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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.

Keywords

Ring-stiffened cylinder; Orthogonally stiffened cylinder; Denting damage; Large imperfection; Axial compression; Nonlinear FEA

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-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.

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 yielded consistent results. The mesh was uniform in all models. Moreover, in the ring-stiffened cylinder specimens, three elements for the ring-stiffener web and four elements for the ring-stiffener flange were used. In the orthogonally stiffened cylinders, to ensure a smooth transition of the stringers through the ring-stiffeners, four elements in the ring-stiffener web and three elements in the stringer web were

used. The weld joints were not taken into account in the numerical modelling. The detail views of the mesh of CY-3 and 3B3 are shown in [Fig. 3](#).

As in the actual tests, the simulations consisted of two steps: first, inducing damage and second, post-damage collapse analysis. Before proceeding to the first analysis step, initial imperfections were introduced into the models. For this purpose, eigenvalue buckling analyses were performed. In general, the first eigenvalue buckling mode was selected as the initial imperfection shape. In the eigenvalue buckling analysis, fixed boundary conditions at both cylinder ends were assumed. In [\[34\]](#), typical imperfection values, such as maximum outward and inward deviation, out-of-straightness and deviation from perfect circles, were given. These values were considered when determining the imperfection magnitude associated with the eigenvalue buckling mode. The imperfection magnitudes were calibrated by comparing numerically-obtained ultimate strength values with the ones calculated using the ultimate strength formulations provided in [\[3\]](#) for ring-stiffened cylinders and in [\[46\]](#) for orthogonally stiffened cylinders. As stated by Das et al. [\[3\]](#), these formulations were calibrated against experimental data, and the statistical properties of the modelling uncertainty factors, the mean and coefficient of variation (COV), were acceptable. Therefore, they can be used as datum for benchmarking the numerical results. For the sake of completeness, these formulations are provided in the Appendix. The numerical assessment of the ultimate strength of the test specimens in intact condition was performed using the modified Riks method in ABAQUS, with the same boundary conditions as in the eigenvalue buckling analysis. When determining the imperfection magnitude, the test results were also considered, such that the ultimate strength in intact condition was kept larger than in damaged condition. The ratio of the ultimate strength values calculated using simple formulations over the numerical predictions had a mean of 0.90 and a COV of 14.14%. It must be noted that these simple formulations yielded, in most

of the cases, even smaller ultimate strength values than the ones observed in the actual experimental tests of damaged specimens. Therefore, care must be taken when using these simple formulations to calibrate the numerical models.

3.1 Inducing damage

Rather than simulating the exact force–displacement response of the test specimens during denting, the aim of this step was to obtain an initial geometric deformation, defined with a single parameter, namely the dent depth, for the subsequent collapse analysis. This approach is somehow similar to that incorporated by Paik et al. [39] and Paik [40] in their studies on residual strength of plates. The main difference between these studies and the current one is that in the former the mesh is modified directly imposing imperfections through node translations. In the present study, the denting step serves for the same purpose. The damage simulation was conducted quasi-statically using the dynamic-explicit solver in ABAQUS. To retain an economical solution time while keeping the inertial forces insignificant. The loading rate was increased artificially. The simulation time was determined using the first natural frequency (as obtained through a modal analysis) and the corresponding natural period of the specimens.

The knife-edged indenter was modelled as a rigid surface and meshed with a 4-node three-dimensional bilinear rigid quadrilateral element R3D4 from the ABAQUS element library. The tip of the indenter was rounded with a 3 mm radius and meshed with six elements to ensure the face of the element was in contact with the target surface. The rigid surface was forced to move perpendicularly to the cylinder axis up to the permanent dent depth obtained in experiments. The indenter was not retracted, as such elastic spring-back of the specimens was not considered. The displacement was applied by smoothly ramping up from zero, to ensure that no stress wave propagated through the model. The contact between the indenter and the specimen was defined

as a general contact algorithm in ABAQUS that uses the penalty method for the contact constraint. The mass of the indenter was assumed to be 10 kg, which is of the order of the mass of the specimens. The boundaries of cylinders were constrained in all degrees of freedom.

