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Influence of mesh size, stress triaxiality and damage induced softening on ductile fracture of large-scale shell structures

Mihkel Kõrgesaar*, Jani Romanoff

Aalto University, Department of Applied Mechanics, Otakaari 3, Espoo, Finland

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ABSTRACT

In this investigation, ductile fracture in stiffened and unstiffened panels is simulated employing the fracture criterion, which depends on the mesh size, stress state and damage induced softening. The aim of the study is to show that employed fracture criterion removes mesh size effects more efficiently than traditional fracture criteria adjusted only on the basis of uniaxial tension. Fracture model is implemented into Finite Element software ABAQUS using user-defined material, VUMAT-subroutine, available for shell elements. Mesh size sensitivity analysis is carried out. Finite element simulation results are validated with experimental measurements available in literature. Comparison of numerical and experimental results shows that simulations effectively capture most of the experimentally observed features, especially when considering different mesh densities. In most cases, mesh size effects are considerably reduced compared with the fracture criteria adjusted on the basis of a uniaxial tension.

1. Introduction

Simulating ductile fracture in large shell structures has been of considerable interest recently [1–6]. In these simulations, shell elements are preferred over solid elements because of the computational efficiency. The efficiency is gained by discretizing the structure with large shell elements compared

* Corresponding author. Tel.: +358 50 5648878.
E-mail address: mihkel.korgesaar@aalto.fi (M. Kõrgesaar).

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with small solid elements. However, the large structural shell elements cannot capture the strain localization at large deformations making the FE solution mesh size dependent, whereby the fracture strain increases as the mesh is refined. Therefore, a key question in such analyses is to establish a reliable fracture criterion: in the context of large structures such criterion must yield mesh size independent results as well as handle multi-axial stress states.

In the failure analysis of materials and structures, size effects are an important issue [7,8]. Mesh size effects appear after necking, which is a form of strain localization. For example, in the tensile specimen in Fig. 1(a), strains localize in the middle of the specimen. Mapping a finite element into the middle of the specimen, as shown in Fig. 1(a), indicates that average strain in the small element is much higher than in the large element. Such mesh size effects deduced from the tensile test are commonly given in the form of Barba's law [9] as shown in Fig. 1(b). Barba's law gives the equivalent plastic strain to fracture, i.e. the fracture strain $\overline{\varepsilon}_f$, as a function of the element length and plate thickness ratio L/t. In the sequel, the failure criterion based on the critical equivalent strain is referred to as *shear* criterion and term element size is used to refer to L/t ratio.

The *shear* criterion has been widely used for design purposes. The assumption is that the stress state corresponds to uniaxial tension and does not change during the simulation. However, in real structures such idealistic conditions rarely occur due to the changing load conditions and structural discontinuities, e.g. stiffeners, welds, notches etc. Under multi-axial stressing, fracture ductility depends markedly on the pressure (hydrostatic stress, σ_h) or the stress triaxiality (hydrostatic stress divided by the equivalent von Mises stress, $\eta = \sigma_h/\overline{\sigma}$) as noticed by Refs. [10,11] and later shown in various experimental studies, e.g. Refs. [12–15]. Bai and Wierzbicki [16] fracture locus for one steel type vividly illustrate this dependence in Fig. 2(a). For instance, in plane strain tension ($\eta = 1/\sqrt{3}$), fracture strain can be significantly lower (up to 50%) than the fracture strain measured during uniaxial tension ($\eta = 1/3$) and biaxial tension ($\eta = 2/3$): shell elements under these stress states are shown in Fig. 2(b). Therefore, a reliable fracture criterion used for large structures must incorporate the effect of stress state observed in these small-scale analyses. This was first recognized by Lehmann and Yu [17] who used the concept of Rupture Index and later by Törnqvist [18] who presented a so-called Rice–Tracey–Cockcroft–Latham criterion (RTCL). Although both of these studies include the effect of stress triaxiality on the fracture ductility, the adjustment of the criteria to account for the mesh size effects is solely based on the fracture strain determined with the uniaxial tension test. Hogström and Ringsberg [19] also employed Barba's law to account for the mesh size effects. They simulated fracture with damage induced softening model. Damage initiated at the point of necking given by the forming limit diagram (FLD), but the point of element removal was defined with Barba's law. Alternatively, to avoid mesh size effects elements can be removed at the point of necking as with the Bressan–Williams–Hill (BWH) criterion presented by Alsos et al. [20]. However, this approach has been criticized for removing elements too early [19].

Moreover, Kõrgesaar et al. [21] showed that the mesh size sensitivity is a strong function of the stress state. The fracture strain is much more sensitive to mesh size in the uniaxial tension than in the plane strain and biaxial tension. These results imply that proper use of a triaxiality based fracture

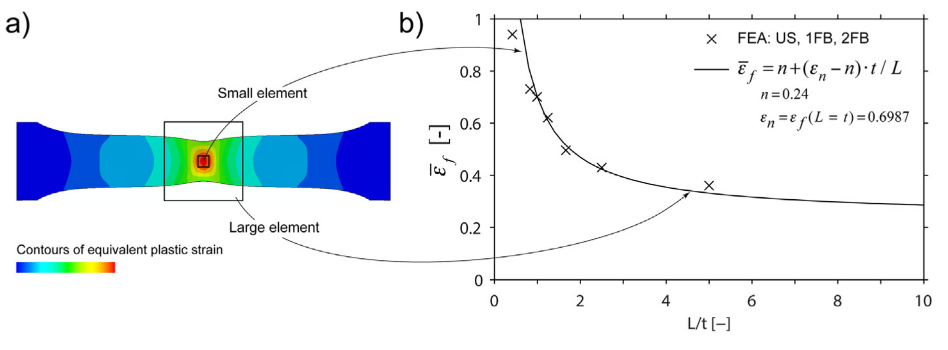

Fig. 1. a) Necking in tensile specimen. b) Barba's law derived from uniaxial tension test for steel S235JR EN10025 (data from Alsos et al. [35]).