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Passive twisting of composite beam structures by elastic instabilities

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ABSTRACT

This paper introduces a purely passive shape adaptation mechanism for applications in lift generating structures, such as wings. We focus on tailoring the bending-twisting response to a spanwise loading of thin-walled rectangular composite beam structures by intentionally inducing elastic instabilities. For this purpose, the component is designed with a particular material anisotropy utilising unidirectional fibre reinforced composites. Tailoring the fibre orientation and web thickness enables the onset of buckling to be triggered purely passively at a prescribed level of external loading. We utilise the modified load-structure interaction resulting from the deliberate occurrence of externally triggered elastic instabilities to achieve a desired buckling-induced sectional twist. Analytical and numerical models are developed to obtain bounds on the attainable stiffness and shape adaptability by exploiting purposely induced elastic instability. The accuracy and validity of the obtained predictions are confirmed with experimental results from composite beam demonstrators. The study demonstrates the possibility of creating functionality exploiting elastic instabilities, resulting in a novel passive shape adaptation mechanism for simple composite structures.

1. Introduction

Conformal shape adaptation in aerospace systems, widely known as morphing, offers the potential for realising optimal performance on a wide range of operational conditions [1–3]. This capability is achieved by designing structures that allow to arbitrarily change the outer profile and planform of aircraft wings.

To achieve shape adaptation, the vast majority of researchers have relied on active means to deform the structure, utilising conventional [4–8] and smart actuators [9–17]. Semi-active [18–20] and passive [21–27] morphing techniques have also been investigated, although are comparatively rarer [28,29]. In the latter approaches, shape changes are achieved by means of selectively compliant structures, therefore attaining the desired deformation under external load. In general, such selective compliance can be achieved by either modifying intrinsic material properties [18,19,30] or the geometry of the structure [20,31–34].

A hitherto largely unexplored concept in the context of adjusting structural properties for achieving morphing is to exploit elastic instability as a reversible shape adaptation mechanism. Local instabilities not only change the shape of the involved structural elements, but also lead to load redistributions. The modified load-structure-interaction resulting from the occurrence of buckling affects the compliance of the system. These effects are commonly considered a drawback [35,36], although design techniques that tolerate local buckling can be structurally beneficial in certain applications [37–40]. Following this idea, a comparatively novel research field was recently born, not only tolerating buckling, but aiming to create functionality by exploiting instability [41]. In this context, the potential of elastic instabilities has attracted attention in many engineering disciplines such as energy harvesting [42], sensing [43], extreme mechanical properties [44–46], and also shape adaptation [24–26,47–51].

This paper presents a novel approach exploiting the effects resulting from elastic structural instabilities for attaining purely passive shape adaptation of compliant morphing structures, such as wings. The concept is illustrated by controlling the bending-twisting coupling, which is of particular interest for such lightweight systems and has been previously studied through several different approaches [19,20,52–56]. Raither et al. [19] introduced a semi-active control technique for a wing with a wing box comprised of two spars. Utilizing smart materials with adjustable shear stiffness for the spar design, the shear centre location and torsional stiffness of the structure is changed actively [19,55]. Due to the external loads, the wing twists, changing its aerodynamic

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characteristics and hence aeroelastic response. Beside the intrinsic material properties that were actively changed by Raither, the geometry of the structural components is decisive for the resulting compliance of the lightweight system. Following this approach, we study the effect of local elastic instabilities triggered in thin-walled closed-section beam structures to selectively activate a particular bending-twisting deformation mechanism for morphing applications. The herein presented methodology is based on designing one shear web of the beam such that it deliberately undergoes instability at a prescribed level of external loading. This morphing mechanism is demonstrated on a composite beam model under spanwise loading, of which the buckling shear web is designed utilising unidirectional fibre composites. For this case, the predominant load on the webs triggering the instability is shear, causing this component to undergo diagonal tension in the postbuckling regime. The postbuckling response, namely the change in effective shear stiffness of the web undergoing buckling, is utilised to affect the shear centre location and the torsional stiffness of the structure, thus leading to a purely passive shape adaptation.

A simplified plate model is utilised to study the dependence of the attainable shear stiffness reduction from the fibre angle and the applied load, conducting nonlinear finite element simulations. Assigning effective material properties to the buckling shear web, the buckling-induced twist angle of the composite beam is calculated analytically. Exploiting material anisotropy, the buckling behaviour is investigated for a desired structural response, i.e. for triggering the onset of buckling at a prescribed load level, as well as obtaining desired changes in torsional compliance and shear centre relocation in the postbuckling regime without leading to structural failure.

