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Nonlinear buckling strength of out-of-roundness pressure hull

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ABSTRACT

This study employed experiments and numerical simulations to investigate the impact of pressure hulls' degree of out-of-roundness on their buckling strength and buckling modes. In addition, post-buckling simulations were conducted to analyze the post-buckling behavior of the said pressure hull. Regarding numerical simulations for analyzing pressure hull buckling, the common analysis method is to first calculate the eigenvalue and the eigenmodes of buckling and then introduce an appropriate number of eigenmodes based on the initial defect of the structure before conducting a nonlinear buckling simulation. In addition to employing this common nonlinear analysis method (in which ABAQUS was used), this study adopted the PD-5500/33 specification to measure the circularity of the pressure hull for experimentation to confirm that the circularity satisfied the PD-5500/33 specification. Finally, this study compared the differences in nonlinear buckling strength between two numerical models and compared the numerical simulation results with the experimental results. This study verified that by employing the analysis method of eigenmode superpositioning, the buckling and post-buckling behavior of an out-of-roundness pressure hull could be more accurately simulated.

1. Introduction

Pressure hulls of underwater vehicles are equipped with ring stiffeners to increase the structural buckling strength of the vehicles. However, the buckling strength of pressure hulls is affected by more than just ring stiffeners; it is also affected by the circularity of the pressure hulls, which has a great impact on compressive strength and structural stability. Therefore, when manufacturing pressure hulls, attention must be paid to plate-bending and welding of the structure to ensure that the circularity of the pressure hulls satisfies the given specifications.

This study primarily focused on investigating the impact of circularity on the buckling strength of pressure hulls and conducted experiments to verify the accuracy of numerical simulation data. The circularity of the pressure hull model for the experiment in this study needed to satisfy PD-5500/33 requirements [1]. The Riks method in Abaqus (referred to as "Abaqus/Riks" hereafter) was utilized in numerical simulations for nonlinear buckling analysis to calculate the post-buckling strength and post-buckling mode of an out-of-roundness pressure hull with a view to understanding the impact of out-of-roundness on the stability of the pressure hull structure.

The buckling behavior of cylindrical shells was first studied by Tokugawa [2] and is commonly considered in structural designs for underwater vehicles. Initially, to ensure that underwater vehicles had sufficient structural stability to prevent pressure hull buckling, strict safety factors were often adopted into designs; the United States Armed Forces often set the buckling threshold between 1.5 and 2.0, and Germany set it between 2.0 and 2.5 [3]. Because of considerable improvements in the function and accuracy of numerical simulation software in recent years, nonlinear structural problems can now be analyzed. This section reviews studies on pressure hull buckling conducted in recent years.

Pressure hull buckling is a structural stability problem. In recent years, several studies have investigated the structural stability of ring-stiffened cylindrical shells. Haixu [4] established equilibrium equations for a double cylindrical shell stiffened longitudinally and transversely. In addition, an adjacent equilibrium method and implementing theories were used to calculate the critical external pressure that induces panel buckling and interframe shell buckling. Radha and Rajagopalan [5] employed Johnson–Ostenfeld inelastic correction, an imperfection method, and the finite element approach to investigate the ultimate strength of pressure hulls and its failure under inelastic buckling. Bai et al. [6] utilized the reduced stiffness method to study the impact of reducing stiffness on the stability and carrying capacity of a cylindrical shell and discovered that the stiffness of the ring stiffener affected the buckling strength and buckling mode of the shell. Based on the thin shell theories of Donnell and Sander and von Karman's nonlinear assumptions, Salahshour and Fallah [7] discussed the local elastic buckling of a long thin cylindrical shell under pressure and derived the potential energy of pressure hulls. Subsequently, the Rayleigh–Ritz

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method was employed to determine the buckling load.

As analysis software improves, engineering analyses are increasingly employed to tackle nonlinear scenarios. Nonlinear behavior commonly observed in structural analyses include geometric nonlinearity and material nonlinearity. Regarding pressure hull-based nonlinear buckling simulations, Liang et al. [8] considered large geometric deformations and material nonlinearity in investigating the structural dynamic responses of pressure hulls under water pressure and impact loading. Lee et al. [9] utilized Ansys to study the nonlinear buckling behavior of pressure hulls with initial defects and observed that the nonlinear buckling strength was approximately 0.7 times the eigenvalue buckling. Sreelatha [10] analyzed the linear and nonlinear buckling of stiffened cylindrical submarine hulls. MacKay and Keulen [11] conducted experiments and utilized finite element analysis (FEA) to nonlinearly evaluate the geometry of pressure hulls; the researcher employed probabilistic analyses to examine experimental-numerical comparisons, and the partial safety factor was consequently designed. The results proved that under the premise of following the prescribed finite element methodology, over 95% of the simulation results contained less than 10% errors. Iwicki et al. [12] conducted linear buckling sensitivity analyses on the structural stability of cylindrical steel silos and subsequently employed Abaqus for nonlinear buckling analyses; suggestions regarding optimal design for cylindrical steel silos were also proposed. Chen et al. [13] studied the buckling of cylindrical shells with measured settlement under axial compression. The researcher primarily adopted the Fourier series expansion method to transform measured settlement data into differential settlement data. Subsequently, the researcher considered geometrically nonlinear large deformations and employed the finite element method to simulate the buckling behavior of cylindrical shells under axial pressure loading.

