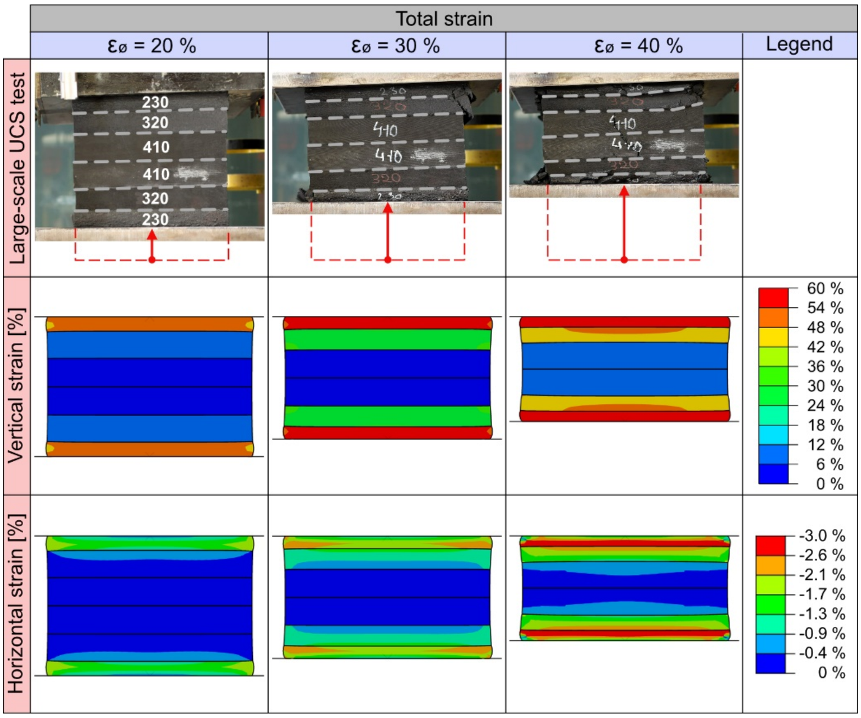

Figure 7 2D numerical modelling of large-scale uniaxial compressive strength (UCS) tests showing pictures of laboratory tests at vertical strains 20, 30 and 40% total strain, and the corresponding model results with vertical and horizontal internal strain contours. Initial sample size = 350 × 300 (L × H) (modified after Entfellner 2024)

3.2 Installation process

From the perspective of mine operators and contractors, achieving a safe and efficient installation process is crucial. This can be achieved with the novel, lightweight HS-EPS yielding element. Unlike its heavier counterparts made of steel or concrete (weighing between 60 and 120 kg), the HS-EPS element is remarkably lightweight, ranging from 7 to 20 kg. The HS-EPS installation process is straightforward: after spraying a shotcrete flash coat and bolting, fastening of the elements can be accomplished using steel bars, rebars, or L-shaped wire mesh as auxiliary measures (Figure 8). Once placed, the elements are installed with binding wire. Thanks to the lightweight HS-EPS material, installation can be handled by a single person or small auxiliary machines. A wooden cover-plate is used to protect the elements during shotcreting. Finally, the shotcrete lining is sprayed. Maintaining a constant shotcrete thickness and employing well-rounded geometries are essential for optimal stress flow. For ductile linings, conventional wire-mesh reinforced shotcrete is still commonly used instead of fibre-reinforced shotcrete to counteract local tensile and bending loads during the initial deformation process.

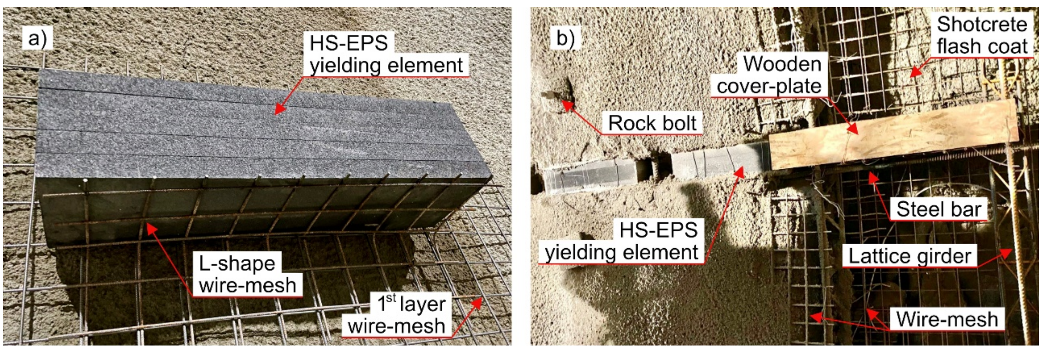

Figure 8 Installation options of the high-strength expanded polystyrene yielding elements, showing (a) fixation with L-shape wire-mesh and (b) fixation with steel bar and wooden cover-plate for shotcreting (Entfellner 2024)

