Ocean Engineering 161 (2018) 242–256

Contents lists available at ScienceDirect

Ocean Engineering

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

Ultimate strength formulation considering failure mode interactions of ring-stiffened cylinders subjected to hydrostatic pressure

Sang-Rai Cho[a,*], Teguh Muttaqie[b], Quang Thang Do[a], Ha Young So[c], Jung-Min Sohn[d]

[a] School of Naval Architecture and Ocean Engineering, University of Ulsan, Ulsan, Republic of Korea
[b] Agency for the Assessment and Application of Technology, Center of Technology for Defense and Security Industries BPPT, Indonesia
[c] Hyundai Mipo Dockyard, Ulsan, Republic of Korea
[d] Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, Republic of Korea

ARTICLE INFO

Keywords:
Ring-stiffened cylinder
Ultimate strength formulation
Collapse pressure
Failure mode

ABSTRACT

This paper outlines empirical formulas to provide adequate predictions of the ultimate strength of ring-stiffened cylinders under hydrostatic pressure. The ultimate strength formulation was derived from published test data found in the open literature. The formulas consider the failure mode interactions, which include the parameter of shell yielding, inter-frame buckling, overall buckling, and stiffener tripping. The failure modes were inserted in the quadratic Merchant-Rankine formula. Afterward, the knockdown factors were empirically derived to best fit the actual collapse pressure. It is found that the proposed formulation can predict the ultimate strengths of ring-stiffened cylinders more accurately and consistently than other codified rules (PD5500, GL, ABS, API). The simple criterion for the assessment of failure modes was also provided. Furthermore, parametric studies were conducted to observe the effect of the design parameter on sizing the ring-stiffened cylinder when the failure modes can be predicted.

1. Introduction

Submarines are designed to operate in deep water. In its basic form, the submarine structure has to provide optimum structural efficiency to withstand the hydrostatic pressure. One method to improve the structural capacity is by using ring-stiffened cylinders for the submarine pressure hull; some approaches regarding the use of the ring-stiffened cylinder as the primary structural member for large underwater structures were also conducted by Ross and Waterman (2000) and Ross (2006). Similarly, the study of the strengthened cylindrical shell under the external pressure were performed by Ghanbari Ghazijahani et al. (2014, 2015a, 2015b) and Ghanbari Ghazijahani and Showkati (2013). They have performed numerous number of ultimate strength investigation of the corrugated and longitudinal stiffened cylindrical shells which carried out by internal vacuum. Their extensive test works contribute to an improved design in enhancing structural capacity of shell structure by the minimum weight. These structural units are mainly designed based on the concept of ultimate strength as stated by Ellinas et al. (1983). This fundamental form also has some similarities with those used in the offshore oil and gas industry (Das et al., 2003).

In reality, under the loading conditions, the ring-stiffened cylinders can fail in one or coupling with more failure modes: shell yielding, local and overall buckling, and instability of the ring stiffener (Faulkner, 1991; Cho et al., 2018). Buckling phenomena occur when most of the stored strain membrane energy is converted to bending energy, which can cause catastrophic failure (Kendrick, 1955). In light of these complicated buckling phenomena, accurately assessing their behaviour is great importance in the structural engineering field. Recently, many theoretical and experimental types of research have been conducted with various high-pressure model tests by many researchers: Slankard and Nash (1953), Kirstein and Slankard (1956), Lunchick (1959), Kendrick (1955, 1964, 1965, 1970), Reynolds (1960), Miller and Kinra (1981), Yokota et al. (1985), Yamamoto et al. (1989), Frieze (1994), Cerik and Cho (2013), Cho et al. (2017, 2018). These comprehensive works have led to a general understanding of the failure mechanism for this cylinder and recommendations of some adequate formulas that can be the guidance for failure prevention.

Furthermore, it is essential to precisely predict the ultimate strength of ring-stiffened cylinders subjected to hydrostatic pressure. The early concept for ultimate strength of a cylindrical shell was expressed by von

* Corresponding author.
E-mail addresses: srcho@ulsan.ac.kr (S.-R. Cho), teguh.muttaqie@bppt.go.id (T. Muttaqie), thangdq@ntu.edu.vn (Q.T. Do), hyso@hmd.co.kr (H.Y. So), jminz@pknu.ac.kr (J.-M. Sohn).

https://doi.org/10.1016/j.oceaneng.2018.04.083
Received 8 December 2017; Received in revised form 18 March 2018; Accepted 23 April 2018

