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Benchmark study of failure criteria for ship collision modeling using purpose-designed tensile specimen geometries

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Finite element analysis is extensively employed to predict the structural response of marine structures when subjected to operational loads. The quality of the obtained results is to a high degree dependent on the models used to describe the mechanical behavior of the materials involved. The present study reports on an extensive experimental program setup to evaluate constitutive models for shipbuilding materials. Models used for the elasto-plastic behavior, strain rate sensitivity and material failure are presented for a carbon steel sheet. Four failure criteria developed particularly for ship collision modeling are critically assessed: the Equivalent Plastic Strain criterion (EPS), the Germanischer Lloyd criterion (GL), the Rice-Tracey-Crockroft-Latham criterion (RTCL) and the Bressan-Williams-Hill criterion (BWH). To evaluate these failure criteria performance over a wide range of triaxialities, tensile experiments are carried out on six purpose-designed coupon geometries. The plastic strains, strain rates and triaxialities are evaluated using experimental full-field photogrammetric techniques and numerical finite element simulations. Comparison of the experimental and numerical results shows a good performance of the RTCL, BWH and EPS criteria.

1. Introduction

Most catastrophic accidents with ships are caused by collision and grounding. The risk of collisions has increased with the growth of the global ship fleet. The consequences of ship collision are manifold: oil spill, ship structure damage, marine environment degradation, explosions, human losses, blocking of ship traffic and permanent structural damage. The necessity of reformulating many safety aspects of maritime transportation has become increasingly relevant, which hinges upon a more advanced ship design as well as on thorough knowledge of the behavior of materials used in ship construction.

In this respect, numerical modeling plays a very important role to predict marine structure behavior when subjected to collision. The first efforts to numerically model ship collision were based on analytical methods applied to simple geometric structures. In fact, until the early 1990s, finite element (FE) modeling was rather limited compared to analytical approaches due to the poor computational power. However, in the last decade, faster computers and more efficient FE algorithms allow full scale modeling of ship collision events, including complex structural geometries and material failure prediction.

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Given the thin thickness of shipbuilding plates when compared to marine structure dimensions, shell elements are highly recommended for modeling when compared with solid elements due to their superior computational efficiency achieved by the significantly smaller number of elements needed for meshing. Furthermore, studies into FE modeling of marine structures have demonstrated that shell elements are suitable for numerically reproducing collapse modes of marine structures subjected to collision provided that an adequate mechanical characterization of the structural material is performed, including its strain rate sensitive elasto-plastic and failure behaviors [7,8,15,30].

The elasto-plastic behavior of metals is most often obtained from standard uniaxial tensile tests. Although, these tests provide valuable information for material modeling purposes, they have some limitations. Indeed, after necking, stresses and strains are no longer homogeneous in the gauge section and non-axial stresses arise in the neck. To obtain data on the materials stress-strain behavior in this region, the material curve has to be corrected based on empirical formulations [10] or by revisiting more traditional studies [2,6]. Alternatively, one can rely on inverse methods for the identification of material parameters based on optimization techniques, which directly relate the numerical response to the experimental one [26]. In this regard, full-field non-contact photogrammetric deformation measurement techniques, such as the Digital Image Correlation (DIC) technique, became powerful tools. These techniques provide much more input data for the optimization procedures [13].

Shipbuilding steels are known to be sensitive to strain rate [9,24]. The strain rate sensitivity is very important because high loading rates generally lead to a higher resistance and lower ductility of shipbuilding steels and marine structures [25]. However, notwithstanding the fact that ship collision events unavoidably involve dynamic deformations, only a small part of the studies took this aspect into account by including the strain rate sensitivity in the materials stress-strain curves [8].

Furthermore, an adequate description of material failure is of utmost importance for the numerical simulation of ship collision events because material failure strongly affects the global structural energy absorption and the collapse mode of the ship structure [1,8,14,19,22,30]. As mentioned, shell elements are highly recommended for FE modeling due to the large size of marine structures. Unfortunately, however, more sophisticated material failure and fracture models are based on three-dimensional stress and/or strain fields, which require the use of a high number of very small elements both over the thickness direction and in the plane. Hence, the numerical modeling of rupture initiation and crack propagation is still the most challenging task in a marine structural crashworthiness analysis [8].

When using large element sizes, variables such as plastic strains, stress concentrations and stress triaxialities are not well captured and an adequate calibration dependent on the mesh size is required [30]. A simple method is to calibrate all failure parameters by relating the material response observed in an experiment with its numerical model, and subsequently use the same mesh size for all parts of the ship model [16]. Other methods deal with the implementation of the mesh size sensitivity in the crack initiation criterion [1,21,30,35] or even in the post-failure behavior [19].

The objective of the present work is the evaluation of an elasto-plastic material modeling framework, including strain rate dependent hardening and failure, for steels used in FE modeling of ship collision event [7]. In a first step, the Voce hardening law [34] combined with the Cowper-Symonds strain rate sensitivity law [12] was calibrated based on static and high strain rate tensile tests using dogbone-shaped samples. The static tensile tests were carried out on a conventional tensile test machine. High strain rate data were obtained in universal testing machine, dynamic testing machine and a split Hopkinson bar tensile test facilities. Next to the force-displacement curves, full-field strain data were obtained by application of the DIC technique. The tensile test results were used to determine the parameters of four well known failure criteria specifically developed for ship collision modeling, namely the Equivalent Plastic Strain criterion (EPS) [27], the Germanischer Lloyd criterion (GL) [35], the Rice-Tracey-Crockroft-Latham criterion (RTCL) [30] and the Bressan-Williams-Hill criterion (BWH) [1]. In a next step, the materials constitutive models were extensively validated by comparing test results with FE analysis of the tests. For the tests, six geometries were developed with the aim to cover a wide range of triaxialities and to represent the different straining patterns of stiffened panels when crushed [20]. The samples were subjected to tensile loads at different deformation rates. Local information on the strain was again obtained by the use of DIC. For the FE simulations, shell elements commonly used in ship models are considered, with various mesh sizes being analyzed.

2. Mechanical characterization and modeling of material

A cold rolled SAE 1008 carbon steel sheet material with 0.25 mm thickness was considered in this work, whose mechanical properties are comparable with a standard Grade A shipbuilding steel. This material was also used in the manufacturing of 1:100 reduce scale marine structures subjected to collision loads [7].

For the FE analysis, the explicit code LS-Dyna v971 was used. In all models, shell elements with Hughes-Liu formulation and five through thickness integration points were considered. Described material models for elasto-plastic behavior and strain rate sensitivity are available in LS-Dyna code, subroutines with user-defined material models needed to be developed to include the four failure criteria.

2.1. Elasto-plastic behavior

Tensile tests with a standard specimen, Fig. 1a, allowed the evaluation of the static elasto-plastic and failure behavior of the carbon steel. The uniaxial tensile tests were performed using an Instron universal testing machine, model 3369, with a clamp velocity of 0.0025 mm/s. Force was measured using the load cell of the testing machine and displacement using an external