4 Design aspects of yielding elements

From a structural perspective, the strain-dependent stress $\sigma_{YE}(\varepsilon)$ of the yielding elements must always be lower than the time-dependent strength of the shotcrete $f_{ck,SpC}(t)$ to prevent overstressing. The shotcrete degree of utilisation $\mu_{SpC} = \sigma_{SpC}(t)/f_{ck,SpC}(t)$ is often highest in the area of the first excavation rounds behind the face, where the deformation rate is the highest, and the time-dependent shotcrete strength $f_{ck,SpC}(t)$ the lowest (Figure 9a). The shotcrete utilisation must be $\mu_{SpC} \leq 100\%$ to avoid cracks and spalling in the lining (Figure 9b). Additionally, increasing the support resistance during the deformation process is essential to achieve deformation equilibrium within the excavated space. Besides the increasing stiffness of the shotcrete $E_{SpC}(t)$, the stress–strain response of the yielding elements $\sigma_{YE}(\varepsilon)$ also needs to increase (Figure 6). Since displacement development affects the strain-dependent stiffness of the yielding elements and varies with the distance from the tunnel face and time [u(x,t)], an adaptable excavation- and support concept during mining operations is necessary. Depending on the deformation development, different stress–strain responses for the yielding elements may be required. Following the *New Austrian Tunnelling Method* (NATM) principles (OeGG 2014), deformation-based monitoring and data interpretation during implementation are used to perform back-calculations and to optimise their performance.

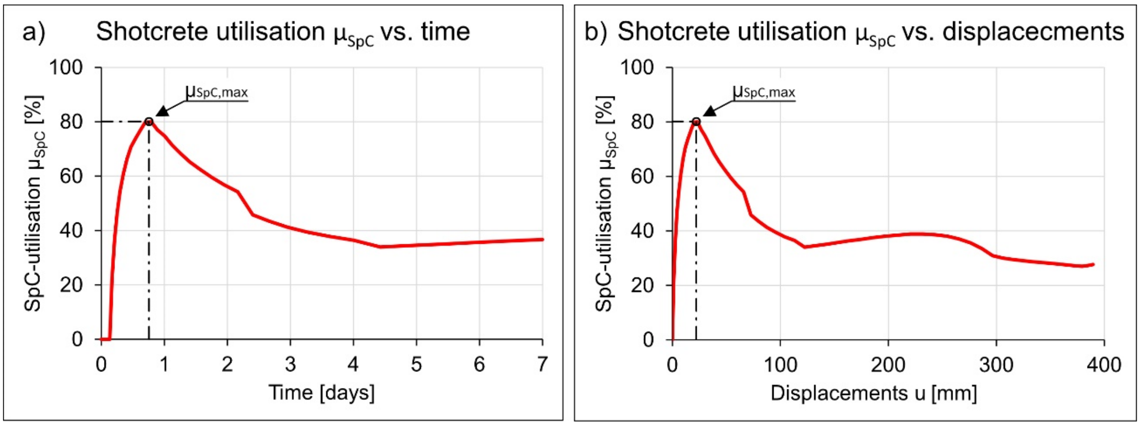

Figure 9 Calculation of the shotcrete utilisation, showing (a) utilisation–time curve and (b) utilisation–displacement curve

5 Case study

This case study analyses a section of highly overstressed weak rocks of an Alpine base tunnel. The tunnel alignment intersects a major, inactive strike-slip fault system over 1,200 m long. The fault zone consists of highly tectonically disturbed sericite-phyllites down to a depth of 520 m, with a uniaxial compressive strength of less than 1 MPa. The rock mass exhibits a moderate content of plastic cataclasite and features a relictic foliation, striking at an acute angle to the tunnel face. The dip angle is oriented steeply against the face, and intersections of low-friction joints with the foliation create unfavourable blocks and potential face instabilities. Based on the engineering geological classification system of Fasching & Vanek (2011), the geology can be classified as non-cemented, cohesive fault rocks without blocks (cataclasite).

This study focuses on a pilot tunnel drift, which is excavated ahead of the main tunnel. The initial radius of the shotcrete lining at the top-heading is R = 3.90 m, and the tunnel geometry is nearly circular. Based on exploration results, only a conventional tunnel excavation is feasible, as described by Daller et al. (2011). Initial calculations predict radial displacements of the unsupported tunnel exceeding 100 cm. The design recommended a ductile shotcrete lining with HS-EPS yielding elements and a sequential top-heading and bench/invert excavation. The final design is utilised by applying a deformation-based NATM support approach (OeGG 2010), as shown in Figure 10.

