USING THE INCREMENTAL HOLE-DRILLING TECHNIQUE FOR MEASURING RESIDUAL STRESSES IN FIBRE-REINFORCED POLYMER COMPOSITES

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Abstract

The Incremental hole-drilling technique (IHD) seems to be a promising technique, among the destructive (relaxation) techniques, to determine in-depth non-uniform residual stresses in fibre-reinforced polymer composites. Hence, valid theoretical approaches for IHD residual stress determination in composite laminates, based on a set of strain-depth relaxation curves, are needed. Nevertheless, the influence of the drilling process itself on the initial residual stress state, i.e. existing prior to hole drilling, must be verified first. In this work, the IHD residual stress evaluation procedures in composite laminates will be reviewed and an original hybrid experimental-numerical methodology will be used to quantify the residual strain induced by the drilling process. Thus, residual strains induced by ultra-high speed drilling processes on carbon-epoxy laminates (CFRPs) have been quantified. The results seem to show that IHD technique can be improved to be successfully applied for measuring residual stresses in CFRPs.

1 Introduction

Mechanical performance of the polymer matrix composites can be highly influenced by the residual stress state, which can have a beneficial or detrimental effect. Warpage, interface debonding and matrix microcracking are examples of detrimental effects caused by residual stresses, which can reduce the stiffness, the strength and life of the composite component [1,2]. The study and the knowledge of its exact influence on composite systems imply the accurate determination of the residual stress state. In the case of orthotropic materials, such as advanced lightweight, high-performance carbon-fibre reinforced polymers (CFRP), or glass-fibre reinforced polymers (GFRP), the hole-drilling method seems to be a promising technique to determine residual stresses since, in these cases, the usual non-destructive methods cannot be applied or have highly restrictive application [1,3-5].

This technique basically consists on drilling a small hole in the surface of the test material and measuring the surface strain produced by the local stress relaxation induced by the hole (typically 1 to 5 mm diameter) on the existing residual stress field. Hole-drilling technique was originally developed for isotropic materials [6] and later for orthotropic materials [3,4]. In the case of isotropic materials, based on the theory of linear elasticity, the well known Kirsch's solution can be used to relate the measured strain relaxation field with the existing residual stresses prior to the hole-drilling. Apart the higher importance to find the best theoretical approach to determine residual stresses from a set of in-depth strain relaxation curves, in the case of fibre-reinforced polymer composites, it is necessary first to verify the influence of the drilling operation itself on the initial residual stress state existing prior to hole drilling.

In this work the residual stress evaluation procedures for IHD technique, for its application to composite laminates, will be reviewed and the effect of the drilling process itself on the stress state existing prior to hole drilling will be studied using a new hybrid experimental-numerical methodology. This methodology allows the residual strain induced by the drilling process to be quantified. This way, the applicability of the IHD technique for measuring residual stresses in fibre-reinforced polymer composites could be evaluated.

2 IHD Residual Stress Evaluation Procedures for Composite Laminates

Figure 1 shows a schematic representation of ASTM type A strain-gauge rosette [7] to be used in hole-drilling residual stress measurements. When a hole is drilled into a test material at centre of the rosette, the Kirsch's solution allows the surface radial strain relief (ε_r), in β direction relatively to L axis, to be related to the relieved stresses (σ_L, σ_T and τ_{LT}) by the relationship:

$$\varepsilon_r = A(\sigma_L + \sigma_T) + B(\sigma_L - \sigma_T) \cdot \cos 2\beta + C \cdot \tau_{LT} \cdot sen 2\beta \,. \qquad (1)$$

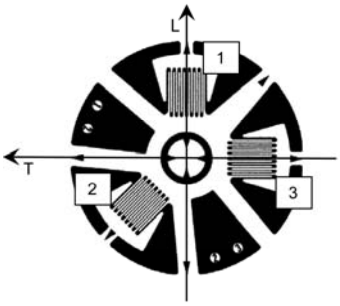

Figure 1. ASTM type A strain-gauge rosette for the hole-drilling method [7], showing reference axis for equation (1), also considering the principal laminate axis system L-T.

