Ocean Engineering 135 (2017) 52–62

Contents lists available at ScienceDirect

Ocean Engineering

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

Analysis of the influence of stiffness reduction on the load carrying capacity of ring-stiffened cylindrical shell

Xu Bai[a], Weijun Xu[b,*], Huilong Ren[b], Jinhua Li[c]

[a] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China
[b] College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China
[c] Institute of Oceanographic Instrument, Shandong Academy of Sciences, Qingdao 266001, China

ARTICLE INFO

Keywords:
Load carrying capacity
Ring-stiffened cylindrical shell
Buckling load
Reduced stiffness method
Stability

ABSTRACT

Load carrying capacity is of importance in the evaluation of the stability of submarine pressure shell structure. During the buckling process of cylindrical shell under hydrostatic pressure, the total potential energy of ring-stiffened cylindrical shell can be divided into constant component, linear component and square nonlinear component. Based on the derivations of buckling loads of smooth cylindrical shell and ring-stiffened cylindrical shell, the reduced stiffness method (RSM) is applied to assess the role of different stiffness reductions in the evaluation of stable load carrying capacity of cylindrical shell. This study shows: (1) the circumferential membrane stiffness is influence the stability of cylindrical shell largest; (2) the ring ribs have a significant effect on the overall stability of ring-stiffened cylindrical shells under hydrostatic pressure; (3) the circumferential buckling wave number of ring-stiffened cylindrical shell may not depend on the membrane stiffness reduction of shell, but it increases with the bending stiffness reduction of ring ribs.

1. Introduction

Thin-walled ring-stiffened cylindrical shell structure has been widely used in many fields of naval architecture and ocean engineering. Evaluation of bucking load has been attracting the attention of many scientists and researchers. Earlier contributions were dealing the problem in the elastic range, for instance, elastic post-buckling and imperfection sensitivity (Hutchinson and Koiter, 1970; Budiansky and Hutchinson, 1979; Citerley, 1982). Plasticity was taken into account at a later stage, for instance, the work of Bushnell (1982), who examined the buckling problems and analyzed the post-buckling behavior of various shell structures including ring-stiffened cylindrical shells. In the subsequent decades, many analytical and experimental studies have been made to clarify the different buckling load evaluation theories for ring-stiffened cylindrical shell buckling (Teng, 1996).

In addition to the linear and nonlinear analytical theories, numerical methods for studying the buckling problems of cylindrical shells have been discussed so far. Gavrilenko (2003), by applying an analytical and also a numerical method, studied the stability of a cylindrical shell structure with a single dent. Gavrilenko and Krasovskii (2004) carried out a theoretical and experimental study on the smooth and ring stiffened elastic shell structure with local periodic dents. The critical load was obtained by a finite difference method and compared with experimental results. Kougias (2009) applied a finite element method to study the stable load carrying capacity of cylindrical shell with out-of-roundness imperfections under axial load. It was found that local out-of-roundness imperfections due to manufacture have an influence on the buckling load of cylindrical shells. For out-of-roundness of 1%, 10%, 50%, 100%, the buckling load of cylindrical shell reduces by 8.3%, 37.8%, 65.9% and 75% respectively. Fakhim et al. (2009) carried out an experiment to study the influences of the shell thickness and geometric imperfections on the buckling and post-buckling behavior of cylindrical shell structures under hydrostatic pressure. The results showed that the shell thickness variation has an influence on the failure mode, and the failure takes places in the thinnest parts of the shell. By applying a numerical method, Gavrilenko and Matsner (2010) investigated the influence of local imperfections on the critical load of ring stiffened shell structures, accounting for initial imperfections, coupling stress, and pre-buckling non-linearities. Gou and Cui (2010) applied collaborative optimization to the structural system design of underwater vehicles which decomposed into three subspaces: pressure hull, exostructure and performance. The structural behavior constraints of pressure hull include the general instability, the buckling of the shell between stiffeners, local shell instability, shell yield, stiffener yield, local buckling of stiffener and the buckling of the hemispherical head. Gillie (2011) proposed a simple method for

* Corresponding author.
E-mail address: xuweijun@hrbeu.edu.cn (W. Xu).

http://dx.doi.org/10.1016/j.oceaneng.2017.02.034
Received 16 June 2016; Received in revised form 5 December 2016; Accepted 27 February 2017
0029-8018/

measuring the out-of-roundness and capturing its profile. MacKay (2011) performed an experimental study to investigate influence of out-of-roundness imperfections on the strength of pressure cylindrical shells. It was found that out-of-roundness imperfections can significantly reduce the critical load. Edalat et al. (2015) applied an extended Kantorovich-Ritz method to study the free vibration of stiffened open shell with variable radii of curvature. The energy relationship is derived by using the first-order shell theory as well as implementing the assumptions of global vibration mode. Natural frequencies and mode shapes related to the first five vibrational modes are extracted using extended Kantorovich–Ritz method (EKRM). Smith et al. (2015) proposed an advanced, integrated approach to structural modelling, design and analysis of submarine structures, incorporating out-of-circularity imperfections in pressure hull geometry, and representing localized variations in plating thickness using thickness zones.

