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Elastic lateral-torsional buckling analysis of permanent means of access structure

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A B S T R A C T

International Maritime Organization (IMO) adopted a new regulation to request permanent means of access (PMA) for a regular inspection of ship structure. Horizontal platforms for an inspector to walk on should be provided at specified locations. The platform is attached perpendicular to longitudinal bulkheads or side shell like a common longitudinal stiffener. Since the platform is much wider than ordinary stiffeners, a mid-flat-bar is welded in the middle of the platform. The wide platform (i.e. the tall web plate) makes PMA structure prone to lateral torsional buckling prior to overall flexural Euler buckling subjected to axial compression. This study employs the Rayleigh–Ritz method to treat the elastic lateral-torsional buckling of the PMA structure. The deformation of the cross-section can be expressed using six independant parameters. Compared to the previous research for an ordinary stiffened plate (Hughes and Ma, 1996a), two additional parameters are employed to model the deformation of the mid flat bar. This study also proposes a new strain distribution of lateral bending introducing two respective neutral axes for the flange and the mid-flat-bar. Two mathematical models are developed for two cases; one without associated plating, and the other with both the plating and its rotational restraint. In the former, the coupling between the lateral torsional buckling ("tripping") and the Euler buckling is investigated. In the latter, a plate rotational spring constant is suggested based on extended deformed shape of the plating. For each model, the validity of the proposed method is verified by a comparison with a number of linear buckling analyses carried out using the NASTRAN finite-element program.

1. Introduction

International Maritime Organization (IMO) adopted a new regulation of the International Convention for the Safety of Life at Sea (SOLAS) and technical provisions for permanent means of access (PMA) for inspections in 2002, in short, PMA regulations (SOLAS, 2002). The purpose of the regulation is to enable a ship to be surveyed or monitored by flag state inspectors, classification society surveyors or crew during her in-service life. This can ensure that they are free from damage such as cracks, buckling, or deformation due to corrosion, overloading, or contact damage and that thickness diminution over the life time is within established limits. For bilge hopper tanks, ballast tanks, or cargo tank, access to the continuous longitudinal PMA should be provided in the vicinity of the tank access. Generally, a longitudinal plate is welded perpendicular to side or centerline longitudinal bulkhead just as other longitudinal stiffeners. Its web height, i.e. platform width is 550–600 mm larger than an ordinary longitudinal stiffener in order to provide the space for a hull inspector to walk on as shown in Fig. 1. Since it is integrated with hull structure, it is regarded as a structural member and to be designed to withstand the applied loads. Due to its large web height, a flat bar is attached along the web plate to prevent web local buckling. Classification societies have provided simple formulas or nonlinear buckling programs for the estimation of lateral torsional strength for an ordinary stiffened plate (ABS, 2004; DNV PULS, 2006; DNV, 2002). However, they are not applicable to PMA structure (hereafter, PMA structure is defined as a combination of web, flange plate, mid-flat-bar, and associated plating). It is because the large web height of PMA structure is out of the range that the classification methods can cover and the existence of mid-flat-bar cannot be taken into account in the methods. Even if common structural rule (CSR) adopted the PMA regulations, it does not provide any specified rule or any buckling check formula for the design of PMA structure. Thus, the scantling requirement of local support member described in CSR Sec.10 Pt.2 (IACS, 2006) has been implicitly applied, which has led to excessive scantlings.

In academic fields, there have been researches on developing mathematical formulations for lateral torsional buckling behavior ("tripping") of a stiffened plate. Adamchak (1979) used the Jonson–Ostenfeld formula for inelastic lateral-torsional buckling strength of stiffeners to make the plasticity correction of the elastic buckling

