Composites Science and Technology 105 (2014) 134–143

Contents lists available at ScienceDirect

Composites Science and Technology

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

High performance carbon fibre reinforced epoxy composites with controllable stiffness

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ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 3 September 2014
Accepted 10 September 2014
Available online 28 September 2014

Keywords:
A. Carbon fibres
A. Polymer–matrix composites
A. Structural composites
Interleaved composites
B. High-temperature properties

ABSTRACT

The mechanical properties of polystyrene-interleaved carbon fibre reinforced epoxy composites, which exhibit controllable stiffness, have been investigated. DMTA and flexural tests showed that the storage modulus and flexural stiffness of these composites could be reduced by up to 98% when heated from 20 °C to 120 °C and the stiffness was fully recoverable on cooling. The flexural stiffness of the interleaved composites at room and elevated temperatures were predicted using simple beam theory and were found to be in good agreement with the measured values. Compressive and tensile properties were significantly reduced at 120 °C due to the presence of the softened polystyrene interleaves. Flexural strength tests at 20 °C indicate that there is a need for improvement of the adhesion between polystyrene and carbon fibre reinforced epoxy plies.

1. Introduction

Controllable stiffness materials possess the characteristic that the stiffness can be changed on demand. Such materials have potential applications in deployable structures, e.g. instrumentation booms on satellites [1,2], and in shape adaptive structures such as morphing wings [3–6]. In both cases the ability to reduce the stiffness prior to deployment, or prior to the required shape change, can significantly reduce the requirements of the actuation system.

Various forms of controllable stiffness materials have been proposed such as a controllable stiffness composite consisting of an elastomer matrix containing braided composite tubes which could be pressurised to change the stiffness and shape of the composite [7–9]. However this paper will focus on materials in which the stiffness can be varied by controlling the resistance to shear displacement between constant stiffness elements. One such material, proposed by McKnight and Henry [10], consists of a laminate formed by layers of discontinuous steel plates (the constant stiffness material) separated by, and bonded to, layers of a variable stiffness, polyurethane-based shape memory polymer (SMP). The gaps between the steel plates in a layer of this composite were positioned to be 'out of phase' with those in adjacent layers so that the membrane and flexural stiffnesses of the composite are a function of the shear distortion of the SMP in the overlap regions between the steel plates in adjacent plies. On heating to temperatures above the transformation temperature of the SMP, the shear modulus of the SMP reduced significantly and so the stiffness of the composite was also reduced. High losses (up to 99%) in storage modulus were measured.

McKnight and Barvosa-Carter subsequently patented concepts for variable stiffness structures [11]. The patent includes various configurations using combinations of constant and variable stiffness materials; among these is an interleaved laminate form consisting of continuous constant stiffness layers separated by, and bonded to, variable stiffness interleaf layers. Fig. 1 illustrates, for an interleaved laminate consisting of carbon fibre reinforced polymer (CFRP) layers and thermoplastic interleaves, how the flexural stiffness of the laminate depends on the shear stiffness of the interleaf material. The thermoplastic interleaf material is chosen so that its glass transition temperature (T_{g-t}) is less than that of the fibre reinforced composite plies (T_{g-c}). At temperatures less than T_{g-t} the laminate is in a high flexural stiffness state but when the temperature is increased to above T_{g-t} (but less than T_{g-c}) the loss of

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http://dx.doi.org/10.1016/j.compscitech.2014.09.008
0266-3538/

shear stiffness of the interleaf layers results in a reduced flexural stiffness [12]. Maples et al. [12,13] have conducted preliminary experimental investigations of a polystyrene (PS)-interleaved carbon fibre reinforced epoxy composite, which indicated that large reductions of over 90% in flexural stiffness are possible. In addition to simply controlling the flexural stiffness, Raither et al. [14] were able to demonstrate that the bend-twist coupling could be reduced by a factor 10 in a CFRP multidirectional laminate containing elastomer interleaf layers when heated above the T_g of the elastomer.

Controllable stiffness interleaved configurations have also been examined by Ghandi et al. [15,16] who investigated a laminated beam consisting of aluminium plates separated by layers of cast acrylic or polyvinyl chloride (PVC). Ultra-thin electric heating blankets were embedded into the polymer layers to heat them through T_g and the resulting flexural stiffness were reported to reduce by a factor of between two and four in initial experiments, depending on the geometry. Subsequent finite element modelling has shown that much greater reductions (over 95%) can be achieved in other interleaved beam configurations [17].

The interleaved laminate strategy uses a variable stiffness interleaf layer to control the relative shear displacement between adjacent constant stiffness layers. Bergamini et al. [18] took an alternative approach to control the shear displacement by using electrostatic coupling. A laminated beam consisting of CFRP and glass fibre reinforced polymer layers was manufactured in which the layers were not bonded together but an electric field was applied through the thickness to prevent or allow relative shear displacement between adjacent layers. Experiments were performed to demonstrate that this approach could be used to adjust the flexural stiffness of such a beam to suppress vibration due to resonance.

