OPEN ACCESS

University of BRISTOL

Garza Rodriguez, C., Smith, D., Shterenlikht, A., & Pavier, M. (2015). Advances in the deep hole drilling technique for the residual stress measurement in composite laminates. In Proc 5th Thematic Conf. Mech. Response Composites, Bristol, UK, 7-9 September.

Publisher's PDF, also known as Version of record

License (if available):
Unspecified

Link to publication record in Explore Bristol Research
PDF-document

This is the final published version of the article (version of record). It first appeared online via ECCOMAS at http://www.eccomas.org/spacehome/1/10. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research
General rights

ADVANCES IN THE DEEP-HOLE DRILLING TECHNIQUE FOR THE RESIDUAL STRESS MEASUREMENT IN COMPOSITE LAMINATES

C. Garza[*], D.J. Smith, A. Shterenlikht and M.J. Pavier

Department of Mechanical Engineering, University of Bristol
Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom
[*]E-Mail: carlos.garza@bristol.ac.uk

Keywords: Composite Laminates, Deep Hole Drilling, Residual Stresses

ABSTRACT

The deep-hole drilling (DHD) method is a residual stress measuring technique commonly used in isotropic materials. This paper provides an investigation into using DHD to determine residual stress fields in orthotropic laminated composite materials. In this method, a reference hole with a small diameter is drilled through a component that has residual stresses. The diameter of the hole is carefully measured using an air probe as a function of depth and angular position inside the hole. The residual stresses are then released by trepanning a core of larger diameter from around the hole. The diameter of the hole is afterwards re-measured at the same angular positions and depths as in the original measurements. Changes in the shape of the hole are related to the residual stresses that were present before the hole was drilled. For orthotropic materials, the calculation of residual stresses requires the evaluation of distortion coefficients which rely on the mechanical properties of the components. In this work, the finite element method and analytical approximations are used to determine these coefficients. Using this technique, the in-plane residual stresses in an AS4/8552 composite laminate are experimentally measured and compared to finite element predictions as well as to classical laminate theory. It was determined that when using DHD in laminated materials the ratio between the thickness of the layers and the reference hole and trepan diameter needs to be sufficiently high, otherwise remaining interlaminar shear stresses in the trepanned core leads to inaccurate measurements.

1   INTRODUCTION

Deep-Hole Drilling (DHD) is a technique that allows the measurement of residual stress fields through very thick components. This technique requires that a small diameter hole is drilled through a component that contains residual stresses. The hole diameter is accurately measured (generally using an air probe) as a function of both depth and angular position inside the hole. The residual stresses in the component are afterwards released by machining away a core of larger diameter from around the hole. The relaxation of residual stress distorts

the shape of the reference hole. The reference hole diameter is subsequently re-measured at the same angular positions and depths. The reference hole distortion is lastly related to the residual stresses that existed in the component before drilling the hole.

The main assumption of this method is that the drilling of the reference hole has no effect on the residual stress state and that removing the core causes the residual stresses around the hole to be fully released [1, 2]. The deep hole drilling technique has usually been used on metal parts such as in welds [3-5] and railway tracks [6]. In metallic components, EDM can be used to trepan a central core around the reference hole since additional residual stresses introduced by this method are not significant.

An attempt to apply this technique to a laminated carbon-fibre composite was made by Bateman et al. [2]. In this investigation, EDM could not be used to machine the core around the reference hole because CFRP is not conductive and for this reason a diamond encrusted hole saw was selected instead. Moreover, the analytical model to allow the change in hole shape to be related to the original residual stresses was extended to take into account the use of an orthotropic material.

2 ANALYTICAL MODEL

The DHD technique is based on the measured radial distortion to determine the components of the residual stress from the reference hole. The formulation to the case of far field biaxial stresses plus shear stress can be stated as

$$\bar{u} = \frac{1}{E}\left[f_{\theta_i}\sigma_x + g_{\theta_i}\sigma_x + h_{\theta_i}\tau_{xy}\right] \tag{1}$$

where for isotropic materials

$$f_{\theta_i} = 1 + 2\cos 2\theta_i$$
$$g_{\theta_i} = 1 - 2\cos 2\theta_i$$
$$h_{\theta_i} = 4\sin 2\theta_i$$

and $(\theta_i = 1 \dots N)$ is the measurement angle.

