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# Extension of the Incremental Hole-Drilling Technique for Residual Stress Measurement

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# Abstract

Incremental hole-drilling (IHD) is one of the most widely used residual stress measurement techniques as it is practical to implement, low cost, semi-destructive and yields reliable and accurate results. The unit pulse integral computational method is used extensively with IHD and can be used to determine residual stress distributions in almost any material type. IHD has a standardised test procedure for isotropic materials which includes the use of Tikhonov regularization with the integral method to smooth the calculated stress distribution and remove noise artefacts. However, the use of Tikhonov regularization with the integral method has not been extended to fibre reinforced plastic (FRP) laminates. Therefore, the integral methods currently employed in FRP laminates are sensitive to measurement errors which can result in large stress uncertainties. Existing variations of the integral method are also not able to measure discontinuous residual stress distributions in complex angle ply laminates that may have steep stress gradients through a single ply, while maintaining tolerance to measurement errors and high depth resolution. Series expansion is an alternative computational method that was first introduced with IHD in isotropic materials in 1981. However, for 40 years it has seldom been used, due to the suspected issues around instability at higher orders. Series expansion has the potential to overcome some shortcomings of the integral method, particularly in FRP laminates, as it is less sensitive to noise in the experimental data or to single erroneous measurements due to least-squares curve fitting in the inverse solution.

The primary aim of this thesis is to address limitations of IHD in FRP laminates by extending the use of separate series expansion to IHD for the measurement of residual stress distributions in laminates of arbitrary construction, and to extend the use of Tikhonov regularization with the integral method to cross-ply laminates. The discontinuous nature of residual stresses in FRP laminates at changes in fibre orientation, coupled with the typically small thickness of individual plies, means that the residual stress distribution within each ply orientation has low complexity and can, therefore, be well approximated by separate series expansion stress distributions of low order that are less susceptible to numerical instability. The least-squares inverse solution allows the amplitudes of each term in the series to be determined simultaneously in each ply, and consequently the residual stress distributions to be completely defined. Separate series expansion can be applied to laminates with any number of plies, orientated in any direction, or in any layered composite material where stress discontinuities

exist. A method to incorporate Tikhonov regularization with the integral method in cross-ply laminates is developed and it is demonstrated that regularization significantly reduces error sensitivity of the stress distribution while maintaining high depth resolution such that stress variation within a single ply can be captured correctly.

The secondary aim of this thesis is to demonstrate that series expansion is indeed a viable computational alternative to measure highly non-uniform residual stress distributions in isotropic materials. The use of finer depth increments and a means to select an appropriate series order have resolved issues around instability. A physical characteristic of IHD is that near-surface stress measurements are susceptible to large uncertainties, independent of the stress computation method used. Therefore, near-surface X-ray diffraction (XRD) measurements are commonly used to complement IHD results in isotropic materials and fully define the through-thickness stress distribution. To overcome this limitation of IHD, novel approaches to combine residual stress measurements from XRD and IHD into a single least-squares or regularized solution using series expansion and the integral method, respectively, is presented and demonstrated. These approaches allow XRD measurements to be incorporated into IHD results which showed strong correlation with standard series expansion and regularized integral methods and greatly reduced stress uncertainty near the surface. By incorporating XRD results into IHD, the advantages of both measurement techniques can be exploited while minimising the effects of their shortcomings.