Thin-Walled Structures 94 (2015) 129–134

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Concept for morphing airfoil with zero torsional stiffness

Stephen Daynes [a], Xavier Lachenal [b], Paul M. Weaver [c,*]

[a] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne 3083, Australia
[b] senseFly SA, Route de Genève 38, 1033 Cheseaux-Lausanne, Switzerland
[c] Advanced Composites Centre for Innovation and Science, University of Bristol, Bristol BS15TU, UK

ARTICLE INFO

Article history:
Received 30 November 2012
Received in revised form
22 March 2015
Accepted 14 April 2015
Available online 2 May 2015

Keywords:
Morphing
Multistability
Composites
Zero-stiffness
Nonlinear structures
Prestress

ABSTRACT

A morphing wing structure is presented which is designed to have zero torsional stiffness to minimise actuation requirements. The concept consists of carbon fibre reinforced plastic strips which are initially curved prior to being flattened and assembled into a grid-like structure in a heightened state of elastic strain energy. Varying the initial curvature of the strips, material properties and the assembled geometry enables the torsional stiffness to be tailored. A state of zero torsional stiffness can be obtained when there is a balance between the changes in strain energy associated with bending and twist deformations.

1. Introduction

The conventional approach to achieve shape change in structures is to use heavy and complicated actuation mechanisms, such as motors, and structurally non-optimal articulations, such as hinges and bearings. An example of which is an aircraft wing where the main structure supports the majority of air loads while hydraulically actuated hinged surfaces provide aerodynamic control. Morphing structures have the potential to enable a step change in capability where the structure can carry both loading and still be able to change shape with the aim of both increasing performance and decreasing the mass and complexity of designs. There has been significant research efforts into the application of smart materials, such as piezoelectric and shape memory alloy actuators, to achieve shape change in morphing structures [1]. However, the performance of such smart materials is often significantly limited when they have to work against both external loading and also the stiffness of the structure they are attached to. If morphing structures are considered as part of a system where the stiffness of the structure is tailored in response to external loading then small actuation inputs can potentially have an amplified effect [2]. This paper describes a new twisting structure concept which could find applications where there is a need for tailored torsional stiffness or a requirement to augment the performance of smart material actuators.

Tailoring the stability of structures as a means of morphing has been an active area of research for over three decades now [3]. Early work focussed on using unsymmetrically laminated composites which can possess two or more stable geometries [4–12]. A transition between stable states can be made with a snap-through action. Multistability can occur in such laminates through a combination of geometrically non-linear effects and the thermal moments that occur upon cool-down of the laminate from a higher curing temperature to a lower ambient temperature. However, the application of such multistable laminates into aircraft-like adaptive control surfaces has proven very challenging. Some of the challenges include geometric variability due to hygrothermal effects [13] and integrating such laminates into part of a larger structure without a detrimental effect on the multistable behaviour [14–16]. Potential solutions to these challenges have been proposed including using metal–composite hybrid laminates [17] and fibre-prestressing techniques [18,19]. Multistable effects have also been demonstrated in twisting structures consisting of pre-curved shells which are clamped together in a heightened state of strain energy [20]. Similar effects can be achieved through a combination of curvature and prestress in isotropic materials [21]. In some situations where there is a balance between the change in elastic strain energy associated with bending and twisting respectively a state of zero torsional stiffness can be realised [22,23].

There have also been several concepts for rotorcraft applications to manipulate the torsional stiffness of blades. Such concepts have included using pairs of pre-compressed springs attached to the blade root to null the passive stiffness of a root actuator along the feathering axis [24]. Another means to manipulate blade stiffness is

* Corresponding author. Tel.: +44 1173315381.
E-mail address: paul.weaver@bristol.ac.uk (P.M. Weaver).

http://dx.doi.org/10.1016/j.tws.2015.04.017
0263-8231/

to create a discontinuity in the external skin at the trailing edge where an actuated screw thread is attached. Creating a discontinuity in the skin, and thereby creating an open walled cross-section, reduces the torsional stiffness significantly. The actuated screw thread is able to resist torsion while enabling controlled twisting of the blade [25,26].

A new type of multistable twisting structure is presented in this paper which has no moving parts or mechanisms. The concept is first described using an analytical model along with finite element (FE) analysis. This is followed by details of the design and manufacture of a morphing wing which has zero torsional stiffness. The wing's shear centre is aligned with its aerodynamic centre to create a neutrally stable system.

2. Governing equations of deformation

2.1. Concept overview

The twisting structure consists of carbon fibre reinforced plastic (CFRP) strips which are assembled to form a grid-like structure. Each of these CFRP strips occupies a plane which is at a perpendicular distance R away from the axis of twist of the assembled structure. Fig. 1 gives a representation of the position of a single strip (dark grey) assembled as part of a larger twisting structure (light grey). Each strip is initially manufactured in a 'stress free' configuration which can include an initial pre-bend κ_x and an initial pre-twist κ_{xy}. The strips are then forced flat during the assembly of the structure. This increase in strain energy due to prestressing can cause a twist to develop in the assembled structure as it moves to a stable, lower energy, equilibrium. The structure can be given either a positive or negative twist by applying opposite twisting moments, $M(\phi)$, over the length l. As the structure twists by $\Delta\kappa_{xy}$ each CFRP member that is a non-zero distance R away from the twist axis will also be subject to a change in curvature $\Delta\kappa_x$ due to geometrically non-linear effects. The interaction between pre-bending and this source of geometric non-linearity can lead to a change in the torsional stiffness of the structure.

