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# Functional buckling behavior of silicone rubber shells for biomedical use

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ABSTRACT

*Background:* The use of soft elastic biomaterials in medical devices enables substantial function integration. The consequent increased simplification in design can improve reliability at a lower cost in comparison to traditional (hard) biomaterials. Functional bi-stable buckling is one of the many new mechanisms made possible by soft materials. The buckling behavior of shells, however, is typically described from a structural failure point of view: the collapse of arches or rupture of steam vessels, for example. There is little or no literature about the functional elastic buckling of small-sized silicone rubber shells, and it is unknown whether or not theory can predict their behavior. Is functional buckling possible within the scale, material and pressure normally associated with physiological applications? An automatic speech valve is used as an example application.
*Method of approach:* Silicone rubber spherical shells (diameter 30 mm) with hinged and double-hinged boundaries were subjected to air pressure loading. Twelve different geometrical configurations were tested for buckling and reverse buckling pressures. Data were compared with the theory.
*Results:* Buckling pressure increases linearly with shell thickness and shell height. Reverse buckling shows these same relations, with pressures always below normal buckling pressure. Secondary hinges change normal/reverse buckling pressure ratios and promote symmetrical buckling. All tested configurations buckled within or closely around physiological pressures.

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*Conclusions:* Functional bi-stable buckling of silicone rubber shells is possible with adjustable properties in the physiological pressure range. Results can be predicted using the proposed relations and equations.



## 1. Introduction

Elastic materials enable possibilities in mechanical design that cannot possibly be achieved with traditional hard materials. Soft materials used in biomedical applications are also mechanically more compatible with soft biological tissue than the traditional hard plastics and metals used for implants. For that reason, they are accepted very well by the body. Examples of elastomers that are used for implantable biomedical applications are silicone rubber, polyurethane (PUR) and a number of thermoplastic elastomers (TPEs) such as SIBS30 (El Fray et al., 2006) or even biological rubber-like materials (Lv et al., 2010).

The mechanical properties of rubber create new applications. One such geometry that allows for new applications is the small spherical shell in its function as a bi-stable snap-through buckling shell (Fig. 2). Due to their large elastic range they do not deform plastically during the snap-through process and are therefore able to buckle back (so called "reverse buckling"). This geometry can function as or within check valves, servo valves, bi-state mechanical memory cells and the like, as a separate part or within a rubber mechanism.

This paper describes how to predict the properties of such small bi-stable shells in theory and (with an example application) in practice.

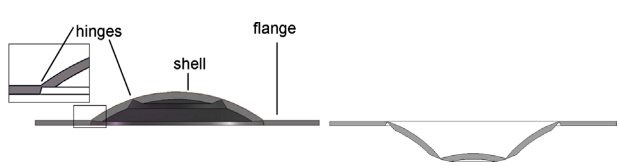


**Fig. 1 – Cross-section of a specimen with secondary hinge (left) and a shell in normal condition (left) and buckled (right).**

### 1.1. *Bi-stable buckling*

When a spherical shell or cap as depicted in Fig. 1 is submitted to mounting external pressure, it may retain its spherical shape and only experience uniform compression. (Timoshenko and Gere, 1961) When the pressure increases beyond a certain value, the spherical shape of the compressed shell may become unstable and buckling occurs. Snap-through buckling (snapping, buckling, oil-canning) is characterized by a visible and sudden jump from one equilibrium configuration to another equilibrium configuration (Fig. 1, right). The load or pressure under which the shell buckles is called the "buckling load", whereas the "critical load" is designated as the load at which buckling occurs according to calculations from theoretical models (Simitses, 1976; Allen and Bulson, 1980) A system is considered bi-stable if it can exist in either of two stable states between which buckling can take place.

The stability of spherical shells has been studied for several decades.

Applications are found in structures such as steam pressure vessels, storage tanks (Blachut and Magnucki, 2008) and church domes, for example, and typically cover structural failure: the collapse of arches or the rupture of pressurized vessels, etc.

Studies of metal spherical structures indicate that the stability of a spherical shell can be predicted by its geometry (Ball and Burt, 1973; Ball, 1975; Budiansky and Roth, 1962; Budiansky, 1966; Holzer, 1979; Huang, 1969; Hyman, 1971; Klöppel and Jungbluth, 1953; Lock and Okubo, 1968; Simitses, 1967, 1974; Song and Jones, 1983; Taeprasartsit and Tao, 2005). In literature, a distinction is made between "thick" and "thin" shells. Whereas thin shells are said to follow the predictions of "classical theory", calculating the critical pressures for thick shells "involves solving a fourth-order system of highly non-homogeneous differential equation" (Hill, 1976).

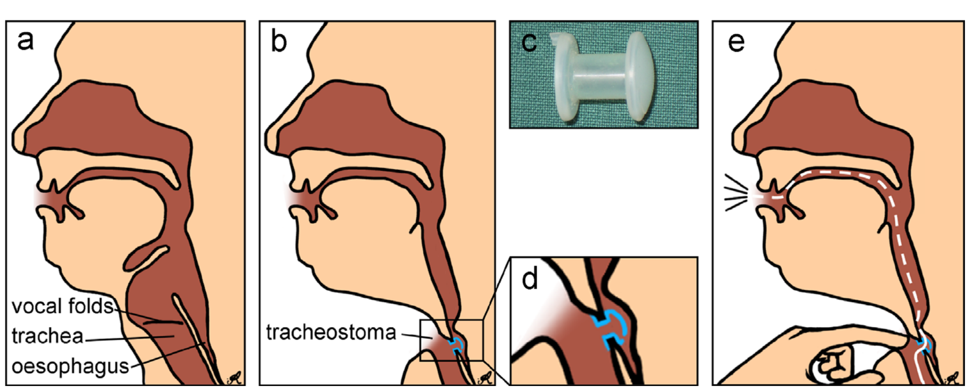


**Fig. 2 – Laryngectomy: A healthy patient (a) and a laryngectomy patient (b) missing the vocal folds. A shunt valve (c) is routinely implanted between the esophagus and trachea (d) so that after inhalation and closure of the stoma (e), all exhaled air is rerouted via the esophagus, which will vibrate: an artificial voice.**