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Evaluation of a Gradient Enhanced Damage Plasticity Model for Shotcrete

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Micro Abstract
A damage plasticity model representing the time-dependent and nonlinear material behavior of shotcrete is discussed. In order to obtain mesh-insensitive numerical results upon strain softening, an over-nonlocal implicit gradient enhancement is employed. The capabilities of the model are demonstrated by means of finite element simulations, employing meshes of different size and orientations.

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Introduction

The use of shotcrete (sprayed concrete) is an essential securing measure within the New Austrian Tunneling Method for stabilizing the surrounding rock mass during tunnel advance. In the context of numerical simulations of tunnel advance, the complex material behavior shotcrete, characterized by time-dependent evolution of material properties like stiffness and strength, hardening and softening behavior, creep and shrinkage is described using advanced constitutive models. One recently proposed constitutive model for shotcrete is the SCDP model, presented in [5]. In order to obtain objective results in case of softening material behavior in finite element simulations with respect to the employed mesh, an appropriate regularization technique has to be employed. In the present contribution, the over-nonlocal gradient enhancement for regularizing the softening material behavior, presented in [6], is adopted and validation by means of numerical simulations of the experimental tests by Winkler [7] is presented.

1 The SCDP model

The SCDP model (Shotcrete Damage Plasticity model) is based on three well established constitutive models for concrete, which are the damage plasticity model for concrete by Grassl and Jirásek [3], the solidification theory for concrete creep by Bažant and Prasannan [2] and the shrinkage model by Bažant and Panula [1], with the latter two models being incorporated into the framework of the former model. Accordingly, the stress–strain relation in total form is expressed as

$$\boldsymbol{\sigma} = (1-\omega)\,\mathbb{C} : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\mathrm{p}} - \boldsymbol{\varepsilon}^{\mathrm{ve}} - \boldsymbol{\varepsilon}^{\mathrm{f}} - \boldsymbol{\varepsilon}^{\mathrm{shr}}), \tag{1}$$

in which $\boldsymbol{\sigma}$ denotes the nominal stress (force per total area), ω the isotropic scalar damage parameter and $\mathbb{C}$ the fourth order stiffness tensor. The total strain $\boldsymbol{\varepsilon}$ is decomposed into the instantaneous elastic strain $\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\mathrm{p}} - \boldsymbol{\varepsilon}^{\mathrm{ve}} - \boldsymbol{\varepsilon}^{\mathrm{f}} - \boldsymbol{\varepsilon}^{\mathrm{shr}}$, the viscoelastic strain $\boldsymbol{\varepsilon}^{\mathrm{ve}}$, the flow (viscous) strain $\boldsymbol{\varepsilon}^{\mathrm{f}}$, the shrinkage strain $\boldsymbol{\varepsilon}^{\mathrm{shr}}$ and the plastic strain $\boldsymbol{\varepsilon}^{\mathrm{p}}$.

The evolution of the viscoelastic strain and the flow strain is described by means of the solidification theory, which is modified in order to account for the accelerated hydration of shotcrete compared to concrete, and the evolution of the shrinkage strain is treated by the model by Bažant and Panula. To delimit the elastic domain, a single yield surface is employed, and a nonassociated flow rule is used for describing the evolution of the plastic strain. Isotropic hardening material behavior is modeled by a single, scalar strain-like internal variable α_{p}, with a fully hardened state attained at $\alpha_{\mathrm{p}} = 1$.

The evolution of ω is driven by a strain like internal variable α_{d} by means of an exponential softening law given as

$$\omega = 1 - \exp\left(-\frac{\alpha_{\mathrm{d}}}{\varepsilon_{\mathrm{f}}}\right), \tag{2}$$

with ε_{f} representing the softening modulus. The evolution of α_{d} is related to the plastic strain rate $\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}$:

$$\dot{\alpha}_{\mathrm{d}} = \begin{cases} 0 & \text{if } \alpha_{\mathrm{p}} < 1, \\ \dot{\varepsilon}^{\mathrm{p}}_{\mathrm{V}} / x_{\mathrm{s}}(\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}}) & \text{otherwise.} \end{cases} \tag{3}$$

Therein, $\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{V}}$ denotes the first invariant of the plastic strain rate tensor and $x_{\mathrm{s}}(\dot{\boldsymbol{\varepsilon}}^{\mathrm{p}})$ is a measure of ductility.

