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Buckling of externally pressurized steel toriconical shells

J. Błachut

The University of Liverpool, School of Engineering, Liverpool L69 3GH, UK

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ABSTRACT

The inclusion of toroidal (knuckle) segment between cylinder and conical vessel end closure is a natural way for diffusing the stress jump at the junction. But there is very little experimental data in support of the knuckle's role and its influence. Hence eight steel toriconical shells have been buckled by quasi-static external pressure in order to measure this problem. Diameter of all models was 200 mm at the base and their wall thickness was 2 mm. The apex semi-angle was 45 deg for all shells. Experimental buckling pressures varied from 3.9 MPa to 4.4 MPa despite large variations in shape. Comparisons of experimental failure pressures with numerical predictions based on several approaches to modelisation are given. The latter are based on axisymmetric modelling as well as on measured geometry and wall thickness. The ratio of experimental to numerical failure loads varies from 1.05 to 1.16.

1. Introduction

Thin-walled shells of revolution are frequently used as pressure vessels, silos, liquid storage tanks, buoyancy units, etc. In a typical configuration they are built from cylindrical shell capped by two end closures. The end closures can take different shapes ranging from flat plates to domed ends. The latter can include spherical caps, hemispherical, ellipsoidal, torispherical or toriconical geometries. Typical loading conditions such domes are subjected to include internal or external pressure (vacuum). The load carrying capacity of some of these shells can be affected by buckling and this constitutes one of design limitations. It is known that the load carrying capacity of domed ends strongly depends on their geometry, boundary conditions, material behaviour, type of applied load and the presence, or absence, of initial geometric imperfections. Despite of decades of research effort not all aspects of buckling of domed end closures are fully understood and/or codified for practical use. Wealth of information on buckling of domed ends exists and it can be found, for example, in Refs. [1–5], where it becomes clear that over the recent decades testing methods have improved, they have become more focused. Rigorous computational models have also been developed. Refs [1,2], for example, provide a thorough review of experimental techniques and give buckling data for various structural components (including domed ends). Buckling of externally pressurized torispherical heads have been studied numerically and experimentally in Refs. [3,4] for a range of geometries and material properties. Recent review paper, Ref. [5], addresses different aspects of structural behaviour of domed ends – including buckling and their structural optimization. Many aspects of design methodology for variety of domed ends have been codified and they are available in the form of design codes, Refs [6–8].

Background information on internally pressurized toricones can be found in Refs. [9–11] with static stability being addressed in Ref. [12]. Information on externally pressurized toriconical shells, on the other hand, is rare. Early experimental work into buckling of externally pressurized toriconical shells is reported in Ref. [13]. Five toricones (137 mm base diameter), were machined from high-strength aluminium with their semi-vertex angle being, $\beta = 35°$, $45°$, and $60°$. The knuckle-radius, r, to diameter, D, ratio was in all five models kept the same, i.e., $r/D = 0.20$. Models had cylindrical portions and they were capped by the toricones of the same geometry at both ends. The diameter to wall thickness ratio, (D/t), was equal to 100. Apart from test data, discussion of numerical estimates based on early FE algorithms are also included. Results of numerical studies of elastic-plastic buckling of cylinders with toriconical heads are available in Ref. [14], and with additional results given in Ref. [15].

The current paper provides test data and the corresponding theoretical/numerical results for buckling of externally pressurized mild steel toricones.

E-mail address: em20@liverpool.ac.uk.

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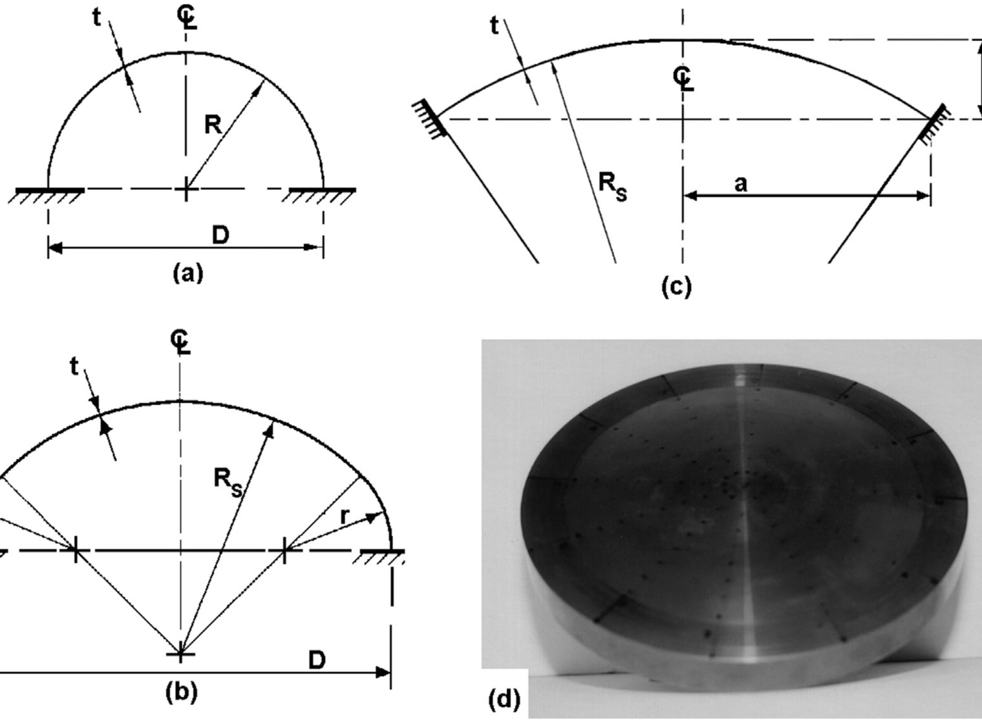