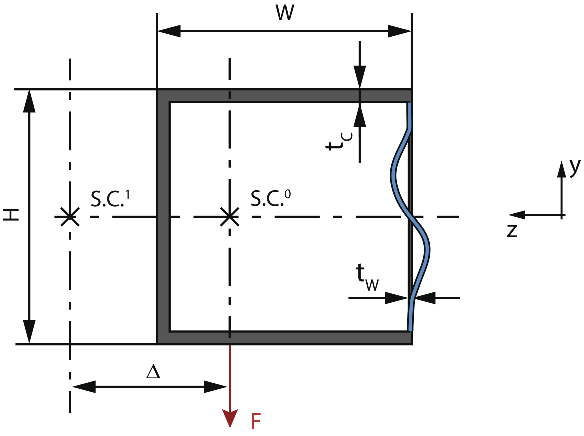
The presented morphing system can be designed for different bending-twisting couplings defined by the postbuckling behaviour of the buckling web. For designs in which the applied loads do not significantly exceed the buckling load, a large shear stiffness reduction of the buckling web close to the bifurcation load is desired, allowing to selectively switch between two particular bending-twisting couplings. Design of the morphing system for loads significantly exceeding the buckling load enables to achieve a particular bending-twisting coupling following the nonlinear development of the shear stiffness reduction in the postbuckling regime. For two particular buckling web designs the results of analytical, numerical and experimental studies on the buckling-induced twisting of composite beam structures are compared, showing very good agreement amongst the followed approaches. This investigation therefore demonstrates the possibility of creating functionality beyond the load-carrying capability by utilising elastic instabilities on a structural level, resulting in a novel passive shape adaptation mechanism for simple composite beam structures.

The paper is organised as follows: in Section 2, the passive shape adaptation concept is introduced focusing on the analytical description of the buckling-induced twist. In Section 3, a structural tailoring procedure is conducted for the desired buckling behaviour of the shear web. Section 4 establishes design guidelines for beam structures, determining the influence of the fibre angle of the buckling web on the resulting variation in torsional compliance, shear centre location, applied force and, consequently, sectional twist. The experimental setup is described in Section 5. The numerical, analytical and experimental results of the buckling-induced twisting of the chosen composite beam design are compared in Section 6. Section 7 concludes the paper.

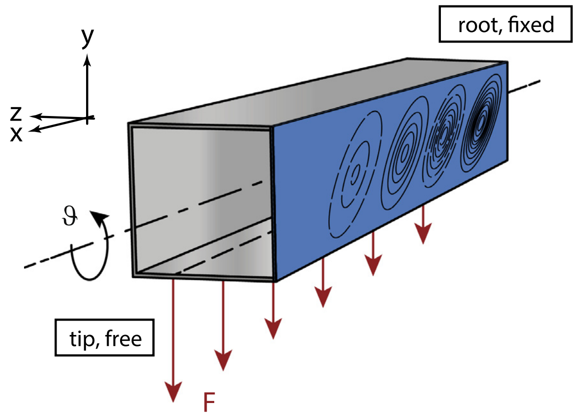
2. Concept and analytical model

We investigate a morphing technique controlled by elastic instabilities. The onset of buckling as well as its effects on the overall structure resulting from the postbuckling behaviour are the key aspects in the structural design herein introduced for realising the passive shape adaptation functionality. The approach aims to achieve a controllable twisting of wing-like structures in a purely passive manner, concentrating on a wing box assumed to carry most of the structural loads. This structure is comprised of two flanges and two webs, one of which is designed as the buckling component with a particular material anisotropy utilising unidirectional fibre reinforced composites. Fig. 1 shows the hollow beam section where the web undergoing instability is coloured in blue.

In the following, the properties of the buckling web are denoted with the subscript *W*, and the properties of the remaining structure (two flanges and one web) are denoted with the subscript *C*. For a beam section with a symmetric profile made of one material ($G_W = G_C$) and equal flange and web thicknesses ($t_W = t_C$), the shear centre location is $y_{S.C.} = z_{S.C.} = 0$, where the coordinate system is located at the geometrical centre of the beam section. If the thickness and/or shear modulus of the buckling web is reduced, while keeping the remaining structure unchanged ($G_W t_W < G_C t_C$), the shear centre moves in the direction of positive *z*-coordinates [18]. The *z*-position of the shear centre before the onset of buckling is denoted $S.C.^0$, as shown in Fig. 1a. Hence, loads acting at positions $z < S.C.^0$ ($z > S.C.^0$) in negative *y*-direction result in a negative/clockwise (positive/counterclockwise) twisting of the



(a) Cross section with qualitative position of shear centre for the unbuckled ($S.C.^0$) and buckled ($S.C.^1$) case.



(b) Profile beam geometry and loading with qualitative drawing of the resulting buckling field.

Fig. 1. Concept of buckling-induced twisting.