2 Over-Nonlocal Gradient Enhancement of the SCDP model

It is a well known issue that without proper regularization softening material behavior leads to a pathological mesh sensitivity in finite element simulations, associated with the loss of ellipticity of the boundary value problem. A commonly employed remedy is a mesh adjusted softening modulus, based on the characteristic size of a finite element. However, sensitivity with respect to the orientation of the mesh and determination of the characteristic size for higher order elements remain unresolved issues [4]. One possible remedy to overcome these problems are nonlocal approaches, which incorporate gradients of internal variables. In this context, a gradient enhancement for the damage plasticity model by Grassl and Jirásek was proposed by Poh and Swaddiwudhipong [6]. Adopting this approach for the SCDP model, the local damage driving variable α_{d} in (2) is replaced by an averaged strain-like variable $\hat{\alpha}_{\mathrm{d}}$ as

$$\omega = 1 - \exp\left(-\frac{\hat{\alpha}_{\mathrm{d}}}{\varepsilon_{\mathrm{f}}}\right). \tag{4}$$

Therein, $\hat{\alpha}_{\mathrm{d}}$ is defined as

$$\hat{\alpha}_{\mathrm{d}} = m\,\bar{\alpha}_{\mathrm{d}} + (1 - m)\,\alpha_{\mathrm{d}}, \tag{5}$$

in which $\bar{\alpha}_{\mathrm{d}}$ denotes the nonlocal counterpart of α_{d}, implicitly defined by the solution of the partial differential equation

$$\bar{\alpha}_{\mathrm{d}} - l^2\,\nabla^2\bar{\alpha}_{\mathrm{d}} = \alpha_{\mathrm{d}}. \tag{6}$$

The latter is in the context of nonlocal gradient enhanced constitutive models commonly denoted as the Helmholtz-like partial differential equation and leads together with the equilibrium equation to a fully coupled problem. Parameter l represents a length scale for describing the width of the softening process zone and is considered as a material parameter. In (5), m denotes the weighting parameter. A value of m larger than unity yields the so-called over-nonlocal formulation, which is employed in order to prevent a spurious broadening of the process zone with increasing damage, as reported in [6].

3 Application

The regularization capabilities of the over-nonlocal gradient approach are evaluated by means of finite element simulations of the experimental test on a L-shaped concrete specimen, presented by Winkler [7]. The corresponding experimental test setup is illustrated in Figure 1.

The L-shaped specimen with a uniform thickness of 100 mm is fixed at the bottom edge and a displacement of 1 mm in vertical direction is applied at the right end of the specimen. A crack is expected to emanate from the central reentrant corner, and to evolve horizontally across the specimen to the opposite side. To assess the regularization capabilities of the gradient