Fig. 1. Geometry of typical domed ends (a,b,c), and view of shallow mild steel spherical cap (d).

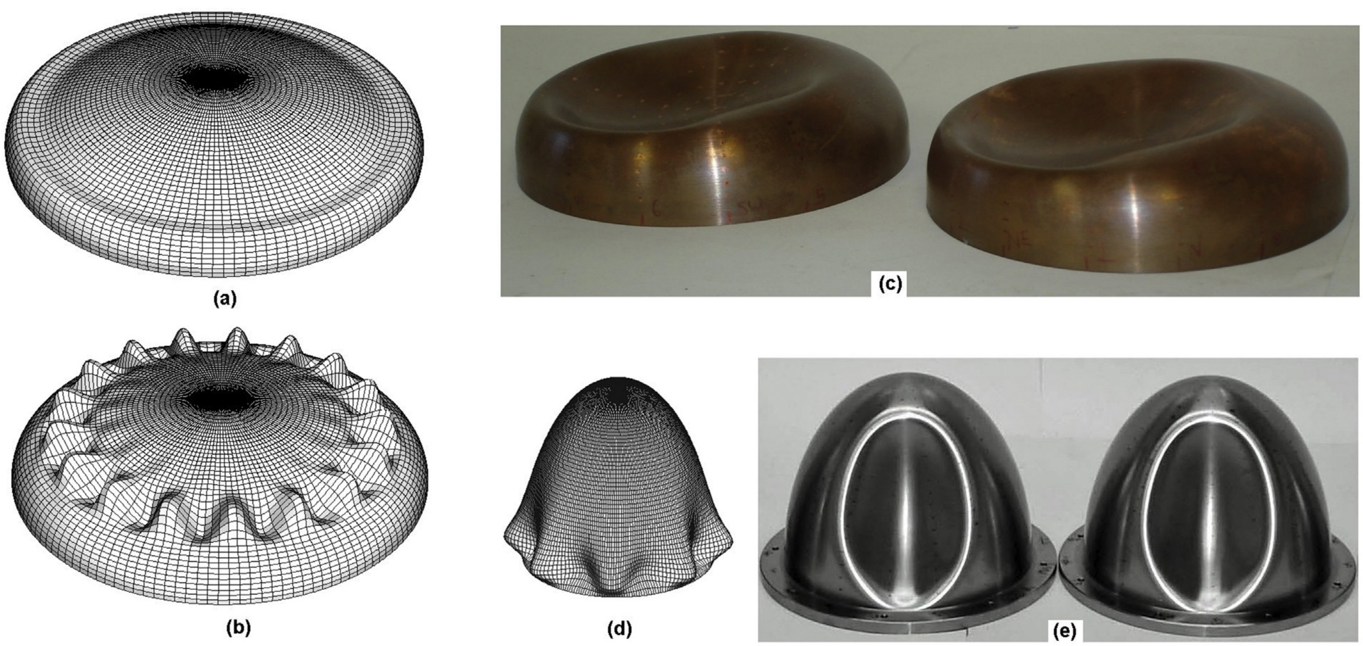

Fig. 2. Computed failure modes and photographs of tested models – all cases subjected to external pressure.

2. Buckling of externally pressurized domes – brief background

As mentioned earlier, typical geometries of end closures onto cylindrical vessel can include: torisphere, toricone, hemisphere, spherical cap, ellipsoids of prolate/oblate profiles of the generator, or flat plate. Externally pressurized hemispherical and torispherical domes have been relatively widely researched. Toricones, on the other hand, have received little attention. Consider three typical heads, as sketched in Fig. 1, hemisphere, torisphere, and spherical cap in order to highlight issues surrounding their buckling behaviour. Assume that all three have uniform wall thickness, t, all are clamped at the base and subjected to uniform external pressure, p. Under incremental loading the torispherical shell will deform as illustrated in Fig. 2a. Most of the spherical portion will remain in a membrane state whilst in the transition region from spherical