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Publishing Services by Elsevier
International Journal of Naval Architecture and Ocean Engineering xx (2017) 1–11
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Influence of initial imperfections on ultimate strength of spherical shells

Chang-Li Yu [a,b,*], Zhan-Tao Chen [a], Chao Chen [a], Yan-ting Chen [a]

[a] *School of Naval Architecture and Ocean Engineering, Harbin Institute of Technology, Weihai, China*
[b] *Post-Doctoral Station of Materials Science and Engineering, Harbin Institute of Technology, Harbin, China*

Received 12 April 2016; revised 26 July 2016; accepted 8 February 2017
Available online ■ ■ ■

Abstract

Comprehensive consideration regarding influence mechanisms of initial imperfections on ultimate strength of spherical shells is taken to satisfy requirement of deep-sea structural design. The feasibility of innovative numerical procedure that combines welding simulation and non-linear buckling analysis is verified by a good agreement to experimental and theoretical results. Spherical shells with a series of wall thicknesses to radius ratios are studied. Residual stress and deformations from welding process are investigated separately. Variant influence mechanisms are discovered. Residual stress is demonstrated to be influential to stress field and buckling behavior but not to the ultimate strength. Deformations are proved to have a significant impact on ultimate strength. When central angles are less than critical value, concave magnitudes reduce ultimate strengths linearly. However, deformations with central angles above critical value are of much greater harm. Less imperfection susceptibility is found in spherical shells with larger wall thicknesses to radius ratios.

Keywords: Ultimate strength; Spherical shells; Residual stress; Initial imperfections; Submersibles

1. Introduction

Deep-sea submersibles are essential to ocean resource development, where spherical shells have been widely utilized because they are able to bear less stress than other structures under the same external pressure (Yu et al., 2004). Various imperfections are generated when manufacturing spherical shells, which can have great impact on spherical shells' ultimate strength. Specifically, residual stress and deformations can be introduced during welding process because of incomplete expansion caused by large temperature gradient. The residual stress is significantly concentrated in the girth welding zone and circumferentially concave deformation is generated (Tian et al., 1996; Lee and Chang, 2013), but research on their influence on ultimate strength is still incomprehensive.

Theories estimating ultimate strength of spherical shells have been widely established. On the one hand, elastic buckling theory has been studied by Zoelly (1915) for spherical shells under external pressure. It is considered as the limitation of structural stability and can be expressed by Eq. (1),

$$P_e = \frac{2E}{\sqrt{3(1-\nu^2)}} \cdot \left(\frac{t}{R}\right)^2 \tag{1}$$

where E is Young's Modulus, ν is Poisson Ratio, t is wall-thickness, R is radius of shell middle plane. On the other hand, the ultimate strength of spherical shells is regarded as the largest external pressure that leads to material yielding, which can be expressed by Eq. (2),

$$P_y = 2\sigma_s \frac{t}{R} \tag{2}$$

where σ_s is yield stress of material. Spherical shells must not bear external pressure greater than either P_e or P_y to avoid collapse. The P_e disregards material yielding and presents load

* Corresponding author. School of Naval Architecture and Ocean Engineering, Harbin Institute of Technology, Weihai, China.
E-mail address: yuchangli@hitwh.edu.cn (C.-L. Yu).
Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2017.02.003

Please cite this article in press as: Yu, C.-L., et al., Influence of initial imperfections on ultimate strength of spherical shells, International Journal of Naval Architecture and Ocean Engineering (2017), http://dx.doi.org/10.1016/j.ijnaoe.2017.02.003

