Marine Structures 39 (2014) 255–286

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Approximate approach to progressive collapse analysis of the monotonous thin-walled structures in vertical bending

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A R T I C L E I N F O

Article history:
Received 29 January 2014
Received in revised form 30 June 2014
Accepted 18 July 2014
Available online 15 September 2014

Keywords:
Monotonous thin-walled structure
Ultimate hull girder bending capacity
Progressive collapse analysis
Vertical bending
Warping
Nonlinear finite element method

A B S T R A C T

Present article proposes improved assessment of the ultimate bending capacity (ultimate bending moment), i.e. enhancement of the ultimate limit state evaluation in the concept design of the monotonous thin-walled structures predominantly subjected to vertical bending loads during their exploitation. An alternative progressive collapse analysis method is proposed, which incorporates direct consideration of various relevant distributed load effects and consequently enables more sophisticated evaluation of the ultimate bending capacity and more accurate and reliable identification of the critical cross section and its collapse sequence. Relevant aspects of the employed approximate model for the cross sectional warping due to vertical bending are considered and determination of the (longitudinal) warping displacements and strains, shear strains and stresses, as well as the corrected longitudinal strains is described. Influence of the (ultimate) shear capacity on the (ultimate) bending capacity is discussed and detailed description and critical overview of the proposed method is given. Finally, various aspects of the considered problem and accuracy of the proposed approach are discussed and demonstrated on example of the thin-walled box-girder, whereby detailed comparison of the results obtained by the proposed approach and nonlinear finite element method analyses is given.

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http://dx.doi.org/10.1016/j.marstruc.2014.07.008
0951-8339/

1. Introduction

Contemporary approaches to the ultimate load capacity assessment of the complex thin-walled structures are based on explicit evaluation of their ultimate limit state. This enables accurate and reliable determination of the inherent structural safety level and a corresponding structural safety margin. Furthermore, since the flexural load resistance capability is of a predominant importance in the ultimate limit state design and analysis of the numerous ship structures, the ultimate load capacity expressed in terms of the ultimate bending moment can be considered as one of the most important global safety measures in a multi-criteria concept design of various ship structures. In this context, the ultimate limit state is synonymous to the structural collapse which is induced by a progressive decrease in the load capacity of structural members when imposed with the effects of the extreme global bending loads.

The most accurate results in this respect can be obtained by means of the materially and geometrically nonlinear finite element analysis (further in text: NLFEA) of the entire (discretized) structural model, which enables simulation and evaluation of the nonlinear structural response for various loading levels. On the other hand, a significant amount of time, knowledge and experience is still required for a successful completion of the whole NLFEA procedure (especially for pre/post processing). Furthermore, substantial effort required for the realization of an automatic execution of the complete NLFEA procedure considerably limits possibility of the NLFEA application within the optimization based concept design procedures, e.g. Ref. [1]. Hence, demand for development and employment of the appropriate (sufficiently fast, robust and accurate) alternative analysis methods still exists. Among the most widely utilized contemporary alternative methods are various incremental-iterative progressive collapse analysis methods based on the Smith's approach [2]. Although generally characterized by the lower fidelity with respect to more sophisticated methods (e.g. NLFEA), the ultimate limit state evaluation based on the Smith's approach can represent a sufficiently accurate safety measure which is able to provide the correct ordering of the design variants generated within the framework of the optimization based concept design procedures.

Smith's approach employs Euler–Bernoulli beam bending theory for evaluation of the hull girder bending. However, kinematic assumptions of the Euler–Bernoulli beam bending theory are fully accomplished only in the pure bending case, i.e. when distribution of the bending moment $M_y(x)$ is constant along the considered structure and distributions of the shear force $Q_z(x)$ (first derivative of the $M_y(x)$ distribution) and the distributed load $q_z(x)$ (second derivative of the $M_y(x)$ distribution) are nonexistent. However, various complex thin-walled structures (e.g. ships, airplanes, etc.) are commonly submitted to the realistic vertical bending cases during their exploitation, which are characterized by a non-constant $M_y(x)$ distribution. Non-constant $M_y(x)$ distribution implies existence of the $Q_z(x)$ distribution, which induces warping of the structural transverse cross sections, imposing them with the corresponding shear strain and stress distributions. Furthermore, distributions of an additional longitudinal strain and stress are generated along the transverse cross sections if acting $Q_z(x)$ distribution is also non-constant, i.e. when $M_y(x)$, $Q_z(x)$ and $q_z(x)$ distributions exist simultaneously.

Disregard for the warping effects will often introduce only negligible error into the analysis of many realistic problems of the common structural engineering practice. However, when analyzing a structural response on a bending load of the extreme magnitude, disregard for the warping effects can lead to erroneous predictions of the pronounced significance. Hence, influence of the shear lag effects on the bending capacity should be incorporated into evaluation of the ultimate limit state of the complex thin-walled structures submitted to an extreme bending loads, especially if the considered structure is characterized by a significant flange (deck) breadth to web (side) height ratio (e.g. ship hull girder, aircraft fuselage and/or wing, etc.). Although this topic is scarcely addressed by the contemporary researchers, some relatively current research work exists [3,4].

This article aims to propose an alternative ultimate bending capacity evaluation approach, which enables inclusion of the various distributed load effects arising when the monotonous thin-walled structures are subjected to the usual vertical flexural loads $M_y(x)$, $Q_z(x)$ and $q_z(x)$. Proposed progressive collapse analysis method is developed as an extensive modification of the incremental-iterative method prescribed by the IACS Common Structural Rules [5,6] (further in text: basic method), previously encoded and incorporated into the OCTOPUS [7] computer program.