Thin-Walled Structures 76 (2014) 118–144

Contents lists available at ScienceDirect

Thin-Walled Structures

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

A numerical investigation into the effects of slamming impulsive loads on the elastic–plastic response of imperfect stiffened aluminium plates

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ARTICLE INFO

Article history:
Received 5 June 2012
Received in revised form
1 October 2013
Accepted 17 October 2013
Available online 11 December 2013

Keywords:
Stiffened aluminium panel
Slamming
Initial imperfections
Finite element analysis
Heat affected zone (HAZ)

ABSTRACT

Nowadays stiffened aluminium panels have been widely used for marine applications such as building high speed vessels. The panels of high speed vessels are subjected to different in plane and out-of-plane loads. One of the most important out-of-plane loads is the impulse caused by bottom slamming. In the present study, the transient large deflection elastic–plastic responses of a number of stiffened aluminium panels subject to slamming impulsive loads are investigated. The impulsive loads are exerted on the finite element models of aluminium panels proposed by Ultimate Strength Committee of ISSC 2003. Several impact conditions are considered to study the influence of several structural factors such as heat affected zone (HAZ) arrangement, boundary conditions, thickness of plating, number of transverse frames and in-plane fixation. Based on these studies, several design-oriented conclusions are issued. Moreover, this paper outlines the various aspects of the influence of the HAZ presence on the strength of the slam-loaded panels with respect to loading time ratio.

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1. Introduction

Stiffened plates are used as main supporting members in many civil as well as marine structural applications. They normally consist of a plate with equally spaced stiffeners welded on one side, often with intermediate transverse stiffeners or bulkheads. The most regular 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 were implemented for marine applications like construction of boats and high speed catamarans, during 1990s for the first time [1]. The main role of these panels is strengthening against in-plane compression. Ultimate strength formulations used for steel panels could not be directly applied for estimating the ultimate strength of aluminium panels. This is due to 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 behavior of aluminium structures where as 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 behavior of aluminium structures, where as its effect in steel structures is of very little importance [2]. The most important investigation done in field of aluminium structure were held by Clarcke, Moflin [1] Alberg et al. [3], Zha et al. [4], Hopperstad et al. [5] and Paik et al. [6–8].

Rigo et al. [9] published a sensitivity study on the ultimate strength of aluminium panel based on a benchmark analysis carried out for the Ultimate Strength Committee of the 15th ISSC. Using the same extrusion cross-section as Aalberg et al.'s experimental work, several different finite element codes were compared to predict the compression collapse, with good agreement. A sensitivity study was then carried out to investigate the effects of the volume of the HAZ, the locations of the HAZ including transverse welds at mid and quarter span, residual stresses, initial out-of-plane deformations, and material properties. The location and size of the HAZ seemed most significant, especially for transverse welds at mid-span, with the other factors having smaller impacts on ultimate strength. The finite element models proposed by this committee were selected and implemented for the present investigations. The aim of the above mentioned investigations were to realize the behavior of aluminium stiffened plates under the pure in plane compression or the combined in plane compression or lateral pressure. These kinds of loads have significant effects on aluminium panels and their different aspects need to be investigated. Furthermore, different kinds of loads are also exerted on these panels as the main constituents of the structures operating in the harsh environments like seas and oceans. One of the dominating hull design loads is the slamming induced hydrodynamic impact loads. The impact between ship

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http://dx.doi.org/10.1016/j.tws.2013.10.016

Nomenclature

L	overall length of the panel (m)
a	distance between transverse frames (m)
b	distance between longitudinal stiffeners (m)
t	plate thickness (mm)
E	Young's modulus (N/m^2)
ν	Poisson's ratio (dimensionless)
σ_Y	yielding stress (MPa)
V	impact velocity (m/s)
$C(t)$	wetted half beam t s after initiation of the impact (m)
β	impact angle (dead rise) (deg)
P_e	outer region pressure (Pa)
P_i	inner region pressure (Pa)
$(P_i)_e$	common pressure (Pa)
P_a	atmosphere pressure (Pa)
ρ_f	water density (kg/m^3)
$\delta(t)$	spray thickness (m)
σ_{rcx}	yielding residual compressive stress in plating and stiffener in x direction (MPa)
b_t	breadth of tensile residual stress transverse region (m)
a_t	breadth of tensile residual stress longitudinal region (m)
σ_{Ys}	yielding stress of stiffener (MPa)
σ_{Yp}	yielding stress of plating (MPa)
DLF	dynamic load factor
T_S	splash time (s)
T_{np}	natural period of panel (s)
NDST	non-dimensional splash time (T_S/T_{np})
h_w	height of stiffeners (m)
U	displacement along x-axis
V	displacement along y-axis
W	displacement along z-axis
θ_x	rotation about x-axis
θ_y	rotation about y-axis
θ_z	rotation about z-axis