The constants A, B and C depend on the material properties, the rosette geometry, the hole diameter and the hole depth. It can be determined experimentally or numerically. All residual stress evaluation procedures for isotropic materials are based on this equation [8]. For these materials C = 2B. Thus, some authors proposed residual evaluation procedures for orthotropic materials based on this trigonometric-based equation, e.g. [4,9], for which C will be independent from A and B. However, Schajer and Yang [3] have shown that the displacement field around a hole in a stressed orthotropic plate does not have such simple trigonometric form and, therefore, the application of equation (1) to orthotropic materials can lead to erroneous results. In addition, based on Smith's work [10], they proposed an evaluation procedure for determination of uniform residual stress field in some class of orthotropic materials. More recently, Pagliaro and Zuccarello [11], following the work of Schajer and Yang [3], implemented an alternative formulation for analysis of the residual stresses on orthotropic laminates. In complex cross-ply or angle-ply orthotropic laminates, elastic properties of the material change suddenly from ply to ply and, consequently the residual stresses could not be uniform through the depth. Using a formulation similar to Schajer and Yang [3] for uniform orthotropic materials, those authors extended the method to the analysis of the through thickness non-uniform residual stresses (not equilibrated) in a generic orthotropic laminate due to in-plane initial loads, as those in a tensile calibration test. Shortly, although the residual stresses are not uniform through the laminate thickness, the residual strains are uniform (considering the in-plane loading) and simple relationships between surface relaxed strain and residual stresses can be detected by using the Classical Laminate Theory. The relationship that allows the user the evaluation of the residual stresses components in each ply, from the relaxed strains measured on surface, can be determined by solving the Pagliaro-Zuccarello's equation [11]:

$$\begin{Bmatrix} \sigma_{L,i} \\ \sigma_{T,i} \\ \tau_{LT,i} \end{Bmatrix} = \left[\tilde{E}\right]_i \cdot \left[\overline{E}\right]^{-1} \cdot [C]^{-1} \cdot \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} \quad \mathrm{i}=1,2,..,\mathrm{n}\,. \tag{2}$$

Where $\{e_1, e_2, e_3\}^T$ is the vector containing the surface strain relaxation values measured by the strain-gauges 1, 2 and 3, respectively (see Figure 1), which strain-gauge 1 was aligned with the principal laminate axis L. $\{\sigma_{L,i}, \sigma_{T,i}, \tau_{LT,i}\}^T$ contains the stresses existing in a given ply *i*, relatively to principal laminate system L–T. [Ẽ] is the stiffness matrix of the ith ply in the principal laminate system L–T given by:

$$\left[\tilde{E}\right]_i = \begin{bmatrix} \dfrac{E_L^i}{1-\upsilon_{LT}^i\upsilon_{TL}^i} & \dfrac{\upsilon_{LT}^i E_T^i}{1-\upsilon_{LT}^i\upsilon_{TL}^i} & \dfrac{\eta_{L,LT}^i}{G_{LT}^i} \\ \dfrac{\upsilon_{LT}^i E_T^i}{1-\upsilon_{LT}^i\upsilon_{TL}^i} & \dfrac{E_T^i}{1-\upsilon_{LT}^i\upsilon_{TL}^i} & \dfrac{\eta_{T,LT}^i}{G_{LT}^i} \\ \dfrac{\eta_{L,LT}^i}{G_{LT}^i} & \dfrac{\eta_{T,LT}^i}{G_{LT}^i} & G_{LT}^i \end{bmatrix} \quad (\mathrm{i}=1,2,..,\mathrm{n})\cdot \tag{3}$$

Where E^i_L, E^i_T, ν^i_{LT}, ν^i_{TL}, $\eta^i_{L,LT}$, $\eta^i_{T,LT}$ and G^i_{LT} are the elastic properties of the ith ply in the principal coordinate system L–T of the laminate, which is, in general, different from the principal coordinate system 1–2 of each ply/fibre. [Ē] is a dimensionless stiffness matrix given by:

$$\left[\overline{E}\right] = \begin{bmatrix} \dfrac{\overline{E}}{\overline{E}-\overline{\upsilon}^2} & \dfrac{\overline{\upsilon}}{\overline{E}-\overline{\upsilon}^2} & 0 \\ \dfrac{\overline{\upsilon}}{\overline{E}-\overline{\upsilon}^2} & \dfrac{1}{\overline{E}-\overline{\upsilon}^2} & 0 \\ 0 & 0 & \dfrac{\overline{G}}{\overline{E}} \end{bmatrix} \quad . \tag{4}$$