In the denting step, material strain hardening was included to obtain a more realistic damage profile. A simple power-law expression for a true stress–strain relation, proposed by Zhang et al. [47], was utilised:

$$\sigma = C\varepsilon^n \quad (1)$$

where

$$n = \ln(1 + \varepsilon_u) \quad (2)$$

$$C = \sigma_u (\exp/n)^n \quad (3)$$

ε_u is the strain corresponding to ultimate tensile strength σ_u . For a given value of σ_u , ε_u can be calculated as follows:

$$\varepsilon_u = 1 / (0.24 + 0.01395\sigma_u) \quad (4)$$

Ultimate tensile strength of the material of all specimens was taken as 396 MPa, which is given in [34]. Engineering stress–strain and true stress–strain curves of CY-2, as obtained from the formulations given, is shown in Fig. 4

By means of the damage-inducing procedure, as shown in Fig. 5, the damaged geometries of the specimens were obtained. In Fig. 6, the deformed shape and cross-section of CY-4 are shown. The dent is associated with a flattened segment around the circumference, and there is an outward bulging in the zone adjacent to the dent and semi-elliptical zones on both sides of the dent in longitudinal direction. In most of the cases, the bulging is negligible. The idealised

cross-section of the damaged cylinders is shown in Fig. 7. From the geometrical relations, the length of flattened section L_f can be expressed as a function of the dent depth d :

$$L_f = 2\sqrt{R^2 - (R - d)^2} \quad (5)$$

Because of the flattening of the upper segment of the cylinder section, the section becomes asymmetric and the plastic neutral axis shifts downwards.

In short and stocky cylinders with large D/t , local indentation is the dominant deformation mode. Therefore, the global deformations, in the form of beam bending, were not considered.

3.2 Post-damage collapse analysis

ABAQUS is capable of importing any imperfection state, such that the deformed configuration can be defined as the initial geometry for the collapse analysis. This feature was utilised in post-damage ultimate strength assessment of the test specimens. By doing so, however, the residual stresses caused by denting in the damaged segment were lost. Xu and Guedes Soares [43] performed a numerical study on the residual strength of stiffened panels under axial compression that retained their residual stresses after denting. Xu and Guedes Soares concluded that, with residual stresses, the ultimate strength of the dented stiffened panels was slightly larger than without inclusion of the residual stresses, due to the tension stresses in damaged area. In this current study, the effect of residual stresses is neglected. Only the mesh configuration of the models was updated prior to the collapse analysis.

In the post-damage collapse analysis, the modified Riks method was used, and large deformations and plasticity were included. The material was assumed to be elastic-perfect plastic, i.e. the effect of strain hardening was neglected. Although this assumption is pessimistic, it is believed that it does not lead to significant discrepancies between the tests and the numerical simulations, as far as the ultimate limit state is concerned. The residual stresses

induced by welding were not considered. To apply purely axial compression, as in the experiments, suitable boundary conditions had to be constructed. For this purpose, as shown in Fig. 8, at one end of the cylinders all degrees of freedom were constrained, while all nodes at the other end were coupled to a reference node to which an axial displacement was applied. At this reference node, the remaining five degrees of freedom were constrained. The axial force and displacement values were obtained from the reference node.

As previously mentioned, to evaluate the reduction in load carrying capacity and to compare with the damaged condition response, intact specimens can be analysed using the same assumptions. The analysis procedure is summarised in Fig. 9.

4. Benchmarking numerical predictions with the test results

The test results and the ultimate axial load values obtained from the numerical analysis are presented in Tables 3–5. As an indicator of the accuracy of the numerical analysis, the bias X_m (modelling uncertainty factor) is given as the ratio of the experimentally obtained value over that obtained through the nonlinear finite element analysis. In general, for all specimens the bias is close to unity, though an underestimation of the ultimate strength, in particular for all orthogonally stiffened cylinder specimens, is noticeable. The mean of the modelling uncertainty factor is 1.043. In addition, there is a small scattering marked with a COV of 6.53%. These values are within the recommended limits of any of the good strength prediction tools in [48]. All numerical predictions and test results are compared in Fig. 10. The ultimate strength values σ_{xu} were normalised with the yield strength σ_Y .

The sources of the errors can be attributed to the actual imperfections in the test specimens, the uncertainties in the boundary conditions and perhaps, the residual stresses after denting. However, because the numerical predictions are in very close agreement with the test results, it can be concluded that the geometrical distortion due to denting plays a more important role

than the other parameters of influence. Thus, it can be concluded that the numerical modelling strategy proposed in this study is able to represent the effect of denting damage in stiffened cylinders.