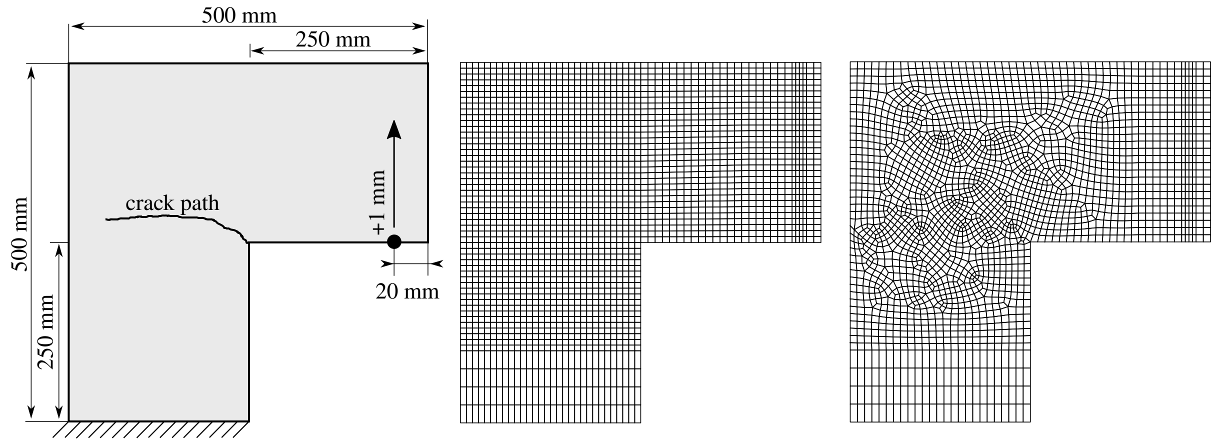

Figure 1. L-shaped specimen investigated by Winkler [7], fixed at the bottom and subjected to a vertical displacement of 1 mm at the right end: Test setup (left), the 8 mm structured mesh (center), and the 8 mm unstructured mesh (right).

q_1 (MPa^{-1})	q_2 (MPa^{-1})	q_3 (MPa^{-1})	q_4 (MPa^{-1})	ν (−)
23.2×10^{-6}	169.3×10^{-6}	6.6×10^{-6}	6.8×10^{-6}	0.18
$f_{\mathrm{cu}}^{(28)}$ (MPa)	$f_{\mathrm{cy}}/f_{\mathrm{cu}}$ (−)	$f_{\mathrm{cb}}/f_{\mathrm{cu}}$(−)	$f_{\mathrm{tu}}/f_{\mathrm{cu}}$(−)	$\varepsilon_{\mathrm{cpu}}^{\mathrm{p}(24)}$ (−)
31.0	0.3	1.16	0.1	−0.0011

Table 1. Material parameters for the SCDP model [5] for representing the concrete composition employed by Winkler [7].

enhancement for mode I fracture, three different refinements of the finite element mesh in the vicinity of the crack path are investigated, i.e., elements with sizes of 8 mm, 4 mm and 2 mm. Additionally, structured meshes, aligned with the boundaries of the specimen, and unstructured meshes are investigated, resulting in a total of 6 finite element meshes to be studied. Fully integrated quadrilateral elements with linear shape functions are used, and plane stress conditions are assumed. The 8 mm structured mesh and the 8 mm unstructured mesh are shown in Figure 1.

The parameters of the nonlocal approach are chosen as $l = 10$ mm and $m = 1.05$, and a softening modulus of $\varepsilon_{\mathrm{f}} = 0.0017$ is employed. The remaining parameters of the SCDP model are chosen to resemble to material behavior of the concrete composition employed in the experimental tests, and are listed in Table 1. For the sake of brevity, the reader is referred to [5] for a description of the model and its material parameters. Due to the time-dependency of the constitutive model, a material age of 28 d is assumed in the numerical simulations, and the displacement is applied within 0.1 h. Homogeneous Neumann boundary conditions are employed for the Helmholtz-like equation (6).

The resulting load–displacement curves are shown in Figure 2. Comparing the obtained load–displacement curves for the structured and unstructured meshes of the same size, it can be seen that the results can be considered as objective, i.e., they are independent of the mesh orientation. Furthermore, for sufficiently fine meshes, i.e., for element sizes of 4 mm and 2 mm, the obtained curves are nearly identical, while the peak load is somewhat overestimated for the coarse 8 mm mesh. In general, it can be seen that the predicted peak load decreases slightly with decreasing element size.

