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ESTIMATING PLASTICITY AND DUCTILE DAMAGE MODEL PARAMETERS FOR S355-S690 STEEL FROM MILL TEST CERTIFICATE DATA

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Abstract

Accurate finite-element simulation of the fracture of metals requires the calibration of plasticity and fracture modelling parameters based on mechanical tests on the material. Depending on the complexity of the model, each different material that is modelled requires a number of non-standard tests followed by a calibration process. This paper derives relationships between mill test certificate data and the plasticity and damage model parameters for S355-S690 steel in order to enable the quick application of generally representative plasticity and damage models to these steels without the need for repeated manual calibration of each material. The relationships are obtained by regression analysis between a database of 2597 mill test certificate results (of tensile and Charpy tests) and a parametric finite element study in which the parameters of a Hollomon-type stress-strain model and the Modified Mohr-Coulomb damage model were varied.

Introduction

Models for describing the ductile fracture of metals require material-specific experimental calibration involving fracture at a minimum number of stress-states. Widely used models such as the micromechanical GTN [1] model and the phenomenological maximum shear stress, Johnson-Cook [2], Hosford-Coulomb [3] and Modified Mohr-Coulomb [4] models typically involve between one and five tests for calibration. This includes calibration against the stress-strain curve from tensile testing to describe the true stress-strain curve. In many situations in engineering practice however, the only mechanical test results reported on mill test certificates are that of the tensile and Charpy impact tests: the yield stress σ_y, ultimate tensile strength σ_u, failure elongation ε_f and Charpy impact energy C_v, *without* the full stress-strain curve. This work derives relationships that enable the use of a generally representative ductile fracture model given only mill test certificate data, without the need for manual calibration, from the analysis of parametric numerical results that are mapped against empirical data.

Methodology

A finite element parametric study is performed to find relationships between the mill certificate data σ_y, σ_u, ε_f and C_v and the material modelling parameters for describing plasticity and damage. Known analytical and empirical relationships from the literature are used to the reduce the number of unknowns in the description of the true stress-strain curve without losing its representativeness. The resulting parametric analyses are compared against and mapped to the empirical results of a database of 2597 mill test certificate results and regression analysis is performed to derive the relationships between the mill certificate data and the material modelling parameters.

Plasticity and damage modelling

The material is assumed to have an elasto-plastic behavior with a Young's modulus E of 200 GPa, a Poisson's ratio of 0.3 and yielding based on the von Mises criterion with the associated flow rule. A Hollomon-type power-law hardening curve with a yield plateau is assumed for the true plastic stress-strain curve, as given by Eqs. (1) and (2):

$$\sigma = \begin{cases} \sigma_y \left(\dfrac{\varepsilon_{sh} - \dfrac{\sigma_y}{E}}{\varepsilon_{sh,p}} \varepsilon_p + \dfrac{\sigma_y}{E} + 1 \right) & \text{for} \quad 0 < \varepsilon_p < \varepsilon_{sh,p} \\ K \varepsilon_p{}^n & \text{for} \quad \varepsilon_p \geq \varepsilon_{sh,p} \end{cases} \tag{1}$$

$$\text{with} \qquad \varepsilon_{sh,p} = \ln(1+\varepsilon_{sh}) - \ln(1+\frac{\sigma_y}{E}) \tag{2}$$

where σ is the true stress; ε_p is the true plastic strain; ε_{sh} and $\varepsilon_{sh,p}$ are respectively the total engineering strain and the true plastic strain corresponding to the end of the yield plateau; K is the strength coefficient; and n is the strain hardening exponent.

The parameter ε_{sh}, which indicates the length of the yield plateau, is found from an empirical equation which is derived in [5] from regression analysis of 455 engineering stress-strain curves of structural hot-rolled steels with nominal grades up to S690. Additionally assuming that the ultimate tensile stress σ_u satisfies the Considère [6] criterion for necking and considering that the power curve intersects with the yield plateau at a true plastic strain $\varepsilon_p = \varepsilon_{sh,p}$ enables K, n, ε_{sh} and $\varepsilon_{sh,p}$ and hence the whole true stress-strain curve to be approximated, given only σ_y, σ_u and E. For modelling the Charpy test specimen, the plastic stress-strain curve is scaled appropriately based on the Cowper-Symonds model to take the strain rate into account [7].

To describe the initiation of damage, the Modified Mohr-Coulomb [4] fracture model with von Mises yielding, which has two calibration parameters c_1 and c_2, is used. A suitably averaged damage evolution parameter is used to describe the subsequent degradation of the material stiffness.

Based on this, finite element Charpy tests and uniaxial tensile tests are simulated for a range of materials by varying the input parameters σ_y, σ_u, c_1 and c_2. The resulting numerical analyses are compared and mapped against a database of 2597 mill test certificate results of Charpy and tensile tests to find relationships between the material certificate's σ_y, σ_u, ε_f and C_v and the finite element material parameters K, n, ε_{sh}, $\varepsilon_{sh,p}$, c_1 and c_2.

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