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Large inelastic deformation resistance of stiffened panels subjected to lateral loading

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ABSTRACT

This paper presents a simplified formulation for the assessment of large deformation resistance of stiffened panels subjected to lateral loading. The method is based on rigid plastic material assumptions and the use of yield functions formulated in terms of stress resultants. The method considers the flexibility of the panel ends with respect to inward motion, while the rotational boundary conditions are free or clamped. Concentrated and distributed loads are considered, as is patch loading. The resistance-deformation curves predicted by the proposed method are compared with results from experiments and using LS-DYNA, and good agreement is obtained for panels that are not dominated by shear failure and tripping or local buckling of stiffeners at the early stage of deformation. The formulation provides a useful tool for quick estimates of panels subjected to abnormal or accidental static and transient lateral loads such as ship collisions, dropped objects, explosions, slamming, hydrostatic pressure and ice actions.

1. Introduction

Stiffened panels are widely used in ships, offshore platforms and other engineering structures. A typical stiffened panel structure on a ship side or bottom is shown in Fig. 1. Such structures are often exposed to the risk of explosions, ship collisions, violent water slamming, ice pressure and impacts from dropped objects. Potential consequences may vary from minor local deformation to major structural damage and plate rupture, causing compartment flooding or oil leakage. In extreme cases, the loads may cause the entire structure to collapse and put human lives in jeopardy. Consequently, it is crucial to estimate the resistance and damage of stiffened panels with good efficiency and accuracy, notably when they are loaded to their extreme performance limits during accidental events.

Several methods are available for structural response analysis, including nonlinear finite element methods (NLFEM) [1,2], experimental methods and simplified methods. In the design stage, a number of scenarios and structural configurations need to be assessed. For this purpose, nonlinear finite element analysis is not practical due to significant modeling efforts and computational costs. Experimental methods will provide accurate results if the scaling law is properly handled, but the disadvantages include high cost and a long period of time from test preparation to results. Thus, simple analytical methods that can perform a quick and realistic assessment of the resistance during inelastic deformations are desired. A few design standards contain simple resistance expressions, such as DNV RP C204 [3] and the NORSOK N004 standard [4].

Numerous formulations of the resistance and energy dissipation of structural components and subassemblies during accidental actions are available in the literature. They are typically based on plastic theory and the assumption of idealized deformation modes inspired by deformation patterns observed in actual accidents, model tests or numerical simulations. Wierzbicki and Abramowicz [5]

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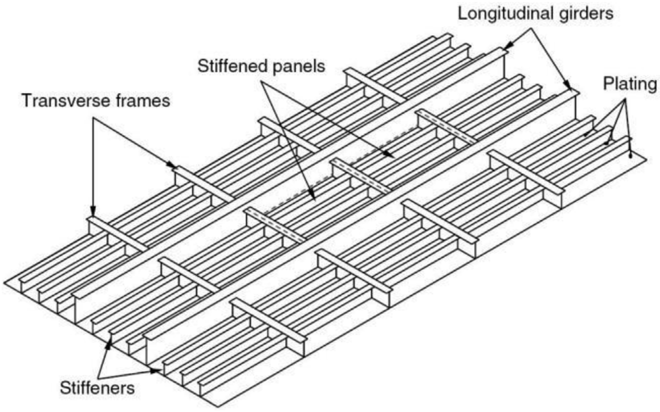

Fig. 1. Stiffened panel.

presented pioneering work on the crushing resistance of thin-walled structures. Amdahl [6] derived simplified formulas for the crushing resistance of a ship bow. Jones [7] presented useful analytical models for the impact response of beams, plates and shells. Both static and dynamic responses were addressed. The effects of transverse shear and rotatory inertia were discussed.

As for the deformation resistance of stiffened panels, a simple way to address stiffened panels may be to smear the thickness of stiffeners onto the attached plate, but the accuracy was shown to be crude [8]. Considering the confinement effect in the longitudinal and transverse directions, the deformation resistance models of stiffened panels under blast loads can be found in Refs. [9–12]. For beam deformation of stiffened panels with only longitudinal confinement, Schubak et al. [13,14] and Yang and Peng [15] presented rigid plastic models with clamped ends and partial end fixity subjected to uniformly distributed blast loads. However, the neutral axis was assumed to coincide with the centroid axis. The resulting yield curve was asymmetric and was simplified as a linear piecewise curve, which is not accurate. The DNV RP C204 [3] standard presented the static resistance of laterally deflected stiffened frames by using a practical approximation of the interaction function of the bending moment and the membrane force. Amdahl [16] proposed a model for the resistance of stiffened panels with fixed end conditions subjected to explosions with more refined yield functions. Daley et al. [17] presented a model for overload response of simple flat bar stiffened frames subjected to ice loading, and the effect of bending and shear is discussed while the axial force is neglected. A series of full-scale experiments for the lateral indentation resistance of single stiffened frames and ship grillages were conducted and reported by Daley and Hermanski [18] and Kim [19], which provide valuable results for the investigation of the ultimate strength of stiffened frames.

Considering the flexibility of beam ends, Jones [20] proposed an analytical formulation that accounted for the effect of inward flexibility of beam ends. A drawback to this method was that the flexibility was proportional to the square of the deflection, which made it difficult to associate it with the physical properties of a structure. Hodge [21] and De Oliveria [22] presented simple expressions for the resistance of rectangular and tubular beams respectively under lateral loading, and boundary translational and rotational flexibilities were accounted for. They showed that the translational stiffness of beam ends was crucial for the development of membrane forces in large deformation conditions.

This paper presents a simplified formulation for the large beam-deformation resistance of stiffened panels with T-profile and L-profile stiffeners. The effects of distributed loads, different loading positions and boundary translational and rotational stiffness are accounted for. Results from experiments and numerical simulations are used to verify the proposed analytical model. A number of cases are simulated with LS-DYNA, covering a broad range of impact scenarios. The shear and dynamic inertia effects are discussed as well. The proposed model may serve as design equations in the design standards of marine structures.

2. Yield functions based on generalized forces

The object of this study is a stiffened panel with a vertically asymmetric I-profile, as shown in Figs. 1 and 2 (a). The areas of the plate flange, the top flange and the stiffener web are denoted A_p, A_t and A_w, respectively. h_w denotes the height of the web. It is presupposed that the area of the plate flange is larger than or equal to the area of the small flange and the web such that $A_p \geq A_w + A_t$. This assumption is valid for most stiffened panels used in ships and offshore installations. The material is assumed to be rigid perfectly plastic with a yield strength of σ_y .

First, pure bending of the cross section is considered. The stress distribution in the fully plastic state is shown in Fig. 2(b). The plastic neutral axis is located such that it divides the cross section into two equal areas. This implies that the axis is initially located in the plate flange, given by the coordinate z_1:

$$\frac{z_1}{t_p} = \frac{A_p - A_w - A_t}{2A_p} = 1 - \frac{A_e}{2A_p} \tag{1}$$

where t_p is the thickness of the plate flange and A_e is the total area of the stiffened panel cross section, i.e. $A_e = A_p + A_w + A_t$. As the area relation of $A_p \geq A_w + A_t$ is assumed, z_1 must always be smaller than $\frac{t_p}{2}$; i.e. $2z_1 < t_p$.