Where Ē, Ḡ and ῡ are dimensionless elastic constants, given by:

$$\overline{E} = \frac{E_L}{E_T};\; \overline{\mathrm{G}} = \frac{\mathrm{G_{LT}}}{\mathrm{E_T}};\; \overline{\upsilon} = \upsilon_{LT}\,. \tag{5}$$

Being E_L, E_T, ν_{LT} and G_{LT} the elastic properties of an equivalent homogenous orthotropic material, having the same in-plane elastic behaviour of the composite laminate to study, whose elastic properties can be related to those of each ply by using the well-known relationships of the Classic Laminate Theory (CLT). Note that, in the case of an unidirectional laminate, $[\tilde{E}]_i = E_L.[\bar{E}]$, and equation 2 can be simplified.
Finally, [C] is the matrix of the so called dimensionless influence coefficients c_{ij} (i,j=1,2), or calibration coefficients, given by:

$$[C]=\begin{bmatrix} c_{11} & c_{12} & 0 \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & 0 \end{bmatrix} \quad . \tag{5}$$

Where each coefficient c_{ij} can be determined numerically, or analytically using the approach proposed in reference [11]. The compliances c_{13} and c_{33} equal zero, if the directions of the rosette, corresponding to strain-gauge 1 and 3, coincide with the principal elastic directions L-T of the orthotropic material, respectively – as shown in figure 1 (β_1=0°, β_2=135° and β_3=270°). If the same rosette is installed with gauge 1 aligned with the cross material direction T, i.e., β_1=90°, β_2=225° and β_3=0°, equation 2 still applies if ε_1 is changing with ε_3 and c_{23} replaced by $-c_{23}$. Thus, the application of the hole-drilling method to a given orthotropic material involves seven distinct calibration coefficients. In particular, if the orthotropic material is balanced (i.e., $E_L=E_T$ and then $\bar{E}=1$), due to symmetry it follows that $c_{11}=c_{32}$, $c_{12}=c_{31}$, $c_{21}=c_{22}$ and the number of coefficients will only be four. In addition, for an isotropic material $\bar{G}=1/[2(1+\bar{\upsilon})]$ and $c_{11}=c_{32}$; $c_{12}=c_{31}$; $c_{21}=c_{22}=(c_{11}+c_{31})/2=(c_{12}+c_{32})/2$, so that the number of independent calibration coefficients reduce to two. In fact, in this case, equation 1 can be rewritten using the three strain relaxation values measured for each strain-gauge of the rosette, as follows:

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} = \begin{bmatrix} A+B & A-B & 0 \\ A & A & -2B \\ A-B & A+B & 0 \end{bmatrix} \cdot \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{Bmatrix} . \tag{6}$$

The theoretical background presented above represents the best theoretical approach to determine residual stresses in each ply of a given composite laminate, after measuring the surface strains relieved by hole-drilling. However, the presented theory was developed to analyse the residual stresses on orthotropic composite laminates, caused by initial in-plane loads. It cannot be applied for measuring in-depth non-uniform residual stresses yet. Some additional work must be performed first. Nevertheless, to apply the IHD technique to composite laminates it is necessary, previously, to verify how the cutting process can modify the stress state existing in the composite laminate before drilling. In the following, the results of a methodology developed to quantify the induced drilling strains will be presented [12].

3 Evaluating the induced drilling strains

The residual strains induced by drilling operation in fibre-reinforced polymer composites, due to thermo-mechanical phenomena related to cutting process, can affect either the functional behaviour in service of the composite laminate or the accuracy and reliability of the hole-drilling residual stress measurement technique. The hybrid experimental-numerical methodology presented in Figure 2 allows the determination of induced drilling strains. Shortly, the methodology consists on drilling, incrementally, specimens subjected to a given differential applied stress, using purpose-built tensile devices. Thus, a set of strain-depth relaxation curves can be determined experimentally. Next, a numerical simulation of the whole experimental procedure is carried out using the finite element method, allowing a set of ideal set of strain-depth relaxation curves to be determined. The direct comparison between the experimental and numerical curves enables the determination of the effect of the drilling process, i.e., the quantification of the induced drilling strains.

