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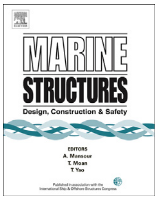

Elastic-plastic buckling of deep sea spherical pressure hulls

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ABSTRACT

This paper focuses on the buckling of titanium alloy spherical pressure hulls subjected to uniform external pressure. Hulls were spherical shells with 1000 mm median radius and had uniform wall thickness of 25–80 mm. The linear and nonlinear buckling of geometrically perfect hulls were examined numerically and verified analytically in linear range. The nonlinear buckling of hulls with eigenmode geometrical imperfections were evaluated numerically using the modified Riks method, in which imperfection size ranged from 2 to 10 mm. The critical buckling load of geometrically perfect and imperfect hulls was obtained based on elastic-perfectly plastic material modelling, in which the yield strength varied from 800 to 1300 MPa. A semi-analytical formula to predict the load carrying capacity of hulls was derived based on the numerical computations, which was verified against previous laboratory experiments conducted years ago and numerical benchmark study. Results of analytical, numerical, and experimental investigations were given in tables and figures.

1. Introduction

Deep manned submersibles have generated considerable recent research interest, by which marine scientists could reach deep sea to conduct various underwater studies, viewing and sampling organisms in their natural environment [1]. The manned pressure hull is the most important component of deep manned submersibles, which could not only provide a living space for the carried persons but also act as an important buoyancy unit. The deep manned pressure hull often takes the form of medium-thick spherical shell particularly in the hadal zone [2,3]. However, working in deep sea environment up to full ocean depth, such shells tend to buckle in elastic-plastic range due to the subjected extremely high external pressure [4,5].

Buckling of spherical shells under uniform external pressure has been an interesting problem in structural mechanics. Early in 1915, Zoelly first proposed a formula to evaluate the critical buckling load of a thin-walled spherical shell subjected to uniform external pressure [6], which will be detailed in the following section (Section 2.2). For decades, this evaluation was found to be much higher than the experimental results due to geometrical imperfections and material properties. Later, in 1945, Koiter made a breakthrough to the buckling of spherical shells by putting forward the initial post-buckling theory for elastic systems subjected to conservative loading, and investigating the imperfection sensitivity of the buckling of shells [7].

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Furthermore, Pan et al. experimentally and numerically explored the critical buckling load of spherical pressure hulls used in deep manned submersibles. According to the results obtained from nonlinear finite element analysis with equivalent geometrical imperfection included, they proposed a phenomenological model to predict the ultimate strength of spherical pressure hulls [8,9]. In addition, Blachut et al. performed a series of experimental and numerical studies regarding elastic-plastic buckling of medium-thick shells of revolution with positive Gaussian curvature, including spherical shells considered as a special case, under external pressure. They found that both geometrical imperfections and material plasticity could lead to a severe decrease in the load carrying capacity of shells [10–15]. However, although the effect of geometrical imperfections and material properties on the buckling of spherical shells was demonstrated in previous studies, little attention has been paid on the establishment of a mechanism model to predict the critical buckling load of deep sea spherical pressure hulls at the preliminary design stage or being used in the classification society rules [e.g 16], considering the sensitivities of shape deviations and material plasticity simultaneously to the buckling.

This work was devoted to elastic-plastic buckling of deep sea spherical pressure hulls. Firstly, the buckling of geometrically perfect and imperfect spherical pressure hulls was analyzed numerically in the case of various wall thicknesses. Some of the numerical results were verified analytically. Secondly, the effect of yield strength on the buckling of spherical pressure hulls was investigated at various wall thicknesses and imperfection sizes. According to these findings, a semi-analytical mechanism formula, including the plasticity reduction factors and geometrical imperfection reduction factors, was put forward. Finally, the formula was verified by collapsing four laboratory scale models and benchmarked by the numerical results. The proposed formula extended our previous achievements, which could be used to evaluate the load carrying capacity of deep sea spherical pressure hulls at the preliminary design stage.

2. Buckling analysis of geometrically perfect and imperfect spherical pressure hulls

This section examines the buckling of geometrically perfect and imperfect spherical pressure hulls in line with ENV 1993-1-6 (2007) [17]. For the geometrically perfect hulls, linear elastic buckling analysis was carried out, along with geometrically and materially nonlinear analysis. For the geometrically imperfect hulls, geometrically and materially nonlinear analysis with eigenmode imperfections included was conducted. The study is entirely numerical and partially theoretical.

2.1. Geometry and material

Consider a spherical pressure hull with its geometry given by the median radius, $r = 1000$ mm, uniform wall thickness t ranging from 25 mm to 80 mm, and subjected to uniform external pressure, p_0, see Fig. 1. Let the pressure hull be made from Ti-6Al-4V(TC4), the material properties were as follows: Young modulus $E = 110$ GPa, yield strength $\sigma_y = 830$MPa, tensile strength $\sigma_t = 869.7$MPa, Poisson ratio $\nu = 0.3$.

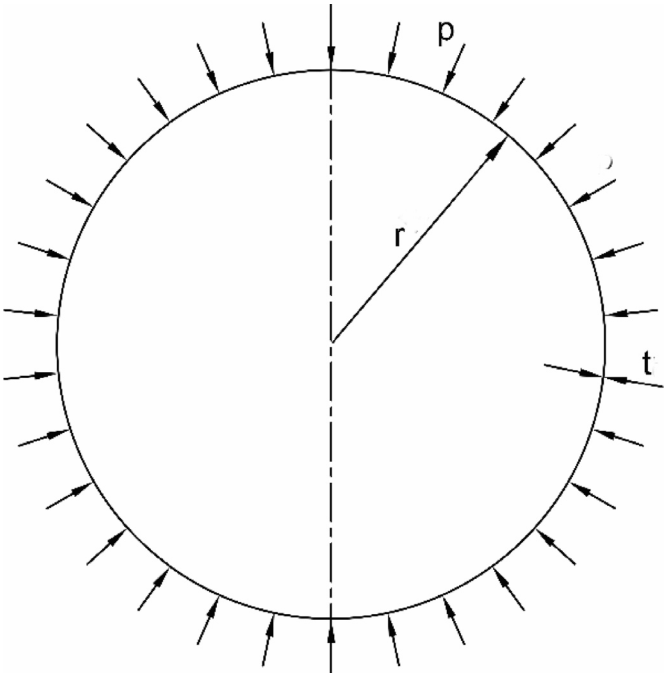

Fig. 1. Geometry of a spherical pressure hull.