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Numerical derivation of strain-based criteria for ductile failure: Discussions on sensitivity and validity

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ABSTRACT

The structural application of HSLA steels can be fostered by considering their ductile failure properties in design. To achieve this we discuss an approach to numerically derive Johnson–Cooks criterion from GTN simulations. The critical state is assumed to be the onset of softening within a global neck. Due to the non-uniqueness of the GTN parameters a calibration scheme is required to enhance the reliability of the procedure. Such a scheme is proposed and tested on the basis of a GTN sensitivity study. With the proposed procedure the strain-based design criterion can reliably be derived for triaxialities higher than 1.0.

1. Introduction

Modern high-strength steels are characterised by excellent mechanical properties. Their application allows a lightweight, efficient design. This provides economic and ecological advantages, for example in the automotive industry [1]. Grades with such properties are also available as heavy plates, e.g. the high strength low alloy steels (HSLA). They are typically applied in large scale structures, such as mobile cranes, steel constructions, pipelines and pressure vessels. But in industries subjected to regulation, e.g. civil engineering or the energy sector, their application is hindered by conservative design standards, which do not consider the improved toughness and the resulting increased resistance to ductile failure [2,3].

Therefore, new methods for a consideration of ductile failure properties in structural simulations have to be found. Damage mechanics models, such as the Gurson model [4], could be used since they are able to describe ductile damage [5]. However, these models are not optimal for the simulation of ductile failure in large scale structures due to computational requirements and internal length scales [6,7]. They can be successfully applied to such applications (e.g. [8,9]) but only if the critical spot is known so that an area of fine elements can be limited to e.g. a crack surrounding region. Efficient strain-based criteria, such as the Johnson–Cook (JC) model [10], are better suited for simulations in these dimensions.

Damage mechanics models as well as strain-based failure criteria are experimentally calibrated on laboratory specimens. However, a purely experimental calibration is not possible in application fields subjected to standardisation since the design process is based on nominal material properties. These have to be guaranteed by the producers and are defined in the corresponding standards. A strain-based design criterion in accordance with the standards must consequently refer to these nominal properties, hence to a "virtual" material. Therefore, a numerical derivation of strain-based criteria is necessary.

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Nomenclature

a	fatigue pre-crack depth
D	damage parameter
D_i	fitting parameter for Johnson–Cook failure curve
F	force
f_0, f, f_c, f_f	void volume fraction: initial, current, onset of coalescence, failure
f_N	secondary void volume fraction
J_2	2nd invariant of stress deviator
k	Hollomon coefficient
n	hardening exponent
q_1, q_2, q_3	fitting parameters for GTN model
r	notch radius
S_N	standard deviation for void nucleation
T	temperature
$\dot{\bar{\varepsilon}}^{pl}$	equivalent plastic strain rate
$\dot{\varepsilon}^{pl}_{kk}$	rate of plastic volume dilatation
$\bar{\varepsilon}^{pl}$	equivalent plastic strain
$\dot{\varepsilon}$	strain rate
$\Delta\varepsilon_p$	increment of equivalent plastic strain
ε	strain
ε_f	failure strain
ε_N	characteristic strain for void nucleation
η	stress triaxiality
κ	acceleration factor
σ_e	von Mises stress
σ_h	hydrostatic stress
σ_y	yield stress
$\bar{\sigma}$	flow curve

Münstermann et al. have recently proposed such a procedure [3], which is based on simulations with the Gurson–Tvergaard–Needleman (GTN) model [3]. In brief, a GTN parameter set for a steel grade is identified, which meets the nominal properties in the simulation of the relevant tests. The corresponding critical strains of the JC model are then computed via a cell element with the GTN model and the nominal parameter set. By this, a strain-based ductile failure criterion can be derived purely numerically.

The European material delivery standards, such as EN 10028 and EN 10025, prescribe nominal values for yield and tensile strength and the results of Charpy impact toughness tests (CITT). These values should consequently be considered in the numerical derivation of a strain-based criterion for ductile failure for materials subjected to regulation. Subsequently, such a criterion can be applied in structural simulations to support a discussion on the optimisation of the current regulatory framework.

The main drawback of such a procedure is that the parameter sets of damage mechanics models are non-unique [11–13]. Consequently, a detailed investigation on the sensitivity and validity of the derivation procedure is necessary. The scope of this paper is therefore to explore the reliability of the numerically derived JC criterion. A sensitivity analysis is performed to investigate the influence of the GTN material parameters on the derivation procedure. Due to the non-uniqueness a calibration scheme for the GTN parameters is required to ensure a reliable application of the procedure and a comparability of the results. Such a calibration scheme is proposed and tested. By this, the applicability of a numerically derived strain-based design criterion for structural applications is investigated.

This paper consists of four sections. Section 2 describes materials and methods, including an overview on the calibration procedures for strain-based criteria as well as Gurson models, the methodology of the sensitivity analysis and the re-calibration of the parameters according to the proposed procedure. Corresponding results are presented along with the discussion in Section 3. Conclusions are given in Section 4.

2. Materials and methods

The theoretical background of JC and GTN models, possible calibration procedures for material parameters and existing sensitivity analyses are presented in Sections 2.1. Section 2.2 gives a detailed description of the numerical derivation of critical strain criteria and an outlook on its application. The method of the performed sensitivity analysis is explained in Section 2.3 while Section 2.4 describes the tests that were performed to validate the approach.