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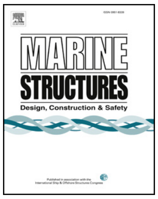

Modelling of the ductile-brittle fracture transition in steel structures with large shell elements: A numerical study

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ABSTRACT

In this paper, the strain energy density (SED) criterion is proposed for predicting the ductile-brittle fracture transition (DBFT) in ships and offshore structures. In finite element simulations, these structures are discretized by relatively large shell elements which precludes the modelling of the local stress and strain states in the vicinity of a crack. Critical values of the SED are determined based on local simulations of fracture for a range of temperatures and plane stress states. The local simulations of fracture are based on combined use of the Gurson model for ductile damage and fracture and the Richie-Knott-Rice (RKR) criterion for brittle fracture. After calibrating the Gurson model and the RKR criterion to existing experiments on offshore steel, critical values of the SED are found by analysing a representative plate element with a generic through-thickness crack using a refined solid element mesh. The proposed failure model is evaluated by simulating drop tests on steel-plated structures found in the literature. The present study indicates that the SED criterion is a useful concept for practical design of ships and offshore structures at sub-zero temperatures, but further assessment against experimental data is necessary to fully establish its credibility.

1. Introduction

Crashworthiness is an important issue in the design of ships and offshore structures to meet safety level requirements. Despite of the worldwide effort to prevent accidents in the oceans, an average number of 23.8 collisions per year is reported by the international maritime organization in the last 10 years [1]. These collisions often lead to enormous damage in terms of environmental pollution and economic loss, and sometimes even loss of life. To avoid severe casualties, ship classifications societies and authorities recommend criteria to be considered and applied in the design of ships and offshore structures. For accidental actions, the design must be carried out following the principles of Accidental Limit State (ALS) design. In ALS design, substantial damage to the target structure (or the struck structure) is tolerated after the action of the abnormal event, but the damage should not result in progressive degradation of the structural integrity. Based on the ALS scenarios, the design of ships and offshore structures needs experimental tests and numerical analyses to examine the crashworthiness. It is practically impossible to conduct large scale experiments on real structures and small scale experiments often have limited validity for direct application in the design because the test setup only approximately realizes the true nature of the problem. Thus, it is necessary to resort to numerical simulations in the design of these

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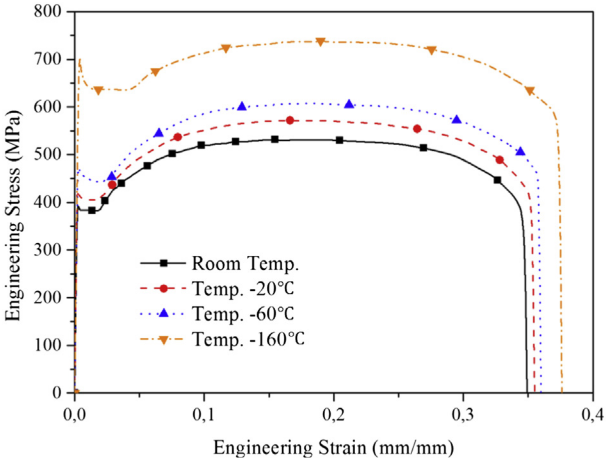

Fig. 1. Engineering stress-strain curves of the high-strength steel DH36 at several temperatures, reproduced from Park et al. [9].

structures. There has been a rapid development of computer capacity and nonlinear finite element analysis (NLFEA) methods in the past decades, and several commercial NLFEA codes are available. These codes have improved greatly the ability of engineers and designers to perform numerical analyses of the response of marine structures to accidental actions. The damage obtained by simulation of an accidental action such as a ship collision is critically influenced by the mechanical properties of the material, the finite element mesh size, the modelling of material failure and even the expertise of the engineers performing the simulations, e.g. Paik [2], Ehlers [3], Ehlers and Østby [4], Högstrom and Ringsverg [5], Choung et al. [6], and Storheim and Amdahl [7]. The material characteristics include yield strength, Lüders plateau, strain hardening, damage softening, as well as the effects of strain rate and temperature.

In the past few decades, we have seen significant increase in Arctic activities partly due to global warming, e.g. marine transport along the northern sea route (NSR) and extraction of natural resources such as oil and gas. While the decrease of the ice cover in Arctic regions may provide substantial economic benefit, structures operating in these regions are exposed to harsh environmental conditions, particularly sub-zero temperatures (average −50 °C) and the risk of iceberg impact. The crashworthiness of structures for such events should be confirmed in the design phase, but proper design guidelines for modelling of material behaviour at low temperatures are lacking.

High-strength steel has been used by the shipbuilding industry in ships made for the Arctic environment. Ehlers and Østby [4] and Park et al. [8] conducted numerical analyses to investigate the resistance of high-strength steel structures subjected to Arctic temperatures. Fig. 1 shows results from tensile tests on a high-strength steel. The engineering failure strain increases with decreasing temperature as do the yield stress and the ultimate stress, and there is an apparent increase in the energy absorption capability of the material at lower temperature. In Ehlers and Østby [4] and Park et al. [8], the simulations were based entirely on the result of quasi-static uniaxial tensile tests (cf. Fig. 1). Local failure was predicted by a ductile fracture criterion, while the possibility of brittle fracture was not considered explicitly. These authors concluded that structures built with high-strength steel have more strength in Arctic regions. This contradicts general experience; with temperatures down to −50 °C in Arctic regions the ductile-brittle transition temperature (DBTT) could be reached and thus induce brittle fracture during abnormal events.

Examples of abnormal events that could induce brittle fracture in offshore structures are collision with other structures or icebergs in extreme Arctic temperatures (in the range of −50 °C) as well as cryogenic spills (liquid natural gas), where the steel temperature may become even lower. Owing to the lack of relevant experimental data, numerical studies of large-scale structures should be performed to investigate the consequences of such events. There is, therefore, a need for an accurate, efficient and robust modelling framework to analyse numerically the ductile-brittle fracture transition in large-scale structures. To this end, Nam et al. [10] performed numerical simulations of Charpy V-notch tests of a high-strength steel presented by Min et al. [11]. The Charpy V-notch tests were conducted at temperature from 20 °C to −160 °C, and fracture transition was observed at −40 °C to −50 °C both in the experiments and the numerical simulations. In the simulation of these tests, a shear failure criterion was used to model ductile fracture, while the RKR criterion proposed by Ritchie, Knott and Rice [12] was used for brittle fracture. Isothermal and rate-independent von Mises plasticity was used to describe the material behaviour while accounting for the influence of temperature on the yield strength and strain hardening. It was found that the combined use of the shear failure criterion for ductile fracture and the RKR criterion for brittle fracture successfully described the ductile-to-brittle transition observed in the Charpy V-notch tests, while the shear failure criterion alone would significantly overestimate the crashworthiness of structures built by high-strength steel at low temperatures.

The change of the local fracture mode from ductile to brittle depends on several factors such as the ambient temperature, the strain rate and the stress state. Ductile-to-brittle fracture transition (DBFT) studies have been presented in several papers, e.g. Tvergaard and Needleman [13,14], Needleman and Tvergaard [15], Batra and Lear [16], Hütter et al. [17] and Türtük and Deliktas [18]. In Ref. [15], the ductile-brittle transition was simulated numerically using the Gurson model [19] to describe ductile damage

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