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Calibration of Abaqus CDP model parameters

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Summary. This article proposes a relaxed strategy for the calibration of the Abaqus Concrete Damaged Plasticity (CDP) model in order to avoid the use of computationally expensive optimization techniques.

Key words: Concrete Damaged Plasticity (CDP), model calibration, Abaqus

Introduction

The Concrete Damaged Plasticity (CDP) built-in material model available in the Abaqus commercial finite element software, [1], is widely used for beyond design criteria analyses of reinforced concrete structures within the Abaqus users community. In particular, the CDP model has proven to be versatile enough to be used in beyond design basis earthquake analyses, [2, 3, 4], as well as in benchmark impact test analyses, [5, 6, 7], and full scale airplane crash simulations, [8].

Originally developed on top of the "Barcelona" yield surface, [9], and later on the isotropic hardening laws proposed by Lee and Fenves, [10, 11], that separate the internal plastic variables into a tensile and a compressive parts, the CDP model in Abaqus enables also field variable dependent customized approaches. For example, a user enhanced Abaqus CDP model with confinement stress dependent compressive hardening evolution and strain rate dependent tensile softening evolution was proposed in [12]. Such custom material models are, indeed, necessary in special applications, in case of the previous example, in hard missile impact simulations.

Material model calibration as an optimization problem

Formally, the material model calibration is an optimization problem: "For a given material defined by its physical properties, X_{exp}, find material model input data, X_{sim}, such that the distance between the experimental test output data, $Y_{\text{exp}} = \mathcal{T}(X_{\text{exp}})$, and the simulated test output data, $Y_{\text{sim}} = \mathcal{S}(X_{\text{sim}})$, is minimum." Figure 1 shows the mapping diagram relative to material model calibration. One can, therefore, consider the formal (constrained) minimization problem of with the following objective function: $F(X_{\text{sim}}) = \text{dist}\big(\mathcal{T}(X_{\text{exp}})\,,\,\mathcal{S}(X_{\text{sim}})\big)$.

The fundamental difficulty which arises in the context of concrete modeling, is that the physical properties of a given material, such as cement chemical composition and aggregate size distribution, are totally unrelated to the material model input data. In case of the Abaqus CDP model the material input data is a collection of elasto-damage-plasticity parameters that define the elastic properties, the initial shape of the yield surface and its evolution with the increase of the internal hardening variables. On the other hand, the mechanical properties of concrete defined in the Eurocode and the FIB model code, [13, 14], are values that depend on the experimental setup such as sample size, boundary conditions and loading speed. Typically, the concrete material experiment set includes uniaxial monotonic or cyclic compression tests to

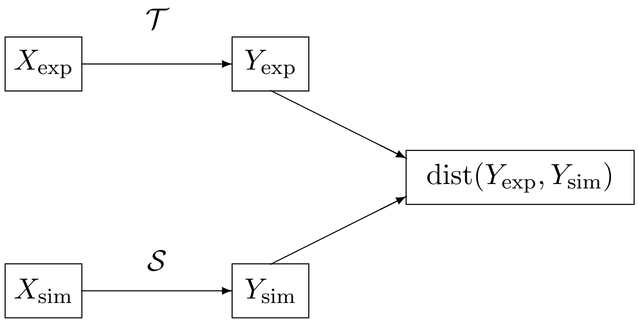

Figure 1. The basic structure of material model calibration.

determine elastic and compressive behavior and three point bending tests on notched specimen as well as split tensile tests to determine tensile behavior. In addition, the experiment set may include triaxial and/or biaxial tests to determine the failure surface shape and confinement dependency, as well as tensile and compressive split Hopkinson pressure bar tests to determine loading rate sensitivity.

Table 1. Mechanical material parameters for concrete defined in Eurocode

Denomination	Symbol	Unit
Compressive peak strength	f_{cm}	(MPa)
Total strain at compressive peak strength	ϵ_{c1}	(%)
Tensile peak strength	f_{ctm}	(MPa)
Fracture energy	G_{f}	(N/m)
Secant modulus of elasticity	E_{cm}	(MPa)
Poisson ratio	ν_{cm}	(-)
Confinement increase factor for compressive stress	CIF	(-)
Dynamic increase factor for tensile stress	DIF_{f}	(-)
Dynamic increase factor for tensile fracture energy	DIF_{g}	(-)
equibiaxial to uniaxial initial yield ratio	$\sigma_{\text{b0}}/\sigma_{\text{c0}}$	(-)
tensile to compressive meridians slope ratio	K_{c}	(-)

Therefore, it would be a mistake to consider the Eurocode mechanical concrete properties as intrinsic material parameters that can be mapped one-to-one to the material model parameters. Nevertheless, by comparing the contents of Table 2 and Table 1, one can conclude that at least some of the Eurocode mechanical concrete properties can be used as an initial guess, $X_{\text{sim}}^{(0)}$ for the minimization problem defined by the objective function F. On the other hand, it is clear that carrying out all the experiments cited above is a tough requirement. Therefore, one has to figure out a relaxed strategy to calibrate the material model with fewer experimental results.

