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Ultimate strength of intact and dented steel stringer-stiffened cylinders under hydrostatic pressure

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ABSTRACT

The aim of the study is to examine the effect of damages on the load carrying capacity of stringer-stiffened cylinders under external hydrostatic pressure. Experiments were conducted on three small-scale steel stringer-stiffened cylinder models that were fabricated by cold bending and arc welding. Drop tests with a knife-edge indenter were conducted on two test models to induce damage on the cylinders. Hydrostatic pressure tests of all models including an intact model were performed to characterize the ultimate strength behaviour of the stringer-stiffened cylinders in damaged and intact conditions. The results indicated that the effects of damage on the ultimate strength of stringer-stiffened cylinders were extremely low. Interestingly, during the collapse tests, it was also discovered that the shell failed several times after an initial failure, as evidenced by a sudden decrease in pressure. Subsequently, the shell recovered as "hardened-up" to reach a higher pressure level prior to the final collapse. Furthermore, the drop tests and hydrostatic pressure tests were simulated by using the finite element software package ABAQUS. The agreements between the tests and numerical predictions were satisfactory.

1. Introduction

A fabricated steel-stringer-stiffened cylinder is a well-known structural element as the typical structural component of a tension leg platform, spar, and buoyancy column of a floating offshore wind turbine foundation. Specifically, stringers are combined with ring-stiffeners to form an orthogonal reinforcement against axial compression and hydrostatic pressure loading. Stringer-stiffened cylinders are damaged owing to various impact loadings such as accidents from ship collisions, mass impacts, and slamming wherein ship collisions are emphasized as possessing the highest damage potential [1]. The collisions between floating offshore installation columns and supply vessels were summarized by Kvitrud [2]. A typical damaged column of a platform is shown in Fig. 1. When structural elements are potentially damaged in service, it is necessary to consider the effects of the damage on the strength of the structure and serviceability at the design stage. Thus, it is necessary to understand the form of damage that can potentially occur. The immediate repair of the damage may be difficult and sometimes impossible owing to economic and technical requirements. Therefore, efficient and accurate assessment methods to estimate the damage effects are essential for decision-making through residual strength assessment procedures.

Several extant studies experimentally described the ultimate strength of intact model for hydrostatic pressure [4–6] and a combination of axial compression/tension and radial pressure [7–15]. The effects of residual stresses (cold bending and welding) and initial shape imperfections due to the fabrication processes performed on the ultimate strength of stringer-stiffened cylinders subjected to hydrostatic pressure are discussed [16–19]. Furthermore, the formulations to predict the ultimate strength of stringer-stiffened cylinders were derived by Cho et al. [20], Das et al. [21], DNV [22], API [23], and ABS [24] Rules, which were considerably accurate and reliable. However, there are only a few studies focused on the residual strength of a damaged stringer-stiffened cylinder. Quasi-static denting was conducted to generate the

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Fig. 1. Damaged platform column [3].

Table 1
Measured dimensions of test models (unit: mm).

Model		SS-I	SS-C-1	SS-C-2
Radius, R		550	550	550
Shell thickness, t		2.99	2.98	2.97
Total length, L		1060	1060	1060
Stringer-stiffener	web height, h_{sw}	65.0	65.0	65.0
	web thickness, t_{st}	4.93	4.89	4.87
Ring-stiffener	web height, h_{rw}	200	200	200
	web thickness, t_{rw}	4.91	4.90	4.92
	flange width, b_{rf}	50.0	50.0	50.0
	flange thickness, t_{rf}	4.91	4.89	4.88

