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Nonlinear structural behaviour and design formulae for calculating the ultimate strength of stiffened curved plates under axial compression

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ABSTRACT

Cylindrically curved and stiffened plates are often used in ship and offshore structures. For example, they can be found in the cambered decks, fore and aft side shells and circular bilge parts of ships. A number of studies have investigated curved plates in which the buckling/ultimate strength is increased according to the curvature under various loading scenarios and design formulas. However, information regarding the nonlinear structural behaviour and design formulas for calculating the ultimate strength of the stiffened curved plates is currently limited. In this paper, a series of finite element analyses are performed on stiffened curved plates with varying geometric parameters. The existing curvatures are also analysed to clarify the effects of these parameters on the buckling/post-buckling characteristics and collapse behaviour under axial compression. The results are used to derive closed-form expressions to predict the ultimate compressive strength of curved stiffened plates for marine applications.

1. Introduction

Thin-walled cylindrical shells are widely used as structural elements, such as for oil and gas storage, offshore structures, cooling towers and ship hulls. It is therefore important to clarify the elastic and plastic stability of cylindrical shells under various loading conditions.

In particular, cylindrically curved plates are used extensively in ship structures, such as for cambered deck plating, side shell plating at fore and aft and for circular bilge parts. The structural modelling and investigation of unstiffened and stiffened curved plates can be fundamentally treated as part of a cylinder. To understand the structural behaviour and strength of these curved plates, they should first be subjected to axial compression loading conditions. Then, they can be observed under combined loading conditions (biaxial compression with lateral pressure) specific to certain ships.

Studies on the buckling theory of curved panels are not numerous due to the complexity of the problem and to its late application in marine structures compared with land-based structures [1–5]. A brief review follows of recent research related to buckling and ultimate strength behaviour of cylindrically curved plates and stiffened plates used in design formulae for marine and/or ship structures. Maeno et al. [6] performed a series of large deflection elastoplastic analyses to investigate the buckling and plastic collapse behaviour of ship bilge strakes, which are unstiffened curved plates subjected to axial compression. Based on the results, a simple formula was derived to calculate buckling and ultimate strength and to simulate the average stress-average strain relationship of the bilge structure under axial compression. It was found that a bilge structure of conventional shape and size when reaching ultimate strength will yield before buckling. Therefore, hard corner elements can be used for bilge parts in the ultimate hull girder strength evaluation applying Smith's method, and the effects of buckling of bilge parts should be accounted for in addition to ultimate strength to provide comparative estimates in the post-ultimate strength range.

Yumura et al. [7] investigated the buckling and plastic collapse behaviour of cylindrically curved plates under axial loading. They performed a series of elastic eigenvalue analyses while changing the curvature of the plate to clarify the fundamentals of its elastic buckling behaviour. Park et al. [8] performed non-linear finite element model (FEM) analyses using a commercial program for the actual stiffened curved plates of a container ship while varying curvature and stiffener spacing. In the analysis, initial shape imperfections and residual stresses were considered and combined axial compression and hydrostatic pressure loads were applied. Kwen et al. [9] performed non-linear FEM analyses using a

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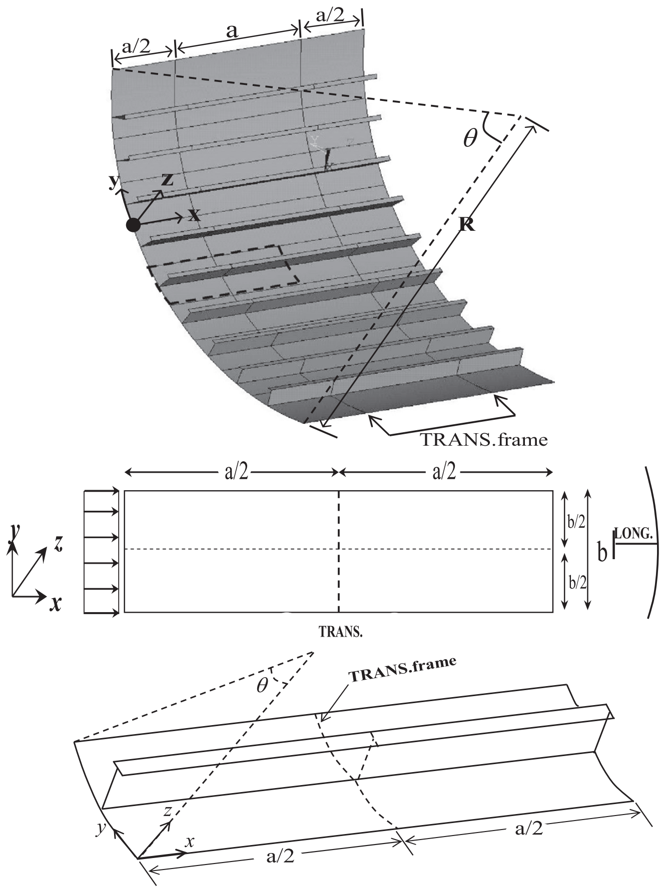

Fig. 1. FEM of a stiffened curved plate (Double-span & double-bay).