Next, the sensitivity of the modelling uncertainty factor to dent depth was checked. A plot of X_m versus dent depth, normalised with cylinder diameter D , is shown in Fig. 11. It is inherent that the scattering particularly occurs at small dent depths and this was observed in the ring-stiffened cylinder specimens. The predictions are quite consistent for orthogonally stiffened cylinders specimens, which have larger dents.

In addition to the ultimate strength values, the axial shortening curves can be used for benchmarking and give more insights about the response of the specimens. In Fig. 12, the axial shortening curves of the orthogonally stiffened cylinder specimens obtained from the numerical analyses are compared with the curves reproduced from [45]. Here $\sigma_{x,ave}$ and $\varepsilon_{x,ave}$ denote average axial stress and strain, respectively. These quantities are normalised with yield strength σ_Y and yield strain ε_Y . Unfortunately, the available curves for ring-stiffened cylinder specimens do not extend beyond collapse; hence, they are excluded. The main discrepancies between the test and numerical results were the differences in stiffness, particularly during the initial stages of loading. This might be primarily due to the load application in actual tests where eccentricity of the applied compression is inevitable. Another cause of this discrepancy might be non-uniform loading, due to the initial outward bulging of the specimens. Ronalds and Dowling [27] states that, after denting, the end blocks were detached, which caused additional strain and yielded a new equilibrium configuration with negligible residual stresses. This led to an outward bulging curve in the straight angle between the two cylinder ends, causing a non-uniform distribution of stresses in the initial stage of the axial compressive loading. Despite these discrepancies, the agreement between the experimental and numerical results is close.

The stiffness before collapse and the post-collapse behaviour was accurately predicted. Slight deviations in the post-collapse regime can be attributed to the uncertainty in the initial imperfections.

Lastly, the post-collapse shape of the specimens was checked. Harding and Onoufriou [24] indicate that lobular buckling occurred in models CY-4 and CY-7, as would be expected for the corresponding intact models. In Fig. 13, the numerically obtained views of several test specimens after collapse are shown; these specimens failed with several lobes extending over the circumference in the mid-bay. In all test specimens, the collapse was triggered by the high level of concentrated stress adjacent to the dent zone. The flattened segments deflect inwards and lead the adjacent shell to deform outwards, and this pattern extends over the entire circumference. In some of the specimens, these buckles were not limited to the damaged bay and spread to the adjacent bays.

5. Case studies

The results of the numerical analyses confirmed that the proposed numerical modelling strategy accurately predicts the ultimate strength of locally damaged stiffened cylinders. To compare the collapse behaviour under intact and damaged conditions and to determine the reduction in ultimate strength with increasing dent depth, which may reach larger values than in the tests investigated in previous section, further numerical studies were performed on generic models.

5.1 Ring-stiffened cylinder

The first target structure was the ring-stiffened cylinder of a spar platform, given in [49]. It was assumed that this ring-stiffened cylinder was a structural element of a cell spar with a multi-cylinder column. The dimensions and the material properties of the model are shown in Table 6. The cylinder was divided into five bays with four T-shaped ring-stiffeners. The R/t ratio was 120.92.

The finite element model was created with the techniques described in previous sections. The geometric model was meshed with S4R shell elements, with a global mesh size of 80 mm. The initial imperfection shape was taken as the first eigenvalue buckling mode, shown in Fig. 14. After calibrating with the simple ultimate strength formula, the imperfection magnitude was taken as 6.05 mm. The boundary conditions were the same as in the benchmarking study.

For this model, first, a series of finite element analyses that varied the dent depth were conducted. The range of d/D was determined by examining the collision database given in [10] for floating offshore structures and supply vessels and taken as 0.01 to 0.08 in 0.01 increments. The dent was applied through a knife-edged indenter with a 45° edge angle and a 50 mm tip radius. The knife-edged indenter was modelled as a rigid surface. In Fig. 15, the axial shortening curves for the intact case and each damaged case are shown.

