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Strength of steel and aluminium alloy ship plating under combined shear and compression/tension

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ABSTRACT

The load shortening curves are essential to the estimation of ultimate strength of ship structures under longitudinal bending in the simplified progressive collapse method. Longitudinal bending is the dominant load on ships structures, but in cases where the ship is heading to oblique seas and/or there are large openings in the structure due to its design (i.e. containerships) or due to damage (i.e. grounding, collision, blast), torsional loads may also be important when calculating ultimate strength and further investigation is required. Torsional loads on ship structures generate shear stresses which are carried primarily on the ship's plating, therefore the effect of shear on the in-plane load shortening behaviour of ship plating is thoroughly investigated in this paper. Initially, marine grade steel and aluminium alloy plates with different aspect ratio (1–4) and slenderness (1–5) are subjected only to shear loads. These results show that the plate aspect ratio does not significantly affect the progressive collapse behaviour of plates under shear, hence only square plates are investigated further. Steel and aluminium alloy square plates (5083-H116 and 6082-T6) with slenderness ratio 1–4 are subjected to shear, in-plane compression/tension and combined shear and compression/tension applying the same complex set of boundary conditions for all cases and using ABAQUS CAE. Finally, the generated interaction diagrams of shear and compressive/tensile loads provide essential information for the effect of shear on the progressive collapse of in-plane loaded plates allowing for the incorporation of torsion in the simplified progressive collapse method.

1. Introduction

A ship structure is mainly subjected to vertical hogging and sagging bending moment throughout its life due to extreme wave induced loading. However, when there are large openings in the structure due to wide hatch openings or due to damage, this inevitably results in reducing the torsional rigidity of the hull girder. The effect of torsional moment has been recognised to be important for ships with low torsional rigidity [1], especially in oblique seas. The torsional loads on the structure generate shear forces on the ship plating which does not affect the stiffeners of the panel.

Therefore, the shear effect on marine grade steel and aluminium alloy (5083-H116 and 6082-T6) ship plating with slenderness ratio (β) 1–5 is thoroughly investigated in this study. In Benson and Dow's study [2] the progressive collapse assessment of steel and aluminium plates and panels has been investigated taking into account the effect of initial imperfections, residual stresses and Heated Affected Zone (HAZ). Benson and Dow based on this data developed a code, ProColl (Progressive Collapse), for the progressive collapse assessment of ship structures under longitudinal bending. Therefore, the same parameters i.e. initial imperfections, residual stresses, material properties and HAZ for the plates are taking into account in this study aiming to future incorporation of torsional load into ProColl.

Initially, steel and aluminium plates (5082-H116) with slenderness ratio (β) 1–5 and aspect ratio (a/b) 1–4 are subjected only to shear load using the non-linear finite element method (NLFEM). The results show that the aspect ratio does not affect the progressive collapse behaviour of the plate under shear. Therefore, square plates which are assumed as the most conservative/severe estimate for the ultimate strength assessment of plates under in-plane compression are investigated further. A complex set of boundary conditions is applied for ship plating subjected only to axial compression/tension and only to shear load. The ultimate strength of the plates under these loads is compared to experimental results, other studies and analytical formulas. Since, these boundary conditions are validated, the plates are subjected to combined compressive/tensile and shear load.

Finally, the interaction diagrams of combined compression/tension and shear are generated for steel and aluminium alloys 5083-H116 and 6082-T6 ship plating with slenderness ratio (β) 1–6 investigating two cases for the unloaded edges, unrestrained and constrained edges.

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These diagrams do not only provide useful information for the progressive collapse behaviour of steel and aluminium alloy ship plating under combined compression/tension and shear but also are essential for the incorporation of torsion to the simplified progressive collapse method.

2. Background

In the literature, the ultimate strength of marine grade steel and aluminium alloy ship plating under in-plane compression/tension has been thoroughly investigated by different numerical approaches and experimental data. Plates subjected to shear loadings have been investigated mostly in the field of aeronautical and civil engineering and less by marine engineers. Finally, very few studies have been carried out to establish the criteria for plates under combined axial compressive/tensile and shear loads. The main studies and formulations which are taken into account for the establishment of the design criteria of steel and aluminium alloy ship plating under these loads are presented as follows:

2.1. Steel and aluminium alloy plates under axial compression/tension

Firstly, the Johnson-Ostenfeld formula, Eq. (1), provides correction due to plasticity for the elastic buckling stress formula, Eq. (2.1) to Eq. (2.2), calculating the critical/ultimate strength of steel and aluminium plates under axial compression.

$$\sigma_{cr} = \begin{Bmatrix} \sigma_E, & for\ \sigma_E \leqslant 0.5\sigma_F \\ \sigma_F[1-\sigma_F/(4\sigma_E)], & for\ \sigma_E > 0.5\sigma_F \end{Bmatrix}, \begin{Bmatrix} \sigma_F = \sigma_o \\ \sigma_{E,Eq.(2.1)} \end{Bmatrix} \tag{1}$$

$$\sigma_E = \frac{k\pi^2}{12(1-\nu^2)}\left(\frac{t}{b}\right)^2 \tag{2.1}$$

$$k = [a/(m_o b) + m_o b/a]^2,\ where\ m_o = 1\ for\ 1 \leqslant a/b \leqslant \sqrt{2} \tag{2.2}$$

Secondly, Faulkner's formula, Eq. (3.1) to Eq. (3.2), a well-known and established empirical formula for predicting the collapse of simply supported unwelded steel plates with no constraints on the unloaded edges and average level of initial distortions ($0.12\beta^2 t$) [3]. Faulkner's formula can be also applied to aluminium plates under axial compression providing good correlation with other studies [2].