Relaxed strategy for material model calibration

The proposed relaxed strategy for the CDP material model calibration relies on the assumption that not all of the material model parameters mentioned in Table 2 are equally important. To define the most important material parameters, the sensitivity of the model to the material parameters was studied first. Based on observations of the model behavior, an iteration order for material test simulations is proposed as per Table 3. For each simulation, model parameters to be determined by iteration as well as fixed parameters are prescribed. The value for a given

Table 2. CDP model input parameters

Denomination	Symbol		Expression
Elastic stiffness modulus	E	$\approx$	E_{cm}
Elastic Poisson ratio	ν	$\approx$	ν_{cm}
Yield surface shape parameter	α	$=$	$\big(\sigma_{\mathrm{b}_0}/\sigma_{\mathrm{c}_0} - 1\big)/\big(2\,\sigma_{\mathrm{b}_0}/\sigma_{\mathrm{c}_0} - 1\big)$
Yield surface shape parameter	γ	$=$	$\big(3(1 - K_{\mathrm{c}})\big)/\big(2\,K_{\mathrm{c}} - 1\big)$
Uniaxial compressive hardening function	$\sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}})$	$=$	$\sigma_{\mathrm{c}_0}\big((1 + a_{\mathrm{c}})\,e^{-b_{\mathrm{c}}\,\epsilon_{\mathrm{c}}^{\mathrm{p}}} - a_{\mathrm{c}}\,e^{-(1+k)b_{\mathrm{c}}\,\epsilon_{\mathrm{c}}^{\mathrm{p}}}\big)$
Uniaxial tensile hardening function	$\sigma_{\mathrm{t}}(\epsilon_{\mathrm{t}}^{\mathrm{p}})$	$=$	$\sigma_{\mathrm{t}_0}\,e^{-b_{\mathrm{t}}\,\epsilon_{\mathrm{t}}^{\mathrm{p}}}$
Uniaxial initial compressive yield stress	σ_{c_0}	$\approx$	$0.4\,\mathrm{CIF}\,f_{\mathrm{cm}}$
Uniaxial initial tensile yield stress	σ_{t_0}	$\approx$	$\mathrm{DIF}_{\mathrm{f}}\,f_{\mathrm{ctm}}$
Characteristic length	l_{ch}	$\approx$	average element dimension
Characteristic fracture energy	g_{F}	$=$	$\mathrm{DIF}_{\mathrm{g}}\,G_{\mathrm{F}}/l_{\mathrm{ch}}$
Ratio	μ	$=$	$\max\,\sigma_{\mathrm{c}}/\sigma_{\mathrm{c}_0}$
Compressive hardening parameter	a_{c}	s.t.	$k^k\,(1 + a_{\mathrm{c}})^{1+k} - (1 + k)^{1+k}\,\mu^k\,a_{\mathrm{c}} = 0$
Compressive hardening parameter	b_{c}	$=$	$-\frac{1}{k\,\mathrm{argmax}\,\sigma_{\mathrm{c}}}\ln\frac{1+a_{\mathrm{c}}}{(1+k)a_{\mathrm{c}}}$
Compressive hardening parameter	k	$\in$	$\{1, 2, 3, \ldots\}$
Tensile hardening parameter	b_{t}	$=$	$\sigma_{\mathrm{t}_0}/\big(g_{\mathrm{F}} + \frac{1}{2}\,(\sigma_{\mathrm{t}_0})^2/E\big)$
Dilation angle	ϕ		
Eccentricity of Drucker-Prager hyperboloid	e		

fixed parameter is obtained from an appropriate simulation result on the previous iteration round. If there is no appropriate simulation result available, then an Eurocode value is applied as suggested by Table 2.