hulls and waves will induce impulsive pressure loads, which consequently affect the structures of the ships both locally and globally. In rough seas, this impact load is so large that in many ships local structural damages due to the slamming were reported especially in heading waves with high forward speed [10]. This impulsive impact on the water will induce global transient elastic vibrations of the ship hull denoted as whipping. There have been enormous investigations devoted to the prediction of the pressure distribution and the global effects of slamming (e.g., Ochi et al., Kawakami et al., Belik et al., Yamamoto et al., Molin et al., Guedes soares, Tao and Incesik, Sames et al., Chu and Abramson, Howison et al., Mizuguchi and Tanizawa, Mei et al. and Faltinsen) most of which are based on the Wagner approach for calculating the slamming impulsive pressure [11].

Design against slamming loads is a concern of ship designers from the view point of strength. In the current design methods that are based on the design rules presented by the classification societies, these transient loads are treated as uniformly distributed static design pressures. The design situation is further also treated as unaffected by the flexibility of the structure. This simplified way of treating the actual design conditions limits the prospects of reaching optimized hull structures [12].

By adopting direct calculation methods, the design accuracy could be significantly increased and it helps the designers to achieve more optimized structures. Direct calculation methods are, however, greatly simplified by the assumption that the hydrodynamic induced impact loads can be applied quasi-statically and there would be no hydro elastic interaction. Recently, the quasi-static analysis has been widely used to determine and distinguish the hydro elastic aspects of panel water impact problems (e.g., Faltinsen et al. [13], Stannius et al. [12], Hua et al. [14] and Luo et al. [15]). If the water entry of the panel is treated as a problem in which both kinematic and inertial effects are interacting, this problem is treated as a hydro elastic problem. If both inertial and kinematic effects are unconsidered in the analysis, then, the problem is treated as rigid-quasi static. Furthermore, if the inertial effects of the problem are taken into consideration, then the problem is considered as a dry vibration problem. A dry vibration analysis is, in fact, an uncoupled problem solving method in which the hydrodynamic problem is solved separately and when the load is exerted on the panel to study structural ramification of the impact phenomenon (e.g., Luo et al. [15] and Datta et al. [16])

The effect of slamming on the panels with several stiffeners has also been studied. Faltinsen [13] presented one solution based on Wagner theory and orthotropic plate theory to study the water entry of an elastic wedge with three stiffeners. Strain responses on the stiffeners were investigated and compared with the catamaran trial's results. Hua et al. [14] investigated the effects of asymmetric impact on the structural dynamic responses. They employed orthogonal plate theory to model the bottom plate structure. A method derived by Toyama was applied for the calculation of the transient pressure distribution on an asymmetric edged body under water entry. The hydro elastic effects were also considered in this study and the hydro elastic problem was solved for different roll angles using the Vlasov–Galerkin method. This study demonstrated that the application of the orthogonal plate theory is a practical approach in modeling the structural dynamic response of ship bottom structure.

When the structure is more complex, the finite element method (FEM) is the best tool in the structural analysis. Korobkin et al. [17] developed an efficient and very general method for elastic wedge impact by combining the FEM for the structural part and Wagner theory for the hydrodynamic loads. There are also some other numerical solutions attempting to predict hydro elastic impact. Stenius et al. [12] investigated the fundamental mechanisms involved in panel-water impact related hydro elastic problems. The aims of that investigation were identification and separation of the different hydro elastic effects, quantification of different hydro elastic effects, realization of the influence of boundary condition and in-plane effects on the hydro elastic problem and influence of impact envelope on the hydro elastic problem. For the modeling of the hydro elastic problem, the commercial explicit finite element code LS-DYNA was used based on the work presented by Stenius et al. [18]. Luo et al. [15] implemented an uncoupled method based on the matched asymptotic theory and the FEM to predict the slamming response of test specimens of the Wang's [15] experimental investigation. Measured and predicted results of the acceleration, slamming pressures and stress responses were compared and a good agreement was observed between the results of the numerical and experimental studies.

As it is understood from the above mentioned review about the already held research in the field of aluminium panels and slamming phenomenon, there has been no investigation heading to study the transient, non-linear and elastic–plastic response of aluminium stiffened plates to the lateral impact loads due to slamming. Therefore, diagnosing this shortcoming, the aim of the present study is to investigate the impulsive induced effects on aluminium stiffened plate. Non-linear, commercial finite element

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