In the case of orthotropic materials these distortion coefficients depend on the mechanical properties of the component. Additionally, the relationship between the longitudinal direction of the material (fibre direction) and the measurement angle (air probe angular position during experiments) must be taken into consideration, see Figure 1.
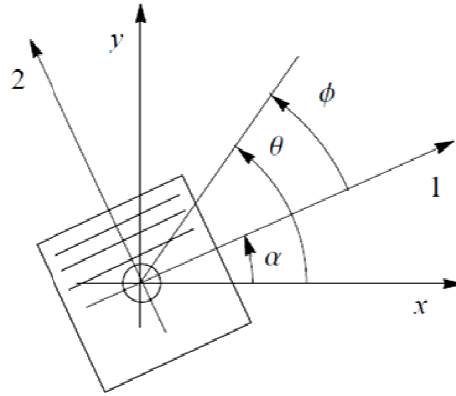
C. Garza, D.J. Smith, A. Shterenlikht and M.J. Pavier

Figure 1: Unidirectional laminate showing the relationship between the fibre direction (α) and measurement (θ) angles in reference to the global axes.

For this analysis, these coefficients for the studied material were calculated analytically and also using the finite element software ABAQUS considering the mechanical properties given in Table 1.

Engineering constant		Value
E_1	[GPa]	135
E_2	[GPa]	9.6
E_3	[GPa]	9.6
σ_{12}	–	0.3
σ_{13}	–	0.3
σ_{23}	–	0.435
G_{12}	[GPa]	5.2
G_{13}	[GPa]	5.2
G_{23}	[GPa]	3.4

Table 1: Mechanical properties of AS4/8552.

Lekhnitskii [7] demonstrates an approximate solution to determine the distortion of a hole in an orthotropic material after applying a far field stress in the principal material direction. In his analysis the distortion of the circular hole is related by the variation in diameter in the loading direction and normal to the loading direction. Lekhnitskii's analysis can only be applied to determine the coefficients related to direct stress using equations (2) and (3).

$$f_{\theta_i} = \frac{1}{2}\left[1 + n_1 - \sqrt{\frac{E_1}{E_2}}\right] + \frac{\cos 2\theta_i}{2}\left[1 + n_1 + \sqrt{\frac{E_1}{E_2}}\right] \tag{2}$$

$$g_{\theta_i} = \frac{1}{2}\left[(1 + n_2)\frac{E_1}{E_2} - \sqrt{\frac{E_1}{E_2}}\right] - \frac{\cos 2\theta_i}{2}\left[(1 + n_2)\frac{E_1}{E_2} + \sqrt{\frac{E_1}{E_2}}\right] \tag{3}$$

3

Nevertheless, the authors present an approximate solution to calculate the remaining coefficient corresponding to far-field shear stress using equation (4).

$$h_{\theta_i} = \left[\frac{E_1}{2G_{12}} + \frac{n_1(k+1)}{2} + k - v_{12} \right] \cos 2\theta_i \tag{4}$$

where

$$n_1 = \sqrt{\left[2\left(\sqrt{\frac{E_1}{E_2}} - v_{12} \right) + \frac{E_1}{G_{12}} \right]}$$

$$n_2 = \sqrt{\left[2\left(\sqrt{\frac{E_2}{E_1}} - v_{21} \right) + \frac{E_2}{G_{12}} \right]}$$

$$k = \sqrt{\frac{E_1}{E_2}}$$

For the ratios of material properties of an uni-directional AS4/8552 laminate, the coefficients provided by finite element analysis are given by

