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On the resistance of steel ring-stiffened cylinders subjected to low-velocity mass impact

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ABSTRACT

This paper addresses the impact response of large-diameter thin-walled steel ring-stiffened cylinders subjected to low velocity mass impact and resulting local damage. Drop-weight impact tests with a striking mass, which had a knife-edge indenter, were conducted on two fabricated steel small-scale models. Details of the experiment setup, the procedure and the tests to obtain both quasi-static and dynamic material properties are described. With these observations, the experimental data, which include the final deformed shape, dynamic force-displacement curves and strain gauge measurements, are reported to be useful for future benchmark studies. The numerical prediction accuracy of the impact response of the test models were evaluated using the explicit solver of the finite element software package ABAQUS. The effect of the strain-rate hardening definition on the results is highlighted. Finally, the results that were obtained using a simplified analysis method based on smearing ring-stiffeners to obtain an equivalent circumferential bending strength were evaluated. The limitations of this simplified method were also discussed.

1. Introduction

Large diameter thin-walled cylinders are widely used in several industrial applications, such as the structural components of offshore platforms, submarine pressure hulls and pressure vessels. Cylindrical shell structures are prone to damage because of the impact loads, which may arise from such accidents as mass impact and impulsive pressure loading. Amongst these cases, the problem of low-velocity mass impact loading on a ring-stiffened cylindrical shell is of interest in this paper, such as collisions between ships and buoyancy columns of floating offshore installations [1] and dropped objects on submarine structures [2].

In the literature, many available studies are related to the deformation behaviour of offshore tubular members [3–11]. Offshore tubular members are relatively thick-walled unstiffened cylinders with large span and widely used as components of fixed offshore installations, such as jacket structures and braces of floating structures. Tubular members have different deformation characteristics from large-diameter cylinders where the overall bending deformation is more dominant than the local shell denting. Only a small number of studies can be found on the behaviour of large-diameter unstiffened or stiffened thin-walled cylinders, which have relatively higher radius-to-thickness ratio and are used as columns or legs of offshore installations. Walker and Kwok [12] presented experimental and analytical work on quasi-static denting on cylinders. Harding and Onoufriou [13] and Karroum et al. [14] conducted quasi-static denting tests on small-scale ring-stiffened cylinder specimens. Walker et al. [15,16] reported quasi-static denting tests on both small-scale ring-stiffened and orthogonally stiffened cylinders. One advantage of imposing a specified damage using quasi-static denting is that it provides continuous recording of the damage process, which can be used to develop simplified analysis methods. However, dynamic effects, such as the strain-rate effect and inertial forces, are not taken into account. In fact, most experimental works that investigated the collision of marine structures at the structural component level follow the quasi-static approach and assume that the response of the structure under dynamic load caused by a low-velocity mass impact is similar to the static force-displacement response. For the local denting damage on cylinders due to collision, inertial forces may be neglected because the impact duration is usually longer than the natural period of the structure, but the strain-rate effect should be

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considered to predict the impact response and permanent damage extents accurately. The latter has a practical importance because the design against accidental impact loading includes consideration of the residual strength in damaged condition. Recent experimental and numerical studies on basic ship structural components [17–20] that are subjected to dynamic mass impact loading show that an accurate prediction of the structural response using nonlinear finite element analysis is not straightforward unless the details of the experimental conditions and exact material characteristics are accounted for. In addition, Jones [21] noted that dynamic material properties particularly affect the credibility of numerical predictions. It is emphasised that there is a lack of understanding on many aspects of dynamic material properties and limited available data in this field.

There are analytical studies on unstiffened cylinders subjected to concentrated load, which causes local denting deformation, such as [22–26]. Hoo Fatt and Wierzbicki [27] extended the work of Wierzbicki and Suh [10], which focused on the denting of cylindrical shell of ring-stiffened cylinders. Simplified analysis methods can rapidly assess collisions as long as they comply with the actual structural response. Because these studies are purely theoretical, extensive validation studies with reliable experimental data are required.

In the given context, first, this paper describes the experiments on small-scale steel ring-stiffened experiments that were subjected to mass impact. The experimental work is of significant importance and can be used to validate any predictions for low-velocity mass impact loading. The tests were simulated using a nonlinear finite element analysis. The experimental study included an assessment of dynamic material properties, which was used to highlight the effect of the strain-rate hardening definition in numerical impact simulations. The effect of stiffening the cylinders in circumferential direction with rings was studied by evaluating the experimental and numerical results. Finally, an existing model for the local denting behaviour of unstiffened cylinders was revisited and the results obtained by modifying this model were compared with the experimental response.

