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# Sensitivity analysis on the elastic buckling and ultimate strength of continuous stiffened aluminium plates under combined in-plane compression and lateral pressure

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ABSTRACT

In this paper, the results of an investigation into the post-buckling behaviour of high-strength aluminium alloy stiffened plates subjected to combined axial compression load and different magnitudes of lateral pressure using non-linear finite element approach is presented. Both material and geometric non-linearities have been taken into account. The principal variables studied are the plate thickness, boundary conditions and the stiffener geometries beside the geometrical imperfection, the width of the welding heat-affected zone (HAZ) and welding residual stresses. The influence of these variables on the post-buckling behaviour and ultimate strength of such stiffened plates has been investigated in details.



## 1. Introduction

Stiffened plates are used as main supporting members in many civil as well as marine structural applications. They typically consist of a plate with equally spaced stiffeners welded on one side, often with intermediate transverse stiffeners or bulkheads. The most common stiffener cross-sections are bulb, flat bar or T- and L-sections. Such structural arrangements are common for both steel and aluminium structures.

Aluminium panels have been used in a variety of marine structures, with applications such as hull and decks in high-speed boats and catamarans and superstructures for ships. Other applications are box-girder bridges, and walls and floors in offshore modules and containers. These panels are primarily required to resist axial compressive forces, even though transverse loads and in-plane shear forces may in general interact.

The ultimate strength design formulae available for steel plates cannot be directly applied to aluminium plates even though the corresponding material properties are properly accounted for. This is partly due to the fact that the constitutive stress–strain relationship of the aluminium alloys is different from that of structural steel. In the elastic–plastic range after the proportional limit as compared to structural steel, the strain hardening has a significant influence in the ultimate load behaviour of aluminium structures whereas in steel structures, the elastic–perfectly plastic material model is well adopted. Besides, the softening in the heat-affected zone (HAZ) significantly affects the ultimate strength behaviour of aluminium structures, whereas its effect in steel structures is of very little importance.

The ultimate strength of stiffened steel plate panels has been the subject of many investigations, both experimentally [1–5] and numerically [6–10], with the most significant contributions in the field of ship structures and bridges. The literature on stiffened aluminium panels is more limited. Clarke [11] reports on buckling tests on an aluminium AA5083 plate with welded T-bar and flat-bar stiffeners. His experimental programme comprised eight compression tests on panels with different plate and stiffener sizes, with buckling over two spans as the failure mode. The ultimate strength of stiffened aluminium AA6082-T6 plates under the axial compression was investigated by Aalberg et al. [12,13] using numerical and experimental methods. Kristensen and Moan [14] demonstrated numerically the effect of HAZ and residual stresses on the ultimate strength of rectangular aluminium plates (AA5083 and AA6082) under the bi-axial loading of plates.

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**Notation**

| | |
|---|---|
| $A$ | cross-sectional area of stiffener with attached plating |
| $a$ | length of local plate panels |
| $b$ | overall breadth of plate |
| $c$ | coefficient of maximum magnitude of initial deflection |
| $I$ | moment of inertia of stiffener with attached plating |
| $L$ | overall length of plate |
| $r(-\sqrt{I/A})$ | radius gyration of the stiffener with attached plating |
| $t(=t_p)$ | plate thickness |
| $t_w$ | thickness of longitudinal stiffener web |
| $h_w$ | height of longitudinal stiffener web |
| $t_f$ | thickness of longitudinal stiffener flange |
| $b_f$ | breadth of longitudinal stiffener flange |
| $t_{wt}$ | thickness of transverse frame web |
| $h_{wt}$ | height of transverse frame web |
| $t_{ft}$ | thickness of transverse frame flange |
| $b_{ft}$ | breadth of transverse frame flange |
| $v$ | poisson's ratio |
| $E$ | Young's modulus |
| $\sigma$ | average stress |
| $\sigma_Y$ | yield stress |
| $\sigma_{iY}$ | initial yielding stress |
| $\sigma_{cr-p}$ | elastic buckling strength of un-stiffened simply supported plate under pure in-plane compression |
| $\sigma_U(=\sigma_{Ult})$ | ultimate strength |
| $\varepsilon$ | average strain |
| $\beta(=b/t\sqrt{\sigma_Y/E})$ | slenderness parameter of the plate |
| $\lambda(=a/\pi r(\sqrt{\sigma_Y/E}))$ | column slenderness parameter of the stiffened plate |
| $\theta_x$ | rotation about $x$-axis |
| $\theta_y$ | rotation about $y$-axis |
| $\theta_z$ | rotation about $z$-axis |
| $U$ | displacement along $x$-axis |
| $V$ | displacement along $y$-axis |
| $W$ | displacement along $z$-axis |

