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Empirical formulations for estimation of ultimate strength of continuous stiffened aluminium plates under combined in-plane compression and lateral pressure

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ABSTRACT

The present research was undertaken based on the results obtained by the same authors in a sensitivity study on the buckling and ultimate strength of continuous stiffened aluminium plates. Empirical expressions are developed for predicting ultimate compressive strength of welded stiffened aluminium plates used in marine applications under combined in-plane axial compression and different levels of lateral pressure. Existing data of the ultimate compressive strength for stiffened aluminium plates numerically obtained by the authors through the previously performed sensitivity analysis are used for deriving formulations that are expressed as functions of two parameters, namely the plate slenderness ratio and the column (stiffener) slenderness ratio. Regression analysis is used in order to derive the empirical formulations. The formulae implicitly include effects of the weld on initial imperfections, and the heat-affected zone.

1. Introduction

Stiffened plates are basic building elements in many civil as well as marine structural applications and, as such, accurate strength assessment of individual stiffened plate components is one of the key parameters to perform general strength analysis. These structural components typically consist of a plate with equally spaced stiffeners (bulb, flat bar or T- and L-sections welded on one side) and often with intermediate transverse stiffeners, frames or bulkheads.

Stiffened plates in high-strength aluminium alloys have been used in a variety of marine structures, with applications such as hull and decks in high-speed boats and catamarans and superstructure for ships. Other applications are bridge box girders, and walls and floors of offshore modules and containers. These elements are primarily required to resist axial compressive forces (induced by hull bending moment) as well as lateral loads arising from different sources like hydrostatic/hydrodynamic pressures or cargo weight. Also, other loads such as transverse tension/compression, longitudinal tension, in-plane bending moments and shearing forces may act on these structural elements.

The ultimate strength design formulae available for steel plates cannot be directly applied to aluminium plates even if the corresponding material properties are properly accounted for. This is partly due to the fact that the constitutive stress–strain relationship of aluminium alloys is different from that of structural steel. In the elastic–plastic range after the proportional limit as compared with structural steel, 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, 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 and Narayanan [11] report 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

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Notation

A	cross-sectional area of stiffener with attached plating
A_P	cross-sectional area of plate
A_S	cross-sectional area of stiffener
$L=a$	length of local plate panels
b	breadth of local plate panels
b_e	effective breadth of local plate panels
c	coefficient to define the maximum magnitude of initial deflection
C_1–C_5	constant coefficients
I	moment of inertia of a stiffener with its attached plating
$r=(\sqrt{I/A})$	gyration radius of a stiffener with its attached plating
$t(=t_p)$	plate thickness
t_w	web thickness of longitudinal stiffener
h_w	web height of longitudinal stiffener
t_f	flange thickness of longitudinal stiffener
b_f	flange breadth of longitudinal stiffener
h	water head (pressure) in meters
e_i	residuals
P_{ult}	ultimate load
R^2	parameter for accuracy control of regression model
x and x_i	independent variables
x_{max} and x_{min}	maximum and minimum values, respectively, of x
y and y_i	functional variables
Z_0	distance between outer surface of plate and neutral axis of plate – stiffener combination
ν	Poisson's ratio
E	Young's modulus
η_P, η_S	constants related, respectively, to the plate and stiffener
σ	average stress
σ_{el}	elastic buckling strength of stiffened plate
$\sigma_{c\text{-}plate}$	elastic buckling strength of stiffened plate for plate buckling mode
$\sigma_{c\text{-}lateral}$	elastic buckling strength of stiffened plate for stiffener tripping buckling mode
$\sigma_{c\text{-}torsional}$	elastic buckling strength of stiffened plate for torsional buckling mode
$\sigma_{c\text{-}web}$	elastic buckling strength of stiffened plate for stiffener web buckling mode
$\sigma_{c\text{-}flange}$	elastic buckling strength of stiffened plate for stiffener flange buckling mode
σ_Y	yield stress
σ_{Ys}	yield stress for the stiffener
σ_{Yp}	yield stress of the plate
σ_{Yseq}	equivalent yield stress for the stiffened plate
$\sigma_U(=\sigma_{ult})$	ultimate strength
ε	average strain
ε_Y	yield strain
β	slenderness of the plate
β_j	exact coefficients in the equation of regression models
$\widehat{\beta}_j$	estimated coefficients in the equation of regression models
λ	column slenderness of the beam column element (stiffener and the associated plate)

mode. The ultimate strength of stiffened aluminium AA6082-T6 plates under 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 bi-axial loading of plates. Some initial experimental and numerical simulations on torsional buckling of flat bars in aluminium panels have been also presented by Zha et al. [15,16] and Zha and Moan [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 ultimate strength of stiffened aluminium plates was studied by Paik et al. [21] and Collette [22]. Paik et al. [21] defined fabrication related initial imperfections of fusion welded stiffened aluminium plate structures at three levels. Also Paik [23] derived empirical formulations for predicting the 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]. Recently, Paik [27] studied buckling collapse testing of friction stir welded aluminium stiffened plate structures. Most recently, Khedmati et al. [28] made an extensive sensitivity analysis on buckling and ultimate strength of continuous stiffened aluminium plates under combined in-plane compression and different levels of lateral pressure.

Following the study made by Khedmati et al. [28] on post-buckling behaviour and ultimate strength characteristics of stiffened aluminium plates under combined axial compressive and lateral pressure loads, a set of empirical formulations or equations are derived in this paper to estimate the ultimate strength of such stiffened plates under above-mentioned load combinations. The ultimate compressive strength data numerically obtained by the authors through their sensitivity analysis [28] are used for deriving the formulations, which are expressed as functions of two parameters, namely the plate slenderness ratio and the column (stiffener) slenderness ratio. Regression analysis is used in order to derive the empirical formulations. The formulae implicitly include effects of weld induced initial imperfections and softening in the heat-affected zone.

2. Numerical data used for formulae derivations

2.1. Structural arrangements and geometrical characteristics of analysed stiffened aluminium plates

In order to derive the ultimate compressive strength formulae for stiffened aluminium plates, a database of the ultimate strength values for a number of such structural elements is required. The database may be gathered either based on expensive experimental tests or on results of a set of numerical analyses. Thus, in this paper a series of elastic–plastic large deflection analyses is performed applying the finite element method. A total of 199 prototype stiffened aluminium plates were designed for this