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Tailoring the elastic postbuckling response of thin-walled cylindrical composite shells under axial compression

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ABSTRACT

The buckling of cylindrical shells has long been regarded as an undesirable phenomenon, but increasing interests on the development of active and controllable structures open new opportunities to utilize such unstable behavior. In this paper, approaches for modifying and controlling the elastic response of axially compressed laminated composite cylindrical shells in the far postbuckling regime are presented and evaluated. Three methods are explored (1) varying ply orientation and laminate stacking sequence; (2) introducing patterned material stiffness distributions; and (3) providing internal lateral constraints. Experimental data and numerical results show that the static and kinematic response of unstable mode branch switching during postbuckling response can be modified and potentially tailored.

1. Introduction

Buckling and postbuckling behavior is a complex response in slender structural elements that has been historically regarded as failure limit state but otherwise lacking much practical meaning due to the resulting catastrophic capacity reduction and associated large deformations. However, a paradigm shift has emerged during the past decade pointing to an exciting research area dealing with the harnessing of such unstable events for "smart" purposes, such as energy harvesting, sensors, actuators, energy dissipation, etc. [1–3]. For example, the postbuckling response and unstable axial stiffness of a column has been used shown to serve as a vertical vibration Euler spring isolator [4]. Functional origami-like folding structures have been investigated to utilize buckling as a possible gating mechanism for structured spherical shells [5] and energy harvesting with piezoelectric generators have been studied based on the response of buckling events, such as the snap-buckling of a beam operating as a kinetic-to-electrical energy converter [6]. Following a similar motivation, this paper explores the modification and control of the postbuckling behavior of cylindrical shells for their potential use in smart structures.

The structural prototype selected for this study is an axially compressed thin-walled laminated composite cylindrical shell. There is a long history of research since the early 20th century aimed at predicting the critical buckling load of cylindrical shells under axial compression with the goal of determining this limit state with more accuracy. Consequently, most of the efforts have been on determining the critical bifurcation point in the primary static loading branch, shown as path (a) in Fig. 1. However, experimental evidence has shown the importance of material and geometric imperfections on the critical load, which has challenged the development of analytical and numerical models. Geometric imperfections are known to reduce the critical buckling as shown in path (b). Thus, buckling and postbuckling occur at a much lower capacity and efforts to characterize this response experimentally and numerically have been motivated by the interest in using the residual strength as a safeguard.

Aided by advances in computational mechanics and computer technology, investigations on the postbuckling behavior of shells since late 1980s have mostly been carried out through numerical modeling approaches. The archived literature shows that it has taken about two decades of progress in numerical methods for simulation results to match experimental ones, again due to the governing role of geometrical imperfections. Thus, in spite of the significant advances in numerical modeling approaches for predicting the buckling and postbuckling response of cylindrical shells, without the measurement of actual geometric imperfection, the disagreement of predicted and measured responses still exist [7–11].

Compared to conventional shell design aims, recent research studies have turned to recognize postbuckling behavior as a desirable response. Rather than a response path with a single bifurcation point and a large critical buckling load, path (c) in Fig. 1

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Nomenclature

A	dissipated strain energy (enclosed area of response curve)
K_e	end stiffness before the unloading point
K_i	initial stiffness before the first bifurcation
P_{cr1}	first buckling load
P_{max}	maximum buckling load
n	number of mode transitions
δ	spacing between snap-through events
δ_{max}	maximum spacing between snap-through events
ΔP	load drop between first bifurcation and unloading point
ΔP_{max}	maximum load drop between first bifurcation and unloading point

shows a relatively more flexible response during initial loading and a lower critical load, but a postbuckling response with multiple bifurcation points (also termed mode transitions or mode jumps) due to changes in the deformed geometry after each critical point.

Endeavors to understand the mechanisms behind the postbuckling response of axially compressed cylindrical shells have been carried out analytically since the pioneering work by Koiter in the early 1940s [12]. Due the problem's complexity analytical studies have mainly focused on determining the first or second buckling loads and the initial postbuckling equilibrium paths [13–16]. On the other hand, several numerical methods have been proposed to trace the mode jumping phenomena in the postbuckling regime [17–20]. Many of the developed numerical techniques have been incorporated into general purpose finite element programs and evaluation of the postbuckling response has been demonstrated to be feasible with these tools [21–25]. Finally, numerous experimental studies on the postbuckling response of cylindrical shells have also been carried out to validate analytical and numerical models [26–30], with perhaps the most significant performance gain coming from the ability to scan the initial geometric imperfections and thickness variations of manufactured shells for use as input to the analytical and numerical models.