The present study primarily employed Abaqus to simulate the nonlinear buckling strength of out-of-roundness pressure hulls and compared the results with the experimental results. In recent years, many research results on the buckling strength of pressure hulls with initial defects have been released. Combescurea and Gusicb [14] used a cylindrical structure with defects in thickness to investigate the impact of the said defects on nonlinear buckling. The results revealed that defects in geometric shapes intensified defects in thickness, and vice versa; thus, to effectively enhance the critical buckling strength of a structure, geometric defects must be reduced. Prabu et al. [15] employed cylindrical shells with defects to discuss the impact of geometric defects on critical buckling pressure; the results revealed that critical buckling pressure decreased as defective factors increased in number. Shahandeh and Showkati [16] studied the impact of the out-of-roundness of ring stiffeners on the buckling strength of pressure hulls. Ismail et al. [17] utilized the eigenmode-affine method and single perturbation method to investigate buckling problems in aluminum piles with initial defects and fiber-reinforced polymer cylindrical pipes under axial pressure.

Damage and cracking in materials affect their buckling strength. Akrami and Erfani [18] employed analytical and numerical methods to investigate the relationship between crack length in cracked cylindrical shells and the buckling strength of the said shells; based on numerical simulation results, the researcher proposed empirical equations for estimating the buckling strength of cracked cylindrical shells. MacKay et al. [19] conducted experiments to evaluate the strength and stability of pressure hulls with defects from corrosion and discovered that when a structure was affected by force, local corrosion led to heightened structural eccentricity and local stress concentration, resulting in the early onset of yielding and inelastic buckling and further reducing the collapse strength of the structure. Considering material and geometric nonlinearities, Iwicki et al. [20] adopted Abaqus to conduct static and dynamic stability analyses on cylindrical steel silos. Actual geometrical defects were measured for nonlinear analyses and the researcher provided suggestions for silo designs.

Although many methods can be employed to analyze nonlinear buckling, to predict structural instability, further verifications from theories and experimental data are required. MacKay et al. [21] conducted a literature review by comparing previous experimental collapse results with conventional submarine design formulas and nonlinear numerical simulations to verify the accuracy of said formulas and simulations. Ross et al. [22] designed three types of ring-stiffened conical shells and conducted experiments to investigate the elastic buckling of these shells. The researcher established design charts and defined plastic knockdown factors. Based on elastic theory, plastic knockdown factors could be employed to predict actual buckling stress. Pan and Cui [23] reviewed studies on the buckling and ultimate strength of spherical pressure hulls and observed considerable differences between the methods used for predicting ultimate strength and those used for predicting buckling strength. Based on this observation, Pan conducted systematic studies and proposed a consistent method for predicting both types of strength.

In the final stage of the present study, Abaqus/Riks was adopted to conduct postbuckling analysis on pressure hulls. Several studies have investigated postbuckling. Under the assumption of boundary layer theories, Shen et al. [24] proposed a method for analyzing the buckling and postbuckling behavior of perfect and imperfect longitudinal beams and stiffened cylindrical shells. The singular perturbation technique was utilized to identify the path of postbuckling, and the results were compared with experimental data. Dung and Hoa [25] analyzed the nonlinear buckling and postbuckling behavior of eccentrically stiffened and functionally graded circular cylindrical shells and obtained a stress–deflection curve, thereby verifying that stiffeners can increase the structural stability of shells. Ge et al. [26] conducted experiments and employed Ansys to investigate the postbuckling strength and modes of subsea separators. In the simulation, material nonlinearity was considered and initial structural defects were provided. The influences of the length to diameter ratio, ovality, and support on global buckling were ultimately determined. By applying Abaqus for postbuckling analysis, a certain degree of accuracy can be achieved; for example, Arjomandi and Taheri [27] employed Abaqus to conduct several postbuckling simulations on sandwich pipes; adhesion among the interfaces of said pipes was considered by the researcher to investigate the impact of design configurations on postbuckling.

The buckling strength of a pressure hull is closely related to its circularity. When circularity decreases, buckling strength undergoes a substantial change. Therefore, several pressure hull design specifications can be applied to define the circularity and defects of pressure hulls to precisely determine actual buckling strength. Pranesh et al. [28] applied DNV and other related specifications to determine the extent of defectiveness in pressure hulls, and conducted numerical simulations. The buckling pressures of perfect and imperfect thin spherical pressure hulls were compared and the results verified that imperfection in pressure hulls must be considered. In this study, the roundness of the pressure hull used in the experiments had to satisfy the PD-5500/33 specification. Regarding the applicability of PD-5500, Ross [29] conducted experiments and numerical simulations to verify that pressure hulls designed under the PD-5500 specification attain relatively conservative stability; thus, the researcher employed the PD-5500 specification to examine the circularity of pressure hulls used in the experiments and ensure that the experimental results would represent the actual critical buckling strength of pressure hulls.

Although many pressure hull designs have been developed and many nonlinear buckling studies have been conducted over the years, related research will continue because the function of numerical simulation software continues to improve and the function of underwater vehicles and features of marine engineering structures continue to evolve. For example, Byun et al. [30] considered that supercavitation vehicles capable of high cruising speeds yield extra buckling load that affects the nonlinear buckling strength and mode when operated underwater at high speeds; the researcher conducted a study on nonlinear buckling for supercavitation vehicles to develop an optimal structural