2.2. Inextensible model

It is assumed that the deformation of the strips is inextensible and that curvature is uniform across the mid-surface of a given strip. The assumption of inextensible deformation is valid for slender structural members where the strain energy associated with bending and twisting is much larger than the strain energy associated with stretching. The large deformations which are possible with bend-twist behaviour for a given strain energy and material strain limitations are desirable properties for shape adaptive structures. An

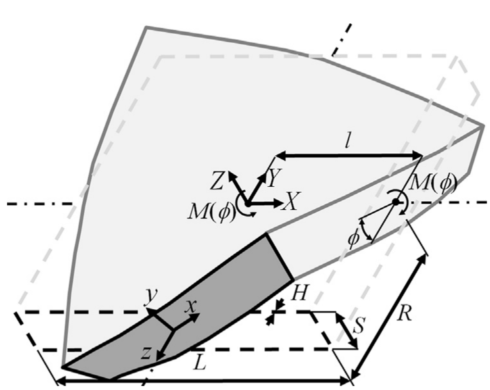

Fig. 1. A single structural member in straight (black dashed line) and twisted (black solid line) states at a distance R from the twist axis of the assembled structure (light grey).

expression for the curvature of a structural member deforming can be expressed in terms of an angle of twist ϕ over a reference length l. When $\phi=0$ it is assumed that the structure is in an untwisted configuration, as shown by the dashed outline in Fig. 1. With the twist axes aligned with the structural axes XY, the twist of the structure is related to out of plane deformation W by the expression

$$\frac{\partial^2 W}{\partial X \partial Y}=\frac{\phi}{l} \rightarrow W=\frac{\phi XY}{l}+aX+b \tag{1}$$

where a and b are constants of integration which must both be zero to satisfy $W(X,0)=0$ and $W(0,Y)=0$. Now consider a plane through the structure which is normal to either the X or Y axis. The in-plane deformations U^0 and V^0 in this plane can be described using von Kármán strains [5]. The following expression can be used to describe the relationship between the mid-plane shear strain in the structure with respect to the out-of-plane and in-plane displacements

$$\varepsilon_{XY}^0=\frac{1}{2}\left(\frac{\partial U^0}{\partial Y}+\frac{\partial V^0}{\partial X}+\left(\frac{\partial W}{\partial X}\right)\left(\frac{\partial W}{\partial Y}\right)\right) \tag{2}$$

Since the structure is subject to pure torsion we can assume $\partial U^0/\partial Y$ and $\partial V^0/\partial X$ are equal and that the shear strain ε_{XY}^0 at the mid-plane is zero. By implementing these assumptions and rearranging Eq. (2) in terms of either U^0 or V^0 yields

$$U^0=-\tfrac{1}{2}\int\left(\tfrac{\partial W}{\partial X}\right)\left(\tfrac{\partial W}{\partial Y}\right)\mathrm{d}Y=-\tfrac{XY^2}{4}\left(\tfrac{\phi}{l}\right)^2+c$$

$$V^0=-\frac{1}{2}\int\left(\frac{\partial W}{\partial X}\right)\left(\frac{\partial W}{\partial Y}\right)\mathrm{d}X=-\frac{X^2 Y}{4}\left(\frac{\phi}{l}\right)^2+d \tag{3}$$

where c and d are two further constants of integration. The curvature of a plane due to in-plane deformation can then be found by taking the appropriate second derivative of Eq. (3)

$$\frac{\partial^2 U^0}{\partial Y^2}=-\frac{X}{2}\left(\frac{\phi}{l}\right)^2, \quad \frac{\partial^2 V^0}{\partial X^2}=-\frac{Y}{2}\left(\frac{\phi}{l}\right)^2 \tag{4}$$

The change in curvature of a plane $\Delta\kappa$ with respect to the local (x,y,z) co-ordinate system can therefore be expressed as

$$\Delta\boldsymbol{\kappa}=\begin{bmatrix}\Delta\kappa_x\\ \Delta\kappa_y\\ \Delta\kappa_{xy}\end{bmatrix}=\begin{bmatrix}\frac{R}{2l^2}\left(\phi^2-\phi_i^2\right)-\frac{1}{R_i}\\ 0\\ 2\left(\frac{\phi-\phi_i}{l}\right)\end{bmatrix} \tag{5}$$

where the prestress of a strip is described by having a manufactured radius of curvature R_i and manufactured twist angle ϕ_i prior to assembly. It is assumed that the change in curvature of a strip described by Eq. (5) has no change in transverse curvature $\Delta\kappa_y$. This is a valid assumption for slender strips where the change in strain energy due to longitudinal curvature and twist will be dominant. The elastic strain energy of the assembled structure Π can then be expressed as [27]

$$\Pi=\frac{1}{2}\sum_{n=1}^{n_t} L_n S_n \Delta\boldsymbol{\kappa}_n^{\mathrm{T}}\mathbf{D}_n^{*}\Delta\boldsymbol{\kappa}_n \tag{6}$$

where $\Delta\boldsymbol{\kappa}_n^{\mathrm{T}}$ is the transpose of the tensor $\Delta\boldsymbol{\kappa}_n$, n_t is the total number of strips and L_n and S_n are the length and width of the nth strip respectively. The bending stiffness of the nth strip is described by the matrix $\mathbf{D}_n^{*}$ using Classic Lamination Theory [28]. For a specially orthotropic composite laminate (where the principal material axes are aligned with the section axes) that consists of plies symmetrically arranged about the mid-surface then there is no coupling between bending and extension and no coupling between bending and twist. The strain energy formulation in Eq. (6) then simplifies significantly. Differentiating Eq. (6), for the case of a specially orthotropic laminate, with respect to the twist angle ϕ yields an expression for the twisting moment M. Furthermore, differentiating the expression of the twisting moment with respect to ϕ yields the expression for the torsional