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Damage assessment of marine grade aluminium alloy-plated structures due to air blast and explosive loads

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ABSTRACT

The objective of this paper is to investigate the response of fusion welded AA5083-H116 rectangular plates and orthogonally stiffened panels, typically found in high-speed vessels and topsides of offshore platforms, under impulsive pressure loading, such as air blast and explosions. Rigorous nonlinear finite element analyses are performed by using ABAQUS/Explicit to determine the deformation of these plated-structures under different impulses. Particular emphasis is given on the effect of the heat affected zone (HAZ), which is due to fusion welding. Based on the extensive numerical results, simple yet accurate formulae to predict the permanent set of the plates are derived as function of a non-dimensional impulse parameter. The derived equations are also compared with the existing analytical and empirical formulae in the literature.

1. Introduction

Despite steel being the standard material in marine vessel constructions, marine grade aluminium alloys have become the primary material choice for conventional high-speed vessels ever since the early 1990s, mainly because it is highly resistant to corrosive sea environment and has desirable strength to weight ratio as compared to steel. The structure of a naval ship must be designed to perform well under various loading conditions, especially unexpected extreme loads such as blast loads, explosions and attack from missiles. Explosion in both air and water causes a shock wave which comprise a high peak overpressure value and a short duration with high propagating speed. Explosive loadings can produce a significant amount of damage to simple structural elements. With that being the case, evaluating the amount of damage a structure can withstand is consequential during the design process. It may not be possible to prevent plastic deformation. However, there is a need to analyse the extents of plastic deformation and its effects on the structural performance of the vessel.

The response of monolithic metal plated-structures to impulsive pressure loading has been subject of many theoretical, experimental and numerical studies in the literature over the past fifty years [1–40], focusing on different aspects of this fundamental problem which are, among others, failure modes, distribution of load (uniform/localised), plate geometry (circular, square, rectangular), effect of boundary conditions. An excellent review of blast loaded plates with emphasis on marine structures is given in [41], while Nurick and Martin [42,43] reviewed the theoretical and experimental studies prior to 1989. Very recently, Chung Kim Yuen et al. [44] updated Nurick and Martin's work covering the experimental work since 1989. From the aforementioned reviews it is apparent that in general the failure modes observed by Menkes and Opat [45] in blast loaded clamped AA6061-T6 beams and theoretically derived by Jones [46], namely, Mode I – large inelastic deformation, Mode II – tensile tearing at support, and Mode III – transverse shear failure at support, are also relevant to impulsively loaded plates. In [42–44], it was shown that simple expressions can be derived for estimation of Mode I – large inelastic deformation of plates with different geometries using a non-dimensional parameter. As emphasised by Chung Kim Yuen et al. [44], those empirical expressions are restricted to mostly mild steel plates, for which, as opposed to aluminium alloy plates, strain-rate sensitivity is highly pronounced. [1]. A survey of the literature reveals that the existing impact tests for marine grade aluminium alloy plates are very few, where impulsive pressure tests are limited to the grade of AA6061-T6 [7,47] and several studies exist focusing on ballistic performance assessment [48–50]. Furthermore, aluminium alloy plated-structures in marine-based applications are fabricated by fusion welding, which results in well-known heat affected zone (HAZ) at welded areas and its proximity. Based on a limited number of studies on fusion-welded aluminium alloy structures under static lateral loads [51–55], it can be inferred that there is a concern about the detrimental effect of the HAZ on the load-carrying capacity, as well as final failure of the structures, in particular, tensile tearing at the supports. The effect of the welded boundaries on the blast impact response of mild steel plates has been assessed in [14], but for aluminium alloy plates there exists virtually no studies. Therefore, it is