2. Dynamic impact tests

2.1. Test models

Two internally ring-stiffened steel cylinder models, which are denoted as RS-C-1 and RS-C-2, were tested. The material of the models is SS41 general-purpose structural steel. The model manufacturing followed the standard methods and techniques of full-scale structures of this type. The cylinder shell was cut from steel sheets of 4 mm thickness, cold-bent using rollers and welded to form a cylinder with an outer diameter of 800 mm. The ring-stiffeners were 4-mm-thick flat-bars, which were cut from flat sheets and internally welded to the cylinder shell. The depth of the ring-stiffener web was 35 mm. The spacing of the stiffeners decreased towards the ends of the cylinder. In the middle three bays, the stiffener spacing was 200 mm whereas it was 150 mm in the next bays and 80 mm in the outmost bays. The cylinder was welded at one end to a circular plate of 20 mm thickness. At the other end, it was welded to a ring of 20 mm thickness. Similar to the effect of heavy bulkheads in actual structures, these end conditions ensured that the cylinder ends remained circular. The end plate and the end ring had extensions at the bottom, which were bolted to the support plates. The scantlings and configuration of these models were determined considering hydrostatic pressure testing to be conducted examining the damaged ring-stiffened cylinder behaviour. The hydrostatic pressure testing facility requires that one end is open and the other end is closed. The thickness of the cylinder shell and the ring-stiffeners were surveyed using an ultrasonic device and found to be 3.80 mm in average, which is less than the nominal value. The main dimensions of the models are summarised in Table 1.

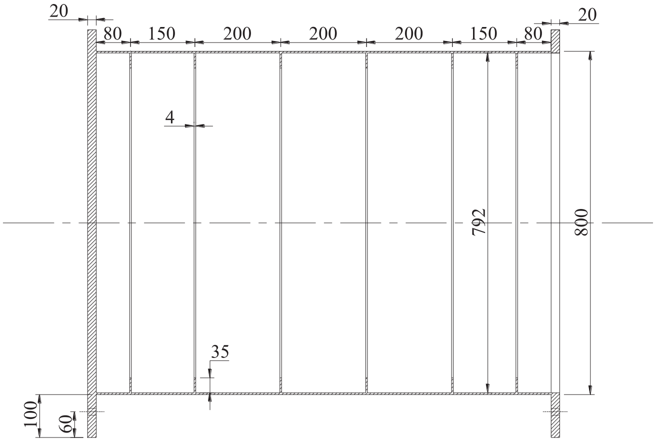

Fig. 1. Geometry of the ring-stiffened cylinder model (Unit: mm).

Fig. 1 shows the model geometry including the end plate and end ring. In Fig. 2, the detailed geometry of the end plate and end ring are shown. The four holes at the bottom of the end plate and the end ring are for bolting with the supports.

The initial imperfections of the models were measured before mounting to the testing frame. On the inner and outer surface of the models longitudinal grid lines were drawn with 10° spacing. In the circumferential direction at each ring-stiffener location and in the middle part of each bay, grid lines were drawn. The out-of-roundness of the cylinders was evaluated at every crossing point of these lines based on the obtained measurements using a two-point bridge gage as shown. This procedure corresponds to a radial measurement of the shape. The measurements were performed from the outside for 36 points at one time. The two-point bridge gage readings were converted to out-of-roundness values by performing Fourier series expansion. The imperfection profiles of each model are shown in Fig. 3. In these graphs, 0° corresponds to the longitudinal weld line. The magnitude of the imperfections is exaggerated by 10 times.

Fig. 3 shows that the maximum out-of-roundness values are confined along the longitudinal weld line. There is an outward deviation at the weld line and inward deviation at the adjacent locations. The results of out-of-roundness measurements are summarised in Table 2. The maximum out-of-roundness values were lower than the upper limit of tolerable imperfection for ring-stiffened cylinders according to PD5500 [28], which is 0.5% of the cylinder radius R.

Table 1
Nominal dimensions of ring-stiffened cylinder models used in dynamic impact tests.

Outer diameter (mm)	Shell thickness (mm)	Inner bay length (mm)	Number of ring-stiffeners	Stiffener web height (mm)	Stiffener web thickness (mm)
800	4	200	6	35	4