In spite of the noted interests on exploring the use of structural instabilities, most of the studies mentioned above on the buckling and postbuckling response of cylindrical shells have focused primarily on two fronts (1) develop an analytical or numerical technique that is able to capture the multiple mode transitions in the postbuckling regime, and (2) investigate the residual capacity near the first or second bifurcation by which postbuckling behavior is considered as a safeguard against ultimate failure.

The objective of this paper is to present a study on how material, geometry and constraint features in axially compressed cylindrical

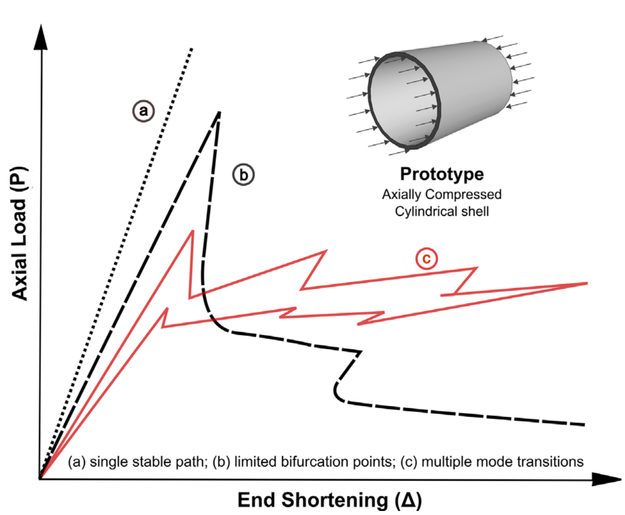

Fig. 1. Schematic representation of different equilibrium paths in the postbuckling response of a compressed cylindrical shell.

laminated composite shells can allow attaining multiple bifurcation transitions and stable equilibrium branches in their elastic postbuckling response, and approaches to modify and potentially control such behavior. Three avenues were explored to achieve the targeted response (1) varying the laminate stacking sequence, (2) introducing patterned material stiffness distributions, and (3) providing lateral constraints. Prior studies [8,21,24,27,29,31] have identified that the variation of fiber orientations, layer thicknesses and stacking sequence of a laminated composite has a significant effect on the first buckling load and near bifurcation postbuckling behavior. A less explored topic is the effect of laminate design on attaining multiple mode jumping characteristics in the far elastic postbuckling regime. Most of the research related to the use of patterned stiffness distributions in shells has focused on increasing their load-carrying capacity through axial stiffeners [28,32] or grid 'skeletons' [33,34]. The present study considered similar design patterns but they are used to obtain multiple mode transitions by providing variations in material distributions to trigger snap-through buckling rather than for reinforcing purposes. Finally, a way to induce multiple bifurcation events in the postbuckling response of slender elements is to provide them with external lateral restraints that limit their transverse deformations [35,36]; however, the use of this approach for tailoring the postbuckling behavior of cylindrical shells has not be studied before.

The paper presents numerical and experimental studies that evaluate the elastic response of thin-walled laminated composite cylindrical shells in their postbuckling regime under axial loading and unloading. Two structural prototypes were considered: a carbon/epoxy cylindrical shell and a hybrid carbon/E-glass/epoxy cylindrical shell. Potential avenues for tailoring such postbuckling response in a predictable and controllable behavior are discussed.

2. Methods and materials

2.1. Numerical simulations

Advances in computational mechanics and computer technology have decreased the difficulty of simulating the chaotic postbuckling response of structures. Reports on numerical investigations [21,23,24] have shown that equilibrium states in the postbuckling regime can be tracked and predicted by general purpose finite element programs by conducting a second-order nonlinear analysis of a shell with imperfection considerations. Geometric imperfections on the shell surface can be introduced in the numerical model in three ways: from actual measurements, by a mathematically determined "worst" pattern, or through eigenvalue-based simulated shapes [37]. From a practical point of view, measured imperfections using laser scanning techniques are not always available, while the determination of the "worst" pattern is theoretically demanding. Thus, mode shapes from eigenvalue buckling analyses are commonly used to define artificially generated imperfections as a small perturbation on the perfect shell. Typically the first eigenmode is chosen to simulate an imperfection with a symmetric shape because the lowest mode is assumed to have