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Numerical investigation and development of design formula for cylindrically curved plates on ships and offshore structures

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ABSTRACT

Although guidelines exist for evaluation of the buckling strength of curved plates on ships and offshore structures, they do not reflect the effects of curvature or detail their geometric characteristics. From estimations made using cylinder models, it is known that curvature is expected to increase the buckling strength and the ultimate strength of a curved plate. Therefore, it may be designed accordingly. This study aims to clarify and examine the fundamental behaviour of cylindrically curved plates under axial compression and lateral pressure via a series of elasto-plastic large deflection analyses. On the basis of these results, the effects of curvature, initial deflection, slenderness and aspect ratio, boundary conditions and secondary buckling behaviour are discussed and developed with a modified Faulkner's formula to obtain a double beta formula to predict the ultimate strength of the curved plate.

1. Introduction

Cylindrically curved plates are extensively used in ship structures, such as in deck plating, side shell plating, and bilge circle parts of ships, in oil and gas storage, in wind towers, and in the SPAR structures of offshore installations. However, the current guideline that is used to evaluate the buckling strength of a ship's curved plate is insufficient to understand the effect of curvature and geometrical characteristics. From estimations that have been made using cylinder models, it is known that, in general, curvature increases the buckling strength of a curved plate that is subjected to axial compression and curvature is also expected to increase the ultimate strength.

The past several decades have witnessed theoretical and practical research on imperfection sensitivity [1–3], elastic critical moments [4,5] and the ultimate strength of a curved plate or/and panel [6,7]. The focus on curved plate studies has mostly concerned idealised structural models and their application to land based structures. However, there has been less investigation of the curved plates of ships and offshore structures compared with land-based structures, due to the implications of the former. Ships and offshores structures have mostly been considered in the design and analysis at the flat stiffened plate level or the flat bare plate level. Therefore, this paper first aims to understand the characteristics of the curved plates of ships and offshore structures that are subjected to axial compression. Applied axial compression mostly governs load according to ship motion and plate curvature (the bilge as shown in Fig. 1). This study considers the effects of curvature, initial deflection, slenderness ratio and aspect ratio.

Recently, structural behaviour of unstiffened and stiffened curved plates have been numerically investigated subjected to various loading conditions and with several geometrical characteristics for ships and offshore structures. We will next review the latest research related to buckling and the ultimate strength of cylindrically curved plates and stiffened plated ships and offshore structures with design formulae.

A series of FE analyses have investigated the elastic and buckling and plastic collapse behaviour of ship bilge strakes of unstiffened curved plates and, based on the results, a simple formula has been derived to calculate buckling and ultimate strength [8,9]. Park et al. [10] considered the curved stiffened shell of container bilge stake under combined axial compression and hydrostatic pressure loads. Kwen et al. [11] performed FE analyses for curved plates that studied the aspect ratio, slenderness ratio and curvature. They then developed a simple formula to predict ultimate strength with plasticity correction. Cho et al. [12] performed numerical analyses and tests on six types of stiffened curved plates that are used on ship structures.

Some details of buckling and post-buckling collapse behaviour have been presented for unstiffened cylindrically curved plates with variations in the curvature, slenderness ratio, aspect ratio, and initial imperfection [13–15]. In addition, a simple formula incorporating the effects of several parameters was proposed for use in predicting the classification society buckling formulae [16,17]. Kim et al. proposed

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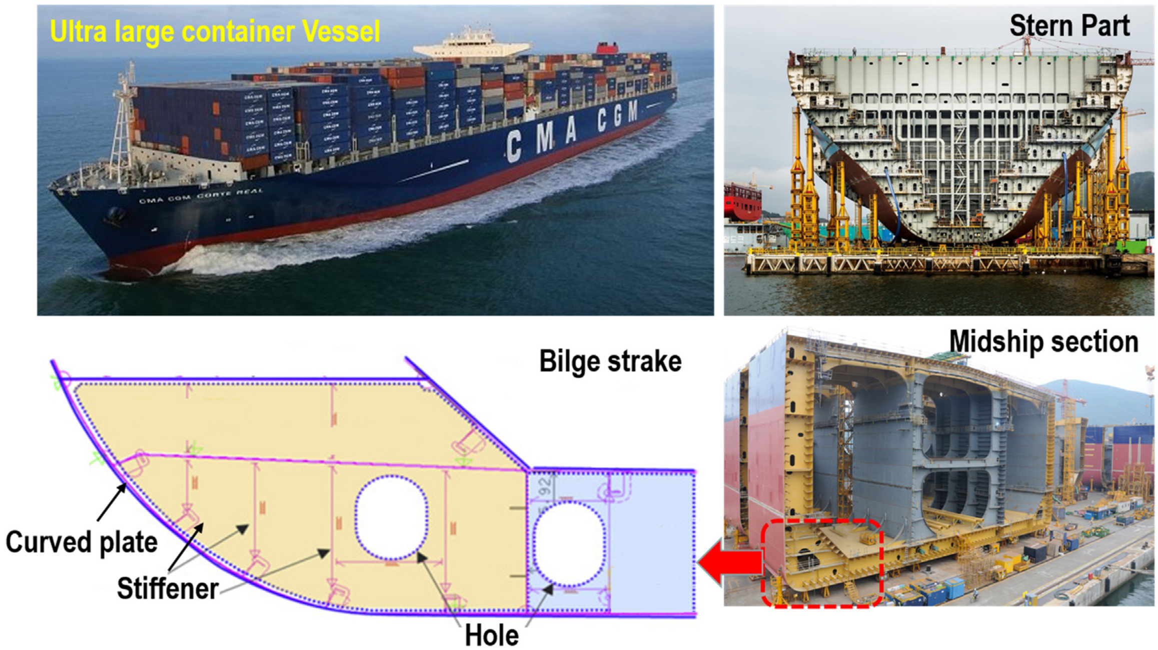