It is evident from Fig. 15 that the presence of the dent significantly affected the collapse behaviour of the ring-stiffened cylinder model. In the pre-buckling stage, the response was linear. In damaged condition, contrary to the intact case, earlier buckling leads to a decrease in stiffness, followed by a collapse after the ultimate strength was reached. The ultimate strength was not reduced to any great extent, as the dent depth increased, i.e. the shell was still able to retain considerable axial loading in its damaged condition. The increase in the dent depth did not appreciably alter the end-shortening response. The post-collapse shapes of an intact cylinder and a damaged cylinder are compared in Fig. 16. It is clear that both models failed via asymmetric shell buckling.

The fluctuations in force–displacement response after collapse indicate the gradual formation of buckles around the circumference. The dents lead to the redistribution of axial stresses around the circumference, in which an early yielding occurs adjacent to the dent, leading to outward bulging of the shell close to the dent zone. Periodic axial stress distribution caused

rapid formation of inward and outward periodic diamond-shape lobes. This process is illustrated in Fig. 17.

The progressive collapse behaviour was further clarified by examining the axial compressive stress distribution around the circumference at various stages of the loading, as shown in Fig. 18. Here, 0° corresponds to the dent location. From Fig. 18, it can be inferred that very little axial load is carried by the flattened dent zone. Moreover, there are high stress concentrations near the ends of the dent zone, which gradually reduce to a uniform value for the remainder of the circumference. High compressive stresses adjacent to the dent zone are balanced with tensile stresses in the dent zone. In the post-collapse regime, the periodic axial stress distribution is noticeable.

To clarify the effect of the damage shape on the strength reduction, additional analyses were conducted, where the damage was induced using hemispherical indenters. The indenters had various hemisphere radii over the stiffener spacing ratio (r/l). For several dent depths, a comparison was made with damage induced using a knife-edged indenter. The main difference in these two cases was that after knife-edged indenter-induced denting, there was a more pronounced flattening of the circumferential cross-section, while the hemispherical indenter resulted in more longitudinal damage. In Fig. 19, the ratio of the ultimate strength in damaged condition σ_{xu} over the one in intact condition $\sigma_{xu,i}$ is shown for various dent sizes and indenters. As is apparent from Fig. 19, the longitudinal damage does not have a considerable effect on strength reduction. The knife-edged induced dents caused larger flattening, thus, a larger reduction in the ultimate strength. This confirms that flattening around the circumference is the governing factor in ultimate strength reduction of cylindrical shells under axial compression.

Lastly, the influence of cylinder slenderness on ultimate strength reduction was investigated. For this purpose, the thickness of the reference cylinder model was varied. In total, four

additional cases were considered. The resulting ratios of ultimate strength in damaged condition σ_{xu} over ultimate strength in intact condition $\sigma_{xu,i}$ are shown in Fig. 20. From Fig. 20, it can be concluded that the R/t ratio had a significant influence on the strength reduction of ring-stiffened cylinders. Since in ring-stiffened cylinders only unstiffened shell segments carry the axial load, the reduction in ultimate strength is sensitive to the shell slenderness, i.e. slender shells experience a larger reduction of strength from damage. Despite the higher susceptibility of slender cylinders to strength reduction, for the range of d/D considered in this study, even in the most severe cases the strength reduction was not more than 35%.

Based on the results calculated for the reference ring-stiffened cylinder model, a closed-form formula may be derived empirically by regression analysis to predict the reduction factor $R_{xu,r}$ as follows:

$$R_{xu,r} = \frac{\sigma_{xu}}{\sigma_{xu,i}} = C_1 \left(\frac{d}{D} \right)^2 + C_2 \left(\frac{d}{D} \right) + 1 \quad (6)$$

where

$$C_1 = -0.0075 \left(\frac{R}{t} \right)^2 + 0.9801 \left(\frac{R}{t} \right) + 163.913 \quad (7)$$

$$C_2 = 0.0935 \left(\frac{R}{t} \right) - 25.223 \quad (8)$$

5.2 Orthogonally stiffened cylinder

The second target structure was an orthogonally stiffened cylindrical shell of a TLP column, as given in [50]. The dimensions and material properties of the model are shown in Table 7.

The cylinder was divided into three bays with two ring-stiffeners. The cylinder radius was much larger than the radius of the ring-stiffened cylinder model investigated in the previous section. Sixty stringers provided additional axial stiffness and strength to the cylinder shell.

The ring-stiffeners and the stringers had T-sections.

