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Elastic postbuckling response of axially-loaded cylindrical shells with seeded geometric imperfection design

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ABSTRACT

Elastic instabilities (such as buckling) have been recognized as a promising phenomenon to design smart materials and mechanical systems. Thin-walled cylindrical shells under axial compression can attain multiple bifurcation points in their postbuckling regime due to the natural transverse deformation restraint provided by their geometry; but harnessing such behavior for smart purposes is lacking extensive study due to its notoriously high imperfection sensitivity. In this paper, the concept of seeded geometric imperfection (SGI) design is proposed to modify and control the elastic postbuckling behavior of cylindrical shells. Eigenvalue-based mode shapes were used as basic geometric forms to generate a seeded imperfection. Prototyped SGI cylindrical shells were fabricated through 3D printing and tested under loading–unloading cycles. Numerical and experimental results suggest that the SGI cylindrical shells are less sensitive to initial imperfections and load variation than uniform ones. Cylindrical shells with seeded geometry can be potentially used in the design of smart devices and mechanical systems such as energy harvesters and self-powered sensors.

1. Introduction

Buckling is a phenomenon that has been known for centuries, since an equation to determine the critical buckling of a column was derived by Leonhard Euler [1,2]. Buckling may be considered as a fully mature field in mechanics from the point of view of determining such critical event for avoidance in design. However, recognition of the positive features of buckling and postbuckling response for use in smart and adaptive materials and structures began approximately 10 years ago. Such increasing interest has rekindled the popularity of studying buckling and elastic instabilities in general. Research activity over this time, as judged by the trend of published literature in the topic, has been increasing and diversifying dramatically. Under this new role, many interesting problems within the topic of elastic instability, in a broader sense, remain to be investigated; including [3]: (1) the mathematical complications in modeling buckling and post-buckling in thin structures; (2) the mechanical instability of materials associated with inhomogeneity and nonlinearity; (3) new phenomena due to the coupling between geometric and material nonlinearities; and (4) the usefulness of mechanical instabilities for broad engineering applications.

The research reported herein is in the vein of increasing interest in smart structures, which aims to turn buckling-induced instabilities from an undesirable feature into a design opportunity. The first and major step for using a specific unstable event is to identify an appropriate structural prototype. Postbuckling behavior in axially-loaded structures has been studied in many forms and for different purposes [4–7], including beams, plates, and rods. Cylindrical shells have been relatively less used since they require more rigorous modeling and, more importantly, because of their high sensitivity to imperfections. The postbuckling response of cylindrical shells is difficult to predict due to the random nature of the imperfection profile. Current efforts have considered modeling imperfection in a statistical manner [8] or using a measured database to obtain a better estimate of the postbuckling response [9]. Fig. 1 provides the evidence that uniform cylindrical shells have been highly studied due to their associated purpose as load-carrying components; but in this study, it is most likely not an appropriate prototype. By contrast, cylindrical shells with varied stiffness (material and geometry) can fit the study's purpose for tailoring the elastic postbuckling response.

Rather than the critical buckling limit, the focus of this study is attaining multiple mode transitions in the elastic postbuckling regime and a recoverable response. Fig. 2 presents a typical postbuckling response curve of an axially-compressed cylindrical shell. There is a long history of research [10,11] since the early twentieth 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

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Notation

The following symbols are used in this paper:

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

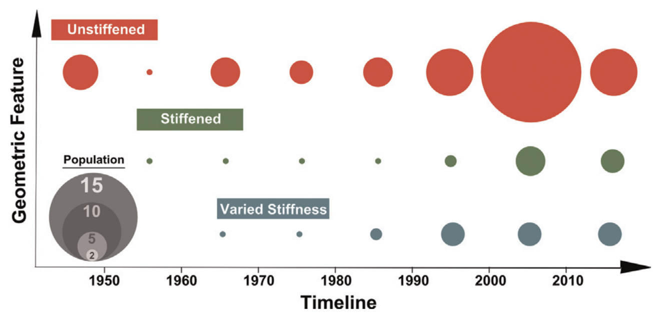

Fig. 1. Bubble chart of existing literature on geometric features of axially-loaded cylindrical shells.

