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Ultimate strength of locally damaged steel stiffened cylinders under axial compression

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ABSTRACT

This paper focuses on the load-carrying behaviour of large diameter thin-walled stiffened cylinders with local damage when subjected to axial compressive loading. The case considered in this study corresponds to the residual strength assessment of columns of floating offshore structures with damage resulting from collisions with supply vessels. Numerical simulations of axial compression tests, which examine the collapse behaviour and the ultimate strength of ring- and orthogonally stiffened cylinders dented by a knife-edged indenter, are presented. The behaviour of eight small-scale ring-stiffened cylinders and four orthogonally stiffened cylinder specimens is analysed. Finite element analyses were performed using the ABAQUS FEA software package, and a close agreement between the experimental test results and the numerical predictions was achieved. To assess the factors influencing the reduction in ultimate strength under axial compression and to clarify the progressive collapse behaviour, further analyses were performed on design examples of ring- and orthogonally stiffened cylinders, considering both intact and damaged conditions.

1. Introduction

In the field of marine structures, ring and/or stringer-stiffened thin-walled large diameter steel cylinders have been widely adopted as compression elements for floating offshore installations, such as the main legs of tension leg platforms, semi-submersibles, spars and more recently as buoyancy columns of floating offshore wind turbine foundations. Ring-stiffeners are very effective at strengthening cylindrical shells against external pressure loading. Stringers (longitudinal stiffeners) are normally used to provide additional stiffness in the axially compressed members. Over many years, a large number of theoretical and experimental studies have been performed on the buckling of stiffened cylindrical shells, with an emphasis on offshore structures [1–3]. Based on the availability of a large database of experiments and design guidance [4–8], the case of intact cylinder buckling in offshore structures is well understood. However, despite the considerable risk demonstrated by accident statistics [9–12], the assessment of residual strength of damaged structures, from damage arising from a collision with an attending vessel, is currently not explicitly considered in the design guidelines. In the light of the advancements in the ultimate limit state assessment of steel-plated structures [13], a better understanding of the collapse characteristics of damaged stiffened cylindrical shells predominantly subjected to axial compression is necessary.

For the case of tubular members, which have a cylinder radius-over-shell thickness ratio of (R/t) in the range of 20 to 80 [14], the residual strength in damaged condition under various loading conditions has been investigated in a wide range of studies [15–23]. According to the statistics [12], a higher collision risk exists for floating platforms than for fixed platforms with mostly tubular members. However, for large-diameter thin-walled stiffened cylindrical shells with R/t larger than 120, there have only been a few studies, which have produced limited experimental data on their impact response and collapse behaviour in damaged condition [24–33]. This is partly due to their manufacturing expense and the difficulties involved in testing small-scale models [34]. To determine the reduction in strength one needs to compare intact and damaged specimens, which should have not only same geometry and material but also same imperfection pattern and magnitude. However, it is impossible to fabricate equivalent welded test specimens with exactly same imperfections. For imperfection-sensitive structures, it is therefore not proper to use the experimental results of equivalent intact and damaged models to determine the reduction of strength. On the other hand, through numerical analysis the uncertainties regarding the imperfections can be eliminated.

With the recent advances in computational tools and in consideration of the difficulty in conducting experimental investigations, nonlinear finite element analysis has become the preferable tool for the condition assessment of mechanically damaged steel-

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plated structures. Numerical assessment of the residual strength of engineering structures under various loading conditions, as exemplified about three decades ago in [35], has recently been applied to several structural elements, including dented cylinders [36,37], pipelines [38], steel plates [39–42], stiffened panels [43] and damaged box girders [44]. Numerical modelling has the advantage of incorporating full geometrical details and allows for the comparison of intact and damaged models that have identical properties. Nevertheless, the modelling parameters such as initial imperfections and residual stresses as well as the solution scheme, may affect the results. Therefore, despite the computational costs involved, a carefully implemented nonlinear finite element analysis that is also validated with reliable experimental test data would be the most effective means of assessing residual strength.

Within this context, the present work assesses the use nonlinear finite element analysis for ultimate strength analysis of damaged steel stiffened cylinders by replicating the results of physical experiments available in the literature. A series of analyses are then conducted on generic models of ring- and orthogonally stiffened cylinders to clarify progressive collapse behaviour and to determine the effects of damage size and shell slenderness on the reduction of axial load carrying capacity.

2. Description of test data

Extensive experimental studies investigating the strength of stiffened cylinders were performed within the scope of the Cohesive Buckling Research Programme, which was composed of several individual research projects focusing on the buckling of shell components of offshore structures and was conducted in various UK Universities between 1983 and 1985 [45]. The Programme provided detailed and reliable experimental data that can be useful for benchmarking of the numerical and analytical ultimate strength prediction methods.

