A theoretical and experimental investigation of externally ring-stiffened cylindrical pressure vessels subjected to external pressure

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Historically, the main use for submarines has been for military purposes, but the need to discover new sites of mineral and fuel deposits means that civil uses of submarines and submarine structures is of paramount importance. To allow structures to survive at greater depths, the two factors that will allow its pressure hull to withstand the increased pressures are its shape and the material used for construction. Another consideration however is that of density so that the submarine can resurface.

Vessels subjected to external pressure fail by lobar buckling, long before the onset of axisymmetric yield. This makes the prediction of failure more difficult, and its onset difficult to identify, and subsequently avert. Each lobar form has its own theoretical buckling pressure, and the form that occurs at the lowest buckling pressure is of primary concern. However, subsequent forms too are also of interest, especially if they are close to the fundamental as the mode, and/or are similar to modes of vibration to which the vessel is subjected.

Traditional submarine pressure hulls are made from steel cylinders reinforced with circumferential stiffening rings welded to the inside. Without these stiffening rings buckling of the shell would occur at pressures of only a fraction of that required to cause axisymmetric yield of the structure. Other novel shapes and materials have been investigated which show potential benefits. However, they introduce some significant design challenges (Little and Ross 1999).

Studies of cylinders under external pressure show that geometric aberrations can adversely affect the performance of pressure vessels under external pressure. Consequently, large safety factors have been used to ensure a safe design. Charts which identify a safe design area have been proposed (Little et al 2008) which are less conservative, yet still effective in the prediction of buckling.

In this study, two sets of UPVC ring-stiffened cylinders with the same stiffener details were investigated in terms of their resistance to buckling. Three were nominally 164 mm long and the other two were 243 mm (five in total), and the inside diameter was approximately 230 mm. Rigid flat ended steel closure plates with O-rings were used to seal the ends of the vessel.

Thorough finite element analyses were carried out using two very different programs. These were Ansys and an in-house axisymmetric shell programme called CONBUCR. In Ansys, the shell of the ring-stiffened vessel was modelled using the SHELL93 element, which is an 8-node quadrilateral structural shell element. It has six degrees of freedom at each node. The stiffeners were modelled with the BEAM44 element, which is an elastic tapered beam with an offset.

CONBUCR was originally written in BASIC (Ross 1984). It is based on truncated conical, axisymmetric elements with two nodal circles at each end; each node had four degrees of freedom, ie 8 per element. This program has been modified to enable additional stiffness to be added at each node,
and can therefore be used to analyse ring-stiffened axisymmetric structures, and it can do so with far fewer elements than if shell elements (such as the Shell93) have to be used.

Finite element models were made of the “long” and the “short” vessels, and two types of end restraints were applied to each vessel, to simulate the closure plates. The initial out-of-roundness of the vessels was measured and all were shown to have an initial out-of-circularity in the order of 0.159 mm. This value of out-of-roundness is relatively small compared to the diameter. The closure plates were fitted to each vessel in turn, prior to installation within the pressure tank. An electric pump was used to gradually pressurise the tank. The pressure was monitored continuously, throughout the test, and failure was indicated by a drop in pressure.

The finite element programs were able to predict the fundamental buckling pressure of a vessel with complex ring-stiffened geometry together with the mode of buckling. The CONBUCR results for the “simply supported” cases are the most variable, in that they showed greater variation from the other predictions as well as from the experimental results. This indicates that the “clamped” ends case describes the actual conditions better than the “simply supported” case. CONBUCR with “clamped” ends gave values that were extremely close to the actual buckling pressures for all vessels. Ansys predicted higher buckling pressures than CONBUCR, which would result in slightly more conservative designs.

Variations of the end fixings (simply supported and clamped) applied to the finite element models were shown to cause greater differences in predicted buckling pressure for the cases with a lower number of circumferential lobes. However, these variations occurred at pressures significantly higher than the predicted fundamental (lowest) buckling pressure. The differences in predicted buckling pressures decreased as the pressure decreased to the fundamental buckling mode (number of lobes). At the lowest buckling pressure prediction, the differences for the simply supported and clamped ends were reasonably small, the greatest being 0.51 MPa results. This figure reduces to 0.33 MPa for the “clamped” cases. A fundamental (lowest) buckling pressure, forming four lobes was predicted by all of the analyses, except for the “simply supported” CONBUCR analysis of the 12 ring vessel. This case predicted failure when n=3, but the pressures for the n=4 and the n=3 cases were very close (1.11 and 0.96 MPa respectively). The experimental results were pleasingly consistent and the finite element prediction of the buckling pressures agreed reasonably well with the testing. The analyses with “clamped” ends are believed to be more accurate than the “simply supported” case, and here the CONBUCR programme for “clamped” ends agreed very closely with the experimental results. The differences between the two types of restraints were not as marked for the Ansys analyses. The experimental results were all very consistent for buckling tests. This combined with the close predictions of the fundamental buckling pressure by CONBUCR (clamped) indicates that the effects of geometric aberrations were probably small.

References