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Measurement of assembly stress in composite structures using the deep-hole drilling technique

Carlos Garza[a], Raj Das[b], Anton Shterenlikht[c], Martyn Pavier[c,*]

[a] Consejo Nacional de Ciencia y Tecnología, Av. Insurgentes Sur 1582, Col. Crédito Constructor, 03940 Mexico City, Mexico
[b] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, GPO Box 2476, Melbourne, Victoria 3001, Australia
[c] Department of Mechanical Engineering, University of Bristol, Queen's Building, University Walk, Bristol BS8 1TR, United Kingdom

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ABSTRACT

The deep-hole drilling (DHD) method is a residual stress measurement method that is widely used for measurements in thick metallic components. In the DHD method a reference hole is first drilled through the thickness of the component. The diameter of the hole is measured accurately and then a cylindrical core of material around the hole is trepanned from the component, relaxing the residual stresses in the core. Finally, the diameter of the reference hole is re-measured and the change in diameter used to calculate the residual stress. In this work the method is used to attempt the measurement of cure and assembly stress in thick AS4/8552 composite laminates. The results indicate that although the DHD method cannot measure cure stress, it is able to measure assembly stress. Futhermore, a modification to the standard DHD method allows the through-thickness component of assembly stress to be measured in angle components.

1. Introduction

The latest generation of civil aircraft use carbon fibre composite components throughout their structure. Some of these components have very large sections, sometimes up to 50 mm or more in thickness. Typical examples are wing skins and landing gear attachment ribs. For such components, residual stresses introduced during the manufacturing process will exist and require quantification to ensure safe and economic operation. A major cause of residual stress in a composite structure is assembly stress. Fig. 1 shows a schematic diagram of the assembly of a wing box from two spars and two wing skins. Distortion of the wing spars during manufacture [1,2] leads to a mis-fit between the components and results in an assembly stress in the final structure. Current practice is to minimise the level of assembly stress by the use of shims [3,4], but this is an expensive and time-consuming procedure.

Of particular concern is the generation of a through-thickness component of assembly stress in the corners of components such as wing spars. In Fig. 1 the flanges of the spars are bent inwards during assembly, giving rise to a compressive through-thickness stress. If instead the flanges were bent outwards, a tensile though-thickness stress would develop, leading to an increased likelihood of delamination [5].

The problem of measuring the residual stress in composite materials has attracted previous attention, although many techniques that have been attempted are not suitable for measurements in thick sections. Schajer and Yang [6] used the hole-drilling method used to measure residual stress in isotropic materials and modified the analysis so that is could be applied to composite materials. In the hole-drilling method a strain gauge rosette is bonded to the surface of the laminate and then a hole is drilled through the centre of the rosette. The residual stress is calculated from the strain changes measured by the rosette. Sicot et al. [7] describe an incremental hole-drilling method to measure residual stress in a 1 mm thick carbon/epoxy laminate. Incremental hole-drilling method is an extension to the original hole-drilling method allowing the variation of residual stress with depth to be measured. More recently, the hole-drilling method has been combined with a moiré technique [8], digital image correlation (DIC) [9–11] and electronic speckle-pattern interferometry [12] to improve the accuracy of the method.

Raman microscopy was used by Filiou and Galiotis [13] to measure the residual strain in individual fibres in carbon-fibre thermoplastic composite. This work is however concerned with what Barnes and Byerly [14] term ‘microstresses’: microscopic residual stress arising from the difference in thermal properties of the fibre and resin.

Guemes and Menéndez [15] used Bragg grating fibre-optic sensors embedded in a 7 mm thick carbon/epoxy quasi-isotropic laminate. A hole was drilled close to the point of intersection of the fibres. Results showed that stresses of the order of 50 MPa were released by the hole drilling. Although suitable for measuring residual stress in the plane of the composite, the technique would be difficult to use to measure

* Corresponding author.
E-mail address: martyn.pavier@bristol.ac.uk (M. Pavier).

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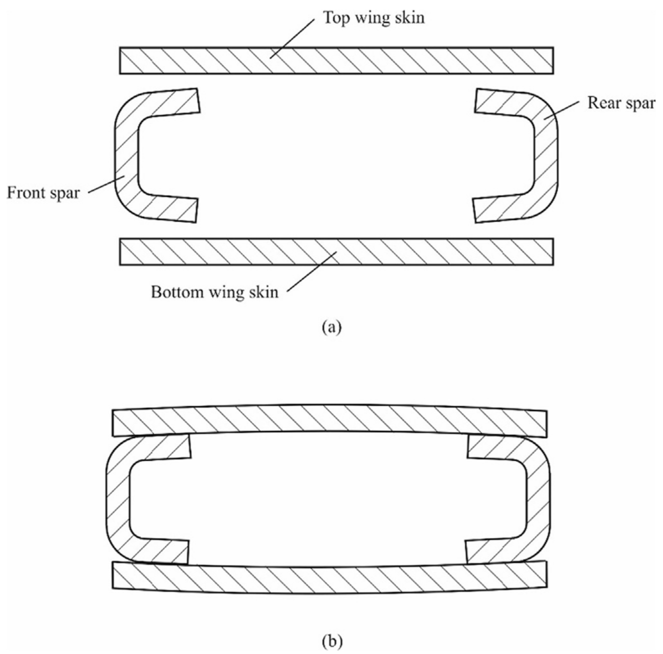

Fig. 1. Diagram showing an example of the generation of assembly stress: (a) wing box components before assembly, (b) wing box structure after assembly.

residual stresses between plies.

