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Variable stiffness characteristics of embeddable multi-stable composites

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ABSTRACT

The possibility to achieve shape adaptation provides structural systems with the potential to adjust for optimal operation in a wide range of conditions. The formidable challenges posed by shape adaptation, and particularly in morphing applications, can be potentially addressed through the development of distributed compliance systems featuring highly directional structural properties. These characteristics can be further enhanced by embedding in such systems elements featuring variable stiffness. In this paper, a novel type of embeddable variable stiffness elements exploiting thermally-induced multi-stability in unsymmetrically laminated composites is presented. A tailored lay-up exhibiting spatially distirbuted stacking sequences is implemented to achieve multi-stability even when restricting two opposing edges. The difference between the structural responses leading exhibited by the multiple stable shapes of the designed composites are numerically investigated. The restoring force for each stable state is examined yielding a significant variability in the stiffness. Experimental specimens are manufactured and tested showing good agreement with the numerical results, validating the proposed variable stiffness implementation.

1. Introduction

The ability to operate optimally in diverse conditions has led to the idea of introducing the capability to adjust the properties of engineering systems in response to environmental changes, resulting in the field of adaptive structures [1]. A set of properties particularly difficult to be adapted, are those concerned with shape variation of structural elements. This problem is exemplified conformal change of the shape of aerospace structures, widely known in the engineering community as morphing. Morphing requires structures exhibiting highly directional properties to meet the conflicting requirements of load-carrying capabilities along the direction of the loads, high compliance in the directions of shape adaptation, while maintaining light-weight constructional characteristics [2]. Several challenges remain to be addressed for the implementation of this promising technology. Distributed compliance structural systems are a promising solution to the formidable challenges presented by shape adaptation requirements, particularly those posed by morphing applications [3,4]. A new trend to significantly augment the directionality of the structural properties of such systems is to embed elements capable of varying their stiffness [5]. The ability to change the structural response of certain components in distributed compliance systems allows for a higher degree of decoupling between the compliance and stiffness requirements. Composite laminates exhibiting multiple statically stable shapes are good candidates to serve as variable stiffness elements embedded within distributed compliance structures [6–8]. Indeed, a significantly different directional structural response characterises each equilibrium configuration. The capability of adopting a number of statically stable states has brought these structures into the focus of extensive research in recent years. Several types of systems including biological [9], and synthetic [10–12] exploit this phenomenon to achieve unattainable performances with conventional structures. Multi-stability in composite materials arises from an induced stress field that can be realised by several mechanisms, including unsymmetrical lamination [13], tailored lay-up [14], pre-stressed cylinders [10], fibre pre-stressing [15] and thickness variation [16]. Amongst multi-stable structures, multi-stable composite laminates have been considered for morphing applications due to the large deformations exhibited when changing between stable configurations [17–20]. Although such structures have shown promising results, the discrete nature of the achievable equilibrium shapes restricts the range of applicability of multi-stable components as a means to obtain large deflections in load carrying elements. The possibility offered by multi-stable components to achieve different structural properties for each of the attainable stable configurations, allowing for the realisation of load-carrying variable stiffness elements, has not been

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thus far explored. Taking advantage these characteristic, multi-stable elements can be designed to exhibit variable stiffness properties arising from the different structural response of the stable configurations.

In this paper, a novel class of variable stiffness elements based on exploiting the significantly different structural characteristics associated to the stable configurations of multi-stable composites is introduced. The components herein presented are specifically designed to be embeddable into larger structures, thus providing the complete system with passive variable stiffness capabilities. In particular, the designed multi-stable laminates allow for integration without conventional fixation parts, which is particularly suitable to enhance the structural directional response of distributed compliance systems through the added capability of stiffness adaptation. A tailored lay-out featuring several sections with different stacking sequences is designed achieving both a significant difference in the structural response, and the capability to embed the components into distributed compliance systems. Thermal stresses induced during the cool-down process arising from sections of unsymmetric lamination are exploited to realise the desired multi-stable behaviour. The Finite Element Method (FEM) is employed to simulate and design the variability of the stiffness characteristics associated to each stable configuration. The room temperature shapes of the designed multi-stable components are calculated with the FEM showing good agreement with manufactured specimens. The structural response of the stable configurations is studied for relevant load cases both numerically and experimentally. Finite Element (FE) simulations demonstrate significant variability in the stiffnesses associated to each stable configuration. Tests on experimental specimens show a close match with the FE results, validating the numerical analyses. The realisation of purely elastic, passive, embeddable load carrying variable stiffness elements can be potentially used to significantly alter the structural response of a load-carrying system in a simple and robust fashion. The variable stiffness offered by the presented multi-stable components can be exploited to enhance the directionality of the structural characteristics of systems for which structural efficiency is of paramount importance, as for instance in morphing structures. Consequently, a reduction of the actuation requirements to obtain large deflections, or altogether passive morphing exploiting the external forces on the structure to induce desired shape adaptation, can be achieved. Furthermore, as multi-stability in these structures is obtained from passive means, the capability to achieve significant variation in the structural response can be realised in a robust manner. Moreover, the stiffness variability can be implemented on applications where structural hysteresis cycles are required, as for instance in energy dissipation applications.

