Composite Structures 116 (2014) 235–242

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Passive load alleviation aerofoil concept with variable stiffness multi-stable composites

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ARTICLE INFO

Article history:
Available online 29 May 2014

Keywords:
Variable stiffness
Multi-stability
Morphing
Load-alleviation
Compliant structures

ABSTRACT

Large loads caused by fluid–structure interaction leading to fatigue failure and added robustness of wing-like structures constitute important design challenges to be addressed. A reduction in the penalties associated to the added structural mass required to withstand rare load scenarios by means of load alleviation control is highly desirable, particularly for efficient light-weight engineering systems, such as aircraft and wind turbine blades. Implementation of morphing for modifying the lift distribution to mitigate the impact of rare, but integrity threatening, loads on wing-like structures offers a potential solution for such challenges. In this paper, a passive load alleviation aerofoil concept featuring variable stiffness multi-stable elements is presented. The adaptability in the structural response of the aerofoil when subjected to aerodynamic forces allows for passively changing from a high lift generation shape, to a load alleviation configuration exploiting the energy of the flow. Passive implementations to achieve load alleviation through morphing result in lighter and simpler designs in comparison to actively actuated solutions.

1. Introduction

Large loads due to fluid-structure interaction (FSI) leading to high bending stresses and fatigue failure, constitute an important challenge in the design of wing-like structures. In aircraft design, airworthiness qualifications require the proof that critical structural loads do not exceed certain limits [1]. This requirement clearly influences the design phase of an aircraft and has an impact on later performances. In particular, the structural efficiency, understood as the ratio of stiffness to mass, of structures subject to aerodynamic forces, such as wings and turbine blades, is compromised by the added robustness required to withstand rare load cases [2]. Such structural inefficiencies can become implementation bottlenecks when necessary high safety margins cannot be met with a light-weight architecture. For wind turbine blades, structural restrictions to the upscaling of rotor blade diameters as a result of rarely occurring load cases represent a major challenge to operate in a cost effective manner, particularly hampering off-shore wind farm development [3]. A possible solution for such design obstacles can be provided by implementing morphing [4]. The idea of morphing has attracted much attention from researchers within the aerospace community given the potential performance gains offered and, in particular, in view of augmented optimal operation across a wide range of conditions. Yet, several challenges remain to be addressed for the implementation of this promising technology. To exploit the full potential of morphing, systems exhibiting highly directional structural properties are required. This is particularly necessary to address the conflicting requirements of load-carrying capabilities along the direction of the loads, while maintaining sufficient compliance in the directions of shape adaptation [5]. Distributed compliance structural systems are a promising solution to the formidable challenges presented by the stated shape adaptation requirements, particularly those posed by morphing applications [6,7]. Most studies for load alleviation have concentrated on actively actuated morphing control surfaces [8]. Less attention has been directed to passive alternatives. One such example showing promising preliminary results for load alleviation is the passive aerofoil concept based on hinged cambering presented by Lambie [9]. Despite the encouraging results shown both for active morphing and passive hinged cambering concepts for load alleviation, the added actuation weight and moving parts required by internal mechanism hinder the applicability of these type of solutions for systems where high structural efficiency is of paramount importance. A preliminary conceptual design of a passive load alleviating morphing compliant structure relying solely on conformal change of shape, as opposed to using conventional mechanisms, employing bi-stable composite laminates is presented in Ref. [10]. Multi-stability arises due to an induced stress field in the composite laminates that can result from

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http://dx.doi.org/10.1016/j.compstruct.2014.05.016
0263-8223/

several mechanisms, including unsymmetrical lamination [11], tailored lay-up [12], pre-stressed cylinders [13], fibre pre-stressing [14] and thickness variation [15]. Amongst multi-stable structures, composite materials tailored to exhibit large differences between their statically stable shapes have been considered for morphing applications [10,16–18]. The concept presented in Ref. [10] mainly exploits the change in shape of a bi-stable wing-shaped laminate. However, the discrete nature of the attainable deflections may restrict the applicability of such implementations. A new trend to significantly augment the structural directionality of morphing systems is to embed elements capable of adapting their stiffness [19]. Recently, an interesting example of such systems showing that multi-stable composites can be monolithically embedded into wider structural systems while exhibiting large stiffness variation when changing between stable states is being presented [20]. Hence, the variability in the structural response offered by multi-stable structures allows to enhance shape adaptation capabilities of morphing structures to a greater extent than merely using them for achieving large deflections.