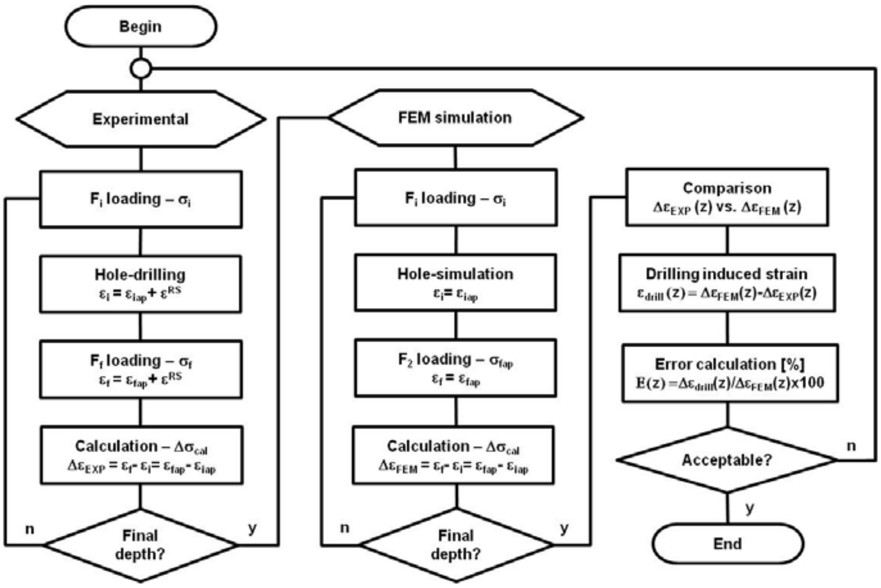

Figure 2. Flowchart of a hybrid experimental-numerical methodology to determine induced drilling strains and to optimize the hole-drilling process

In this work a carbon-epoxy composite laminate was selected as test material. The specimens were manufactured in an autoclave using carbon-epoxy prepreg (M55j/M18) as raw material, using different stacking sequences. Table 1 shows the specimens used and table 2 the elastic properties of single lamina.

Carbon-epoxy laminate	Specimens [mm^3]	Ply thickness [µm]	Depth Increments per ply	Increment's depth [µm]
$[0^o]_4$	165x25x1.1	280	4	70
$[0^o_2/90^o_2]_{2S}$	165x30x1.6	100	2	50
$[0^o/90^o]_{5S}$	280x28x2	100	2	50

Table 1. Composite laminate specimens for tensile tests

E_{11} [GPa]	$E_{22} = E_{33}$ [GPa]	$G_{12} = G_{13}$ [GPa]	G_{23} [GPa]	$\nu_{12} = \nu_{13}$	$\nu_{23} = \nu_{32}$	$\nu_{21} = \nu_{31}$
300	6.3	4.3	2.3	0.32	0.38	0.002

Table 2. Elastic properties for the carbon-epoxy lamina (obtained according to [13])

The drilling process under evaluation was the ultra-high speed milling using a turbine powered by compressed air, a process commonly used with hole-drilling equipments for measuring residual stresses in metallic materials. In a previous work [14] this process showed to give better results than traditional CNC machining. Here, the presented results are only for normal drilling, even if orbital drilling processes could even lead to better results, i.e., decreasing the induced drilling strains. Table 3 shows the most important drilling parameters used in the tests.

Air pressure [bar]	**WC mill diameter [mm]**	**Cutting speed [ms^{-1}]**	**Rotation speed [rpm]**	**Feed rate [mm/min]**
2.7	1.6	~24	280,000	<< 0.01
4	1.6	~18	210,000	<<0.01

Table 3. Ultra-high speed drilling parameters (UHSM)

Following the flowchart of Figure 1, during the experimental calibration tests, the composite specimens were loaded as shown in Figure 3.

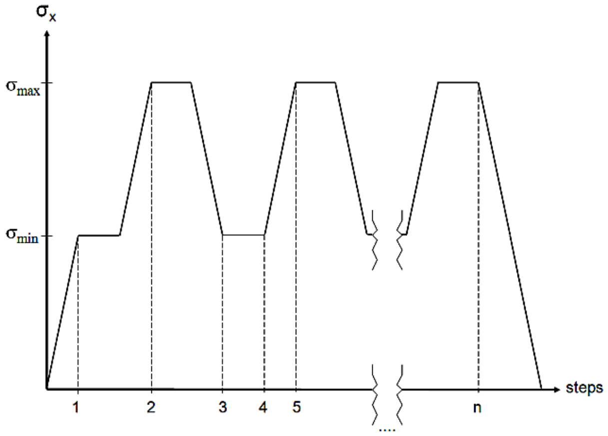

Figure 3. Loading conditions during tensile tests. Each depth increment was always drilled for σ_{min}.