2. Lay-out design

The lay-out configurations for the multi-stable embeddable variable stiffness elements are designed mainly to fulfil two desired characteristics. First, the resulting structural behaviour of the obtained composite components should be so that significant stiffness variability is attained. Equally important, the resulting lay-out should allow for the designed components to be integrated into structural systems, without compromising the desired variable stiffness characteristics. Furthermore, the integration should be realised such that a distributed compliance structure, requiring no conventional fixation components such as rivets or bolts, is achieved.

Previously, multi-stable laminates in a cantilevered configuration, i.e. with one edge completely clamped, have been obtained through a symmetric-unsymmetric stacking lay-out [7,21]. However, the integration of such laminates through clamping two ends into a structural system was not achieved. Simply restraining the curved end of such laminates results in a moment being applied restricting the deflection required to achieve the second configuration, rendering it mono-stable as schematically shown in Fig. 1. Therefore, a smooth transition reducing the curvature of the edges to be clamped is necessary to maintain multi-stability when embedding the laminates. This is accomplished by designing compliant edges allowing for the introduction of boundary forces and moments to the multi-stable laminates. Starting from a rectangular bi-stable section, appropriate elastic boundaries allowing for a smooth reduction of the curvatures in both stable states are added to achieve the objective of the component embeddability. Adding symmetrically laminated sections to the short ends (parallel to the y-axis) of the rectangular unsymmetric sections reduces smoothly the curvature along the short edges. However, these sections impose high bending moments, opposing the straightening of the edges thus impeding the adoption of stable state 2 as shown in Fig. 1. Such a solution would result in a dramatically reduced parameter space for which such a lay-out would exhibit bi-stability. In fact, only a highly directional symmetric part exhibiting compliance in the y-direction of the short edge, while maintaining sufficient stiffness to smoothen the curvature in the x-direction, could result in a multi-stable element. However, the mechanical properties of such a solution would not be satisfactory for load carrying purposes. An alternative for achieving the design objectives to simply adding symmetric sections on either side of the main rectangular unsymmetric region is achieved by inserting sections having spatially distributed compliance on either side of the central unsymmetric region to the lay-out. These are designed to show curvatures in y-direction opposing the deformation in the (longitudinal) x-direction imposed by the main rectangular unsymmetric part, thus smoothening adequately the behaviour of the edges at room temperature. An example of the introduced concept is the seven-section lay-out shown in Fig. 2. Spatially distributed transi-

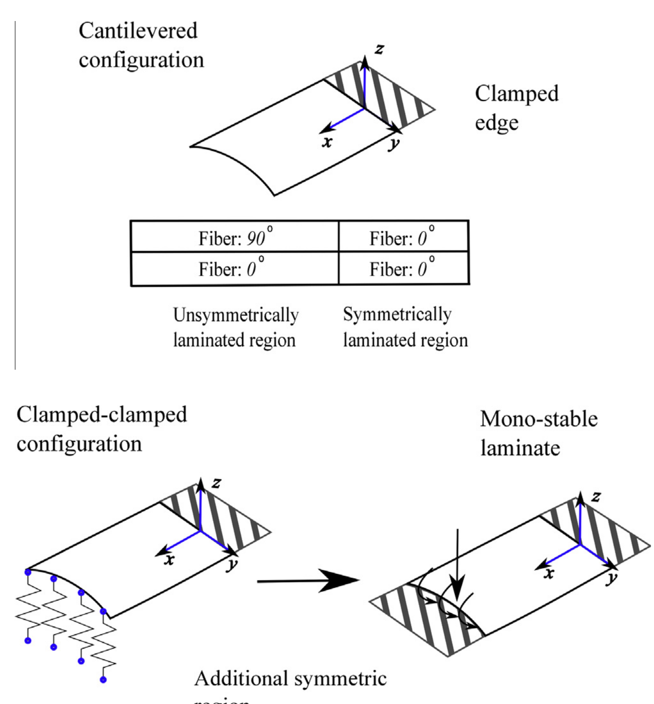

Fig. 1. Effect of clamping the free end of a cantilevered bi-stable laminate configuration. Simply adding an additional symmetrically laminated region results in a mono-stable laminate.