Nomenclature

A	modified ring-frame area
COV	Coefficient of variation
D	Mean diameter (See Fig. 1)
E	Young's modulus
$h_w,\ t_w$	Stiffener height and thickness (See Fig. 1)
I_c	Second moment area of the combined cross-section of the ring-frame and the shell
I_z	Second moment of area of stiffener alone about radial axis
I_o	Stiffener section polar second moment inertia
L_c	Overall length of the cylinder (See Fig. 1)
L_{eff}	Effective length of a combined cross-section of the ring-frame and the shell (Eq. (7))
L_s	Stiffener spacing (Fig. 1)
n	Circumferential wave number
P_c	Hydrostatic collapse pressure
$P_{c.act}$	Hydrostatic collapse pressure provide from the test
$P_{c.pred}$	Hydrostatic collapse pressure obtained from the prediction
	Stiffener parameter
G'	Shear modulus, $E/2(1+)\upsilon$
J	St.Venant torsion, $(w_f t_f^3 + h_w t_w^3)/3$
k_{0n}	Rotational spring restraint, $\frac{Et^3}{3(1-\nu^2)L}\left[1+\left(\frac{nL}{\pi R}\right)^2\right]^2$
P_{yf}	Yield pressure of the stiffener, $\frac{\sigma_y\ t\ R_f}{R^2(1-\nu/2)}\left[1+\frac{A}{t_w t+\frac{2Nt}{\alpha}}\right]$
T_p	Torsional parameter, $I_z z^2+\Gamma$
Γ	Torsional warping constant, $I_z\left(h_w+\frac{t_w}{2}\right)^2$
ξ	Stress and pressure ratio, $\frac{\sigma_{yf}R_f}{P_{yf}R_s}$
P_m	Local buckling pressure (Eq. (5))
P_y	Yield pressure (Eq. (4))
P_n	Overall buckling pressure (Eq. (6))
P_t	Tripping pressure (Eq. (9))
R	Mean radius (See Fig. 1)
R_f	Measured radius from the standing flange (See Fig. 1)
R_s	Measured radius from the centroid of ring stiffener cross-section (See Fig. 1)
t	Shell thickness (See Fig. 1)
$t_f,\ w_f$	Flange thickness and width (See Fig. 1)
z	Stiffener centroid
ρ_T	Tripping knockdown factor (Eq. (10))
ρ_{OA}	Overall buckling knockdown factor (Eq. (11))
ρ_L	Local buckling knockdown factor (Eq. (12))
σ_Y	Yield strength
σ_{yf}	Yield strength of the stiffener
σ_t	Tripping strength, (Eq. (8))
ν	Poisson ratio
α	$\frac{1.285}{\sqrt{\mathrm{Rt}}}$
γ	$\frac{A\left(1-\frac{\nu}{2}\right)}{(A+t_w t)(1+B)}$
B	$\frac{2.t.N}{\alpha(A+t_w t)}$
G	$\frac{2\left(\sinh\frac{\alpha L}{2}\cos\frac{\alpha L}{2}+\cosh\frac{\alpha L}{2}\sin\frac{\alpha L}{2}\right)}{\sinh\ \alpha L+\sin\ \alpha L}$
N	$\frac{\cosh\ \alpha L_s-\cos\alpha L_s}{\sinh\ \alpha L_s+\sin\alpha L_s}$

Mises (1929). The shell was modelled with uniform thickness for a simply supported boundary condition. Winderburg and Trilling (1934) then developed another simplified equation based on von Mises's formulae to predict the collapse pressure under hydrostatic pressure loading. They explained that failure of the vessel might occur in two types of ways. A short vessel with a relatively thick shell fails by stressing the walls and reaching the yield point, while a long vessel with a relatively thin shell will fail because of its instability or when buckling of the shell occurs at stresses that are considerably below the yield point. The types of failure are analogous to the simple column action, i.e., a short and thick column will fail by "yield," while a long and thin column will collapse by "instability."

This work was then continued by von Sanden and Gunther (1952), who developed two equations to predict the pressure at which yielding of the shell occurs at the frame and mid-bay. Reynolds (1960) presented a solution to the buckling pressure, which is a function of the cylinder geometry, tangent modulus (E_t) and secant modulus (E_s), as determined from the stress-strain curve of the shell material. That work proceeded based on the differential equations of equilibrium for the plastic range of cylindrical shells (Pulos, 1963).

A further failure is the overall collapse of the ring-stiffener and the shell, which was satisfied by Bryant (1954). The solution used a modified version of the Bresse pressure as the failure of the single ring-stiffener and associated shell plating and a simplified von Mises pressure for the shell failure of the finite length of a cylinder. Moreover, a brief analytical example has been conducted by Wenk and Kennard (1956) to clarify the failure of overall collapse precipitated by tripping of the stiffener. The analyses show that before global collapse mode, the additional circumferential stresses in the flange of T-stiffeners and radial stresses at the web as its attachment to the cylindrical shell can generate the yielding, which results in a trigger for ring tripping. The criteria for the minimum stiffener tripping stress were merely presented by Kendrick (1972) for the assumed pinned stiffener

Moreover, the consideration of stiffener tripping as the failure of that typical structure has been more extensively studied by Morandi et al. (1996). A closed form solution was proposed for the elastic and inelastic tripping pressure. The elastic tripping pressure arises from the axisymmetric hoop stress at the frame centroid, which is governed based on the interaction form with the von Mises elastic buckling pressure, where the inelastic tripping allowed for the tangent modulus in which the fabrication effects of welding and cold bending are included.

Recently, there are several code recommendations to predict the strength of ring-stiffened cylinders based on the research mentioned above and derived theory. Those include the PD 5500 British standard specification for unfired fusion welded pressure vessels (BSI, 2009); DNV-Germanischer Lloyd, Naval Ship Technology (DNV-GL, 2015); American Bureau of Shipping, Rules for Building and Classing of Underwater Vehicles (ABS, 2002); and API (American Petroleum Institute) from the Bulletin on stability design of cylindrical shells - Bulletin 2U (API, 2000). However, those current design code solutions consider the failure mode independently of each other. The idea of the present work to improve the accuracy and reliability of the design formula is to include the effects of interaction through the simple form strength formulation, which accounts for the shell yield, local, overall buckling, and stiffener tripping such that they are dependent on each other. Then, to accommodate the discrepancy due to the actual initial geometrical shape and material imperfection, the residual stresses by cold rolled forming and welding, knockdown factors were derived by regression analyses applied to the available test data. Subsequently, the accuracy of the proposed formula has been tested with available test data and compared with the existing rules.