$$f_{\theta_i} = 1.49 + 5.21 \cos 2\theta_i$$

$$g_{\theta_i} = 15.89 - 19.51 \cos 2\theta_i$$

$$h_{\theta_i} = 30.04 \sin 2\theta_i$$

On the other hand, the coefficients calculated using the analytical solution are

$$f_{\theta_i} = 1.49 + 5.24 \cos 2\theta_i$$

$$g_{\theta_i} = 15.90 - 19.65 \cos 2\theta_i$$

$$h_{\theta_i} = 30.05 \sin 2\theta_i$$

The results of the finite element simulations and analytical calculations are shown in figures 2(a), (b) and (c) which indicate a significant agreement. The figures show the normalised radial distortion of the hole, which is the radial distortion multiplied by the ratio of the principal material modulus to the applied far-field stress, versus the angle.
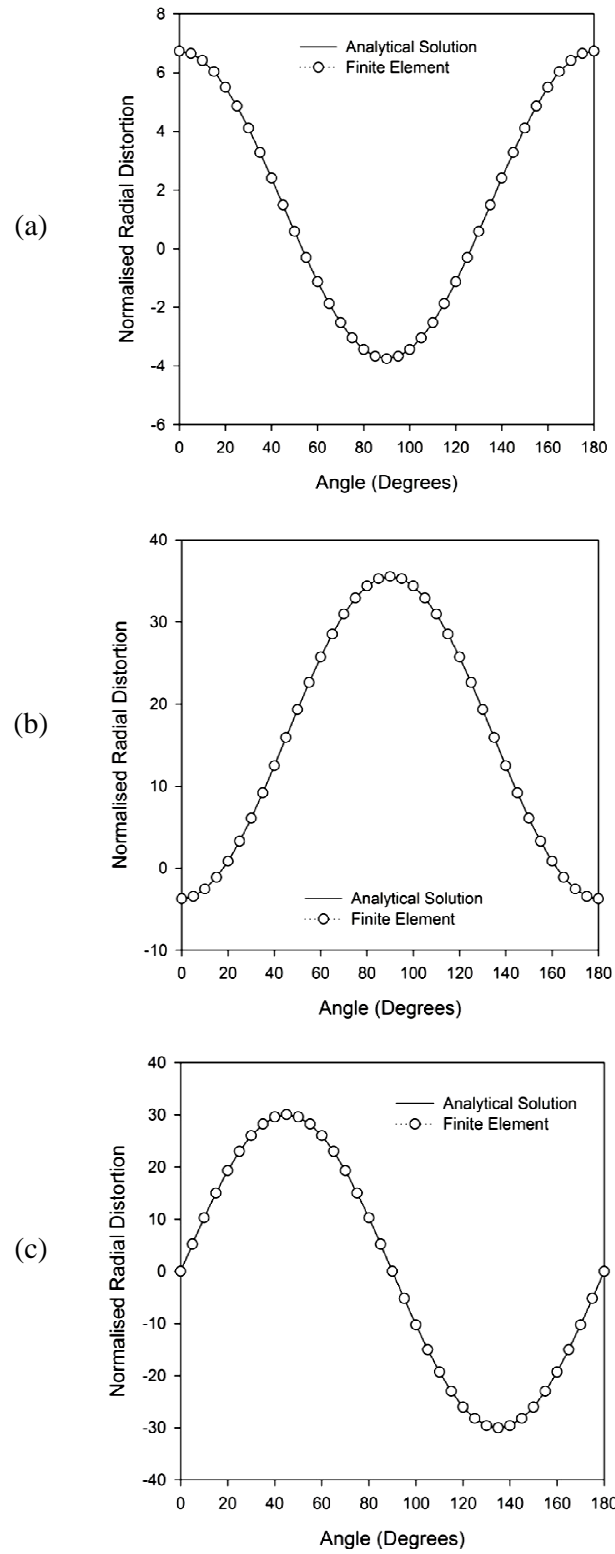
Figure 2: Finite element and analytical calculations of the normalised radial distortion of the hole versus the angle around the hole for (a) far-field direct stress applied in the x direction, (b) far-field direct stress applied in the y direction and (c) far-field applied shear stress.

The radial distortion is normally measured at nine different angles and at least three measurements are required to obtain accurate results. The relation of the measured radial distortions and the residual stress is given by

$$\bar{\mathbf{u}} = -\frac{1}{E_1} \mathbf{M} \cdot \boldsymbol{\sigma} \tag{5}$$

