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# Residual strength of damaged ring-stiffened cylinders subjected to external hydrostatic pressure

Sang-Rai Cho*, Quang Thang Do, Hyun Kyoung Shin

*School of Naval Architecture and Ocean Engineering, University of Ulsan, 93 Daehak-ro, Namgu, Ulsan, 680-749, South Korea*

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A B S T R A C T

This paper presents the experimental and numerical investigation results of the residual strengths of damaged ring-stiffened cylinders subjected to external hydrostatic pressure. The damage generation procedure adopted in this paper could represent the collision accidents of marine ring-stiffened cylinders with floating subjects or support vessels. Three steel ring-stiffened cylinder models were fabricated and among them two were damaged by drop testing using a rigid knife-edge indenter. Hydrostatic pressure tests were conducted on one intact model and two damaged ones. The test results demonstrated that the ultimate strengths of the two damaged models were significantly reduced compared with that of the intact model. The denting and collapse processes were simulated using the Abaqus FEA software package. The numerical predictions show a good agreement with the test results. Further analyses were also conducted on ring-stiffened cylinders using various striker headers with knife-edge, rectangular and hemispherical indenters to clarify the effect of damage shapes on the residual strengths of damaged ring-stiffened cylinders.



## 1. Introduction

Fabricated multi-bay ring-stiffened cylinders have been used by marine structural engineers for a long time as a major component of submarine pressure hulls. Relatively recently, they have been used for structural components of floating offshore structures, providing the required buoyancy, such as the main legs of tension leg platforms, spars and floating offshore wind turbine foundations.

Ring-stiffened cylinders are prone to damage due to impact loadings arising from such accidents as mass impact and impulsive pressure loadings. The collision of a submarine with a fishery training ship was reported in Ref. [1], and Kvitrud [2] summarized the collisions of buoyancy columns of floating offshore installations with supply vessels. Stojko et al. [3] addressed the necessity of considering impact loadings due to dropped objects in submarine structural design.

Ultimate strength tests on intact fabricated ring-stiffened cylinders have been reported by many researchers for hydrostatic pressure loading [4–7] and combined axial compression/tension and radial pressure loading [8–14]. As mentioned earlier, fabricated ring-stiffened cylinders may contain residual stresses and initial shape imperfections. Many researchers [15–19] have investigated their effects on the ultimate strength of ring-stiffened cylinders subjected to external hydrostatic pressure. Based on the results of those experimental works, together with related theoretical investigations, quite accurate and reliable design formulations for predicting the ultimate strength of ring-stiffened cylinders can be found in the BSI [20],

* Corresponding author.
*E-mail addresses:* srcho@ulsan.ac.kr (S.-R. Cho), dothang.ntu.2005@gmail.com (Q.T. Do), hkshin@ulsan.ac.kr (H.K. Shin).

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GL [21] and ABS [22] Rules. Mackay et al. [23] quantified the accuracy of inter-frame and overall collapse predictions using the submarine design formulae to provide a base line for comparison with numerical modelling results.

Regarding the residual strength of a damaged ring-stiffened cylinder, only a few studies have been reported in the open literature so far. Harding and Onoufriou [24] reported axial compression tests on damaged fabricated ring-stiffened cylinders. The local denting damages were induced by the static application of a lateral load. MacKay et al. [25] provided details of experimental and numerical investigations on the strength of damaged pressure hulls, which included machined unstiffened and ring-stiffened cylinders with artificial corrosion damage. MacKay et al. [26] conducted numerical analyses of their corroded ring-stiffened models under hydrostatic pressure. Cerik [27] performed numerical predictions of the residual strengths of damaged ring-stiffened cylinders subjected to axial compression.

The main objective of the study reported in this paper was to provide the experimental investigation results of ultimate strength tests on one intact and two damaged ring-stiffened cylinders under hydrostatic pressure. Numerical studies were also performed to predict the extents of damage on ring-stiffened cylinders subjected to lateral collision load using a rigid knife-edge striker. Ultimate strengths of the intact and damaged models were also predicted via numerical calculations. Further numerical analyses were also performed on ring-stiffened cylinder models, considering various striker header shapes, such as knife-edge, rectangular and hemispherical indenters, to clarify the progressive collapse behaviour and quantify the effect of damage extents on the reduction of hydrostatic pressure carrying capacity.

## 2. Test models

To fabricate marine ring-stiffened cylinders, flat plates are rolled and then welded to the required curvature to form an unstiffened cylinder. The webs of ring-stiffeners are produced using several pieces of flat plate, and then the rolled flanges are welded together to construct ring-stiffeners. After inserting the ring-stiffeners into the cylinder, longitudinal seam welding is performed, and then the cylinder and stiffeners are joined by welding to complete the ring-stiffened cylinder. Of course, this type of fabrication method, incorporating cold bending and welding, leaves initial shape and material imperfections.

Following the fabricating method described, three nominally identical, internally ring-stiffened steel cylinder models were fabricated. The shells were cold-rolled to the required curvature, and then flat bar ring-stiffeners were internally welded onto the shell. Longitudinal seam welding was conducted to form a cylinder, and finally, the end plate and flange were welded to the cylinder. Among them, one, denoted as RS-I, was tested as intact, whereas two, denoted as RS-C-1 and RS-C-2, were damaged using a drop testing machine and then tested. The dimensions, material properties and damage generation process are provided in this section.

### 2.1. Dimensions

The dimensions of the test models are depicted in Fig. 1. The outside diameter ($D_o$) and overall length ($L$) were 800 mm and 1060 mm, respectively. The stiffener spacing reduced gradually towards the ends from 200 mm to 80 mm. The thickness of the shell and stiffener was nominally 4 mm, but the actual values slightly deviated from the nominal value. The measured thicknesses of the shell ($t_s$) and ring-stiffener ($t_w$) are provided in Table 1. The ring stiffeners were cut from flat sheets, and the depth of the ring stiffener web ($d_w$) was 35 mm. A circular plate of 20 mm thickness was welded to the left end of the cylinder, while a flange of 20 mm thickness was welded to the right end.

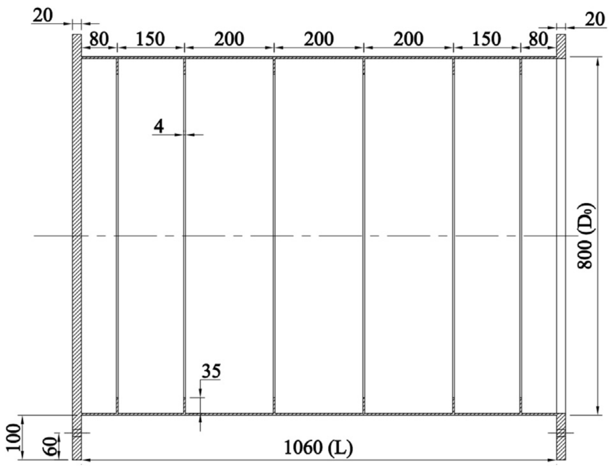


**Fig. 1.** Dimensions of the ring-stiffened cylinder model (unit: mm).