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The effect of low stress triaxialities and deformation paths on ductile fracture simulations of large shell structures

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ABSTRACT

In accidental limit state analysis of ship structures and their components, the common assumption is that failure takes place in the plate field under multi-axial tension, thus most advancements in developing fracture criteria have focused on that region. In contrast, failure in low stress triaxialities is relatively unexplored territory in the context of large-scale crash analysis. The probability of this failure mode increases with the decreasing ductility that is characteristic of high and extra high strength steels. Therefore, ductile fracture simulations are performed with large thin-walled steel structures employing four different fracture criteria that differently account low stress triaxialities and deformation history. Criteria are compared as to their capabilities to reproduce and predict experimentally measured behaviour. Analyses demonstrate that failure under lower stress triaxialities affects the response significantly especially when complex deformation history is considered. Suggestions are made for the further enhancement of fracture criteria as well as experimental configurations employed for benchmarking failure criteria.

1. Introduction

The crashworthiness analyses of large complex steel structures such as ships are currently performed with the non-linear finite element simulations. Since these simulations involve large deformations and ductile fracture, the accuracy of simulations depends on the fracture criteria used to remove elements and thereby simulate fracture propagation. When experimental results are available, accuracy of simulation is evaluated by comparing measured and simulated force-displacement curves. However, measured results are rarely available, but simulations are still used to validate analytical models [1,2] and design novel collision-resistant structures with improved crashworthiness [3]. Therefore, accuracy, reliability and consistency of the simulation approach, i.e., fracture criterion, play a crucial role. Comparative studies, reviews and benchmark evaluations of different fracture criteria employed in collision and grounding analysis of ship structures have been previously reported [4–12]. The main challenges addressed in these studies were the uncertainties in large crash analysis, fracture strain sensitivity to element size, and how and whether to include stress (or strain) state dependence.

In engineering applications, structures are often complex and subject to different loading conditions, meaning that stress state, quantified here through the stress triaxiality parameter (or simply triaxiality) $\eta = \sigma_h/\overline{\sigma}$, also changes depending on the loading. Accordingly, triaxiality gives the ratio of hydrostatic mean stress (relates to volume change) to equivalent von Mises stress (relates to shape change) that allows efficient distinction between loading states. Furthermore, material fracture train is commonly related with triaxiality as shown in Fig. 1 (a) for marine structural steel in Fig. 1 (b). For three-dimensional stress states the fracture locus depends

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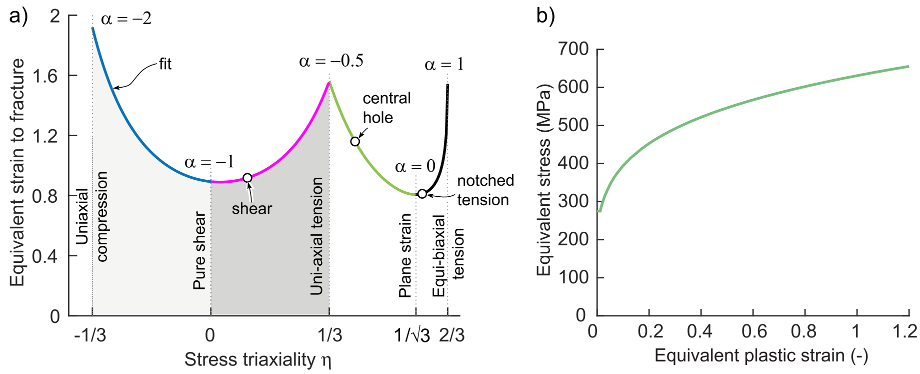

Fig. 1. (a) Stress triaxiality dependent plane stress fracture locus for structural steel shown in (a) calibrated with three different tensile tests. The two zones of interest in this work are highlighted in dark grey (pure shear to uniaxial tension) and light grey (uniaxial compression to pure shear). (a) True stress-strain curve of the structural steel S235JR. Material data from Ref. [13].

also on the Lode angle parameter, but it is not considered here as we limit the attention to plane stress states.