Table 1
Finite element analysis meshing and number of elements.

Part	Number of elements
Plate	10
Stiffener Web	6
Stiffener Flange	4

Table 2
Material properties for stiffened curved plate.

Material	High Tensile Steel
Elastic Modulus (E)	205.8 GPa
Poisson' Ratio (v)	0.3
Yield Stress (σ_y)	352.8 MPa

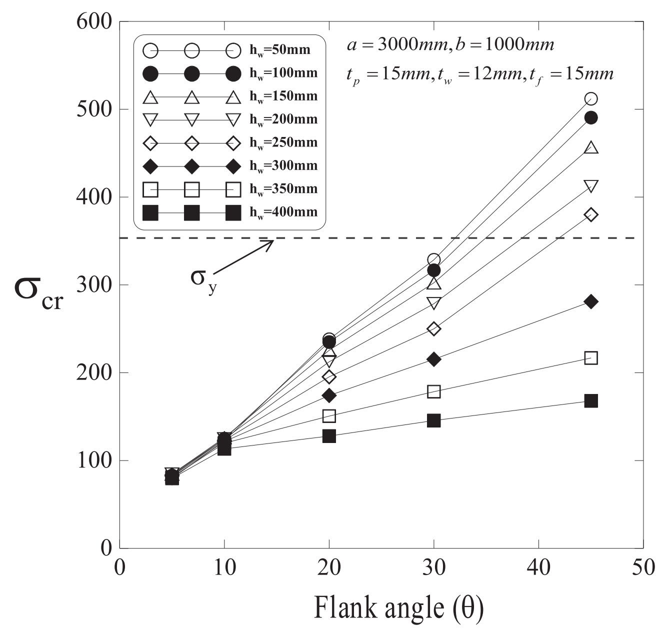

Fig. 3. Elastic buckling strength of stiffened curved plates subjected to axial compression (tee-bar stiffener).

commercial program for unstiffened curved plates, varying the aspect ratio, slenderness ratio and curvature according to load conditions such as longitudinal compression, transverse compression and shear load. Based on the analysis, a simple formula was proposed to predict ultimate strength and then the calculated results were compared with those predicted by the DNV buckling formulae with plasticity correction.

Cho et al. [10] performed both ultimate strength tests and nonlinear finite element analyses on six stiffened curved plates under axial compression. The numerical predictions were compared with the results, and experimental and numerical information regarding curvature effects and collapse patterns under axial compression were given.

Recently, Park et al. [11–13] clarified the buckling, post-buckling and collapse behaviour of unstiffened and stiffened cylindrically curved plates compared with that of a circular cylinder under axial loading. They performed a series of elastic and elasto-plastic large deflection analyses with variations in the curvature, slenderness ratio, aspect ratio, web height, initial imperfection and stiffener type. A simple formula incorporating the effects of several parameters was proposed to predict ultimate strength, which was then compared with the predictions of the classification society buckling formulae [14]. In addition, they investigated secondary buckling behaviour for all cases using the arc-length method.

A large container ship has a greater variety of degrees of curvature in the bottom bilge strake than other ship types, because a sharp hull form is required for higher speeds at sea. Therefore, the curvatures and the slenderness ratio should both be changed with

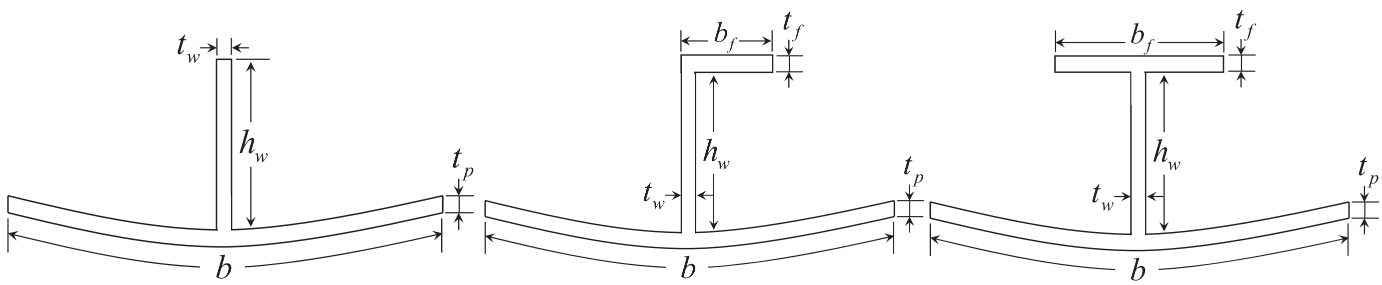

Fig. 2. Typical shapes of curved plate and stiffener combinations.