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Nomenclature

A total cross-sectional area
A_f, A_w, A_p, A_{fb} area of flange, web, plate, and mid-flat-bar
A_{uvf}, A_{uvfb}, A_{uw} cross-sectional parameters due to axial shortening
b_p uniform stiffener spacing
b_f, h_w, b_p, b_{fb} / t_f, t_w, t_p, t_{fb} defined in Fig. 1.
$\{\delta\}$ $= \{\overline{\varphi}_B, \overline{v}_T, \overline{\varphi}_T, \overline{v}_{FB}, \overline{\varphi}_{FB}, \overline{w}\}^T$
D_p, D_w flexural rigidities of plate and web
E, G Young's modulus and shear modulus
ε, ε_f strain due to lateral bending on web plate and at the center of flange, defined in Fig. 3.
f_1, f_2, f_3, f_4, f_5 shape function defined in Eq. (9)
g_{ij} element of geometric stiffness matrix $\mathbf{K}_G$ $(i,j=1,\ldots,6)$
I vertical moment of inertia of PMA structure inclduing associated plating
I_{ns} total vertical moment of inertia of two stiffeners adajecnt to PMA platform
I_{zf} moment of inertia of flange respect to z-axis
I_{zfb} total moment of inertia of mid flat bar, web, and plate respect to z-axis
I_{zyf} product of inertia of flange respect to yz-plane
I_{zyfb} total product of inertia of mid-flat-bar, web, and plate respect to yz-plane
J_f St. Venant torsion constant for flange
J_{fb} St. Venant torsion constant for mid flat bar
k_{ij} element of linear stiffness matrix $[\mathbf{K}_L]$ $(i,j=1,..,6)$
$[\mathbf{K}_G]$ geometric stiffness matrix
$[\mathbf{K}_L]$ linear stiffness matrix
$[\overline{\mathbf{K}}_G]$, $[\overline{\mathbf{K}}_L]$ geometric stiffness matrix and linear stiffness matrix, including plate rotational restraint
k_{spring} plate rotational spring constant
l length of stiffener between transverse supports, i.e. span length
λ $m\pi/l$
m mode number = number of half waves lengthwise
Π_T total potential energy
Π potential energy due to bending-torsional deformation
Π_a potential energy due to axial deformation
Π_{po} potential energy due to plate-out-of plane deformation
σ applied axial stress
u_{wo} strain energy due to web out-of-plane deformation
U_T total strain energy during deformation
U strain energy due to bending-torsional deformation
V work done due to bending-torsional deformation
x,y,z / u,v,w / $\varphi_B, v_T, \varphi_T$ / v_{FB}, φ_{FB}, w defined in Fig. 4
z_0 distance of the neutral axis of vertical bending
a_0, a_1 distances of the neutral axes of lateral bending for flange and mid-flat-bar, respectively
ν Poison ratio
u_f, v_f, w_f / u_{fb}, v_{fb}, w_{fb} / u_w, v_w, w_w / u_p, v_p, w_p displacements of flange, mid-flat-bar, web, and plate
w_{po} plate-out-of-plane displacement
w_{ns} vertical flexural displacement of stiffeners next to PMA platform

strength. Danielson et al. (1990) proposed a mathematical model to predict buckling behavior of thin-walled beams with an enforced axis of rotation subject to longitudinal compressive loading. Hu et al. (2000) proposed a generalized eigenvalue problem for tripping of stiffeners using Galerkin's method. Hughes and Ma (1996a) proposed an elastic tripping model using the Rayleigh–Ritz approach. They extended the elastic model into inelastic range, using deformation theory and an iterative and incremental formulation (Hughes and Ma, 1996b). Despite those successful researches, the developed models cannot be directly utilized for PMA structure since they cannot cover the effect of the mid flat bar on the lateral torsional buckling strength. Recently, nonlinear finite element (FE) analysis has been recognized as a reliable and mature method for the assessment of the ultimate strength of plated structures. Sheikh et al. (2002) presented an investigation of the parameters that uniquely describe the strength and the behavior of stiffened steel plates using a finite element model. Louca and Harding (1996) used a nonlinear finite element analysis to investigate the torsional behavior of flat-bar stiffeners under axial loading. Jang et al. (2009) proposed a strength assessment procedure for PMA structure using a nonlinear finite element (FE) analysis and evaluated its structural adequacy by comparing the ultimate capacity with a set of actual stresses calculated by cargo hold analysis. This study proposes a formulation for elastic lateral-torsional buckling of PMA structure subjected to axial compression. It is based on the model developed by Hughes and Ma (1996a). The main modifications are summarized as follows.

First, two parameters are newly adopted to model the deformation of mid flat bar; lateral displacement (v_{FB}) from the axis along the web plate and the rotation (φ_{FB}) at the baseline of the mid flat bar.

Second, a cross-sectional strain distribution of sideways bending is proposed. Neutral axes of the flange and the mid-flat-bar with respect to the axis along the web plate are treated separately.

Third, the plate rotational spring constant of the previous research (Hughes and Ma, 1996a) is adjusted considering the plate out-of-plane deformation extending over double stiffener spacing and vertical deflection of neighboring stiffeners. In addition, vertical flexural deflections of two neighboring stiffeners are incorporated into the relevant strain energy.

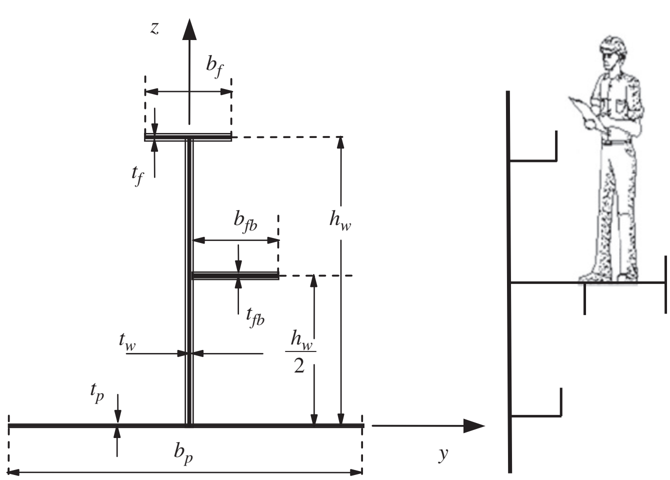

Fig. 1. Geometric parameters of PMA structure.