The created finite element model had a global mesh size of 150 mm. Prior to eigenvalue buckling analysis; the thickness of the cylinder shell in the outer bays was artificially increased, to trigger buckling in the mid-bay. The initial imperfection shape was then taken as the first eigenvalue buckling mode obtained from this analysis, as shown in Fig. 21. After calibrating with the simple ultimate strength formula, the imperfection magnitude was assumed to be 10 mm. The analysis procedures were same as in the benchmarking study.

A series of finite element analyses were performed, varying the dent depths. In Fig. 22, the axial shortening curves for the intact case and each damaged case are shown. In Fig. 22, it is demonstrated that the collapse behaviour of the orthogonally stiffened cylinder considered in this study is not sensitive to local damage. Due to the large axial bending stiffness of the stringer-stiffened shell wall, compared with the unstiffened monocoque shell segments of the ring-stiffened cylinder model, the collapse was not sudden and the post-collapse behaviour was stable. The reduction in the ultimate strength did not increase significantly with increasing the dent depth.

Fig. 23 shows the variation of the ultimate strength of the models for various R/t (only shell thickness is varied) and as a function of d/D . From Fig. 23, it can be inferred that the strength reduction did not vary considerably with shell slenderness. This might be attributed to the effect of the stringers, as they carry significant axial load as beam-column elements and are not individually affected by the damage unless positioned closely to the damaged zone. An empirical expression for the reduction factor $R_{xu,o}$ of the orthogonally stiffened cylinder model considered in this study can be obtained by regression analysis:

$$R_{xu,o} = \frac{\sigma_{xu}}{\sigma_{xu,i}} = 14.25 \left(\frac{d}{D} \right)^2 - 2.333 \left(\frac{d}{D} \right) + 1 \quad (9)$$

The cylinder shapes after collapse, in intact and damaged condition ($d/D = 0.05$), are shown in Fig. 24. In both cases, lobular buckles develop in the mid-bay of the cylinder, coupled with the tripping of the stringers.

The axial stress distribution at various stages of the loading is shown in Fig. 25. In this figure, the contours indicate axial stress σ_x . It is apparent that the shell and stringers in the dented zone were ineffective at carrying axial load, while the undamaged sections remained unaffected and gave a similar response to the intact cylinder. Since the stringers were sturdy, shell buckling was observed in the undamaged segments of the model. The damaged stringers, with their attached plating, were bent inward and carried little axial load. It should be noted that the stringers prevented the spreading of damage. However, as shown in Fig. 13 for 3B3, this might not be the case, if the cylinder shell is stiffened with relatively light stringers and the ring-stiffeners are not closely spaced.

6. Concluding remarks

The aim of this study has been to assess the validity of the proposed nonlinear finite element analysis procedure for the ultimate strength prediction of damaged stiffened cylinders under axial compression and to perform further investigations on the collapse behaviour, the effects of damage size and the strength reduction characteristics. Based on the results developed from the present study, the following conclusions can be drawn:

- The proposed nonlinear finite element analysis procedure is capable of predicting the ultimate strength of locally damaged stiffened cylinders with a reasonable degree of accuracy. Furthermore, general features of the experimental behaviour can be reproduced satisfactorily using the presented numerical analysis methodology. Scope exists for further parametric studies.
- The depth of the denting and the extent of the segment flattening are the most significant

parameters in predicting strength reduction, not the extent of the longitudinal damage. From the close agreement between the numerical and the experimental results, it can be concluded that strength reduction is primarily a result of geometrical distortion from denting.

- In ring-stiffened cylindrical shells under axial compression, the presence of local damage causes a redistribution of the axial stresses and triggers asymmetrical shell buckling in the lobular mode. In end-shortening curves, no significant change in the stiffness prior to collapse and sudden drop in the force were observed. This indicates that the collapse is sudden and catastrophic.
- For the range of damage encountered in the historical records from the collisions between supply vessels and floating offshore structures, for both the ring- and orthogonally stiffened cylinders considered in this study, the residual strength does not decrease significantly with increasing dent depth.
- In ring-stiffened cylinders, the residual strength is influenced by the shell slenderness. As R/t increases, the effect of damage on the load carrying capacity is more severe.
- For the orthogonally stiffened cylinders considered in this study, owing to the sturdiness of the stringers, the strength reduction is not drastic; in the worst case, it is not more than 12%. The damaged stringers become ineffective in carrying the axial load, however, the remaining stringers – with their attached plating – are not affected by the damage and the collapse behaviour remains essentially similar to the intact cylinder collapse.