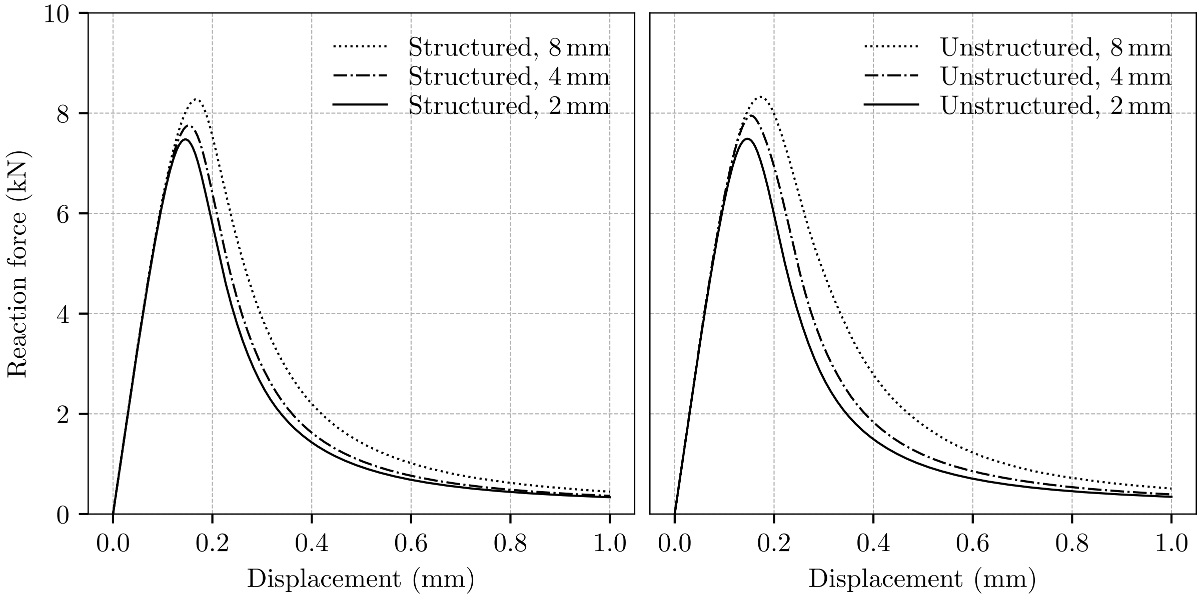

Figure 2. Load–displacement curves employing structured meshes (left) and unstructured meshes (right) with three different refinements each.

Conclusions

The over-nonlocal gradient enhancement presented by Poh and Swaddiwudhipong was employed for regularizing the softening behavior of the SCDP model, and the capabilities of the approach were demonstrated by means of numerical simulations of the experimental tests by Winkler employing finite element meshes of different refinements and orientations. It was demonstrated that the gradient enhancement is able to regularize the softening material behavior very well, leading to mesh insensitive results. While a time-independent softening modulus was assumed in the presented simulations, an extension of the constitutive model to time-dependent softening behavior is currently pending.

References

[1] Z. Bažant and L. Panula. Practical prediction of time-dependent deformations of concrete. *Materials and Structures*, Vol. 11(5):pp. 317–328, 1978.

[2] Z. Bažant and S. Prasannan. Solidification Theory for Concrete Creep. I: Formulation. *Journal of Engineering Mechanics*, Vol. 115(8):pp. 1691–1703, 1989.

[3] P. Grassl and M. Jirásek. Damage-plastic model for concrete failure. *International Journal of Solids and Structures*, Vol. 43(22):pp. 7166–7196, 2006.

[4] M. Jirásek and M. Bauer. Numerical aspects of the crack band approach. *Computers & Structures*, Vol. 110:pp. 60–78, 2012.

[5] M. Neuner, P. Gamnitzer, and G. Hofstetter. An Extended Damage Plasticity Model for Shotcrete: Formulation and Comparison with Other Shotcrete Models. *Materials*, Vol. 10(1):82, 2017.

[6] L. H. Poh and S. Swaddiwudhipong. Over-nonlocal Gradient Enhanced Plastic-damage Model for Concrete. *International Journal of Solids and Structures*, Vol. 46(25):pp. 4369–4378, 2009.

[7] B. J. Winkler. *Traglastuntersuchungen von unbewehrten und bewehrten Betonstrukturen auf der Grundlage eines objektiven Werkstoffgesetzes für Beton.* PhD thesis, Universität Innsbruck, 2001.