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REVIEW ARTICLE

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Residual stress in fiber reinforced thermosetting composites: A review of measurement techniques

Ben Seers | **Rachel Tomlinson** | **Patrick Fairclough**

Department of Mechanical Engineering, University of Sheffield, Sheffield, UK

Correspondence
Ben Seers, Department of Mechanical Engineering, University of Sheffield, Sheffield S1 3DJ, UK.
Email: bseers1@sheffield.ac.uk

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Abstract

Residual stress is inherent in any fiber reinforced composite, created by the laminates processing route and high levels of anisotropy. The aim of this article is to provide an up to date review of the current state of the art in experimental techniques for the determination of residual stress in thermosetting fiber reinforced composites. Residual stress is considered at a micro-mechanical, macro-mechanical, and global scale as each require specific techniques to investigate and offer their own unique challenges to the designer. Many advances have been made in the experimental determination of residual stress in fiber reinforced composites since the last comprehensive review of the topic by Shokrieh in 2014. However, more work still needs to be done to develop a method that is applicable to all cases and can be applied as a universal standard. It remains a significant challenge to experimentally determine residual stress in thermosetting composites.

KEYWORDS

composites, residual stress, thermosets

1 | INTRODUCTION

Residual stress is inherent to any fiber reinforced composite part.[1] The magnitude and type of residual stress will vary due to factors such as: the laminate layup, cure schedule, chemical shrinkage, and differences in coefficients of thermal expansion. It is crucial that the residual stress created during the manufacturing process is understood and quantified to allow for safe and optimal design. Process-induced residual stresses in thermosetting laminates have been modeled extensively in the literature from the initial characterization of thick laminates by Bogetti and Gillespie[2] to more recent numerical methods reviewed by Baran et al.[3] While advances have clearly been made in this area in the past decades, it is still vital that these models are validated by experimental techniques to ensure corroboration between theoretical and experimental results. Residual stress cannot be directly measured. Experimentally, it is only possible to measure various deformations caused by a change in the stress state of an object. Then, by having knowledge of material properties and process history it is possible to calculate residual stress using a variety of models and techniques. This review focuses on the experimental techniques for the measurement of deformations caused by a change in stress state and the experimental limitations associated with these methods. For the calculation of residual stress the current authors points to the comprehensive review of the subject by Baren et al.[3]

Two previous reviews of residual stress measuring techniques of note are works by Shokrieh,[1] who presented a comprehensive review of all residual stress

measurement techniques for all fiber reinforced composite systems and Parlevliet et al,[4] who presented a review focused on thermoplastic matrices. This article aims to summarize and update these previous works, in the context of techniques that will be useful for the study of thermosetting matrices, noting that some techniques are generic to all composites. To better characterize the various experimental techniques, they have been divided into two categories, destructive and nondestructive techniques.

Composites consist of two constituent phases. One reinforcement phase and one matrix phase which, when well designed and manufactured, work in synergy to bring together complementary attributes to form a whole which is stronger than the sum of its parts. In the case of fiber reinforced polymer composites, fibers are used as the reinforcing phase to bring high stiffness and strength to the composite while the polymer matrix phase adds toughness and allows load to be more effectively transmitted along the fibers. Thermosetting polymer matrices are particularly effective at this and as such are the default choice for many highly loaded structural components and therefore, are the focus of this review. This makes composite materials highly anisotropic as each of the three orthogonal principal axes depends upon the principal reinforcement direction. However, this anisotropy is also the key driver in the creation of residual stress in fiber reinforced composites.

Residual stress can form and be measured on three distinct scales: (a) micro-mechanical or intralaminar scale is the direct interaction between fiber and matrix. This is most often caused by a mismatch in the coefficient of thermal expansion (CTE) between the fiber and the matrix which causes them to expand and contract at different rates during heat up and cool down, (b) macro-mechanical residual stress or interlaminar residual stress is caused by the difference in anisotropy of each ply in a laminate relative to one another, and (c) laminate residual stress or global stress is caused by a net variation of heating throughout the entire laminate. This is often caused by uneven heating of a laminate both through its thickness and along its width and length which leads to a variation in degree of cure and thermal expansion/contraction across the entire laminate.

