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On the failure criterion of aluminum and steel plates subjected to low-velocity impact by a spherical indenter

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ABSTRACT

An analytical failure criterion is proposed to characterise ship plated structures manufactured with aluminium or steel materials subjected to low impact velocities. The criterion considers the critical deflection, force and absorbed energy of plates laterally impacted by a hemispherical indenter, and assumes that failure occurs at the presence of necking. The proposed expressions are compared with numerical results validated with drop weight experiments conducted on small-scaled rectangular aluminium and steel plates of the same bending stiffness. Thus, the impact tests and simulations could describe the behaviour of stiffness-equivalent shipbuilding materials subjected to rapidly varying loads. In addition, the criterion uses quasi-static theoretical formulae, including the plate thickness and the material power law coefficients to assess the deformation characteristics and the plate localisation. The experimental results show that the critical deflections are similar for both the aluminium and the steel plates, although differences are observed in the critical forces and energies. Even though the numerical simulations use most definitions reported in previous works, the emphasis is put on the material characterisation, where the fracture strain is obtained by measuring the tensile test pieces of the materials and using simplified equations to define the equivalent strain. The proposed criterion′s theoretical expressions give a good agreement with the numerical results. The criterion shows that the absorbing capabilities of the plates are improved by increasing the strength coefficient of the material and the plate thickness, while other material coefficients could be omitted. It is also demonstrated that the critical defection increases and the force decreases with the strain hardening exponent. Moreover, the specific energy absorption of the material is used to evaluate the impact characteristics of the material.

1. Introduction

Steel and aluminium materials are widely used in the shipbuilding industry. At present, the steel is the most popular due to its high strength and low cost. In order to reduce the lightweight of ships, particularly for those sailing at high-speed, the steel hulls and superstructures have been replaced by aluminium [1,2]. Some advantages and disadvantages of aluminium and steel plates are listed in Table 1. In general, design criteria select aluminium plates with equivalent bending stiffness to that of the replaced steel [1,3]. The coefficients used to replace the steel plates by aluminium are also indicated in Table 1.

The shell plates and the main and secondary supporting members should be designed with sufficient strength in order to minimise the initiation of cracks when subjected to the wave pressure loads. However, during service operation, ships also suffer rapidly varying loads, such as slamming, ice-impact, collision and grounding, thus various types of ship structures should be capable to absorb certain amount of energy during such loads. Since the aluminium and the steel behave as brittle and ductile materials, respectively, their impact strength should be compared in order to guarantee the safety of particular designs.

Experimental tests represent one of the most accurate means to evaluate the impact characteristics of different materials and to compare their impact strength. Experiments on laterally impacted aluminium and steel plates have been conducted to derive analytical expressions for estimating the critical perforation energy [4–10]. These works were concerned on the influence of the plate and indenter geometries, and used the rigid-plastic material model and the Cowper-Symonds strain rate sensitivity coefficients to define the material nonlinearities. However, true stress–strain material relationships should be more accurate than these rigid-plastic material models when is necessary to represent the response of specimens subjected to large plastic deformations. Therefore, Simonsen and Lauridsen [11] and Lee et al. [12] developed theoretical formulae that included a material power

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Table 1
Comparison of aluminium and steel plates.

Aluminium: Lightweight; expensive; no corrosion; low yield stress; low ultimate tensile stress; low fracture strain; may melt in fire.	
Steel: Heavy; cheap; corrosion; simple to fabricate.	
Thickness (t)	$t_{al}=1.42\ t_{st}$
Young's modulus (E)	$E_{al}=0.35\ E_{st}$
Bending stiffness (Et^3)	$E_{al}\ t_{al}^3=E_{st}\ t_{st}^3$
Deflection (w)	$w_{al}=w_{st}$
Density (ρ)	$\rho_{al}=0.34\ \rho_{st}$
Weight (m)	$m_{al}=0.48\ m_{st}$

*Subscript al and st represents aluminium and steel, respectively.

law relation for estimating the deformation and failure of thin clamped circular and square plates punched by a spherical indenter. While Ref. [11] described the material failure by the strain hardening exponent, Ref. [12] used a true fracture strain as the material parameter that defines the critical deflection of the plates.

On the other hand, the finite element analysis is a useful tool that provides a better understanding of the plastic deformation and failure of structural elements subjected to impact loads. Numerical simulations of laterally loaded plates have been presented, obtaining good prediction of the experimental force–displacement response and failure modes [11–18]. In the numerical modelling, an important definition that must agree with the characteristics of each particular impact test and specimen is the material nonlinearity. It is known that plastic strain hardening and critical fracture strain are required for prediction of the extent of damage in structures under low-velocity impact loads. Although relatively good approximations have been derived for the former, the failure due to material rupture is still not well resolved numerically, because the failure strain is highly dependent on the size of the finite elements. In addition the criteria for initiation of ductile fracture are still not well established within the entire range of fracture modes, including compression, shear and tension, which metals suffer when subjected to large plastic deformations.