$$\begin{aligned} \frac{\sigma}{\sigma_o} &= \frac{2}{\beta}-\frac{1}{\beta^2}, \quad \beta \geqslant 1 \\ \frac{\sigma}{\sigma_o} &= 1, \quad \beta \leqslant 1 \end{aligned} \tag{3.1}$$

$$\beta = \frac{b}{t}\sqrt{\sigma_o/E} \tag{3.2}$$

where: σ = ultimate strength of the plate; σ_o = material yield stress; β = plate slenderness ratio defined by Eq. (3.2); b = plate width over which uniform compression is applied; t = plate thickness; E = Young's modulus; ν = Poison's ratio

Furthermore, experimental and analytical/numerical studies by Frieze [4], Dow and Smith [5,6], Chalmers [7] and Benson [2] have established the design criteria for steel plates in-plane loading. In these studies, the effect of boundary conditions, initial distortions and residual stresses on the ultimate strength has been investigated for a wide range of steel plates under compression with different aspect ratio (a/b) and slenderness ratio (β).

Finally, Eurocode 9 class 4 formulations, Eqs. (4.1)–(4.9), and Paik & Duran's formula, Eq. (5), estimate the ultimate strength of marine aluminium alloy plates subjected to axial compressive loads. In addition, Little's [8], Mofflin and Dwight's [9] studies provide the background and design criteria for Eurocode 9 [10], while Hopperstad's [11], Kristensen's [12] and Benson's [2] studies provide a thorough investigation of aluminium alloy plates and comparison of their results with other studies.

The design value for compression force (N_{ED}) according to Eurocode 9 class 4 [10] should be equal to:

$$\frac{N_{ED}}{N_{Rd}} \leqslant 1.0 \tag{4.1}$$

N_{RA} = design resistance to normal forces equal to:

$$N_{Rd} = \frac{A_{eff}\cdot\sigma_o}{\gamma_{M1}} \tag{4.2}$$

Assuming that $N_{ED} = N_{Rd}$ and safety factor to account for design uncertainties (γ_{M1}) equal to 1, the design resistance N_{Rd} becomes:

$$N_{Rd} = A_{eff}\cdot\sigma_o \tag{4.3}$$

where:

$$A_{eff} = 2b_{HAZ}\rho_{oHAZ}t + (b-2b_{HAZ})\rho_c t \tag{4.4}$$

$$\rho_{oHAZ} = \frac{\sigma_{oHAZ}}{\sigma_o} \tag{4.5}$$

$$\beta = \frac{C_1}{\left(\frac{\beta}{\varepsilon}\right)} - \frac{C_2}{\left(\frac{\beta}{\varepsilon}\right)^2} \tag{4.6}$$

$$C_1 = 29; C_2 = 198 \tag{4.7}$$

$$\beta = \frac{b}{t} \tag{4.8}$$

$$\varepsilon = \sqrt{250/\sigma_o} \tag{4.9}$$

The ultimate strength of aluminium plates subjected to compressive loads according to Paik and Duran's formulation [13] derives from Eq. (5) and β is defined in Eq. (3.2).

$$\frac{\sigma}{\sigma_o} = \begin{Bmatrix} -0.13\beta + 0.921, \beta < 3 \\ -0.07\beta + 0.741, \beta \geqslant 3 \end{Bmatrix} \tag{5}$$

2.2. Steel and aluminium alloy plates under shear

The critical shear stress of steel and aluminium plates under shear is estimated by Johnson-Ostenfeld formula, Eq. (6), which applies correction due to plasticity to the elastic shear stress formula for simply supported plates, Eq. (7).

$$\tau_{cr} = \begin{Bmatrix} \tau_E, & for\ \tau_E \leqslant 0.5\sigma_F \\ \sigma_F[1-\sigma_F/(4\tau_E)], & for\ \tau_E > 0.5\sigma_F \end{Bmatrix}, \begin{Bmatrix} \sigma_F = \tau_Y = \sigma_Y/\sqrt{3} \\ \tau_{E,Eq.(7)} \end{Bmatrix} \tag{6}$$

$$\tau_E = \frac{k_s\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{b}\right)^2, k_s = 5.3 + 4(a/b)^2 \& \ a/b \geqslant 1 \tag{7}$$

Further studies on steel plates subjected to shear have been carried out by Rutherford and Zhang [14], Nara [15] and Paik [16] introducing formulations which derived from regression analysis and providing useful knowledge for the design criteria of plates under shear.Zhang and Rutherford's equation for steel plates without taking into account residual stresses is described by Eq. (8) as follows:

$$\frac{\tau_u}{\tau_Y} = \begin{Bmatrix} 1, & for\ \beta_\tau < 1 \\ \frac{2}{\sqrt{\beta_\tau}}-\frac{1}{\beta_\tau}, & for\ \beta_\tau \geqslant 1 \end{Bmatrix}, \begin{Bmatrix} \beta_\tau = \frac{\beta}{1+(b/a)^{3/2}} \\ \tau_Y = \sigma_Y/\sqrt{3} \\ \beta_{Eq.(3.2)} \end{Bmatrix} \tag{8}$$

Nara's equation, Eqs. (9.1) and (9.2), derives from regression analysis of steel plates with average level of initial distortions and residual stresses under shear.

$$\frac{\tau_u}{\tau_Y} = \left(\frac{0.486}{\lambda}\right)^{1/3}, for\ 0.486 \leqslant \lambda \leqslant 2 \tag{9.1}$$