One of the main causes of process-induced residual stress is from a difference between the CTE of the fiber and matrix. During the cooling phase of the curing process (where the stiffness of the matrix is fully developed) a disparity in the contractions of the fibers and matrix is formed in both the longitudinal and transverse directions. This causes the matrix, with a high CTE, to be constrained by the fibers, that have a low and sometimes negative CTE. Therefore, in a simple unidirectional (UD) lamina a longitudinal tensile stress develops in the matrix which must then be balanced by an equal and opposite compressive stress in the reinforcing fibers.[5] These residual micro-mechanical stresses can be high enough to cause matrix cracking and debonding after the manufacturing process.[6, 7] Micromechanical residual stresses tend to be on an order of magnitude less than global and macro-mechanical stresses but they can often lead to voids and other crack initiators, so can still dramatically affect the fatigue performance of the laminate.[8] Similarly, chemical shrinkage of the matrix is another key contributing factor in the formation of residual stress in thermosetting matrices. Chemical shrinkage is caused by the rapid cross-linking of polymer chains causing an increase in density and thus a volumetric contraction. The magnitude of the contribution of chemical shrinkage to the formation of residual stress is dependent upon a number of factors including matrix cure chemistry, volume fraction, cure rate, and ply orientation. The formation of residual stress is driven by the disparity between the fiber reinforcing phase not undergoing a significant volumetric change during cure and cooling due to the much lower CTE of the fibers while epoxy resins will typically shrink by 3% to 7% upon cure.[9, 10] The fibers of the lamina resist this volumetric shrinkage and a stress gradient is formed between the interacting matrix and the fibers. Chemical shrinkage occurs throughout the entire chemical reaction. However, residual stresses only begin to form when the polymer matrix reaches its gelation point and its storage modulus develops. Prior to this the polymer is a viscous liquid and can pass between the fibers with little resistance but after gelation the polymer can no longer flow and its storage modulus increases causing energy to be stored in the system in the form of residual stress.

It should be noted that residual stress cannot be measured directly. However, residual strain or the displacement of the material due to the formation of residual stresses can be measured and the residual stress determined from these. Residual stress determination techniques are commonly referred to in the literature as measurement techniques and therefore in this article we will refer to both determining and measuring residual stresses. Residual stress can often be difficult to determine, especially in composites, as it can be in a self-equilibrated system where the compressive and tensile forces are equal and opposite. In this case there is no observable global strain and techniques must be used which rely on an intrinsic change in a material property due to the applied stress, or a strain must be induced. Strains are typically induced by removing material and observing the resulting strain which is necessary to restore equilibrium in the system. This is the basis for many of the destructive techniques outlined in this review.

2 | DESTRUCTIVE METHODS

2.1 | Layer removal

The layer removal method was first developed in the 1950's by Treuting and Read[11] for the analysis of through-thickness residual stress in metallic plates. Layers are incrementally removed from the surface of a fully equilibrated stressed part. Thus, residual stress is removed from the part and a force imbalance is created in the system. The plate then deforms to restore equilibrium and the resulting strain is measured and used to calculate the residual stress that has been removed. By doing this incrementally through the thickness of the sample, a picture of the through-thickness variation in residual stress starts to emerge.

Attempts have been made to apply the same technique to composite materials with Eijpe and Powell[12] being the first to validate its applicability to composites. However, the method used in this study required machining of the composites surface which imparted additional stresses. More recently, Gower et al[13] incrementally milled individual plies of a laminate to release residual stress and found through observation that there were often visual traces of either incomplete milling of a ply or milling into the subsequent ply. It was suggested that with current technology it would not be possible to mill laminates accurately enough for this technique to be viable. It was also found that this led to quite substantial error when compared to the slitting method, which will be discussed later.

Attempts to overcome the shortcomings of milling have been made with knife splitting techniques,[14] hand sanding methods, and placing films at intervals throughout the thickness of the laminate which could be later removed.[15] However, these suffered from inaccuracies and this latter technique was not able to capture accurately the interply residual stress which forms in the boundary between plies as the film used to separate the layers has a sufficiently different induced stress to that of a laminate without an inserted film. The main disadvantage of using embedded films, as cited by Reid,[16] is that only information about the macro-scale residual stress distribution can be observed. As the layers removed are thicker than that of the individual lamina it is not possible to gain an understanding of the intralaminar stress distribution. Therefore, it is not possible to discriminate between fiber and matrix stresses as these stresses are in a state of equilibrium with each other and if fiber and matrix are removed together no elastic response will be seen. This technique is limited to macro-scale residual stress measurements and even with this caveat it is still limited by the introduction of additional residual stress during the material removal process. Thus, one of the other techniques outlined in this review is generally preferred when investigating composite systems.