Numerous studies for strength and stability of shell structures are investigated to find reliable design criteria without carrying out experimental study, which makes the evaluation of shell structure more precise in mechanics performance, reliability and robustness, and enhances the load carrying capacity of shell structures. However, most buckling design methods for cylindrical shell still have many limitations as summarized by the following several aspects: (1) the reduction factors of shell structure in design are more conservative than test results; (2) in practical engineering, the previous experiment data cannot cover the actual observed range; (3) the theoretical method is difficult to be used for the shell structure that are made from modern materials and are manufactured by using advanced technologies, such as composite materials or aluminum alloy shell with applying friction stir welding method; (4) the influence of boundary condition and shell length on the load carrying capacity is neglected; (5) there are not enough design rules and data to quantify the robustness and reliability of shell structure. Thus it is necessary to develop a reliable method for predicting the buckling load of shell structures with initial imperfections, and exploring the influence of initial geometric imperfections on the stability of shell structures.

A reduced stiffness method (RSM) was put forward by Croll (1995, 2006) and by Croll and Gavrilenko (1999, 2000) to evaluate the lower buckling limit of cylindrical shell and the method provides a good agreement between theoretical predictions and experimental observations. Rapid development has been achieved since the RSM method was proposed. Yamada (1997) developed the RSM method to analyze the buckling behavior of pressure cylindrical shell. The elastic-plastic load carrying capacity analysis was performed with initial imperfection taken into account, and further the final load carrying capacity of cylindrical shell based on the reduced stiffness model of amendatory cylindrical shell can be obtained. Sosa et al. (2006) combined the RSM method with the Finite Element Method to calculate the lower bound of elastic buckling load of cylindrical shell. The result showed that the proposed reduced energy model can effectively estimate the lower bound load for cylindrical shells under uniform pressure. Ohga et al. (2006) studied the lower bound of buckling strength of sandwich composite cylindrical shell under lateral pressure using RSM and FEM. They found that the proposed reduced stiffness lower bound buckling strength can provide effective for layers with different shear stiffness and the safety lower bound of buckling strength does not depend on precise geometrical imperfection spectrum and lateral pressure. Wang and Croll (2008) performed optimization study on the lower bound of load carrying capacity of cylindrical shell, to improve the buckling critical load of the structure with material and geometrical parameters. Sosa and Godoy (2010) performed the sensitivity analysis of initial imperfection for a container with cone on the top subjected to wind load by applying RSM. The lower bound of critical buckling load was compared with the results obtained by using nonlinear analysis based on the same model, which provided a new solution for safety design of container under the wind loading.

Generally, the shell stiffness can be decomposed into axial compressive stiffness, circumferential stiffness and shear stiffness, which include both membrane stiffness and bending stiffness. Not only the form of loading resistance of shell structure can be clarified, but also information about which part of shell structure needs to adjust the stiffness can be obtained. For the cylindrical shell structure, its stiffness can be divided as membrane stiffness and bending stiffness, where membrane stiffness is larger by several orders in magnitude than the bending stiffness, therefore the cylindrical shell can absorb much membrane strain energy with small deflection. If most of strain energy in the form of compressive strain energy is stored in the cylindrical shell structures, the strain energy will be converted to bending strain energy once the critical load conditions are satisfied, whose conversion process indicates buckling. The large deflection shall be accompanied with lots of membrane energy converted into bending strain energy, so the shell buckling occurs completely related to the loading form, geometric shape of shell structure and material property.

Nonlinear factors affect structural buckling in two aspects, one is the change of material properties, and the other is the change of geometric shape. Croll (1995) made three assumptions to thin-walled structures: (1) significant geometric nonlinearity is mainly caused by change of membrane stiffness of thin-walled structures. The membrane stiffness of shell structure is related to the buckling evolution, which causes the shell structure still has a certain load carrying capacity after buckling. For a long cylindrical shell structure, once the axial compressive pressure acting on the structure exceeds the ultimate strength, the load carrying capacity commences to decrease rapidly with the local or total buckling deformation. The collapse behavior is related to the drop of membrane stiffness of shell structure along the initial compressive direction. (2) Only if the initial buckling contains a contribution of membrane energy, will the stiffness of post-buckling decrease. That is, the phenomena of decreasing nonlinear membrane stiffness for any thin-walled structure will occur when the membrane strain energy appears in the initial buckling. (3) For each buckling mode, the lower bound can be determined by the dissipated part of membrane energy.

This paper focuses on the investigation of the effects of different stiffness on the stability of cylindrical shell. The total potential energy of ring-stiffened cylindrical shell that affects the stability will be clarified, which includes constant component, linear and high order nonlinear component. Based on the derivation of cylindrical shell buckling load, the stiffness of cylindrical shell is divided into membrane stiffness, bending stiffness and geometric stiffness influenced by external force. The stiffness reduction factor method is then applied to estimate the each stiffness in the evaluation of stable load carrying capacity of cylindrical shell.

2. Buckling load of cylindrical shell with complete stiffness

2.1. Derivation of buckling load of shell between ring ribs

Consider an intact thin-walled cylindrical shell of length l, thickness t and radius r with a hydrostatic pressure P acting on it. A cylindrical coordinate system with its origin placed on the axis line of the cylinder is defined as in Fig. 1. U, V and W are the displacements in the radial, circumferential and axial direction respectively. Based on the theory of thin shell, the membrane solutions of cylindrical shell under the pre-buckling stress state can be expressed as

$$(\sigma_x^F, \sigma_\theta^F) = \left(-\frac{pr}{2t}, -\frac{pr}{t}\right) \tag{1}$$

$$(E_x^F, E_\theta^F) = \left(\frac{pr}{Et}(\mu - \frac{1}{2}), \frac{pr}{Et}(\frac{\mu}{2} - 1)\right) \tag{2}$$

where E is the elastic modulus of material; σ_x^F, σ_θ^F are the axial and circumferential stress of cylindrical shell in post-buckling state; E_x^F, E_θ^F are the axial and circumferential strain of cylindrical shell in pre-buckling state.