Composite Structures 157 (2016) 265–274

Contents lists available at ScienceDirect

Composite Structures

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

Multifunctional composites with intrinsic pressure actuation and prestress for morphing structures

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A R T I C L E I N F O

Article history:
Received 11 May 2016
Revised 25 July 2016
Accepted 31 August 2016
Available online 4 September 2016

Keywords:
Morphing
Prestressed
Fiber-reinforced elastomer
Active composite
Pressure-actuated

A B S T R A C T

Pressure-actuated elements can be embedded in morphing panels to achieve continuous control of shape and stiffness. This paper presents a multifunctional laminated composite that exhibits a curved geometry due to intrinsic mechanical prestress and a change in curvature when fluid (liquid or gas) contained in one of its laminae is pressurized. The composite is composed of a mechanically-prestressed layer, a fluidic layer, and a constraining layer. The composite can be driven to any desired shape up to a flat limiting shape through modulation of pressure in its fluidic layer. An analytical model is developed to characterize the quasi-static response of such a composite to the applied fluid pressure for various laminate stacking sequences. A parametric study is also conducted to study the effects of the dimensions of the fluid channel and its spatial location. Composite beams are fabricated in the laminate configuration that requires the least actuation effort for a given change in curvature. Pneumatic pressure is applied to the composite in an open-loop setup and its response is measured using a motion capture system. The simulated response of the composite is in agreement with the measured response.

1. Introduction

Morphing structures have gained importance in the aerospace and automotive industries due to their ability to serve multiple functions as adaptive control surfaces. In an aircraft, wings with variable-geometry optimize aerodynamic drag at various operating conditions [1], leading to improved fuel economy and performance. Morphing concepts for aircraft wings have been studied extensively [2,3]. In automobiles, potentially conflicting requirements like aesthetics and aerodynamic efficiency can be met by incorporating morphing panels into the vehicle body [4]. A design requirement encountered quite often in the development of morphing panels is the ability to achieve a large change in curvature. Curvature change is typically achieved by actuating a panel whose stiffness is tailored for the desired shape transition. Curvature in a fiber-reinforced polymeric (FRP) composite can be created by imparting residual stress in its matrix through high temperature curing [5,6]. In symmetric FRP laminates, creation of curvature requires a mechanically applied fiber-prestress in addition to thermally-induced matrix prestress [7,8]. Initially-curved composites with a mechanically-prestressed matrix can serve as morphing elements when installed in a structure [9]. The limitation in the existing designs is that the entire matrix must be prestressed to create curvature. Application of matrix prestress in specific laminae allows combination with a wide variety of other laminae to create multifunctional composites. Chillara et al. [10] demonstrated a curved laminated composite with an intrinsic prestress in the matrix of a single lamina. In this design, the residual stress can only be redistributed within the composite and not relieved.

Embedded actuation is preferred for morphing panels due to the possibilities for reducing weight, size, and complexity. In most cases, the actuation material is either inserted into channels created in a passive composite [11] or is an active layer in a laminated composite [12]. Passive composites can also be actuated through thermal loading [13,14]. However, this method is mostly restricted to thermally-cured FRP laminates. Ideally, an actuation material embedded in a morphing composite should have a high power output per unit volume and operate the composite in a frequency range consistent with the structural dynamics. Piezoelectric materials can generate an adequate amount of force [15] but require stroke amplification to achieve large deflection while maintaining system rigidity and frequency response. Shape memory alloys can provide sufficient force and stroke although their application

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http://dx.doi.org/10.1016/j.compstruct.2016.08.044
0263-8223/

is often limited by their low operating frequency limit of about a few Hz. Continuous shape control is a challenge in the case of shape memory materials. In some cases, hydraulic and pneumatic actuators can produce large force and stroke in the frequency range of the structure, but with a weight penalty. Lightweight and compact solutions for harnessing fluid power are offered by smart material-based miniature electrohydraulic actuators [16] that amplify the small stroke of materials with high frequency bandwidth such as piezoelectrics and magnetostrictives through fluid flow rectification.

Fluid-based actuation systems are of interest in fields like soft robotics, bio-inspired structures, and morphing structures. Linear actuators such as pressurized artificial muscles are often used to create robotic mechanisms that can bend or fold [17]. Flexible pneumatic bending actuators have been proposed by Deimel and Brock [18] for a soft-robotic hand that can grip objects. Marchese et al. [19] developed a compliant structure with embedded fluid channels that is capable of replicating fish-like motion. Philen et al. [20,21] and Feng et al. [22] developed variable-stiffness skins with embedded fluidic muscles that can be used for morphing aircraft wings. The basic design principle in these fluidic actuators is that linear actuation is achieved by restricting radial expansion through fiber-reinforcement while bending is achieved by bonding a constraining layer to a linear actuator.