2.2 | Hole-drilling method

The hole-drilling technique operates on the same principle as many of the following destructive techniques used for measuring residual stress. A self-equilibrated stressed body has material removed and then the resulting biaxial surface strain caused by the equilibrium being restored is measured. This strain change can be measured using a variety of different techniques and then correlated to the relaxed stress. This correlation is typically done by applying a model which assumes that each ply is homogenous. This approach works reasonably well for a macro-scale view of the residual stress but struggles to give a full idea of the micro-mechanical mechanisms at play in the process. As the name suggests, the hole-drilling technique removes material by using a drill bit to incrementally drill a hole through the thickness of the material. Thus, relaxing the residual stress and causing a change in the surrounding strain field which is then measured. This technique is generally preferred to the layer removal method as it is easier to achieve more accurate measurements by virtue of the smaller area being machined and it also has the advantage of being less destructive which makes it more useful in an industrial setting. Additionally, it captures the biaxial surface strain response which allows for the identification of the biaxial residual stress distribution, unlike the slitting method which will be discussed later. However, it only offers a view of the residual stress being released from the drilled area while the layer removal method averages over the entire area being milled which might be beneficial in some cases.

Hole-drilling can be separated into two types: center-hole drilling (or incremental-hole drilling) and deep-hole drilling (DHD). For clarity, this article will talk about center-hole drilling unless otherwise explicitly stated. Center-hole drilling measures the induced surface strains caused by the drilling of a hole through a material and can either be done in one step or incrementally to measure the residual stress variation through-thickness. This is commonly done with strain gauges in a rosette formation to allow for biaxial strain measurements, a typical arrangement can be seen in Figure 1. DHD first drills a reference hole through a material which has its diameter accurately measured. Residual stress is the released by trepanning another hole coaxially around the first. The diameter is then remeasured and the difference is used to

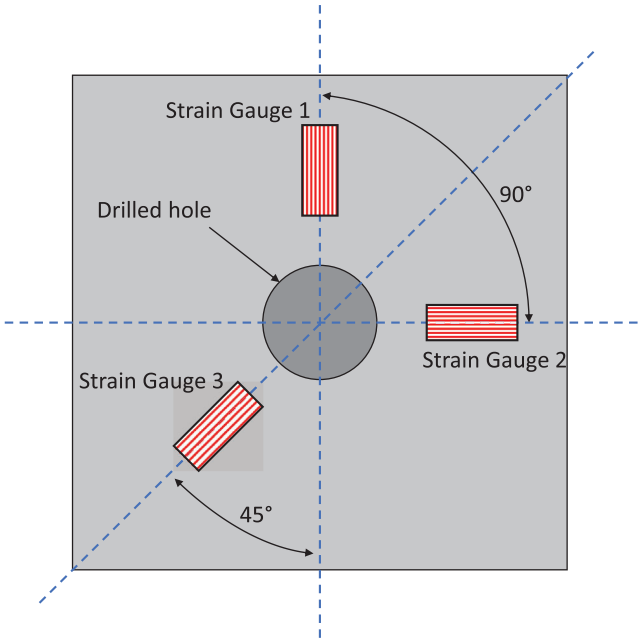

FIGURE 1 Center-hole drilling strain gauge arrangement [Color figure can be viewed at wileyonlinelibrary.com]

calculate residual stress. Both variations of the hole-drilling method can be performed in one step through the entire thickness of the part or incrementally. If the hole is drilled through the entire thickness that is under investigation in one step then only an average stress over the entire depth of cut can be obtained. However, if the process is performed incrementally, a shallow cut is taken, a measurement is made and then the process is repeated. Then, measurements can be made at the same resolution as that of the depth of cut. Therefore, this latter technique is slower but offers a degree of insight into the through-thickness residual stress in a component.