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Nomenclature

a	plate length
b	plate breadth
b_f	stiffener flange breadth
b_p	HAZ width
h_w	stiffener web height
p	pressure
p_o	peak pressure magnitude
t	time
t_p	plate thickness
t_e	equivalent plate thickness of stiffened panels
t_f	stiffener flange thickness
t_w	stiffener web thickness
w	lateral deflection of plate
w_p	permanent set of plate
A	surface area of plate
B	panel breadth
D_1, D_2, D_3	coefficients in Johnson-Cook fracture model
E	Young's modulus
F	lateral force
I	impulse
I_p	impulse per unit plate area
L	panel length
N	strain hardening exponent
R^2	correlation coefficient
T	natural period
V	panel volume
V_o	impulsive velocity
β	plate slenderness ratio
ε_f	critical failure strain
ε_p	plastic strain
λ	non-dimensional impact parameter for plate
λ_c	column slenderness ratio
μ	mass per unit area of plate
ν	Poisson's ratio
ξ_o	defined in Eq. (14).
ρ	volumetric mass density
σ	true stress
σ_o	yield strength
σ^*	stress triaxiality ratio
τ	duration of impulse
ϕ_q	non-dimensional impulse parameter proposed in [43].
ϕ_p	non-dimensional impulse parameter proposed in [39].

necessary to analyse the response of impulsively loaded plates covering the unique features of fusion welded aluminium alloy structures, identify the trends, and finally develop simple equations for design.

Within this context and inspired by Nurick and Martin [42,43] and Chung Kim Yuen et al. [44], the current study aims at developing simple expressions for estimation of permanent set of rectangular aluminium alloy plates in marine specific use. As there is no experimental test data available, this study relies on nonlinear FEA, which allows performing parametric studies to analyse the effects of different geometrical aspects, impulse magnitude and HAZ locations. To understand the effect of welded boundaries on a more global level, the analyses are also extended to orthogonally stiffened panels. Based on the regression analysis of the parametric study results, new empirical formulae are proposed and compared with the existing ones.

2. Methodology

2.1. Description of the models

2.1.1. Unstiffened plates

Rigorous parametric studies were carried out for both unstiffened rectangular plates in order to obtain the data for deriving the design equations. A fixed plate breadth, b, of 500 mm was used for all unstiffened plates having length, a, and plate thickness, t_p, of 1000, 1500, 2000, 2500 and 3000 mm and 8, 10, 12, 14, 16 and 18 mm, respectively. 30 different unstiffened plates models were analysed with the impulse values ranging from 0.5 to 9 kN-s, which are large enough to result in plastic deformation and in some cases even failure by tearing at the plate boundaries. In total, 120 cases were analysed. The plate slenderness ratio, which is calculated by the following formula, ranges from 1.45 to 3.27.

$$\beta = \frac{b}{t_p}\sqrt{\frac{\sigma_o}{E}} \tag{1}$$

Here, E is Young's modulus and σ_o is the yield strength. Thus, a good coverage of both stocky and slender rectangular plates in high-speed vessels in practice is achieved.

2.1.2. Stiffened panels

Stiffened panels with a series of various stiffener configurations with dimensions as shown in Table 1 were considered in the study. These panels have the typical properties of high-speed naval vessels. The panels have ten angle bar longitudinal stiffeners with the scantlings as shown in Table 1 and four flat bar transverse frames with constant scantlings of 360×10 mm. M8 is an exception, which has only two transverse frames. In models M1 to M4, the plate thickness was varied to obtain different plate slenderness ratios. In M5 and M6, the stiffener scantlings are different than the ones in M1-4. Finally, in M7 and M8, the plate length, i.e. transverse frame spacing was altered. For the sake of simplicity, it was assumed that the same material is used to fabricate both the plates and the stiffeners. For the stiffened panels, a total of 72 analyses were performed.

2.2. Material properties

The structural response involving large inelastic deformations is highly dependent on plastic behaviour defined by strain hardening models. Each aluminium alloy grade has a different set of properties,

Table 1
Scantlings of the stiffened panels.

Model ID	a (mm)	b (mm)	t_p (mm)	h_w (mm)	t_w (mm)	b_f (mm)	t_f (mm)	λ_c	β
M1	1200	400	14.8	120	5.5	55	7.7	0.62	1.5
M2	1200	400	11.1	120	5.5	55	7.7	0.56	2.0
M3	1200	400	8.9	120	5.5	55	7.7	0.53	2.5
M4	1200	400	7.4	120	5.5	55	7.7	0.50	3.0
M5	1200	400	14.8	80	4.5	45	6.2	1.09	1.5
M6	1200	400	14.8	170	6.5	65	10.3	0.38	1.5
M7	1000	400	14.8	120	5.5	55	7.7	0.52	1.5
M8	1800	400	14.8	120	5.5	55	7.7	0.93	1.5