Cowley and Beaumont [16] describe a layer removal technique to measure the residual stress by machining away near surface plies and then measuring the resulting curvature of the remaining laminate. Ersoy and Vardar [17] also used a layer removal technique, except that they removed layers by forcing a knife blade between plies. Such techniques are unsuitable for thick section components because the resulting curvature is so small.

In addition to experimental work to measure the residual stress in composites, attempts have been made to predict the residual stress from theoretical models of the manufacturing process. Bogetti and Gillespie [18] used a method based on laminate theory to predict residual stresses arising from shrinkage of the resin during cure and mismatch of thermal expansion coefficients between plies. Other work has used the finite element method to predict residual stress [19]. Such analyses are not straightforward and do not provide reliable predictions of residual stress because the necessary thermal and mechanical properties of the resin are difficult to measure and change during cure.

In this paper, the use of the deep-hole drilling (DHD) method is used to measure the assembly stress in thick section composites. The DHD method is a well-established residual stress measurement method for metallic materials and is particularly suitable for large, thick section components. Initial development of the deep-hole method was carried out by Zhadanov and Gonchar [20], Beaney [21], and Jesensky and Vargova [22]. More recent improvements to the deep-hole method have been made by Smith and his co-workers [23–27]. An attempt has been made to use the DHD method to measure the cure residual stresses in a thick section composite laminate [28] but we will show here that such a measurement leads to substantial error.

2. Deep-hole method for orthotropic materials

In the DHD method, a hole is first drilled through the thickness of the component using a gun drill (Step 1 of Fig. 2). Next the diameter of the hole is measured accurately using an air probe (Step 2 of Fig. 2) and then a cylindrical core of material around the hole is trepanned from the component, relaxing the residual stresses in the core (Step 3 of Fig. 2). For metallic components an electro-disharge machinging method (EDM) can be used to trepan the core but for composite materials a diamond tipped hole saw has been found to be suitable. Finally, the diameter of the hole is re-measured and the change in diameter used to calculate the residual stress (Step 4 of Fig. 2). The DHD method assumes that the relaxation of residual stress at the trepan radius caused by the introduction of the reference hole is negligible and that the residual stresses are completely relaxed in the trepanned core in a linear elastic manner. Fig. 2 also shows the front and back bushes that are adhesively bonded to the component to provide a residual stress free datum.

Fig. 3(a) shows a cross section through the thickness of a component being measured. The air probe measures the diameter d_0 before trepanning and the diameter d after trepanning. Depending on the variation of residual stress with depth, the diameter d will vary through the thickness of the component. Fig. 3(b) shows a cross section of the hole measured at one depth. In general the circular hole will distort into a elliptic hole so that the diameter varies with the angular postition θ.

The calculation of the residual stress from the change in diameter of the hole requires the evaluation of a set of coefficients based on an analysis of the distortion of a hole in a plate loaded by far-field direct and shear stresses. For isotropic materials the evaluation uses the Mitchell solution for the elastic deformation of a hole in a plate [29]. For orthotropic materials the coefficients can be derived from Lekhnitskii's analysis [30,31].

The coefficients used in the DHD calculations of residual stress, f_θ, g_θ and h_θ, are defined by

$$\frac{u_r}{a} = \frac{d(\theta) - d_0}{d_0} = \frac{1}{E_1}(f_\theta \sigma_{11}^0 + g_\theta \sigma_{22}^0 + h_\theta \sigma_{12}^0) \tag{1}$$

where u_r is the radial displacement at the hole edge at angle θ to the major principal material direction, a is the radius of the hole and σ_{11}^0, σ_{22}^0 and σ_{12}^0 are far-field applied stresses in the principal material coordinate system. Fig. 4 shows the global xy coordinate system used for the measurement and the principal material coordinate system. The angle $\varphi = \theta + \alpha$ is the angle between the global x axis and the angular postion of the measurement of radial displacement where α is the angle between the fibre direction and the x axis.

The coefficients f_θ, g_θ and h_θ are dimensionless functions of θ that depend on the orthotropic material constants.

$$f_\theta = \frac{1}{2}[1 + n - k + (1 + n + k)\cos 2\theta] \tag{2}$$

where

$$k = \sqrt{\frac{E_1}{E_2}}, \quad n = \sqrt{2(k - \nu_{12}) + \frac{E_1}{G_{12}}} \tag{3}$$

$$g_\theta = \frac{1}{2}[k^2 + nk - k - (k^2 + nk + k)\cos 2\theta] \tag{4}$$

and

$$h_\theta = \frac{1}{2}(n^2 + nk + n)\sin 2\theta \tag{5}$$

In Eqs. (1)–(5), E_1, E_2 are the Young's moduli of the material in the major and minor principal material directions, ν_{12} is Poisson's ratio for loading in the major principal material direction and G_{12} the shear modulus.

Finite element analysis has been carried out using Abaqus 6.12 to provide validation of these equations [31]. The material properties used for these analysis are for unidirectional carbon/epoxy AS4/8552 as defined in Table 1, giving $k = 3.75$ and $n = 5.733$. Fig. 5 shows a comparison of the values of the coefficients obtained from finite element analysis with those evaluated using Eqs. (2), (4) and (5). In Fig. 5, the coefficients g_θ and h_θ have been divided by k so that the range of values for all coefficients are similar.