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Locally flattened or dented domes under external pressure

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ABSTRACT

The paper provides comparisons of sensitivity of buckling pressures to initial shape imperfections, for the case of externally pressurised steel domes. A priori defined deviations from perfect shape include: Legendre polynomials, increased-radius patch, and localised inward dimple. The latter is created by a concentrated force acting radially. In this case the effects of spring back and/or annealing of the dented patch and the surrounding area on the load carrying capacity are assessed. Some of the elastic solutions related to the lower-bound approach are compared with the available experimental data.

1. Introduction

The quest for oil/gas and other natural resources has pushed the underwater exploration to deeper and deeper environment. Fig. 1 depicts the range of current and planned exploration as the percentage access to the ocean floor bed. Plans for exploration for up to 3 km (zone '**C**' in Fig. 1) are currently being actively pursuit, Refs. [1–4]. Several manned vehicles capable of exploring deep-sea (6 km), have been developed within the last few decades and they are indicated in Fig. 1. Freshly added to this list is JIAOLONG vehicle rated at 7 km depth, Ref. [5]. Pulse-waves generated by controlled implosion of buoyancy units are also actively studied as a part of new warfare (assault and/or protection of existing subsea assets), Refs. [6–8]. One of the bottle-neck in wider underwater activities is the availability of buoyancy units. This is especially true at greater ocean depth. There are two approaches to buoyancy units. In the first one, the buoyancy is provided by foams. It appears that by-and-large the necessary foam-based buoyancy units have been obtained. This can be seen, for example, in the case of DeepSea Challenger where the foam was successfully used as buoyancy during the full ocean depth dive in 2012 (11 km), Ref. [9]. The second type of buoyancy unit is of 'the-vessel-type' frequently referred to as pressure hull. As yet this type of buoyancy unit is not readily available. Geometry of the hull can take different shapes as this depends on applications. Typically these could be cylinders capped by domed closures – see Refs. [10–13], spheres – see Refs. [14,15], or closed toroids, Refs. [16,17]. One of critical issues when designing externally pressurised cylinders and/or doubly curved shells is the sensitivity of their buckling pressure to initial geometric imperfections. Search for sensitivity of buckling loads to initial geometrical imperfections has resulted in an enormous research effort for many of recent decades. Some results related to imperfect domes subjected to external pressure can be found in Refs. [13,18–21]. In order to ascertain sensitivity of buckling pressure to initial deviations from perfect shape one has to decide what these shape deviations are, i.e., how they are defined, where they are positioned, what the maximum amplitude of imperfection is, etc. The above questions still remain open ones. Over the years a number of approaches to modelling shape of initial geometric imperfections have been tried. The shape which reduces the buckling strength the most has always been sought as this would allow the designer to plan for the worst possible scenario. The imperfections in fabricated domes will be distributed randomly and will normally consist of dimples and increased-radius flat spots of various sizes. The analysis is much simpler if the imperfections can be assumed to be axisymmetric. The actual localised initial imperfections may be at the apex (axisymmetric) or away from the pole. In the latter case, it still seems reasonable to assume axisymmetric behaviour if the imperfection is not too near the clamped edge (hemisphere) or not too near the spherical cap/knuckle junction in torispherical shell.

The most frequently adopted forms of initial geometric imperfections include shapes: (i) affine to eigenmode, and (ii) local flattening associated with the increased radius. Another possibility would be an inward dimple created by a concentrated force (Force-Induced-Dent, FID). This approach has been vigorously pursuit for axially compressed cylindrical shells manufactured by filament winding of carbon fibre (with epoxy resin being the binding agent), Refs. [22,23]. Inward dent, representing imperfection, was created by force acting radially and was placed in the middle of cylinder's length. Detailed and comprehensive experimental data was obtained for cylinder's geometry given by $D/t=500$ and $L/R=2$.

The aim of this paper is to explore possible advantages of this

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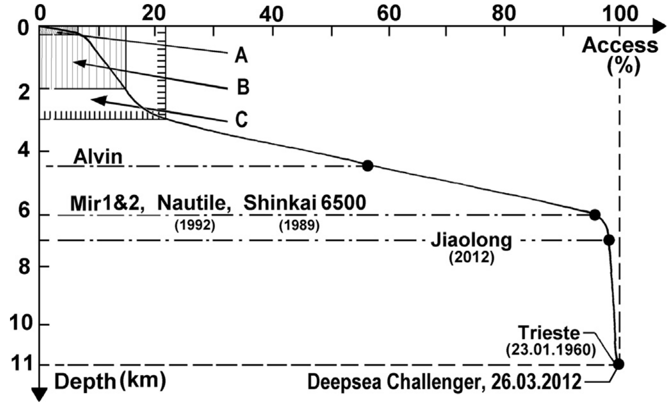

Fig. 1. Current and planned activities at sea bottom (Fig. 1a, A≡North Sea; B≡Gulf of Mexico, Nigeria, Brazil; C≡2020 Horizon research). Also, milestones in depth access by humans.

approach when used in externally pressurised domed ends. Previously used methods for ascertaining imperfection sensitivity are reviewed/expanded, and response of buckling pressures to Force-Induced-Dimples is studied in detail.

The next sections discuss these issues for the case of externally pressurised torispherical, hemispherical and/or spherical cap end closures made from mild steel.