In addition to axial compression, the buoyancy columns of floating offshore installations are subjected to external pressure, as well as to longitudinal bending. Further studies are required

398 for these different types of loads and the combinations thereof. Moreover, the dent depth range
399 considered in the present study does not result in the rupture of the cylinder shell. The residual
400 strength assessment of perforated stiffened cylinders is recommended for future study.

Appendix A

Ultimate strength of ring-stiffened cylinders under axial compression

Das et al. [3] provide the following formulations for the calculation of ultimate strength of ring-stiffened cylinders subjected to axial compression.

The elastic buckling stress of an imperfect ring-stiffened cylinder:

$$\sigma_e = B\rho_n C\sigma_{cr} \quad (\text{A.1})$$

where σ_{cr} is the classical buckling stress for a perfect thin cylinder is given by

$$\sigma_{cr} = \frac{1}{\sqrt{3(1-\nu^2)}} \frac{Et}{R} \quad (\text{A.2})$$

Z_l is Batdorf parameter and given as

$$Z_l = \frac{l^2}{Rt} \sqrt{1-\nu^2} \quad (\text{A.3})$$

C is length dependent coefficient

$$C = \begin{cases} 1 & ; Z_l \geq 2.85 \\ \frac{1.425}{Z_l} + 0.175 & ; Z_l < 2.85 \end{cases} \quad (\text{A.4})$$

ρ_n is the nominal or lower bound knock-down factor to allow for shape imperfections

$$\rho_n = \begin{cases} 0.75 - 0.142(Z_l - 1)^{0.4} + 0.003Z_l & ; 1 \leq Z_l < 20 \\ 0.35 - 0.0003 \frac{R}{t} & ; Z_l \geq 20 \end{cases} \quad (\text{A.5})$$

B is the mean bias factor assessed from elastic test data that compensates for the lower bound nature of ρ_n

$$B = \begin{cases} 1.3 & ; \lambda_n \geq 1 \\ 1 + 0.3\lambda_n & ; \lambda_n < 1 \end{cases} \quad (\text{A.6})$$

λ_n is the nominal slenderness parameter

$$\lambda_n = \sqrt{\frac{\sigma_Y}{\rho_n C \sigma_{cr}}} \quad (\text{A.7})$$

420 A quadratic interaction of $\lambda\sigma_Y$ and σ_e can be used to predict the inelastic collapse stress

421 $\sigma_c = \phi\sigma_Y$ (A.8)

422 where

423 $\phi = \frac{1}{\sqrt{(1 + \lambda_e^4)}}$ (A.9)

424 Slenderness parameter

425 $\lambda_e = \sqrt{\frac{\sigma_Y}{\sigma_e}}$ (A.10)

Appendix B

Ultimate strength of orthogonally stiffened cylinders under axial compression

For ultimate strength assessment of orthogonally stiffened cylinders subjected to axial compression, Das et al. [46] propose the following formulations.

Elastic buckling stress for perfect curved panel of mean radius R , arc length s (stringer spacing):

$$\sigma_{cr} = \begin{cases} 0.904E \left(\frac{t}{s} \right)^2 \left(4 + \frac{3Z_s^2}{\pi^4} \right) ; Z_s \leq 11.4 \\ 0.605E \left(\frac{t}{R} \right) ; Z_s > 11.4 \end{cases} \quad (\text{B.1})$$

Batdorf parameter:

$$Z_s = \frac{s^2}{Rt} \sqrt{1 - \nu^2} \quad (\text{B.2})$$

Knockdown factor:

$$\rho_n = \begin{cases} 1 - 0.019Z_s^{1.25} + 0.0024Z_s \left(1 - \frac{R}{300t} \right) ; Z_s \leq 11.4 \\ 0.27 + \frac{1.5}{Z_s} + \frac{27}{Z_s^2} + 0.008\sqrt{Z_s} \left(1 - \frac{R}{300t} \right) ; 11.4 < Z_s \leq 70 \end{cases} \quad (\text{B.3})$$

