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Towards a unified methodology for the simulation of rupture in collision and grounding of ships

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A B S T R A C T

The aim of the work is the definition of a procedure for the numerical simulation of the response of ship structures under accidental loading conditions, which suffer various different modes of failure, such as tension, bending, tearing and crushing and in particular to investigate the effect of material modeling, i.e. material curve and rupture criterion as well as mesh size and strain rate effect on the results. To this end, different material models and simulation techniques were used for the simulation of eighteen indentation tests conducted by different research groups. The simulations were performed using the explicit finite element code ABAQUS 6.10-2. The tests refer to the quasi-static and dynamic transverse and in-plane loading of various thin walled structures which represent parts of a ship structure. Three rupture criteria are incorporated into VUMAT subroutine, which interacts with the explicit finite element code and refers to an isotropic hardening material that follows the J_2 flow theory assuming plane stress conditions, in order to investigate the prediction and propagation of rupture. The focus is on investigating whether it is possible to define a unified methodology, which is appropriate for the simulation of all different tests. Consistency in the numerical results is observed with the use of an equivalent plastic strain criterion, in which formulation a cutoff value for triaxialities below $-1/3$ is included.

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1. Introduction

In order to simulate in a realistic manner the response, to define the ultimate load carrying capacity and to predict the damage initiation of a ship structure under extreme loading conditions, as is the case in a collision or grounding event, it is required to have an appropriate material model. This includes the definition of a true Mises stress-logarithmic strain relation (true stress-strain curve) until rupture and an appropriate rupture criterion to simulate the initiation and propagation of rupture.

The true stress–strain relationship is usually determined from the engineering stress-strain curve obtained from uniaxial tensile tests. These curves incorporate the localized damage that occurs during tension and capture the stress field generated in the neck, which depends on the thickness of the specimen. Beyond the point of ultimate load in a uniaxial tensile test, uniformity is violated and plastic instabilities prevail until the final stage of fracture. Thus, it is important for the user to supply the finite element code with a true stress-strain curve that corresponds to the actual behavior of the material in large strains beyond necking. A number of researchers have suggested alternative methodologies for the calculation of the true stress-strain curve from the engineering stress-strain curves determined from uniaxial tensile tests, in particular in the range beyond the ultimate applied force and performed benchmark studies to investigate how the structural response of a loaded structure depends on it. As far as the initiation and propagation of rupture is concerned, researchers have proposed various rupture criteria. These may be classified in three main categories: i) strain based rupture criteria, whereby rupture takes place when the deformed material reaches a critical strain value, ii) stress based rupture criteria, whereby rupture takes place in a critical state of stress and iii) energy based rupture criteria, which relate the occurrence of rupture when the energy dissipated during stressing the material or stored within the material volume reaches a critical value.

The paper presents the results of a benchmark study of seven sets of small to medium scale tests that aims to define the appropriate modeling procedure, which should be used for the simulation of the structural response of marine structures under accidental loading conditions. The tests were selected so as to include the various modes of damage that have been identified in actual damages of marine structures subjected to impact loads and were performed by seven research groups in six different countries [4,6,8–10,14–16,18,19]. The models, which represent structural units of a ship structure, have a thickness that varies between 3 *mm* to 10 *mm* and were subjected to quasi-static and dynamic transverse and in-plane loading conditions.

For the determination of the true stress-strain curve beyond formation of the neck, the present study applies the method proposed by Ling [11]. Three rupture criteria were considered for the simulation of the initiation and propagation of rupture. These are a criterion based on the equivalent plastic strain [12,13], which is referred as SHEAR due to a critical change in the shape of the element that precedes rupture, the BWH instability criterion [3] and the RTCL damage criterion [17].

The simulations were performed using the explicit finite element code ABAQUS 6.10-2 and the rupture criteria were implemented into VUMAT subroutine [1], which interacts with the explicit finite element code and refers to an isotropic hardening material that follows the J_2 flow theory assuming plane stress conditions. The modeling investigation includes a) the definition of the material stress-strain curve, b) the modeling of rupture, c) mesh parameters and d) strain rate effect. The effect of the modeling parameters on the simulation results is investigated in the aforementioned tests, by comparing the experimental force and absorbed energy vs. penetration curves with those that are derived from the numerical analysis. Representations of deformations as observed during the tests and as predicted numerically have been also compared. A procedure to determine the relevant material parameters is further identified.

Section 2 of the paper presents the rupture criteria used in the present work. Section 3 summarizes the experiments that have been investigated and the material properties. Section 4 addresses the definition of the material model and shows how the variables of the material and rupture criteria are calibrated, as well as how the critical strain in the cases of SHEAR and RTCL rupture criteria is determined to take into account sensitivity to the mesh size. Section 5 includes presentation and discussion of the numerical results and section 6 reports the conclusions.