In this paper, the potential to obtain significant adaptability of the stiffness characteristics of multi-stable structures is exploited to achieve a distributed compliance aerofoil concept for passive load alleviation. The adaptable structural response of the aerofoil provides a means for selectively activating deformation modes which lead to a reduction of generated lift by the profile when subjected to loads exceeding a prescribed threshold. This is achieved by embedding into the distributed structure multi-stable elements designed to change their structural properties at targeted maximum loads. The structural behaviour of the compliant aerofoil embedding variable stiffness elements is studied both numerically and experimentally for a simple load case. Significant stiffness adaptation is obtained owing to the different stiffness featured by the stable configurations of the embedded multi-stable elements. Taking advantage of this, the aerofoil can be designed to selectively activate a deformation mode for which a low aerodynamic resultant is generated as a limiting load is reached. Hence, the increase in the external aerodynamic force triggers the shape adaptation resulting in a passive alleviation mechanism. The elastic nature of the multi-stability of the designed composites requires no external elements to achieve the stiffness variation resulting in a robust implementation, suitable for fulfilling structural functions. In addition, the multi-stable components herein presented are specifically designed to be embeddable into other structural systems, thus preserving the constructional simplicity offered by distributed compliance structures. Such an implementation is highly desirable as no added complexity in the form of joints and moving parts is necessary to realise the alleviation mechanism.

2. Variable stiffness multi-stable elements

Variable stiffness elements offer the possibility to provide the capability of achieving shape adaptation in load carrying structures. Particularly interesting for our study are passive means of realising such structural adaptability. A recently introduced class of variable stiffness elements based on multi-stability of composite laminates [21,20] are used for adapting the structural properties of a distributed compliance aerofoil. This adaptability allows for selective activation of a compliant deformation mode depending on the state of the embedded variable stiffness component. For the type of multi-stable laminates herein studied the multi-stability is mainly controlled by thermally induced stresses during the cool-down process from the elevated curing temperature due to unsymmetric lamination [11].

A novel composite design featuring a spatially dependent lamination sequence is employed for this purpose. The distribution of lamination sequence over the planform of the composite is hereafter referred as the lay-out. This is composed of a central unsymmetrically laminated section joined to two transition sections on either side, as shown in Fig. 1. The proposed lamination distribution allows for achieving the objective of obtaining a passive variable stiffness element that can be monolithically embedded into a wider structure. The central section controls the main multi-stable behaviour, whereas the transition sections introduce a smooth reduction to the curvature of the edges necessary for the clamping of the laminate while maintaining multi-stability. The transition sections 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 out-of-plane deformation of the edges at room temperature. Fibre continuity regions (s_3 and s_5) are introduced to reduce the possibility for failure at the interfaces between the differently stacking sections.

To study the behaviour of the variable stiffness elements, the cool-down process for the designed lay-out using carbon fibre reinforced polymer (CFRP) prepregs is simulated following standard finite element (FE) modelling for unsymmetrically laminated composites [22,23]. Specifically, the finite element simulations performed with the commercial software ABAQUS/Standard® [24] including nonlinear effects (Nlgeom) arising from large displacements. Quadrilateral four node shell elements (S4R) are used, the sides of which are chosen to be between 0.001 L and 0.003 L, where L is the total length of the laminate as shown in Fig. 1. The aspect ratio of the elements is kept between 0.5 and 2. Thus, the width and length of the studied laminates are divided into 20 and 92 finite elements, respectively. The multiple step simulation starts with the application of the temperature difference field from the curing to room temperature. The temperature field on the laminate is applied to the FE model by setting a ramp-like input from 140 to 0 °C, simulating a curing temperature of 160 °C and a final room temperature of 20 °C. To avoid rigid body displacements, the edges of the laminate are restricted from translation during the cool-down step. This results in the laminate adopting one of the stable configurations. A loading step in which forces are applied at the four corners of the laminate follows to obtain a second stable shape is also implemented. In this step, numerical stabilization obtained with the addition of very small damping (1e−7) is required. The statically stable shapes resulting from the multi-step simulation for specimen 1 (see Table 1), stable straight (state 1) and curved (state 2) shapes, are presented in Fig. 2. The material properties used for the CFRP in the numerical simulations and experimental tests are given in Table 2. The value of the CFRP expansion coefficient α_{22}^{16d} is experimentally identified as moisture absorption reduces the nominal value, which has a significant impact in the response of the variable stiffness plates. However, this value stabilises after 16 days as reported in [20].

In this study, the focus is placed on investigating the variability of longitudinal stiffness exhibited by the designed composite elements as these are envisioned to work mostly supporting in-plane forces when integrated into a wider structure. To demonstrate the variability in the structural response offered by the designed embeddable multi-stable elements, numerical and experimental tests are performed for which the straight and curved configurations are loaded with an in-plane compressive force. The in-plane force is introduced to the laminate following a displacement controlled procedure, where one of the short edges of the element is progressively compressed, while the opposite one is clamped. As the displacement U_1 is changed, increments in the reaction forces in x-direction, F_a, of the nodes at the displaced edge are recorded. The obtained results for specimen 1, show significant variability when comparing the stiffness response exhibited by the laminate on each of the stable states, as can be seen in Fig. 3. Good