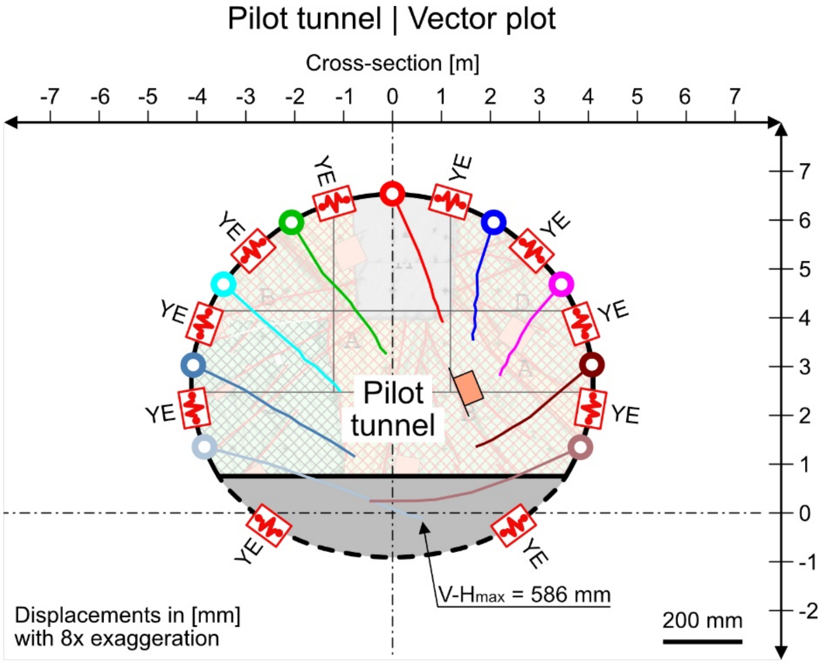

Figure 10 Measured displacement vectors of the pilot tunnel at a face distance of 17 m with the position of the yielding elements (YE) and geological conditions (modified after Entfellner 2024)

The displacements continuously increased when approaching the sericite-phyllite section of this case study with the excavation works. Monitoring data interpretation with 3D displacement plots and a flexible construction process led to frequent adjustments in the pilot tunnel's type and number of HS-EPS yielding elements. Partial face excavation with 6–8 pockets, immediate face support using 10 cm reinforced shotcrete, and 16 bolts (12 m long) became necessary to stabilise the face (Figure 11). Mechanical excavation was carried out using an excavator, with a maximum feasible round length of 1.0 m due to the weak rock conditions and low stand-up time. Overhead protection was provided by a dense spile-umbrella of 4 m in length. The top-heading support system included a ductile lining with 25 cm reinforced shotcrete overlaid by wire-mesh, eight rows of HS-EPS yielding elements (soft configuration) with a height of 250 mm, and systematic fully grouted rockbolts (1 bolt/m², 4 m long). The yielding elements were positioned symmetrically along the lining. Fastening of the elements between the lattice girders was carried out by using an L-shaped wire-mesh and binding wire (Figure 8). In Figure 11, the pocket excavation works and support measures are shown.

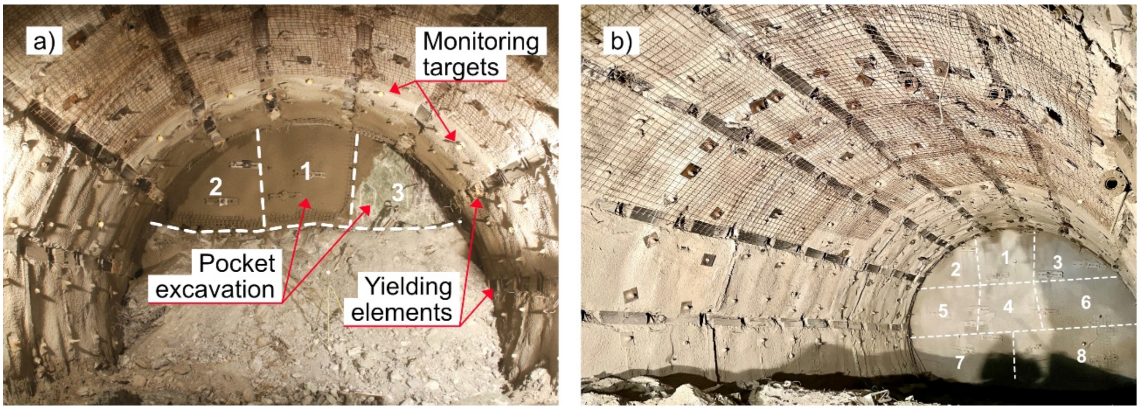

Figure 11 Top-heading advance of the pilot tunnel with partial face excavation, showing (a) mechanical excavation of third pocket and (b) rock support with shotcrete, eight rows of HS-EPS yielding elements and dense bolting (Entfellner 2024)