The use of the minus sign is required because the radial distortions are measured after releasing the residual stresses. The matrices are expressed as

$$\bar{\mathbf{u}} = \begin{bmatrix} \bar{u}|_{\emptyset=\emptyset_1} \\ \vdots \\ \bar{u}|_{\emptyset=\emptyset_i} \\ \vdots \\ \bar{u}|_{\emptyset=\emptyset_N} \end{bmatrix} \qquad \mathbf{M} = \begin{bmatrix} f_{\emptyset_1} & g_{\emptyset_1} & h_{\emptyset_1} \\ \vdots & \vdots & \vdots \\ f_{\emptyset_i} & g_{\emptyset_i} & h_{\emptyset_i} \\ \vdots & \vdots & \vdots \\ f_{\emptyset_N} & g_{\emptyset_N} & h_{\emptyset_N} \end{bmatrix} \qquad \boldsymbol{\sigma} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

where N is the number of angular measurements. Lastly, the residual stresses are determined from the measurements of the radial distortions of the hole by

$$\boldsymbol{\sigma} = -E\, \mathbf{M}^* \cdot \bar{\mathbf{u}} \tag{6}$$

where $\mathbf{M}^* = (\mathbf{M}^\mathbf{T} \cdot \mathbf{M})^{-1} \cdot \mathbf{M}^\mathbf{T}$ is the pseudo-inverse of $\mathbf{M}$.

3 EXPERIMENTAL PROCEDURES AND RESULTS

An AS4/8552 composite laminate of 18 mm in thickness consisting of 10 layers with different orientations was used to perform the DHD measurement, see Figure 3. To allow the measurement of residual stress using DHD, front and rear bushes were bonded using high strength adhesive to the specimen, centred on the location of the measurement.

The use of bushes has several benefits provide a setup for the fixation of the essential components for gun drilling and air probing and contribute to guide the hole saw perpendicularly to the specimen. Additionally, they decrease the effects of the air probe entrance and exit during the measurements of the diameters and help to avoid fibres delamination when the drill enters and exits the specimen.
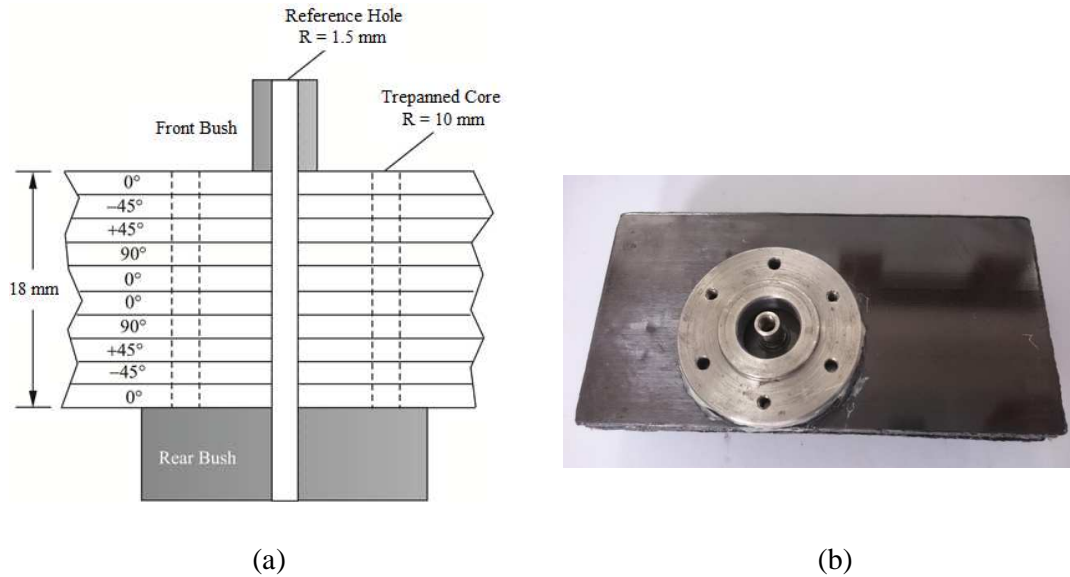
(a)   (b)

Figure 3: (a) Illustration showing the layer arrangement specimens and the bushes required for a DHD experiment (b) Composite laminate after conducting the DHD experiment

After drilling the reference hole, the air probe was introduced to measure precisely the hole diameter every 22.5° around it and at every 0.1 mm through it, resulting in nine measurements of diameter in total for every axial position. The air probe is not able measure accurately near a surface, nevertheless the front and rear bushes allow measurements near the surface of the specimens.