Table 3. Material test simulation iteration order

Order	Simulation	Parameter to be iterated	Fixed parameters
1.	Uniaxial compression	$E, \nu, \sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}})$	$\sigma_{\mathrm{t}}(\epsilon_{\mathrm{t}}^{\mathrm{p}}), \gamma, \alpha, \phi, e$
2.	Triaxial compression	$\gamma, \alpha, \mathrm{CIF}$	$\sigma_{\mathrm{t}}(\epsilon_{\mathrm{t}}^{\mathrm{p}}), \phi, e, E, \nu, \sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}})$
3.	Notched 3 point bending	$\sigma_{\mathrm{t}}(\epsilon_{\mathrm{t}}^{\mathrm{p}})$	$\sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}}), \gamma, \alpha, \phi, e, E, \nu$
4.	Direct shear	ϕ, e	$\sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}}), \sigma_{\mathrm{t}}(\epsilon_{\mathrm{t}}^{\mathrm{p}}), \gamma, \alpha, E, \nu$
5.	Split tensile	$\max\,\sigma_{\mathrm{t}}$	$\sigma_{\mathrm{c}}(\epsilon_{\mathrm{c}}^{\mathrm{p}}), \gamma, \alpha, \phi, e, E, \nu$

Further studies

In order to understand the wider context of this specific study, it is necessary to consider the experimental reinforced concrete slab impact testing, [15, 16] and concrete material model development, calibration and validation work, [12, 7] that has been going on in the Technical Research Centre of Finland (VTT). The primary objective of this research work is to provide a scientifically validated computational analysis tool that enables large scale airplane crash on concrete buildings to be performed. The calibration of the concrete material model parameters is therefore done as suggested in this study using concrete test results from the VTT experimental impact testing program. The validation of the simulation model is then carried out against selected benchmark impact experiments from the same experimental program.

References

[1] Simulia. *Abaqus Manual.* Dassault Simulia, 2016.

[2] V. Jussila and L. Fülöp. Damping estimates based on the level of non-linear response in stiff concrete buildings. *VTT report: VTT-R-05636-14*, 2014.

[3] V. Jussila, Y. Li, and L. Fülöp. Statistical analysis of the variation of floor vibrations in nuclear power plants subject to seismic loads. *Nuclear Engineering and Design, 84-96.*, 2016.

[4] A. Fedoroff and L. Fülöp. Study of the seismic response of a nuclear powerplant building. *VTT report: VTT-R-02604-18*, 2018.

[5] J Rodriguez, F. Martinez, and J. Marti. Concrete constitutive model, calibration and applications. *2013 SIMULIA Community Conference*, 2013.

[6] A. Fedoroff, J. Kuutti, and A. Saarenheimo. A physically motivated element deletion criterion for the concrete damage plasticity model. In *SMiRT-24 transactions.* International Association for Structural Mechanics in Reactor Technology, 2017.

[7] A. Fedoroff and K. Calonius. Using the abaqus cdp model in impact simulations. *Rakenteiden Mekaniikka (Journal of Structural Mechanics), accepted for publication*, 2019.

[8] A. Fedoroff. Parametric study of aircraft impact simulation on nuclear power plant. *VTT report: VTT-R-05152-17*, 2017.

[9] J Lubliner, J. Oliver, S Oller, and E. Oñate. A plastic-damage model for concrete. *Int.J. of Solids and Structure*, 25(3):299–326, 1989.

[10] J.H. Lee. *Theory and implementation of plastic-damage model for concrete structures under cyclic and dynamic loading.* PhD dissertation, University of Berkley, California, 1996.

[11] J.H. Lee and G. Fenves. Plastic-damage model for cyclic loading of concrete structures. *Journal of Engineering mechanics*, 124(8):892–900, 1998.

[12] A. Fedoroff, K. Calonius, and J. Kuutti. Behavior of the abaqus cdp model in simple stress states. *Rakenteiden Mekaniikka (Journal of Structural Mechanics), 52(2), 87-113.*, 2019.

[13] FIB. *Fib Model Code 2010.* International Federation for Structural Concrete, Lausanne, 2010.

[14] CEN European Committee for Standardization. *Eurocode - Basis of structural design.* Finnish Standards Association SFS, 1990.

[15] A. Vepsä, A. Saarenheimo, F. Tarallo, J.-M. Rambach, and N. Orbovic. Impact tests for iris 2010 benchmark exercise. *Journal of Disaster Research, 7(5), 619-628*, 7(5):619–628, 2012.

[16] A. Vepsä, K. Calonius, A. Fedoroff, L. Fülöp, V. Jussila, A. Saarenheimo, P. Varis, B. Fälth, B. Lund, and M. Tuomala. Experimental and numerical methods for external event assessment improving safety (ernest). In *SAFIR2018 The Finnish Research Programme on Nuclear Power Plant Safety 2015-2018: interim report.* VTT, Technical Research Centre of Finland, 2016.