Among these individual projects, Harding and Onoufriou [24] examined the effects of damage on the ultimate strength of ring-stiffened cylindrical shells by testing eight small-scale specimens. In this project, two series of models were tested. In the first series, specimens CY-2 to CY-5 were subjected to mid-bay denting, such that damage was restricted to the wall between the ring-stiffeners. In second series, to assess the effects of damage to the ring stiffeners themselves, specimens CY-6 to CY-9 were primarily subjected to ring-stiffener deformation. The properties of the ring-stiffened cylinder specimens are given in Table 1. In a similar manner, Ronalds and Dowling [28] investigated the collapse behaviour of damaged orthogonally stiffened cylinders. All specimens had flat-bar ring-stiffeners dividing the specimens into three bays. The properties of the orthogonally stiffened cylinder specimens are given in Table 2. The geometrical parameters in Tables 1 and 2 are illustrated in Fig. 1.

Table 2
Properties of the orthogonally stiffened cylinder specimens.

		3B1	3B2	3B3	3B4
Cylinder radius (mm)	R	160	160	160	160
Shell thickness (mm)	t	0.6	0.6	0.6	0.6
Inner bay length (mm)	l_i	96	96	96	96
Total cylinder length (mm)	L	319	319	319	319
Number of ring-stiffeners	n_R	2	2	2	2
Number of stringers	n_S	40	40	20	20
Ring-stiffener web depth (mm)	h_{rw}	6.5	6.5	6.5	6.5
Ring-stiffener web thickness (mm)	t_{rw}	0.82	0.82	0.82	0.82
Stringer web depth (mm)	h_{sw}	4.8	4.8	4.8	4.8
Stringer web thickness (mm)	t_{sw}	0.6	0.6	0.6	0.6
Yield strength (MPa)	σ_Y	332	332	332	332
Young's modulus (GPa)	E	205	205	205	205
Dent depth (mm)	d	7.36	12.48	12.96	17.12

The damage was simulated by slowly applying a round-edged wedge radially to the cylinder, with the edge normal to the cylinder axis. Heavy end-rings were attached at the ends of the cylinders using resin to provide clamped boundary conditions. The specimens were then loaded axially in small increments using a displacement-loading machine.

Due to their small size, the specimens in both projects were fabricated using TIG welding and carefully machined jigs. The material of the specimens had similar characteristics to those of general-purpose structural steel, with respect to their linear elastic response and their clear yield plateau. After fabrication, the specimens were stress-relieved by heat treatment to remove the high levels of residual stresses induced by welding. Fabrication-induced geometrical imperfections of the ring-stiffened cylinders were measured and generally found to be within the code tolerance requirements. The initial imperfections of the orthogonally stiffened cylinder specimens were also found to be within the tolerances, with the exception of one or two locations due to strong local panel imperfections. The details of the fabrication process for these specimens is described by Scott et al. [34].

3. Finite element modelling

For finite element modelling and analysis, the commercial software package ABAQUS (version 6.14) was utilised. As shown in Fig. 2, except for the heavy end-rings, the full geometry of the specimens was modelled. The geometric models of all specimens were meshed using S4R element in ABAQUS, which is 4-node doubly curved finite-strain element with reduced integration and hourglass control and five integration points throughout the thickness. The global mesh size was determined as 3 mm, which

Table 1
Properties of the ring-stiffened cylinder specimens.

		CY-2	CY-3	CY-4	CY-5	CY-6	CY-7	CY-8	CY-9
Cylinder radius (mm)	R	160	160	160	160	160	160	160	160
Shell thickness (mm)	t	0.6	1.2	1.2	0.6	1.2	1.2	0.6	0.6
Inner bay length (mm)	l_i	40	40	80	80	80	80	24	24
Total cylinder length (mm)	L	200	200	400	400	320	320	96	96
Number of ring-stiffeners	n_R	4	4	4	4	3	3	3	3
Ring-stiffener web depth (mm)	h_{rw}	4.8	6.72	4.8	4.8	3	3	3	3
Ring-stiffener web thickness (mm)	t_{rw}	0.6	0.84	0.6	0.6	0.6	0.6	0.6	0.6
Ring-stiffener flange width (mm)	b_{rf}	–	–	–	–	4	4	4	4
Ring-stiffener flange thickness (mm)	t_{rf}	–	–	–	–	0.6	0.6	0.84	0.84
Yield strength (MPa)	σ_Y	344	342	324	349	339	352	376	376
Young's modulus (GPa)	E	201	201	201	201	201	201	201	201
Dent depth (mm)	d	3.36	5.44	6.72	5.44	7.04	7.52	6.24	6.4