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Multistable cantilever shells: Analytical prediction, numerical simulation and experimental validation

Matteo Brunetti[a,*], Lukasz Kloda[b,c], Francesco Romeo[a], Jerzy Warminski[c]

[a]Department of Structural and Geotechnical Engineering, Sapienza University of Rome, via Eudossiana 18, 00184, Rome, Italy.
[b] Department of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, via Brecce Bianche, 60131 Ancona, Italy.
[c]Department of Applied Mechanics, Lublin University of Technology, Nadbystrzycka 36, 20-618 Lublin, Poland.

Abstract

The numerical and experimental validation of multistable behavior of cantilever shells is addressed. The design of the laminated composite shells is driven by a recently proposed semi-analytical shell model, whose predictions are verified and critically examined by means of finite element simulations and stability tests on two manufactured demonstrators. In addition, the influence of the main design parameters on the shells stability scenario is discussed. Despite its simplicity, the reduced model allows to depict a fairly faithful picture of the stability scenario; therefore, it proves to be a useful tool in the early design stages of morphing shell structures.

Keywords: multistability; morphing structures; composite shells; reduced shell models.

1. Introduction

Multistability is the feature characterising structures, or structural components, having more than one stable equilibrium configuration, no matter if they are subjected to external actions or not. This feature can be exploited for designing structures capable of very large shape changes with remarkably low operating costs; as a matter of fact, multistable systems require energy only to move from one stable equilibrium configuration to another, a switch that can be cheaply accomplished by triggering instability phenomena [1, 2]. This chance makes multistable components extremely valuable solutions when designing morphing structures [3–5]; recently, other interesting applications have been proposed, such as gearless motors [6], vibration energy harvesting systems [7, 8], or anti-icing systems [9]. Among multistable structures, shells are probably the most attractive for engineering design purposes, in view of the variety of alternative geometric configurations they provide.

Multistable shells can be obtained in several ways; for example by inducing stresses during manufacture, through thermal effects in non-symmetric composite structures [10–14], prestress or plastic deformations [15, 16]; or by an appropriate choice of natural stress-free shape and material properties [17–19]. While the latter solution may require greater actuation forces, the former calls for special arrangements to control the shapes of the stable states [20].

The design of multistable shell structures poses interesting challenges. In essence, on the basis of some specific performance requirements, it demands to realise shells with a prescribed number of stable configurations, each one having a specified shape. Moreover, for designing an effective actuation strategy it would be desirable to have the chance of tuning the energy gaps in-between the stable configurations. This calls the formulation of *reduced* shell models, that is, shell models having a number of degrees of freedom small enough to perform fast parametric analysis and infer qualitative informations. Reduced models are almost indispensable to guide more detailed finite element (FE) simulations and tests on demonstrators.

Models of this type can be obtained using the Marguerre-von Kárman (MvK) nonlinear shallow shell model [21], together with the assumption of uniform curvature [22]. Such uniform curvature models have been proved to be powerful and effective for shells free at the boundary (see for example [23]); however, they cannot be used when considering constrained shells. Despite constraints have substantial influence on the multistable behaviour of shells [5, 24, 25], the problem has been addressed only recently [26–29].

As shown in [30] by exploiting the linearity of the MvK membrane problem, the assumption of uniform curvature can be weakened and reduced models for non-uniformly curved shells can be inferred without harning their reliability, while simultaneously keeping low the number of degrees of freedom. Starting from this observation, in [26] a 3-degree of freedom semi-analytical model suitable for the study of multistable cantilever shells with rectangular planform has been proposed. Specifically, after chosing a quite general class of shapes for the shell stress-free configuration, the model allowed to derive the stability scenario arising when one of its edges is flattened and then clamped.

The present contribution aims to examine the predictive ca-

*Corresponding author
Email addresses: matteo.brunetti@uniroma1.it (Matteo Brunetti), l.kloda@pollub.pl (Lukasz Kloda), francesco.romeo@uniroma1.it (Francesco Romeo), j.warminski@pollub.pl (Jerzy Warminski)