In practical terms, numerical simulations of tensile tests have been conducted to predict the critical fracture strain used in the finite element models of punching and impact tests of plates; see for example [11–16]. A more accurate method was presented by Ehlers [15] who selected an optical system to obtain the true stress–strain curve and fracture strain from tensile pieces and used this information to predict the plastic response and rupture of circular steel plates punched by a spherical indenter. In addition, the fracture strain for simple structural elements has been evaluated by measuring the thickness and the width at fracture of tension test specimens and using formulation to derive the fracture strain [16]. This indicates that the accurate verification of the tensile test is essential to analyse and predict the material failure of the laterally loaded plates.

In addition, it is important to mention that the equivalent strain to fracture should account for the stress triaxiality since it controls the initiation of the ductile fracture [12,19,20]. Some simulations evaluated the stress triaxiality of the failing elements for both tensile and impact specimens [12,13,15,21]. For example, Lee et al. [12] considered a constant critical damage value for ductile fracture as the product of the magnitudes of fracture strain and average stress triaxiality to evaluate plate punching tests. Ehlers [15] obtained experimentally a constant equivalent strain failure criterion and applied it for simulations of tensile and plate forming tests, demonstrating that the same level of stress triaxiality at the point of failure can be found in both the tensile and the forming tests. The same principle was used by Villavicencio and Guedes Soares [21] to evaluate transversely impacted pre-notched beams and by Liu et al. [13] to assess the response of rectangular laterally impacted plates. In Refs. [13,21] the same stress triaxiality at failure was captured for the simulations of the quasi-static tensile tests and the dynamic drop weight impact tests.

In this paper, drop weight impact tests and finite element simulations are conducted to validate the proposed failure criterion for selecting aluminium or steel plates subjected to lateral impact at relatively low incident velocities. For the purpose, small-scale rectangular aluminium and steel plate specimens of the same bending stiffness are selected. The tests are conducted on a fully instrumented impact tester machine. The obtained force–displacement response and failure mode is compared with the numerical simulations, performed by the LS-DYNA finite element solver.

The boundary conditions of the finite element model are represented by modelling the part of the structural support in order to represent the reacting forces during the impact. The material strain hardening is defined by the exact true stress-strain relationship until the maximum load [22] and beyond necking is approximated by a power law relation [23], as proposed by Villavicencio and Guedes Soares [21]. The fracture strain for the plates is obtained by measuring the tensile test pieces and using simplified expressions to define the equivalent strain to fracture.

The theoretical criterion to evaluate the impact strength of the aluminium and steel materials is based on the theoretical works reported by Simonsen and Lauridsen [11] and Lee et al. [12]. The criterion accounts for the critical deflection, force and absorbed energy, and considers that the onset of failure occurs when necking takes place. Thus, the theoretical point of failure is compared with the numerical plots of the deflection, force and absorbed energy versus the plastic strain of the first failing element. Although the expressions use quasi-static formulae, they are valid for impacts at low velocity since the strain rate effect is relatively small. This is based on a literature search where it is indicated that the aluminium is essentially strain rate insensitivity [24,25], and that the effect of viscoplasticity is very small for high tensile steels since material constant C of the Cowper-Symonds constitutive equation is quite large (3200 s^{-1}) [26]. Even though this material effect is larger for mild steels, the difference found between static and dynamic low-velocity tests reaches only magnitudes of 10–20% in the reaction force and/or deflection [27,28]. Moreover, it should be mentioned that at larger strains the strain rate effect is ignored in almost all theoretical and numerical methods [29].

The proposed material selection criterion is of considerable practical importance in the offshore engineering and naval architecture when it is necessary to assess the safety of stiffness-equivalent aluminium and steel structures subjected to dynamic loads, since the design criteria are only based on the elastic range of the material. Although this work is aim at comparing the stiffness-equivalent aluminium and steel plates, this criterion can be extend to select the material with improved impact characteristics at the preliminary stages of design that consider impact loads and collision.

2. Experimental details

The experimental programme evaluates the plastic response until failure of rectangular plates stuck laterally by a mass with a spherical indenter. The plates are aluminium alloy 5083/H111 (2.0 mm thickness) and mild steel ST12 (1.4 mm thickness). They are selected to ensure the same bending stiffness. The mechanical properties of the aluminium and steel materials are obtained by quasi-static tensile tests carried out on material cut from the same plates from which the impact specimens are taken.