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Strain hardening exponent role in phenomenological ductile fracture criteria

František Šebek [a], [*], Petr Kubík [a], Jiří Hůlka [b], Jindřich Petruška [a]

[a] Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic
[b] Institute of Applied Mechanics, Resslova 972/3, 602 00 Brno, Czech Republic

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ABSTRACT

The performance of ductile fracture criteria often depends on the accuracy of material constants identification. Calibration process of three uncoupled phenomenological models was analysed. All of them contain the strain hardening exponent which is related to material plasticity as one of the fracture criteria parameter. More flexibility, better approximation of the fracture locus and more convenient shape of the fracture envelope might be reached when the strain hardening exponent is considered as another independent parameter of the fracture criteria in the identification process. Results are illustrated on the example of two structural steels, AISI 316L and AISI 1045, respectively.

1. Introduction

The ductile fracture has been extensively studied and amount of different kinds of ductile fracture criteria have been developed (Cockroft and Latham, 1968; Abiri and Lindgren, 2015; Cao et al., 2014; Bai and Wierzbicki, 2015). In spite of intensive research these criteria have not become a standard component of commercial finite element codes yet and potential users have to implement it themselves. Many sophisticated ductile fracture models have been presented in recent literature too. If an attention is limited only to uncoupled models, which do couple the damage with plasticity but not vice versa, the following ones should be mentioned: Xue–Wierzbicki model (Wierzbicki et al., 2005a,b), model proposed by Bai and Wierzbicki (2008), Extended Mohr–Coulomb criterion (Bai and Wierzbicki, 2010), model derived by Lou et al. (2012, 2014), or Hosford–Coulomb model (Mohr and Marcadet, 2015). This paper is focused on the role of strain hardening exponent in three ductile fracture models, namely Xue–Wierzbicki model, Extended Mohr–Coulomb criterion, and Hosford–Coulomb model, respectively.

Bao and Wierzbicki (2004) carried out fifteen tests of aluminium alloy 2024-T351 and found out that the fracture strain is not a monotonic function of pressure as observed by Bridgman (1964). Wierzbicki et al. (2005a,b) developed the so-called Xue–Wierzbicki model due to previous findings. It had a symmetric weighting function of fracture strain because the fracture strain dependence on the stress triaxiality was expressed through exponential functions in the same way both for axisymmetric tension and compression. The fracture strain dependence was described by another exponential function for the plane strain condition. Transition between different stress states, expressed by the so-called Lode dependence, was described by a family of elliptic functions. Thus, the fracture strain was expressed as a limit envelope with the stress triaxiality and Lode parameter as independent coordinates. Wierzbicki et al. (2005a,b) also pointed out that material constants appearing in the exponential functions are related to the strain hardening exponent. Khan and Liu (2012) used this model in comparison with maximum shear stress criterion (Stoughton and Yoon, 2011). Zhou et al. (2012) modified Xue–Wierzbicki model introducing another form of exponential functions for axisymmetric and plane strain conditions.

Xue–Wierzbicki model is not the only fracture criterion related to the strain hardening exponent. Bai and Wierzbicki (2008) derived the metal plasticity with Lode and pressure dependence. This plasticity laid the foundations of Extended Mohr–Coulomb criterion (Bai and Wierzbicki, 2010). This criterion was first expressed through the equivalent stress at the point of fracture in form which did not contain the strain hardening exponent explicitly. It appeared as an independent parameter after transformation

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[*] Corresponding author. Tel.: +420 54114 4925.
E-mail addresses: sebek@fme.vutbr.cz (F. Šebek), ykubik05@stud.fme.vutbr.cz (P. Kubík), hulkaj@uam.cz (J. Hůlka), petruska@fme.vutbr.cz (J. Petruška).

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to the form where the equivalent plastic strain represented the decisive state parameter describing the fracture onset. Li and Wierzbicki (2010) used Extended Mohr–Coulomb criterion to formulate the post-initiation behaviour with introducing the softening law into the model. Dunand and Mohr (2011a,b) studied further the predictive capabilities of this model over the wide range of stress states. Cao et al. (2013) used Extended Mohr–Coulomb criterion in comparison of phenomenological models via hybrid analysis of experiments conducted on a zirconium alloy. Lou et al. (2014) compared their proposed model to Extended Mohr–Coulomb criterion to evaluate its prediction ability revealing that models have similar accuracy.

Another suitable phenomenological criterion for studying the strain hardening exponent role is the Hosford–Coulomb model recently proposed by Mohr and Marcadet (2015). It incorporates Hosford equivalent stress into the Mohr–Coulomb criterion and the localization criterion is employed as a ductile fracture model by fracture stress in the first stage, the same as in case of Extended Mohr–Coulomb criterion. Then, it was transformed into the strain space bringing the strain hardening exponent to appear in the model via the hardening law.

In the criteria mentioned, Xue–Wierzbicki model, Extended Mohr–Coulomb criterion, and Hosford–Coulomb model, the strain hardening exponent related to plasticity can affect the fracture behaviour (Wierzbicki et al., 2005a,b). Nevertheless, parametric study showed that better approximation of fracture locus and shape of fracture envelope might be reached when the strain hardening exponent is replaced by independent parameter in the fracture criteria.