2. Preliminaries – buckling of geometrically perfect domes

This section briefly outlines buckling of externally pressurised, and geometrically perfect domes. The domes are to be taken as torispherical or hemispherical shells – both frequently found as closures of the cylindrical portion of underwater vehicles, buoyancy units, liquid oxygen/hydrogen tanks in aerospace, as well as bulkheads in the second stage LOX tanks. In all of the ensuing computations the following two codes were used: ABAQUS, and BOSOR5, Refs. [24,25].

As an illustration, consider a torispherical head, see Fig. 2a, with its geometry given by the diameter-to-thickness ratio, $D/t=1000$, the knuckle radius-to-diameter ratio, $r/D=0.10$, the spherical-radius-to-diameter ratio, $R_s/D=1.0$, and subjected to uniform external pressure, p. Let the torisphere be manufactured from steel with $E=210$ GPa, $\nu=0.3$, and the yield point of material, $\sigma_{yp}=350$ MPa. Assume that the dome is fully clamped at its equatorial edge. Pre-buckling shape of this externally pressurised torisphere is shown in Fig. 3a. This shell is able to support external pressure for up to a certain magnitude at which the axisymmetric deformation, seen in Fig. 3a, suddenly changes its shape. This pressure, corresponding to an eigenvalue, is also known as bifurcation pressure, p_{bif}. Its magnitude in the current case is, $p_{bif}=0.126$ MPa. Fig. 3b depicts eigenshape, i.e., the shape at pressure equal to bifurcation, and which has $n=17$ circumferential waves. The corresponding FE models are shown in Fig. 3c and d. Fig. 3c shows axisymmetric shape just prior to buckling whilst Fig. 3d illustrates the eigenshape at buckling pressure. The influence of the (D/t)-, (R_s/D)-, and (r/D)-ratios on buckling performance of steel torispheres was addressed in Ref. [26], where results of a wide parametric study are given. A number of design rules for externally pressurised domed ends have been developed – available, for example, in Refs. [27–29]. They make various provisions for initial geometric imperfections. But there is still no convincing argument which approach is the best. The current paper is the extended and revised version of conference contribution, Ref. [30]. The next section outlines some possibilities, including the increased-radius local flattening as a possible worst scenario approach to design.

3. Buckling of geometrically imperfect domes – axisymmetric models

3.1. Increased-radius patch

One of possible imperfection profiles studied in the past is the increased-radius flattening patch – *as sketch*ed in Fig. 2b, see Refs. [19,20]. It is characterised by arc length over which radial imperfections are measured, s_{imp}, and the radius of imperfect portion of torispherical or hemispherical shell, R_{imp}. The relation between the amplitude of the imperfection at the pole, δ_0, and the radius of curvature of imperfection, R_{imp}, is given by:

$$\frac{\delta_0}{t}=\frac{1}{2}\alpha^2\left(1-\frac{R_s}{R_{imp}}\right)\left(\frac{R_s}{t}\right) \tag{1}$$

For a given magnitude of imperfection, δ_0/t, there is an infinite number of geometries defined by the angle, α (or radius R_{imp}) – see Fig. 2b. Only one of them will lead to the weakest dome, i.e., will have the lowest buckling pressure. As an illustration consider hemispherical dome, clamped at its equatorial plane. A series of computations were carried out in order to find the buckling strength of externally pressurised imperfect steel hemisphere. Results are shown in Fig. 4. It is seen in Fig. 4 that for different magnitudes of the angle, α, one obtains different magnitudes of buckling strength. The festooned curve to these response-curves represents the so called lower-bound curve. It is seen in Fig. 4a and

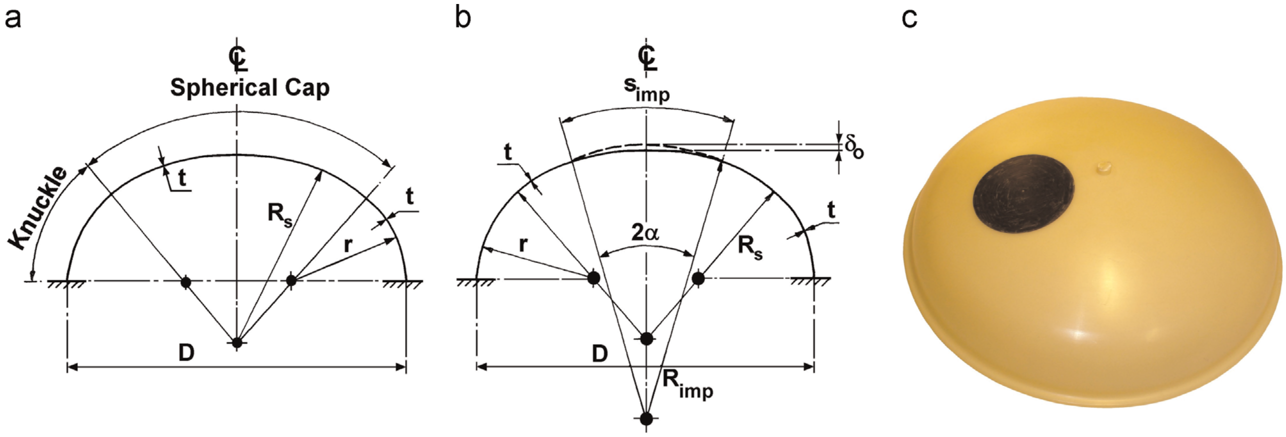

Fig. 2. Geometries of: (a) perfect torispherical dome (Fig. 2a), imperfect one (Fig. 2b), and view of torisphere with flat patch (Fig. 2c, black area, $\delta_0/t=1.0$).