This paper presents a fluidic prestressed composite (FPC) in which fluid power is used to morph its shape from a curved to a flat geometry (Fig. 1). Intermediate curvatures are obtained through the modulation of pressure of the contained fluid. A prestressed elastomeric layer, a fluidic layer, and a constraining layer constitute this composite. While the equilibrium shape of the proposed fluidic composite is created through application of mechanical prestress to the elastomeric layer (Fig. 1(a)), morphing action is accomplished through pressurization of the fluidic layer of the composite (Fig. 1(b)). An elastomeric matrix composite (EMC) exhibits anisotropic stiffness through fiber-reinforcement in an elastomeric matrix [23]. An EMC with unidirectional fibers in the 90° orientation has been proposed as a flexible-skin panel for the span morphing of an aircraft wing [23,24]. The property of near-zero in-plane Poisson's ratio of a 90° EMC is used to create a single cylindrical curvature in the FPC. Daynes et al. [25] presented reinforced elastomers in a prestressed condition in a morphing wing structure but not in a laminated-composite setup. An FPC (Fig. 1) is capable of controlled shape transition from a cylindrical shell to a flat plate through simultaneous actuation of parallel fluid channels that are embedded along the curve. The actuation mechanism is shown in Fig. 2(c). The fluid channels are molded into a reinforced flexible lamina instead of being embedded as individually-reinforced fluidic muscles in a flexible medium as in [21,26], resulting in a simpler fabrication process. Further, molded fluid channels can have an arbitrary cross section, leading to lower composite thickness for a given actuation effort. Complex curvatures in an FPC are possible through a vascular network of fluid channels. Through the design of individual channel dimensions, the maximum force exerted along the fluid path and hence the localized curvature can be regulated. Multiple pressure sources enable sequential actuation of various regions of the composite.

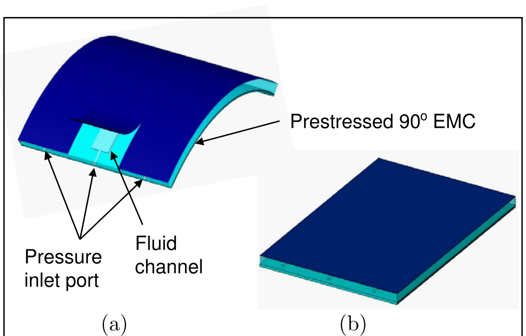

Fig. 1. (a) Geometry of a fluidic prestressed composite in the unactuated state, (b) limiting actuated shape of the composite when the fluid channels are pressurized. EMC stands for elastomeric matrix composite.

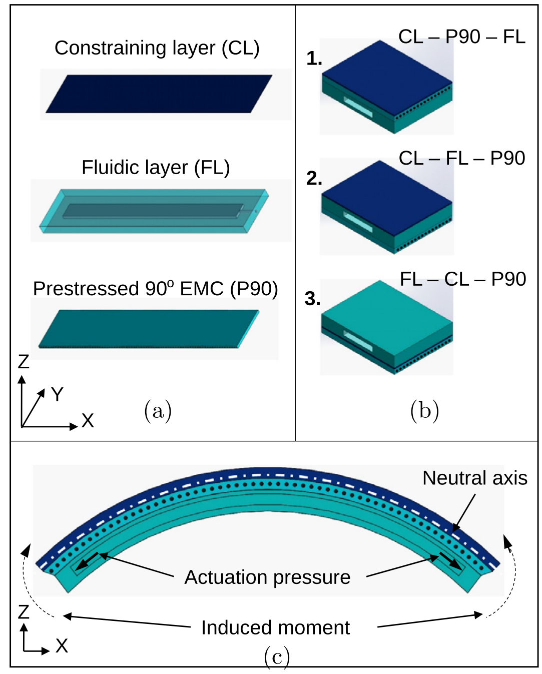

Fig. 2. (a) Participating laminae, (b) possible laminate configurations of a fluidic prestressed composite, (c) for configuration 1, pressurization of the fluidic layer induces moments as shown.

The laminae of the composite and their stacking sequences are described in Section 2. A nonlinear analytical laminated-plate model is developed to characterize the response of a generic FPC (Section 3). The large-deflection problem is defined using a Lagrangian strain formulation based on classical laminated plate theory. Material and geometric nonlinearity of a prestressed EMC is included in this model. Quasi-static equilibrium curvature is calculated as a function of the applied fluid pressure by minimizing the total energy of the composite. The laminate configuration of a morphing panel that requires the least actuation effort is determined through a model-based analysis. A design methodology for an FPC is presented through a parametric study of the effect of fluid channel sizing on composite response (Section 4). A technique for fabricating a fluidic prestressed composite is proposed and demonstrated (Section 5). The fabrication method for the fluidic layer is inspired by fluidic elements designed for applications in soft robotics. The fabricated samples are pneumatically actuated and their quasi-static response is recorded using a motion capture system for model validation (Section 6).

2. Fluidic prestressed composite

The laminae of a fluidic prestressed composite viz., prestressed elastomeric layer, fluidic layer, and constraining layer, are described in this section. Also, the possible laminate configurations, each resulting in a unique response of the composite, are introduced.