Fracture tests necessary for calibration should cover a wide range of stress states. This can be reached either by different types of specimen shapes as shown in Fig. 1 or by universal specimens which reach different stress states by suitable combination of loading.

Butterfly specimen designed by Wierzbicki et al. (2005a,b) and torsion specimen inspired by Lindholm et al. (1980) are such universal specimens. Later, Dunand and Mohr (2011a,b) proposed optimized shape of this specimen. Španiel et al. (2014) showed the importance of modelling the whole butterfly testing device due to non-negligible friction effect in the guiding which makes the calibration simulations more computationally expensive.

Barsoum and Faleskog (2007) developed doubly notched tube specimen for combined tension and torsion loading at a fixed ratio. Gao et al. (2011) also developed an alternative design of Lindholm-type specimen for combined tension-torsion testing under conditions of low triaxiality. Graham et al. (2012) showed that the plastic strain was constant through the thickness of their Lindholm-based specimen, as desired. Experimental results were later extended by Faleskog and Barsoum (2013) down to zero stress triaxiality. Xue et al. (2013) made an extension of Gurson model to simulate tension-torsion fracture tests presented by Faleskog and Barsoum (2013). Haltom et al. (2013) presented approach of direct determination of the stress and deformation directly from the experiment. Another specific design of notched tube specimen is presented in this paper.

2. Ductile fracture criteria

2.1. Characterizing the stress state

The stress state in a material point can be described by three stress invariants, the first invariant of the Cauchy stress tensor and the second and third invariants of the deviatoric stress tensor, respectively. The pressure dependence can be described by the stress triaxiality

$$\eta = \frac{\sigma_m}{\overline{\sigma}}, \tag{1}$$

where σ_m is the mean stress and $\overline{\sigma}$ is the equivalent stress obeying von Mises plasticity.

Finally, the Lode dependence can be described by certain deviatoric state parameter, such as the normalized third invariant of deviatoric stress tensor ξ, Lode parameter μ, Lode angle θ_L, azimuth angle θ_A or normalized Lode angle $\overline{\theta}$. Definitions of these variables and relations between them are, with the use of deviatoric stress tensor **S**, expressed as

$$\xi = \frac{27}{2}\frac{\det(\mathbf{S})}{\overline{\sigma}^3}, \tag{2}$$

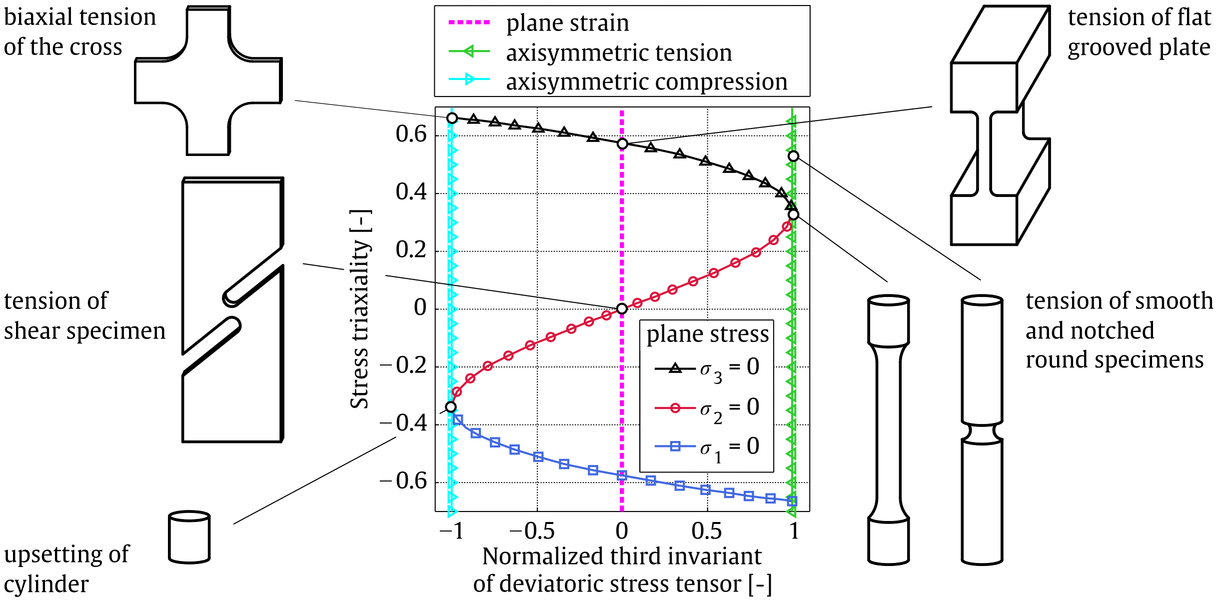

Fig. 1. Plane of stress triaxiality and normalized third invariant of deviatoric stress tensor with specimens describing different stress states.