Bias for the mean knockdown factor:

$$B = \begin{cases} 1.25 ; \lambda_n > 1 \\ 1 + 0.25\lambda_n ; \lambda_n \leq 1 \end{cases} \quad (\text{B.4})$$

$$\lambda_n = \sqrt{\frac{\sigma_Y}{(\rho_n \sigma_{cr})}} \quad (\text{B.5})$$

Mean knockdown factor:

$$\rho = B\rho_n \quad (\text{B.6})$$

Elastic buckling stress for imperfect shell:

$$\sigma_{icr} = \rho\sigma_{cr} = B\rho_n\sigma_{cr} \quad (\text{B.7})$$

Weld induced tension residual stress block parameter in shell:

$$\eta = \begin{cases} 4.5 & \text{; for continuous structural fillet welds} \\ 3.0 & \text{; for light fillet welds} \\ 0 & \text{; for stress - relieved structure} \end{cases} \quad (\text{B.8})$$

Residual stress reduction factor:

$$R_r = \begin{cases} 1 - \left[\frac{2\eta}{(s/t - 2\eta)} \frac{\lambda^4}{(1 + 0.25\pi^4)^2} \frac{\lambda^2}{(1.05\lambda - 0.28)} \right] & ; \lambda > 0.53 \\ 1 & ; \lambda \leq 0.53 \end{cases} \quad (\text{B.9})$$

Shell reduced effective width (minimum) and shell effective width (minimum):

$$\frac{s'_{em}}{s} = \begin{cases} 1 & ; \lambda \leq 0.53 \\ \left(\frac{0.53}{\lambda} \right) R_r & ; \lambda > 0.53 \end{cases} \quad (\text{B.10})$$

$$\frac{s_{em}}{s} = \begin{cases} 1 & ; \lambda \leq 0.53 \\ \left(\frac{1.05}{\lambda} - \frac{0.28}{\lambda^2} \right) R_r & ; \lambda > 0.53 \end{cases} \quad (\text{B.11})$$

Elastic critical stress for column-shell combination:

$$\sigma_e = \frac{\pi^2 E I_e}{l^2 (A_s + s_{em} t)} + \rho_s \frac{0.605 E (t/R)}{1 + A_s / s_{em} t} \quad (\text{B.12})$$

where

$$I'_e = I_s + \left(\frac{A_s (z_s + t/2)^2}{1 + A_s / s'_{em} t} \right) + \frac{s'_{em} t^3}{12} \quad (\text{B.13})$$

$$\psi = \frac{\sigma_e}{\sigma_Y} \quad (\text{B.14})$$

The knockdown factor ρ_s is assumed 0.75. Inelastic buckling stress using Ostenfeld-Bleich structural tangent modulus approach:

$$\sigma_{ic} = \begin{cases} [1 - p_s (1 - p_s) / \psi] \sigma_Y & ; \psi \geq p_s \\ \psi \sigma_Y & ; \psi < p_s \end{cases} \quad (\text{B.15})$$

$$p_s = \frac{\sigma_{ps}}{\sigma_Y} \quad (\text{B.16})$$

$p_s = 0.5$ in general; 0.75 for stress-relieved structures.

460 Revised shell reduced slenderness parameter and effective width of shell:

$$461 \quad \lambda_e = \sqrt{\frac{\sigma_{ic}}{\sigma_{icr}}} = \lambda \sqrt{\frac{\sigma_{ic}}{\sigma_Y}} \quad (\text{B.17})$$

$$462 \quad \frac{s_e}{s} = \begin{cases} 1 & ; \lambda < 0.53 \\ \left(\frac{1.05}{\lambda} - \frac{0.28}{\lambda^2} \right) R_r & ; \lambda \geq 0.53 \end{cases} \quad (\text{B.18})$$

463 Average ultimate collapse stress:

$$464 \quad \sigma_u = \sigma_{ic} \left(\frac{A_s + s_e t}{A_s + s t} \right) \quad (\text{B.19})$$

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Tables

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

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

Table 3. Ultimate strength values of the ring-stiffened cylinder specimens dented at the mid-bay.

	CY-2	CY-3	CY-4	CY-5
Test result (MPa)	258	267	264	212
FEA result (MPa)	242.8	280.7	238.1	182.1
Bias (Test / FEA)	1.062	0.951	1.109	1.164

Table 4. Ultimate strength values of the ring-stiffened cylinder specimens dented at the ring-stiffener.

