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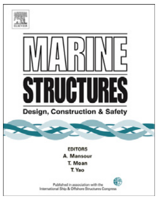

A simple criterion to evaluate the rupture of materials in ship collision simulations

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ABSTRACT

The paper is dedicated to enhance the industry practice in collision simulations of ship structures when only limited time and material data are available. The idea is to establish a simple, but effective procedure to determine the 'critical failure strain' as a function of coarse mesh sizes, so as to predict the critical energy to be absorbed during the impact. For this reason, more complicated effects, such as strain-state dependence, strain concentration on the lateral stiffening, welding, as well as accurate deformation mechanisms, are omitted.

A new expression is introduced to estimate the failure strain of coarse meshed ship structures struck by an indenter with hemispherical shape where the ship side or bottom sustains local penetration during a bulbous bow collision or stranding. The expression is valid for mild and high strength steels, accounts for the size of the elements, and is derived from finite element simulations of coarse meshed plates punched until the onset of necking, which critical point is first determined by using fine meshed plates. This 'simple' criterion is validated against reported experiments of 3 stiffened plates and 6 double-hull structures quasi-statically punched by an indenter. For the 6 double-hull specimens evaluated here, the absorbed energy at the end of the impact event is predicted with sufficient accuracy when a coarse mesh of size 10 times the plate thickness is used (the difference is about 10%).

1. Introduction

Ship collisions can result in loss of human lives and severe environmental damages. Therefore, increased attention has being paid to reduce the risk and consequences of such accidents. Currently, ship collision analyses take relevance not only for the design of large tankers and LNGs, but also for LNG-fuelled vessels, since the LNG tank should not be damaged by a collision.

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Recently, Guidance Notes for Collision Assessment for the Location of Low-flashpoint Fuel Tanks have been published [1]. These Guidance Notes recommend a simplified analytical method to estimate the energy absorbed by destroying ship structural members in tension and crushing mode, as the scatter between experimental results and other alternative methods, such as finite element simulations, is 'still' relatively large. While the accuracy of the simplified method was demonstrated and proven by Zhang and Pedersen [2] with 20 quality model tests from the public literature (absolute deviations $< 10\%$), Storheim et al. [3] found that the 'mean absorbed energy' predicted by 47 simulations (using different mesh sizes and failure criteria) of 3 experiments of stiffened plates, supported between webs, deviates from 2.0% to 52% at peak force and from 6.0% to 26% at the end of the simulations (Table 9 in Ref. [3]). This implies that a ship-to-ship collision simulation relies on an accurate definition of the material nonlinearities, and most importantly, the size of the finite elements considering the large dimensions of ship structures [4].

The nonlinear behaviour of the material includes plastic strain hardening and true fracture strain. Commonly, the mechanical properties of the material are determined by tensile tests. Hence, the true stress-strain relationship is obtained from the recorded engineering stress-strain data in a power law form [5], or by combining the logarithmic flow stress curve until the onset of necking followed by a simple power law relation beyond localisation [6–8]. It should be mentioned that very accurate flow material curves can be obtained by using optical systems that record the strain to failure in a uniaxial tensile test [9,10], but unfortunately, most structural analysts do not have tensile test data to define the flow stress curve as input into their finite element codes [11]. In fact, the information available from standards only includes the yield stress, the ultimate tensile stress and the engineering fracture strain [12]. Therefore, simplified formulae to define the true material curve represent a valuable design tool, as that proposed by Server et al. [13].

The failure due to material rupture is still not well resolved numerically, because the fracture length is much smaller than the side length of finite elements [14]. Thus, it is difficult to establish a procedure suitable for the prediction of failure in the engineering practice, considering additionally, that the failure strain is highly dependent on the mesh size, and that it should account for the stress triaxiality to control the initiation of ductile fracture [15–17].

Storheim et al. [3] reviewed various failure criteria and named, and grouped, them as 'simple strain-state-independent' and 'advanced strain-state-dependent' fracture criteria. The 'simple' criteria assume a constant critical equivalent strain often defined as mesh dependent, thus they are preferred for industrial application. Storheim et al. [3] concluded from the 47 simulations that while at peak force the 'advanced' criteria behave significantly better than the 'simple' ones, as the deformation process becomes complex at the end of the impact event, the 'simple' criteria are able to represent the combined process better than the 'advanced' ones. In practical industrial applications, such as collision assessment for the appraisal of ship structures [1], the interest is on the critical energy at a prescribed maximum penetration. Thus, a simple strain-state-independent criterion should represent advantages as a rapid and fair design tool.

A ship collision simulation with a relatively large mesh size and a true material curve based on a power law expression provides relatively accurate prediction of purely plastic responses [18,19]. However, necking and fracture occur over a narrow zone which is much smaller than the side length of the elements, and thus the large meshes ($>5t$, where t is the plate thickness) cannot capture such local phenomena.

For the assessment of an LNG (as fuel) tank compartment, the worst ship-to-ship collision scenario in terms of side shell indentation occurs when the striking bulbous bow impacts the side shell of the struck ship between the main supporting members (at the mid-span) [1], as illustrated in Fig. 1. In such case, the impact behaviour of the side shell is 'similar' to that found in a plate punching experiment [10,20], in which a spherical indenter penetrates the plate and elongates the material in a plastic flow field below the indenter forming a circular edge (named 'necking circle'), where the material rupture initiates [21,22]. To capture this phenomenon in a finite element model, a very fine mesh is required, probably in the order of the plate thickness [23].

However, a ship collision analysis requires a rather coarse mesh (probably four or five elements between longitudinals, or about ten times the plate thickness) to find equilibrium between practical engineering application and reasonable results. The current element formulations used in explicit dynamic simulation might allow for such simplification since they manage to

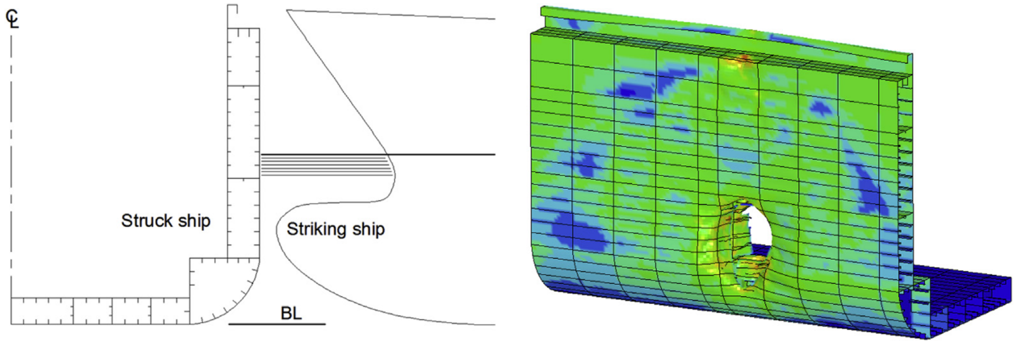

Fig. 1. Striking bulbous bow impacts the side shell of the struck ship between the webs and stringers.