During the experimental calibration test, each depth increment was always machined for the minimum applied load. A special 1.6 mm diameter WC hard coated milling cutter of six blades in inverted cone, usually employed in IHD applications, has been used. After each incremental depth machined, the strain data were recorded and the specimen loaded till maximum load, where the strain data were recorded again. This process was systematically repeated until the total hole depth was reached (≈ half hole diameter). At least two depth increments by each ply were considered. Thus, a set of experimental strain-depth relaxation curves were obtained for each case.

Following the flowchart of Figure 2, the experiments were then simulated by finite elements (FEM) using ANSYS APDL code [15]. The model uses quadratic 20 nodes 3D layered solid elements SOLID186 and has been parameterized to be applied to different stacking sequences and orientation of the plies, minimizing the changing of APDL scripting – see Figure 4.

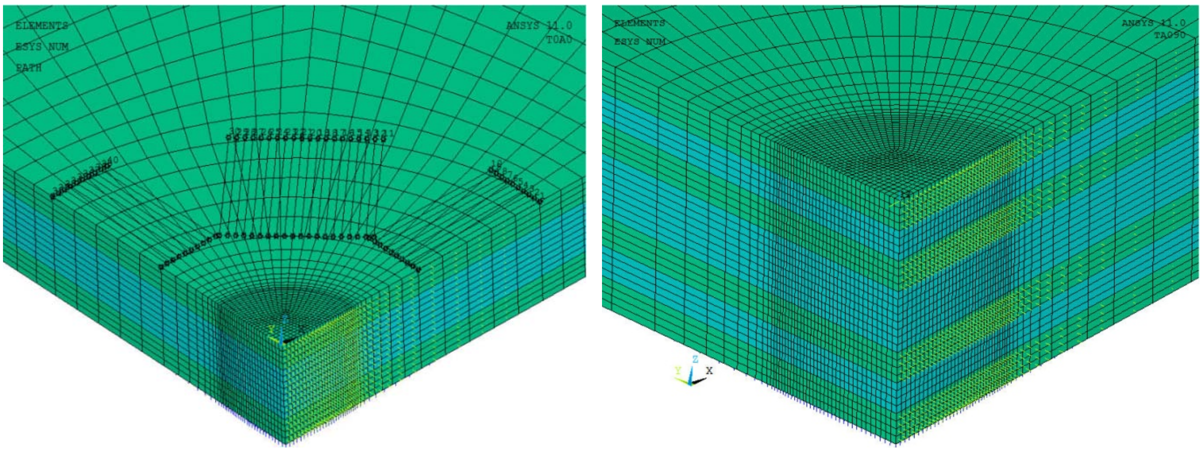

Figure 4. Finite element meshes for hole simulation in tensile specimens of CFRP unidirectional laminates $[0°]_4$, also showing the relative position of the strain-gage grids (left) and CFRP cross-ply laminates $[0°_2/90°_2]_{2s}$ (right)

During the processing phase, the hole drilling was always simulated, incrementally, at the centre of the FEM model using "birth and death" ANSYS code features [15], being the thickness of each depth increment equal to the imposed during the experimental tests.

4 Results and Discussion

Figure 5 shows strain-depth relaxation curves, in the direction of the applied stress and in the cross direction, obtained during the experimental tests on the [0º]$_4$ laminate. The results using the two drilling conditions (table 3), are compared with ideal ones determined by FEM.