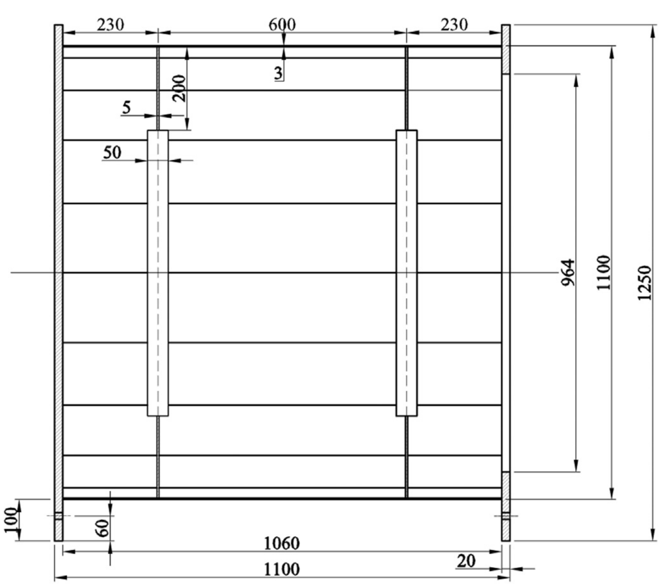

Fig. 2. Dimensions of stringer-stiffened cylinder model (unit: mm).

damaged model prior to performing axial compression tests on damaged fabricated stringer-stiffened cylinders [25–27]. Walker et al. [28,29] also performed quasi-static denting tests on stringer-stiffened cylinders as the first stage and subsequently tested them under a combination of external pressure and axial compression loading. Furthermore, the numerical simulations of the residual strengths of damaged stringer-stiffened cylinders under axial compression were presented by Cerik [30] while the damaged model was generated by using a dynamic denting. However, until now, there is a lack of the experimental information regarding the dented stringer-stiffened cylinders under pure hydrostatic pressure loadings. Therefore, it is necessary to provide some experimental results of this loading. It may useful to researchers for understanding the responses of the dented stringer-stiffened cylinders under various loadings covering the full ranges of the combinations.

In the study, the stringer-stiffened cylinders were further simultaneously investigated by experimental and numerical methods. Three models were tested in which one of the models is the intact model while the other two models are damaged by lateral collision loads under external hydrostatic pressure. The effects of residual stresses from cold-bending and welding and the initial shape imperfection were considered in the FEA models. Finally, the reduction in the residual strength of two damaged stringer-stiffened cylinders was compared to that of the intact model by both experimental and numerical predictions.

2. Experiment models

2.1. Dimension of models

Three internally stringer-stiffened cylinder models were fabricated, namely, SS-I, SS-C-1, and SS-C-2. With respect to the manufacturing process of experimental models, flat plates were cold bent and welded to the form of cylinders. Subsequently, 20 flat-bar stringer stiffeners were welded to a cylindrical shell. The T-rings were also welded to the cylindrical shell. It is noted that the flanges of ring stiffeners were also rolled by cold bending. The outside diameter (D_o) of the cylinder was 1100 mm while the overall length (L) was 1060 mm. The shell thickness was nominally 3 mm although the measured value obtained using an ultrasonic device was determined as an average of 2.98 mm. A circular plate was welded at the end of the cylinder with a 20 mm thickness. A flange with 20 mm thickness was also welded at the other end. The measured thicknesses and dimensions of the test models are given in Table 1, and the test model dimensions are described in Figs. 2 and 3.

2.2. Material properties

The models were fabricated from a general-purpose structural steel material, namely, SS41. The mechanical properties were obtained by performing quasi-static tensile tests following the procedures listed in the Korean Standard KS B 0802 [32]. The average mechanical properties of test models are given in Table 2.

The high speed tensile tests were also performed by following the procedures of ISO 26203–2:2011 [33]. The dimensions and test results of the high speed tensile test coupon for high strain rates are shown in Fig. 4. In this figure, the average thickness of the tensile test coupons is 1.98 mm. The tests were conducted with various strain rate values corresponding to 10/s, 50/s and 100/s. The high speed tensile test setup is shown in Fig. 5. The strain was measured using a high-speed camera while the force was measured by load cells and two strain