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A novel development of bi-level reduced surrogate model to predict ductile fracture behaviors

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ABSTRACT

In this paper, a bi-level reduced surrogate model is developed and presented to identify the material parameters of ductile fracture criterion. Using this method, the identification process becomes feasible with only a limited number of experimental tests. The method assembles local critical elements associated with global models. The surrogate model of fracture strain constructed using Diffuse Approximation and the local elements, reduces the computational effort for searching identified material parameters. Global fracture simulations are preformed to update the target fracture strain and to compute the corresponding failure onset displacement. Convincing results are obtained via *successive* applications of Design of Experiments (DOE) and *enhanced* design space transformation algorithms. The proposed identification protocol is validated for the modified Mohr-Coulomb fracture criterion using DP590 steel. Robustness of this method is confirmed with different initial guess. It orients a new direction for material parameters identification based on surrogate model which can effectively be implemented to predict the fracture behaviors.

1. Introduction

Light weight materials become attractive alternatives for modern engineering applications, particularly in the automotive industry, to reduce the emission of environmental pollutants and increase the fuel efficiency. Hence, dual-phase (DP) steel is a promising candidate for this purpose. Commonly, DP steel consists of hard martensite islands embedded into soft ferrite matrix, thereby it enhances several mechanical properties, such as, relatively high ultimate tensile strength (UTS), low yield to tensile strength ratio, absence of yield elongation [1–6]. However, the application of DP steel in the automotive industry is usually limited by its ductile fracture behavior during forming processes [7–10].

In general, ductile damage occurs as a result of nucleation, growth and coalescence of micro voids that eventually leads to ductile fracture due to crack formation and its propagation [11–15]. In theory, the assumption that the void volume fraction reaches a critical value has been considered as the fundamental hypothesis to explain the ductile fracture criterion. Alternatively, phenomenological models have been proposed to predict ductile fracture without modeling micro-voids.

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Nomenclature

Symbols

A_0	initial cross section aera of tensile specimen
A_f	fractured cross section aera of tensile specimen
c_1	coefficient of friction
c_2	shear resistance
c_3, c_4, c_θ	material constants of MMC fracture criterion
$D(\bar{\varepsilon}_p)$	damage indicator
d_f	predicted fracture onset displacement
d_f^{exp}	measured fracture onset displacement
Δd_f	adaptive deviation of fracture onset displacement
K	material constant of Swift power law
n	material constant of Swift power law
R	notch radius of tensile specimen
ε_0	material constant of Swift power law
ε_f	initial fracture strain
$\bar{\varepsilon}_f$	equivalent plastic strain to fracture
$\tilde{\varepsilon}_f$	predicted fracture strain
ε_f^{exp}	measured fracture strain
ε_p	plastic strain
η	stress triaxiality
$\boldsymbol{\sigma}$	stress tensor
σ	true stress
$\bar{\sigma}$	von Mises equivalent stress
σ_{I-III}	principal stresses
σ_m	hydrostatic stress
σ_n	normal stress
τ	shear stress
θ	Lode angle parameter
$\bar{\theta}$	normalized Lode angle parameter
LES.	least square error
UTS	ultimate tensile strength

The developments of these models are based on a reasonable assumption that the ductile failure appears when a weighting indicator of the accumulated plastic strain reaches a critical threshold value [16,17]. According to Bao and Wierzbicki [18], all these models cannot provide an accurate prediction of fracture behavior for a given material within a large range of stress triaxialities. Therefore, Bai and Wierzbicki [19,20] extended the classical Mohr-Coulomb fracture criterion [21] to predict ductile fracture, which is also called as modified Mohr-Coulomb (MMC) criterion. The weighting indicator of MMC criterion includes the equivalent plastic strain, stress triaxiality and Lode angle parameter.

Recently, numerous experimental investigations [18,22–28] have been performed to characterize and identify the material parameters which are prerequisite of MMC criterion for various ductile metals. Typically, a massive quantity of fracture tests are required to be performed during such experimental works. This requires enormous amount of time and expenses to prepare specimens and analyze experimental data. Therefore, it indicates the needs for further improvement in this technique to simplify the identification process.

For aforementioned reasons, a bi-level reduced surrogate model is proposed as a computationally inexpensive alternative to identify material parameter of the MMC fracture criterion in this paper. In the recent literature [29,30], reduced surrogate model was initially used to parameterize numerical material representation based on proper orthogonal decomposition, extended to approximate the constitutive behavior of local material for a given microstructure in a topology optimization problem [31]. This method is robust and shows high accuracy in both of these numerical applications. Moreover, surrogate model [32–34] utilizes an approximation based on the results computed at various points in a design space to replace a complex one. The approximation obtained from the surrogate model does not represent the low fidelity versions of computational models derived by simplifying the physics of underlying phenomena. Instead, the surrogate-model based approximation aims to reconstruct the input-output relationship implemented by numerical simulations [35]. Particularly, the application of the surrogate model in this identification process significantly reduces the number of required fracture tests. In order to construct surrogate model properly, the Diffuse Approximation [29–31,36–38] is widely used. And, its

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