Another strategy to control the stiffness of a material by exploiting the temperature dependent shear stiffness of a polymer layer has been investigated by us [19,20]. A controllable stiffness composite was manufactured, which consisted of polyacrylamide (PAAm) coated carbon fibres in an epoxy matrix. A current was passed through the carbon fibres to heat the PAAm interphase through its T_g and so permit relative shear displacement between fibres and matrix. This resulted in an 88% reduction in flexural stiffness of the composite. The flexural stiffness was fully recovered when the composite was cooled to room temperature.

This paper presents a detailed investigation of carbon fibre reinforced epoxy laminates containing PS interleaves. Simple beam theory is used to predict the flexural behaviour of the materials and this is compared to the performance observed in the tests.

2. Predictions of flexural stiffness and strength

Simple beam theory can be used to approximate the bending behaviour of the interleaved composites [12,18]. At temperatures T, where $T < T_{g-t}$, the elastic modulus of the thermoplastic interleaf (PS in this case) will be very small when compared to the fibre direction stiffness of the unidirectional (UD) CFRP plies but is assumed to be sufficiently large to ensure that the composite plies act as an integral structural element and that sections initially plane and normal to the axis of the beam remain so when the beam is flexed. At a temperature T, where $T_{g-t} < T < T_{g-c}$, the stiffness of the PS is so low that the CFRP plies act as independent structural elements able to effectively slide freely relative to each other so that initially plane sections no longer remain plane.

2.1. Analysis of room temperature bending behaviour of interleaved composite containing 0° plies

For a symmetric layup, the apparent flexural modulus, E_f^{RT}, of the beam material at room temperature assuming the beam is homogenous, can be calculated using Eq. (1), where E_c is the elastic modulus of the composite ply in the 0° direction. The definitions of the terms are shown in Fig. 2. Note that a composite layer can consist of more than one composite ply.

$$E_f^{RT} = \frac{12E_c}{h^3}\underbrace{\sum_{i=1}^{N}\left(\frac{t_i^3}{12} + t_i z_i^2\right)}_{\text{Composite layers only}} \tag{1}$$

An expression for the apparent flexural strength, σ^*, can also be derived where, again, 'apparent' indicates that this is the strength of the beam if it is treated as homogenous.

$$\sigma^* = \frac{12\sigma^u \underbrace{\sum_{i=1}^{N}\left(\frac{t_i^3}{12} + t_i \cdot Z_i^2\right)}_{\text{Composite layers only}}}{h^3} \tag{2}$$

Using σ^u as the longitudinal flexural strength measured in a pure CFRP specimen, Eq. (2) gives the predicted apparent flexural strength, σ^*, for an interleaved composite.

2.2. Analysis of high temperature bending behaviour of interleaved composites containing 0° plies

Assuming the layers are free to slide, the apparent flexural modulus at a T above T_g of PS but less than that of the epoxy of the interleaved composite is given by Eq. (3).

$$E_f^{HT} = \frac{E_c \underbrace{\sum_{i}^{N} t_i^3}_{\text{Composite layers only}}}{h^3} \tag{3}$$

Failure will occur when the maximum stress in any of the CFRP layers exceeds the strength. Since all layers can be assumed to have the same curvature about their own centroidal axis (i.e. no extension or compression at the mid-plane of each CFRP layer) then the

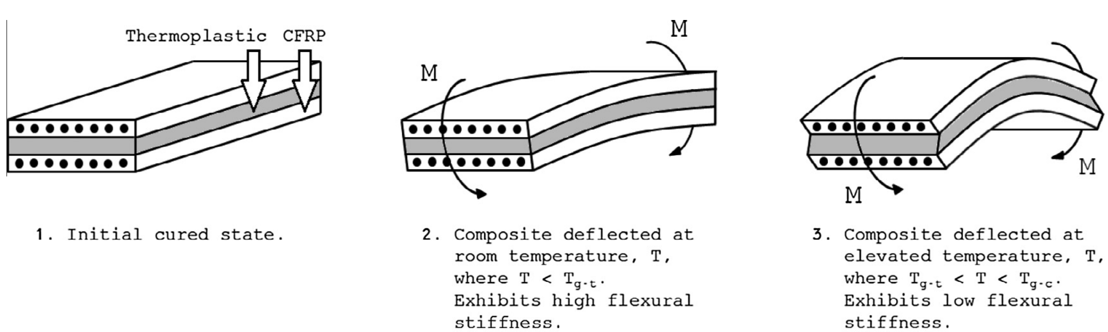

Fig. 1. Flexural stiffness control in an interleaved composite laminate.