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Nomenclature

P_e	Ultimate strength of spherical shells based on structure stability
P_y	Ultimate strength of spherical shells based on material yielding
P_c	Ultimate strength of spherical shells without welding imperfections
P_{cr}	Ultimate strength of spherical shells with welding imperfections
B	Ratio boundary of two collapse modes (P_e or P_y)
t	Wall-thickness of spherical shells
ω	Initial deflection factor
ω_i	Initial deflection factor for elastic buckling mode i
α	Central angle of welding deformation
δ	Concave magnitude of welding deformation
E	Young's modulus
ν	Poisson's ratio
σ_s	Yield stress
T_s	Solidus temperature
T_l	Liquidus temperatures
l	Latent heat
ε	Emissivity
R	Radius of middle planes
R_i	Radius of inside planes
R_o	Radius of outside planes

carrying capacity of perfect spherical shells, which is a structure stability problem. On the contrary, P_y considers it as the max load carrying capacity that its material reaches yielding stress. These two theories are helpful to predict which kind of collapse patterns will happen given *t/R* ratios. For P_e, the *t/R* ratio is squared in the equation, so its output is lower and dominant when the ratio is less than certain boundary (Pan and Cui, 2010). The boundary can be easily obtained by equaling Eqs. (1) and (2), which is $B = 9.48 \times 10^{-3}$ according to the material properties in this paper. In the range above B, also the range of most deep-sea submersibles, spherical shells collapse primarily because material yields and the collapse pattern is usually local concave, which has been verified by experiments conducted by Zheng et al. (1986) and Pan et al. (2012). Both theories are returning higher results because of missing consideration of various imperfections in reality. In order to obtain applicable solutions, imperfections of spherical shells should be sufficiently considered.

Equations adopted by most submersible design rules are generally based on experimental results. One of the most famous experiments was conducted by Krenzke and Kiernan (1963) in David Taylor Model Basin, where a profound empirical formula was established following theory of Gerard (1957) with a coefficient taking all manufacturing errors into account. Theories and experiments of Zheng et al. (1986) have also demonstrated that axially symmetrical imperfection can influence collapse patterns. Wunderlich and Albertin (2002) collected available experimental results and noted that less deformations and residual stresses are generated after production process when aluminum rather than steel is chosen to be material of spherical shells. Pan et al. (2012), who have tested four spherical shells made of titanium alloy, provided further evidences showing that material mechanical properties have significant effects on collapse form. Influence from initial imperfections are considered in the form of safety factors and coefficients by most design rules and equations. According to Pan and Cui (2011), designed wall-thicknesses that are required by various design rules are much larger than actually needed based on external pressure exerted. Unnecessary redundancy of wall thickness can sometimes be adverse, such as reducing working space and increasing submersible weight. The safety factors or coefficients can only offer an overall estimation for all kinds of imperfections instead of specific welding deformations. Particular reduction from each kind of imperfections remains unknown.

Except for experimental tools, the Finite Element Method (FEM) has been applied to predict ultimate strength of spherical shells. Lu et al. (2004) have worked out ultimate strength of spherical shells with and without initial deflections in satisfactory accuracy. Calculations of Wang et al. (2005) demonstrated that ultimate strength is at the lowest stage when imperfection range equals to the critical arc-length, coinciding with the theory of Zheng et al. (1986). Wang et al. (2007) researched the influence of imperfections on spherical shells of different target depths and Pan and Cui (2010) have calculated ultimate strength of perfect spherical shells as a comparison to the theory. The results of finite element methods have been proved accurate and eligible to analyze related issues. However, researches above did not focus on particular deformations from welding process. Most initial deformations are introduced from elastic buckling modes multiplied by factors, which is appropriate but lack of exactness. Specific deformation from welding process is not fully examined and influence from welding residual stress is absent in most former research. It is still hard to understand the influence mechanism of welding imperfections.

In this context, a comprehensive consideration regarding particular imperfections caused by welding process should be taken to veritably evaluate its damage, which requires study on both residual stress and deformations. This paper is to obtain clearer and deeper understandings of influence mechanisms of initial imperfection and provide estimation on reduction in ultimate strength with two kinds of imperfections being studied separately. On the one hand, welding process is simulated by a moving heat source to obtain fields of temperature and residual stress by direct thermal-mechanical coupling. Then elastic buckling and non-linear buckling are combined together to compute ultimate strength of spherical shells with and without residual stress. Remarkable changes in stress conditions and collapse patterns of spherical shells are discovered. On the other hand, circumferentially concave deformations along the welding path is modeled and two independent parameters, central angle of concave zone α and the concave magnitude δ, determining the deformation are

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