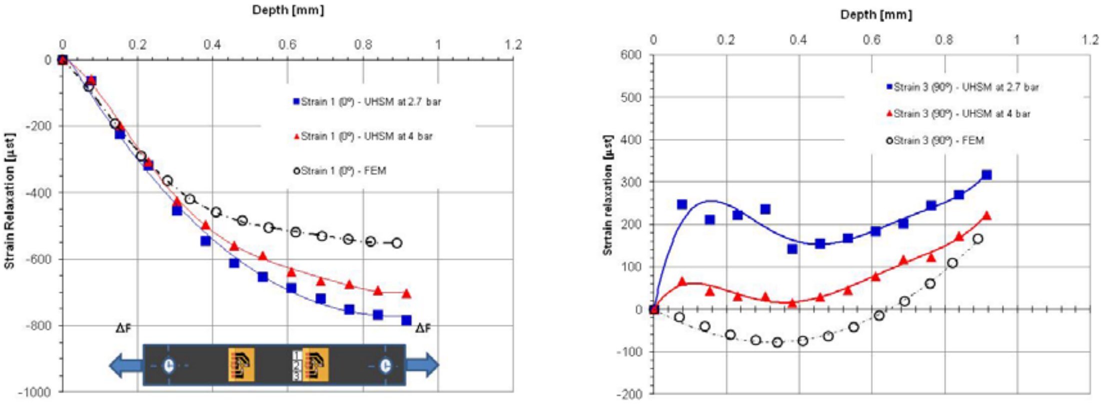

Figure 5. Comparison between experimental and numerical strain-depth relaxation curves for CFRP unidirectional laminates [0º]$_4$, subjected to calibration stress of 265 MPa (direction of the applied stress (left) and cross direction (right)). Experimental UHSM conditions are presented in table 3.

It can be seen that better results are obtained when cutting speed increases from 18 m.s^{-1} to 24 m.s^{-1} (2.7 bar to 4 bar). A similar behaviour is obtained for cross-ply laminates. Figure 6 shows the strain-depth relaxation results obtained on [0º/90º]$_{5S}$ laminate for 18 m.s^{-1} (2.7 bar) and [0°$_2$/90°$_2$]$_{2S}$ for 24 m.s^{-1} (4 bar), in the longitudinal direction. The experimental and numerical strain-depth relaxation curves for 24 m.s^{-1} (4 bar) present an excellent agreement.

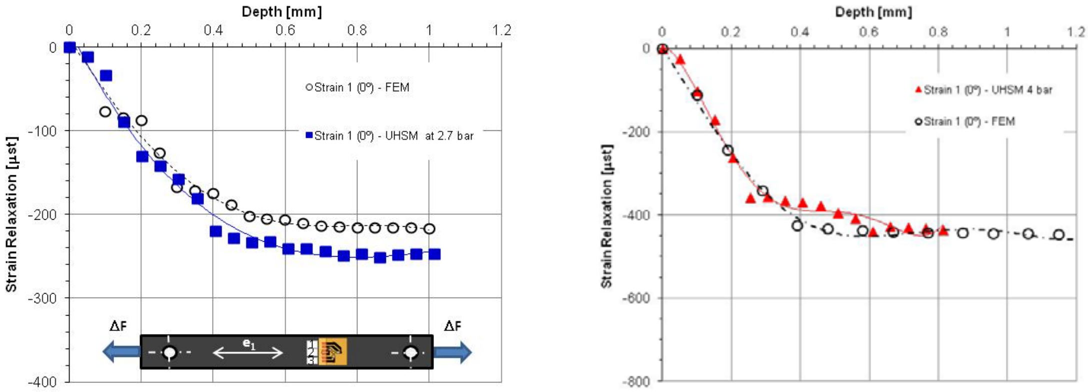

Figure 6. Comparison between experimental and numerical strain-depth relaxation curves for CFRP cross-ply laminates [0°/90°]$_{5S}$, subjected to a calibration stress of 75 MPa (left) and [0°$_2$/90°$_2$]$_{2S}$, subjected to a calibration stress of 125 MPa (right). Experimental UHSM conditions are presented in table 3.

As shown in Figure 6, the strain relaxation measured at surface can be studied considering a continuous behaviour, although the stresses existing in each ply could present a discontinuous behaviour between plies. This calculation, however, is under study yet, using equations presented in section 2. Nevertheless, even if some expectable differences arise, between experimental and numerical curves, the results are very encouraging relatively to the future improvement of the IHD technique for its application to CFRPs.

5 Conclusions

The state-of-the-art for IHD residual stress evaluation on composite laminates was presented. However, the effect of the induced drilling strains must be analysed before any further development of IHD residual stress evaluation procedures. Thus, induced drilling strains in unidirectional and cross-ply CFRP laminates were determined for two ultra-high speed drilling processes. These drilling processes, combined with very slow feed rate, led to relatively low induced drilling strains, especially for the highest cutting speed used in the tests. The comparison between experimental and numerical strain-depth relaxation curves has shown that the incremental hole-drilling can be successfully improved for its application to the CFRP laminates. In addition, very good geometrical hole shape, without appearance of delamination, has been observed. In this context, the hybrid experimental-numerical methodology used can be of great help to improve drilling processes and parameters on CFRPs.

Acknowledgments

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