Figure 10 shows the displacement vector plot with 8× exaggeration in cross-section, with the monitoring targets located in the centre of the shotcrete segments. In total, eight yielding elements with 250 mm height and nine targets were installed in the top-heading. In the bench/invert, two yielding elements have been installed. The vectors show an asymmetrical deformation pattern, typical for anisotropic rocks and heterogeneous fault zones. At the left sidewall and shoulder, the schistosity/foliation of the tectonically disturbed sericite-phyllite is still present. In contrast, at the right part of the face, the cataclastic sericite-phyllites are highly disturbed and almost without structure. The largest displacements of nearly 600 mm can be observed, especially on the left lower sidewall. Although the sericite-phyllite has less cataclasite than on the right side, higher displacements occurred. This observation can be attributed to the low-friction schistosity, which in this case has a less-favourable effect than a high proportion of cataclasite with at least a certain degree of cohesion. The increased horizontal displacements at both sidewalls are primarily attributable to the excavation system with a top-heading advance with hardly any resistance at the sidewalls without ring closure. Besides, the increased horizontal stresses in the strike-slip fault system exacerbate this phenomenon.

Although the pilot tunnel experienced large deformations, it could be constructed without notable damage to the lining and in a technically safe manner. With a total of 10 rows of HS-EPS yielding elements and a soft configuration of 250 mm height, large strains were successfully absorbed. All yielding elements experienced several centimetres of deformation. The highest tangential compression was observed at the yielding element at the right upper shoulder with 181 mm, equal to 72 % axial strain. The total shortening of all eight yielding elements in the top-heading was 877 mm, or on average 110 mm (equal to 44% axial strain). The highly asymmetrical deformation pattern, shown in Figure 10, especially required a yielding element with a high resistance against tilting. These asymmetrical displacements could be successfully counterbalanced by the HS-EPS materials' flexibility and horizontal shifting of single panels of the yielding elements.

6 Discussion and conclusion

Applying a ductile shotcrete lining combined with yielding elements offers several advantages in the context of tunnelling and potentially also for mining within overstressed weak rock conditions. Compared to other ductile systems (e.g. steel sets with sliding connections), the yielding elements allow efficient support capacity utilisation, promoting safe working conditions and controlled deformations. The key to success lies in a comprehensive geotechnical understanding of the ground response and interaction with the ductile lining system. Combined with deformation-based monitoring data interpretation during implementation, there is opportunity to optimise the ductile lining system; mitigating risks associated with costly, hazardous and time-consuming excavation rehabilitation work.

This paper presents a novel, lightweight yielding element made of HS-EPS to address the issues related to the heavy weight and installation efforts of existing yielding elements. The low weight of only 7–20 kg (depending on configuration) significantly reduces the time-critical installation process during construction. Moreover, this development positively impacts working safety, health protection, costs and time.

The ductile shotcrete lining represents the state-of-the-art support technique in infrastructure tunnelling in overstressed weak rocks. The case study highlights the system's effectiveness in challenging rock conditions with large, long-lasting deformations, including anisotropic conditions. Intensive testing and monitoring are continuously carried out and expanded to analyse the long-term behaviour of the novel HS-EPS yielding elements in more detail. In situ monitoring data of tunnels constructed in overstressed weak rocks with large deformations with a monitoring period of currently three years shows a stable system behaviour. The novel HS-EPS yielding elements have been installed in several challenging tunnel projects worldwide and can be an economic viable solution for critical infrastructure components of mine operations, such as permanent mine adits or drifts requiring long-term stability in overstressed weak rock mass conditions. Here, an efficient ductile shotcrete lining solution could be an asset. For example, the system has been successfully implemented at Cameco's Cigar Lake Mine in Saskatchewan, Canada, where severe squeezing ground conditions with high radial deformations were experienced (Morgenroth et al. 2020; Bharadwaj et al. 2024). Other applications may include squeezing sections in hard rock mines, such as experienced at Agnico Eagle's

LaRonde mine in Quebec, Canada, where significant squeezing with maximum deformations of up to 2 m have been encountered (Hadjigeorgiou & Potvin 2023).

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