A hole saw was selected to perform the trepanning process which has the advantages of being faster than electrical discharge machining (EDM) and not requiring an electrolyte to be used. The hole saw used during the experiment has a diameter of 10 mm and was diamond tipped. Following the trepanning procedure, the diameter of the hole was re-measured using the air probe.

Lastly, the residual stresses were determined from the radial distortions of the reference hole to reveal the residual stress distributions shown in Fig 4. The global xy directions have been used instead of the principal material directions in each layer. Therefore, for stresses within the 0° layers, the σ_x stress component is the stress in the fibre direction while for stresses within the 90° layers, the stress component σ_x is the stress in the transverse direction. The experimental results are compared to Laminator (software based on classical laminate theory) predictions and DHD simulations using the same and different reference hole and trepan diameters as in the experiments.

The highest and lowest predicted stresses in the x direction are of the order of 20 and 65 MPa in compression, in the 0° and 90° plies respectively. On the other hand, the expected stresses in the y direction remained approximately on 36-38 MPa on the specimen. The predicted magnitude of the shear stress is very low throughout the entire laminate.
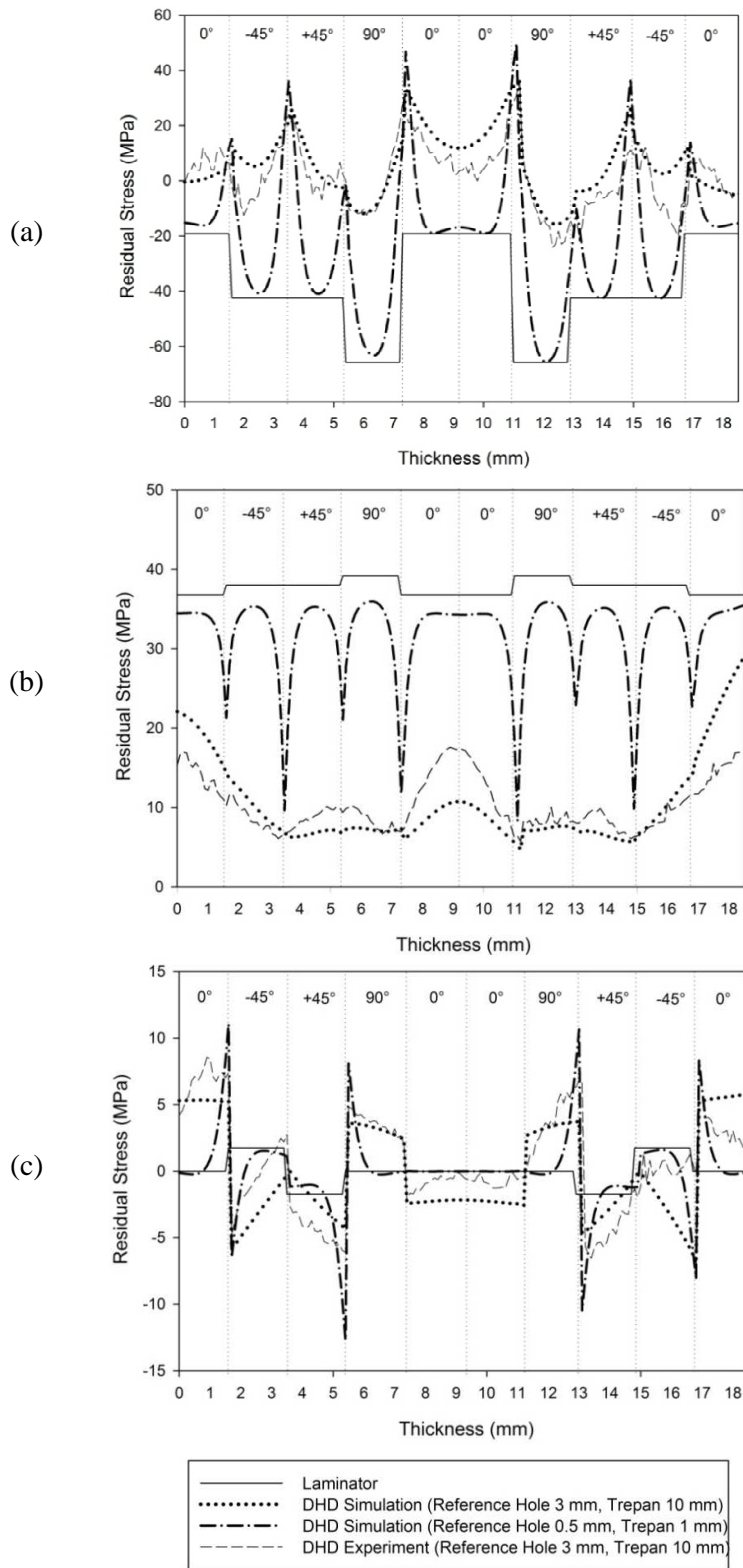
Figure 4: Comparison of the determined residual stresses in the global axes *x* (a), *y* (b) and in-plane shear *xy* (c) using Laminator, DHD experiment and DHD simulations with different reference hole and trepan diameters.