	CY-6	CY-7	CY-8	CY-9
Test result (MPa)	258	253	224	228
FEA result (MPa)	238.5	233.5	239.7	238.6
Bias (Test / FEA)	1.082	1.084	0.935	0.955

Table 5. Ultimate strength values of the orthogonally stiffened cylinder specimens.

	3B1	3B2	3B3	3B4
Test result (MPa)	318	277	202	195
FEA result (MPa)	305.0	268.5	194.8	183.2
Bias (Test / FEA)	1.043	1.032	1.037	1.065

Table 6. Properties of the ring-stiffened model considered in this study.

Property		Value
Cylinder radius (mm)	R	3023
Shell thickness (mm)	t	25
Ring-stiffener spacing (mm)	l	3048
Total cylinder length (mm)	L	15240
Number of ring-stiffeners	n_R	4
Ring-stiffener web height (mm)	h_{rw}	214
Ring-stiffener web thickness (mm)	t_{rw}	11
Ring-stiffener flange width (mm)	w_{rf}	280
Ring-stiffener flange thickness (mm)	t_{rf}	17
Yield strength (MPa)	σ_Y	345
Young's modulus (GPa)	E	200

Table 7. Properties of the orthogonally stiffened model considered in this study.

Property		Value
Cylinder radius (mm)	R	8880
Shell thickness (mm)	t	25
Ring-stiffener spacing (mm)	l	2200
Total cylinder length (mm)	L	6600
Number of ring-stiffeners	n_R	2
Number of stringers	n_S	60
Stringer web height (mm)	h_{sw}	300
Stringer web thickness (mm)	t_{sw}	15
Stringer flange width (mm)	w_{sf}	190
Stringer flange thickness (mm)	t_{sf}	19
Ring-stiffener web height (mm)	h_{rw}	525
Ring-stiffener web thickness (mm)	t_{rw}	25
Ring-stiffener flange width (mm)	w_{rf}	300
Ring-stiffener flange thickness (mm)	t_{rf}	30
Yield strength (MPa)	σ_Y	345
Young's modulus (GPa)	E	200

Figures

Fig. 1. Geometrical parameters.

CY-2

CY-4

CY-6

CY-8

3B1

3B3

Fig. 2. Geometric models of the test specimens.

Fig. 3. Finite element mesh of the models.

Fig. 4. Stress-strain curves for the material of CY-2.

Fig. 5. Finite element analysis setup for inducing damage to specimens.

Fig. 6. Deformed shape and cross-section of CY-4.

Fig. 7. Idealised deformed cross-section.

Fig. 8. Finite element analysis setup for post-damage collapse analysis.

Fig. 9. Procedure for assessment of residual strength.

Fig. 10. Numerical predictions compared with experimental test results.

Fig. 11. Distribution of the modelling uncertainty factor as function of dent depth.

Fig. 12. Axial shortening curves of the orthogonally stiffened cylinder specimens.

Fig. 13. Post-collapse shape of the test specimens as obtained from numerical analysis.

Fig. 14. Initial imperfection shape of the ring-stiffened cylinder model.

Fig. 15. Axial shortening curves of the ring-stiffened cylinder model for various dent depths.

Fig. 16. Post-collapse shape of (a) intact and (b) damaged ($d/D = 0.005$) ring-stiffened cylinder models.

Fig. 17. Deformed cross-section of ring-stiffened cylinder model after collapse.

Fig. 18. Axial stress distribution at various stages of collapse analysis.

Fig. 19. Reduction in ultimate strength for various damage sizes.

Fig. 20. Reduction in ultimate strength of the ring-stiffened cylinder models under axial compression as function of dent depth.

Fig. 21. Initial imperfection shape of the orthogonally stiffened cylinder model.

Fig. 22. Axial shortening curves of the orthogonally stiffened cylinder model for various dent depths.

Fig. 23. Reduction in ultimate strength of orthogonally stiffened cylinder models under axial compression as function of dent depth.

Fig. 24. Post-collapse shape of (a) intact and (b) damaged ($d/D = 0.005$) orthogonally stiffened cylinder models.

Fig. 25. Response stages of a damaged orthogonally stiffened cylinder subjected to axial compression.