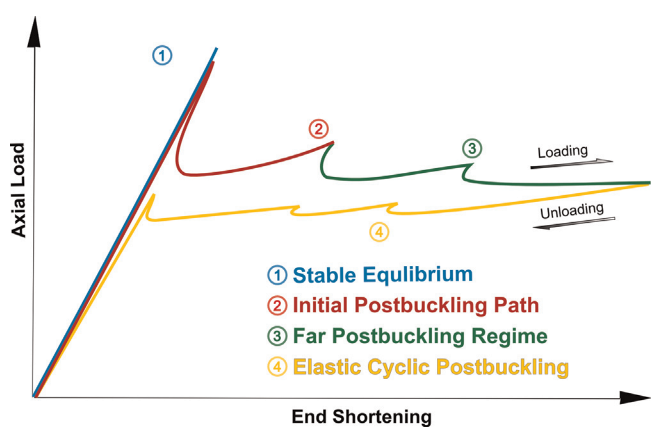

Fig. 2. Schematic representation of the postbuckling response of an axially-loaded cylindrical shell.

of the efforts have been on determining the critical bifurcation point in the primary static loading branch, shown as segment (1). Later, experimental evidence [12,13] identified the governing role of material and geometric imperfections on the critical load, which challenged the development of analytical and numerical models. Geometric imperfections are known to reduce the critical buckling load as shown in segment (2). 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 1940's [14]. Due the problem's complexity, analytical studies have mainly focused on determining the first or second buckling loads and the initial postbuckling equilibrium paths [15–18]. Recent efforts are motivated by the interest of using the residual strength in the postbuckling regime as a safeguard [19,20]. Aided by advances in computational mechanics and computer technology, investigations on the postbuckling behavior of shells since early 1990s have mostly been carried out through numerical modeling approaches. Several numerical methods have been proposed to trace the equilibrium paths in the postbuckling regime [21–24], as shown in segment (3). Multiple bifurcation points (also termed mode transitions or mode jumps) can be observed in the postbuckling response due to changes in the deformed geometry after each critical point. Cylindrical shells can attain a higher number multiple stable configurations in their postbuckling regime due to the natural transverse deformation restraint provided by their geometry without the need of lateral constraints [25]. Segment (4) of the schematic curve shows the recoverable nature of an elastic postbuckling response. Such feature has been recognized by several experimental studies [19,26] but it has been less studied since most research work has focused on postbuckling behavior under monotonic loads.

Recent studies have attempted to use the elastic postbuckling behavior of cylindrical shells in the design of energy harvesters [27] and sensors [28]. When considering energy harvesting, a cylindrical piezoelectric harvester with optimal layout is expected to provide higher energy conversion efficiency than simple forms (e.g., beams or cantilevers). In sensing applications, an axially-loaded cylindrical shell is expected to detect minute loads due to the sudden load drop along the equilibrium path. Another interesting postbuckling feature is the negative stiffness in the response curve, which can be potentially used in the design of advanced dampers and isolators. Such feature has been recently explored in other cylindrical type axially-loaded structures, such as tubes [29] and columns [30,31]. However, the governing role of imperfection sensitivity has limited the potential use of uniform cylindrical shells for the design of smart devices and mechanical systems.

Given that imperfections cannot be avoided, at least with current manufacturing technologies, the design of cylindrical shells for smart purposes requires a relatively less imperfection sensitive structure. Such attempt has been made in the design of stiffened cylindrical shells, where the buckling events are to occur between stringers even though the load-carrying capacity is still reduced by imperfections [32]. The possibility of the noted transition (from high imperfection sensitive to less sensitive, or even imperfection insensitive) was demonstrated by Mang and co-workers in a two-part paper series [33,34]. Several recent studies on shape optimization have thus explored the opportunity of designing the pattern and amplitude of imperfections. Lindgaard et al. [35] carried out shape optimization with buckling mode shapes as the design variables. The resulting mode shapes were used to define a "worst" imperfection pattern for a thin-walled cylindrical shell such that the axially compressed cylinder would minimize the buckling load. Ning and Pellegrino [36] explored the concept of imperfection-insensitive cylindrical shells by designing a wavy cross-section using structural optimization. The noted studies indicate that geometric imperfection may not be necessarily regarded as a detrimental factor in the design of cylindrical shells.

The aim of this paper is to introduce the concept of seeded geometric imperfect (SGI) design for cylindrical shells so as to obtain an elastic postbuckling response with targeted features. The research hypothesis is that the elastic postbuckling response of a cylindrical shell can be modified and made less sensitive to small material and geometric imperfections by providing them with large and strategically placed deformation patterns, then the