Some initial experimental and numerical simulations on torsional buckling of flat bars in aluminium panels have been also presented by Zha and Moan [15–17]. Hopperstad et al. [18] carried out a study with the objective of assessing the reliability of non-linear finite element analyses in predictions on ultimate strength of aluminium plates subjected to in-plane compression. Rigo et al. [19] made a numerical investigation to present reliable finite element models to study the behaviour of axially compressed stiffened aluminium panels (including extruded profiles).

Among most recent works, reference can be made to the work of Paik et al. [20] on the subject of ultimate limit state design of multi-hull ships made in aluminium. The impact of initial imperfections due to the fusion welding on the ultimate strength of stiffened aluminium plates was studied by Paik et al. [21] and Collette [22]. Paik et al. [21] defined the fabrication related initial imperfections of fusion-welded stiffened aluminium plate structures at the three levels. Also Paik et al. [23] derived empirical formulations for predicting ultimate strength of stiffened aluminium plates under axial compression. Future trends and research needs in aluminium structures were outlined by Sielski [24]. Mechanical collapse tests on stiffened aluminium structures for marine applications were performed by Paik et al. [25,26]. Most recently, Paik et al. studied buckling collapse testing of friction stir welded aluminium-stiffened plate structures [27].

In most of aforementioned studies, only the case of in-plane compression has been considered as applied loading condition of the stiffened plate panels. Post-buckling behaviour and strength of such stiffened panels under combined in-plane compression and lateral pressure have not been addressed yet to our knowledge.

In this paper, the post-buckling behaviour and ultimate strength characteristics of stiffened aluminium plates under combined axial compressive and lateral pressure loads are investigated using non-linear finite element method. Plate dimensions, stiffener type and stiffener dimensions are varied in a systematic manner in the analyses. In addition, average initial weld-induced deflection, welding residual stresses and also softening in heat-affected zone are considered throughout the investigation.

## 2. Models for analysis

### 2.1. Structural arrangements and geometrical characteristics

The geometrical characteristics of the analysed stiffened plates are given in Table 1. Three types of models have been considered. In each type, three different shapes of stiffeners (flat, angle and tee) have been attached to the isotropic plate, Fig. 1. The stiffened plates of each type have the same moment of inertia. Types 1, 2 and 3 correspond, respectively, to weak, medium and heavy stiffeners.

**Table 1**
Geometrical characteristics of the aluminium-stiffened plates.

| Type | Model | Shape | Plate | | | Longitudinal stiffener | | | | Stiffened Plate | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $a$ (mm) | $b$ (mm) | $t$ (mm) | $t_w$ (mm) | $h_w$ (mm) | $t_f$ (mm) | $b_f$ (mm) | $I$ (mm$^4$) | $\beta$ | $\lambda$ |
| 1: Weak stiffener | F1 | Flat | 900 | 300 | 7 | 5 | 53.5 | – | – | 226254 | 2.603 | 0.787 |
| | L1 | Angle | | | 6 | 4 | 40 | 4 | 20 | 226380 | 3.037 | 0.790 |
| | T1 | Tee | | | 6 | 4 | 40 | 4 | 20 | 226380 | 3.037 | 0.790 |
| 2: Medium stiffener | F2 | Flat | 900 | 300 | 7 | 6 | 82.2 | – | – | 804521 | 2.603 | 0.426 |
| | L2 | Angle | | | 6 | 5 | 60 | 5 | 30 | 803652 | 3.037 | 0.411 |
| | T2 | Tee | | | 6 | 5 | 60 | 5 | 30 | 803652 | 3.037 | 0.411 |
| 3: Heavy stiffener | F3 | Flat | 900 | 300 | 8 | 10 | 107.6 | – | – | 2503753 | 2.278 | 0.273 |
| | L3 | Angle | | | 6 | 8 | 80 | 8 | 40 | 2505550 | 3.037 | 0.271 |
| | T3 | Tee | | | 6 | 8 | 80 | 8 | 40 | 2505550 | 3.037 | 0.271 |