Fig. 1. Cylindrically curved plate panel of ship structures.

design formulae with fundamental elastic buckling and post-buckling behaviour though FE analyses of curved plates. However, the geometric parameters that they considered are limited, such as flank's angles and thickness. It should be noted that a more detailed investigation with varying geometric parameters and development of a design formula is required for applicable marine industrial practices. Stiffened panel level investigation and the development of design formula are also limited. Most of the results of previous research similarly predict and develop the buckling and ultimate strength of unstiffened plates [18–21].

Although there are guidelines for evaluating the buckling strength of curved plate level, they do not reflect the effects of curvature or detail the geometric characteristics of a cylindrically curved plate. Studies that have attempted to develop design formulae for unstiffened cylindrically curved plates are limited. However, unstiffened cylindrically curved plates are required for modern design requirements for larger, lighter and faster ships. This knowledge should be developed, at least for marine loading intensities and geometries, although some useful formulations for the ultimate compressive strength of unstiffened plates can be found in the literature [23–27]. Therefore, unstiffened cylindrically curved plates should be investigated with details of structural behaviour.

In the present paper, we aim to clarify and examine the fundamental behaviour of cylindrically curved plates under axial compression. Therefore, a series of elasto-plastic large deflection analyses are performed. On the basis of the calculated results, the effects of curvature, initial deflection, slenderness ratio and aspect ratio, and secondary buckling on the characteristics of ultimate strength behaviour under axial compression are discussed and we derive a closed-form expression to calculate the ultimate strength though double beta forms. Double beta formulae are widely used to predict the ultimate strength of unstiffened plates under axial compression. The details of development of this formula are found in Section 4.

2. Numerical modelling of the curved plates

2.1. Target curved plate of ship structure

Target curved plated structures form the bottom bilge strakes of a typical container ship's structure. The numerical model considers bilge stiffened plate structures that are surrounded by bottom girders and by a transverse floor, as shown in Fig. 2. The curved plate has dimensions of length (a), breadth (b), plate thickness (t), and flank angle (θ), where

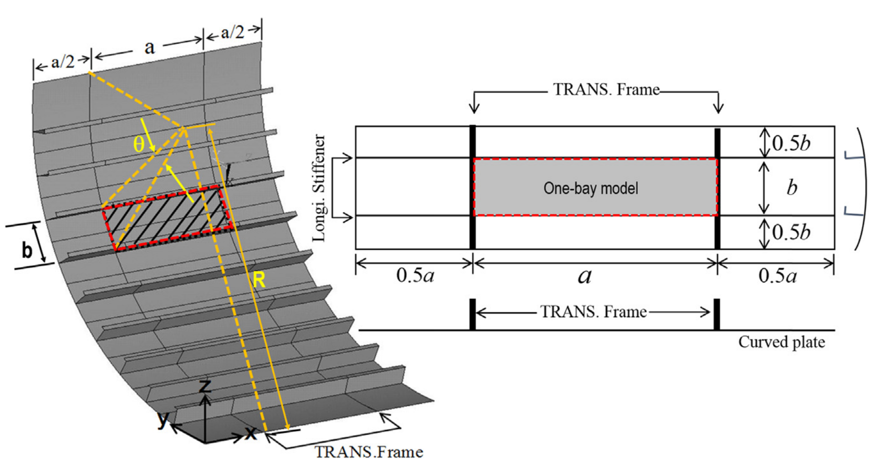

Fig. 2. A cylindrically curved plate subjected to axial loading in ship structures [22].