A comparison between the DHD experiment and the DHD simulation using a reference hole of 3 mm diameter and a trepan diameter of 10 mm shows a close agreement in the longitudinal and transverse components as well as the in-plane shear component. However, these values significantly disagree with residual stress predictions using Laminator, which suggests that a considerable amount of residual stresses were not relaxed after trepanning the core. This issue can be resolved by using a smaller dimension for the reference hole and trepan diameters. After selecting 0.5 mm and 1 mm for the reference hole and trepan diameters respectively in a further DHD simulation the disagreement between the obtained results and Laminator predictions did not exceed a value of 5 MPa in all cases.

4   CONCLUSIONS

The deep-hole drilling technique has become a standard method for the measurement of residual stress in isotropic materials, especially for thick components. The work described here is an extension to the method to allow the measurement of residual stress in orthotropic materials such as thick composite laminates. The analysis of the distortion of a hole in an unidirectional orthotropic material after applying a far field stress is essential in this case. Lekhnitskii's analysis is used to determine the coefficients related to direct stress and the authors present a new approximate solution to calculate the remaining coefficient corresponding to far-field shear stress. All analytically calculated values for the three coefficients were then numerically validated by finite element analyses.

After conducting a deep-hole drilling experiment on an 18 mm thick AS4/8552 composite plate, measurements showed a good agreement with a simulation using the same reference hole and trepan parameters, but a significant discrepancy was found when compared with Laminator predictions. It was determined that, when using DHD in laminated materials, the reference hole and trepan diameters must be much smaller than the thickness of the layers in order to reduce the effect of remaining interlaminar shear stresses in trepanned cores which can significantly lead to inaccurate measurements.

REFERENCES

[1]   A. Mirzaee-Sisan, A.J. Fookes, C.E. Truman, D.J. Smith, T.B. Brown, and T.A. Dauda. Residual stress measurement in a repair welded header in the as-welded condition and after advanced post weld treatment. *International Journal of Pressure Vessels and Piping*, 84(5):265–273, 2007.

[2] M.G. Bateman, O.H. Miller, T.J. Palmer, C.E.P. Breen, E.J. Kingston, D.J. Smith, and M.J. Pavier. Measurement of residual stress in thick section composite laminates using the deep-hole method. *International Journal of Mechanical Sciences*, 47(11):1718–1739, 2005.

[3] P.J. Bouchard, D. George, J.R. Santisteban, G. Bruno, M. Dutta, L. Edwards, E. Kingston, and D.J. Smith. Measurement of the residual stresses in a stainless steel pipe girth weld containing long and short repairs. *International Journal of Pressure Vessels and Piping*, 82(4):299–310, 2005.

[4] T.B. Brown, T.A. Dauda, C.E. Truman, D.J. Smith, D. Memhard, and W. Pfeiffer. Predictions and measurements of residual stress in repair welds in plates. *International Journal of Pressure Vessels and Piping*, 83(11-12):809–818, 2006.

[5] D. George and D.J. Smith. Through thickness measurement of residual stresses in a stainless steel cylinder containing shallow and deep weld repairs. *International Journal of Pressure Vessels and Piping*, 82(4):279–287, 2005.

[6] D. Stefanescu, P. Browne, C.E. Truman, and D.J. Smith. Residual stress measurement within a European UIC60 rail using integrated drilling techniques. *Materials Science Forum*, 440-441:85–92, 2003.

[7] Lekhnitskii SG. Anisotropic plates. *Gordon and Breach*; 1968.