Novel fracture models tailored for analysis of smaller structural components give explicit analytical expression for loci shown in Fig. 1 covering the whole stress space, e.g. see Ref. [14]. However, fracture modelling approaches employed in crash analysis of large structures tend to incorporate latest research findings with delay because the upscaling of the material behaviour from small-scale test coupons to large thin-walled structures is rarely straightforward because of the mesh size dependence, e.g., see Refs. [15–20]. Consequently, modelling approaches for large structures have been mostly concerned with fracture under multi-axial tension regime (triaxialities between uni-axial to equi-biaxial tension, $1/3 < \eta \leq 2/3$) or by ignoring the stress state effect completely with the utilisation of equivalent plastic failure strain criterion, see the review by Calle and Alves [5]. Moreover, omitting some characteristics of the ductile fracture process is often justified on a basis of negligible influence on the large-scale analysis results, particularly on force-displacement curve, although the effect on the fracture path and opening shape can be considerable, e.g. see Ref. [21]. The failure modes associated with the lower triaxialities ($\eta < 1/3$) such as shear and compression (see Fig. 1) have been disregarded mostly because of the latter assumption. Furthermore, failure under these modes is relegated to a secondary role by the assumption that thin-walled structures typically accommodate compression and shear loading by buckling leading to a locally tensile-dominated problem. While some criteria incorporate failure under shear dominated modes [22,23] as well as over the whole triaxiality range [24,25], they neither demonstrate the emergence of shear dominated failure modes ($\eta < 1/3$) nor show the importance of incorporating such modes. First of these issues was addressed by Atli-Veltin et al. [26] who showed that in ship collision analysis shear and compression arise in beams and stiffeners of the struck ship, but disregarded the quantitative significance of this finding.

The second issue affecting the degradation of metallic materials during large plastic deformations is the deformation history or the deformation paths. Experimental observations in the field of metal forming, e.g. Ref. [27], have shown that non-proportional deformations significantly affect the in-plane principal strains at incipient plastic instability, the major strain ε_1 and minor strain ε_2. Recent experimental-numerical works also suggest that fracture strain depends on the strain history [28–30]. According to Hooputra et al. [31] consideration of deformation paths is particularly important for crash applications where highly non-linear paths are expected. For these reasons, recent approaches have focused on the development of non-linear damage accumulation rules accounting deformation history in the context of necking [32,33] or fracture [19,34]. From the failure criteria tailored for coarsely meshed shell structures, only the stress based BWH criterion by Alsos et al. [22] addresses the issue explicitly, as its presentation in stress coordinates is claimed to reduce the path dependence. While in collision and grounding analysis of ship structures the path dependency has not been explicitly considered by criteria that use equivalent plastic strain $\bar{\varepsilon}$ and triaxiality dependent failure strain, the effect of deformation history is still partially considered as the equivalent plastic strain is ever increasing function of plastic straining as noted in Ref. [33]. Moreover, the equivalent plastic strain-based criteria are commonly formulated in terms of damage accumulation rule, which as will be shown is a simple, but effective means to consider the deformation history.

The aim of this paper is twofold: firstly, we attempt to elucidate the effect of lower trixialities in large crash analysis. To this end, the fracture is simulated in large thin-walled structures with four different fracture criteria that are distinguished by the way they handle the fracture at low triaxialities and how they account the history of deformation. The analyses are performed with three carefully selected structures for which the experimental results in terms of force-displacement are available. The sensitivity of the numerical simulations to low triaxiality is presented and analyzed. Secondly, these analyses provide insight into the deformation paths in large crash analysis and thus, we provide some clarity for the notion how various criteria handle complex paths in the context of large-scale crash analysis. The hallmark of the present investigation is the insight it provides to different fracture criteria used in coarsely meshed shell structures and to the way they handle shear deformations and deformation paths up to the point of fracture. This insight is believed to be valuable in making conscious decisions regarding future developments of fracture criteria and experimental techniques that are used in accidental limit state design. The limitation of the study is that all used fracture criteria have been developed for membrane type of loading, thus bending dominated effects are not considered explicitly.