The hole drilling technique was originally developed for homogeneous isotropic materials, commonly metallics, and is a very common method for determining residual stress in these materials.[17] However, with some adaptations this method can also be used for composite, inhomogeneous, and anisotropic materials.[18] In these cases there are often large variations in residual stress through the thickness of a part. Therefore, to understand the true nature of the residual stress within a composite part it is crucial to build up an idea of the residual stress at various depths through the component. Thus, this review will only consider incremental variations of hole-drilling.

Work by Sicot et al[19] used an approach which assumed each depth increment released a unit pulse of uniform stress. Coupling this with taking many small depths of cut this allowed for an approximation of the residual stress through the thickness of a single ply. However, this method requires many regulated depth increments to be used in order to have the required depth resolution to determine variations within a single ply, thus increasing measurement time and complexity. Therefore, it is often impracticable to apply this method to thicker laminates where there are significant variations in stress within each ply. Pagliaro and Zuccarello[20] were the first to apply this method to analyze uniform through-thickness residual stress in a generic orthotropic laminate. This technique gave good correlation between experimental and modeled results for this case. However, high levels of errors were found when using laminates with too few plys (less than 16) and rosette strain gauges were too far away from the hole. This method also assumed that there was constant stress in each ply which gave a low through-thickness resolution of the residual stress. However, they were able to show that this method is generically applicable to composites.

Works done by Baldi[21, 22] aimed to combine both hole drilling and digital image correlation (DIC) as a replacement for the traditional strain gauges. An optical measurement technique was preferred here over the use of strain gauges as it offers high sensitivity, full-field, and noncontact advantages. Previous to this research other authors have proposed using interferometric techniques such as holographic interferometry,[23] moiré interferometry,[24] and speckle interferometry[25] in conjunction with DHD to measure residual stress in a variety of materials. However, these techniques have been found to be highly sensitive to vibrations[21] making their use more difficult in a lab and inappropriate for an industrial setting. In Baldi's work[21, 22] it was found that the classical DIC method was inherently unsuitable to this application as it is not possible to accurately follow the displacements and have a small standard deviation of results which are both required for meaningful residual stress measurements. However, work from Hagara et al[26] has suggested that standard DIC hole-drilling techniques are still suitable in some circumstances, citing an approximately 3% to 19% difference between DIC and strain gauge rosette results. Baldi[21, 22] went on to suggest that these problems could be overcome by implementing an integrated digital image correlation approach. It was shown that this approach gave results that were as accurate as previously proposed methods but also had the ability to measure a wider range of stress values and has a smaller standard deviation of results. However, it should be noted that the standard deviation of the results increased as the depth of the hole increased which could be caused by the weaker response seen when the residual stress is relieved further away from the point of measurement.

One of the shortcomings of the hole-drilling technique is that it struggles to have a high enough resolution to determine the intra-ply and the interply interface stress variations. To overcome this, Smit and Reid[27] successfully implemented a power series evaluation approach and showed it can be used to determine eigenstrains through the thickness of the laminate. These can then be used to determine the stress distribution through the thickness of the ply and ply interface. It was found that this approach was less sensitive to error compared to the standard Legendre function evaluation approach. This makes it possible to take measurements of shallower depths of cut and consequently have a high enough measurement resolution to capture the intra-ply effects.

Meanwhile, Garza et al[28] have shown that DHD is not able to accurately capture cure induced residual stress unless the thickness of stacks of similarly orientated plies is larger than the hole size being used. Therefore, for most cross-plied laminates it is not possible to use the DHD technique to measure cure induced residual stress. However, it was still possible to measure assembly stresses but some significant calculation errors were found. A study from Hu et al[29] went on to modify the approach taken by Garza et al by implementing an integrating stress calculation method, finding this reduced calculation errors and gave results for assembly stress which matched well with simulations.

The machining of composites is an area of research that has had much attention as it poses a unique set of challenges such as delaminations, fiber pull-out and crack propagation[30] and is therefore not trivial. These challenges have the potential to induce large amounts of error into any residual stress measurement techniques that require composite machining, such as hole-drilling. This is because the formation of a delamination or a fiber being pulled out during machining, could potentially relieve residual stresses that were not from the area under investigation which would give a false reading. However, as already shown, it is possible to mitigate these issues if the correct machining parameters are used and to achieve accurate results for residual stress analysis. Typically, high spindle speeds and low feed rates are used in conjunction with composite specific tooling is used to mitigate machining damage in composites.[31] Liu et al[32] has presented a comprehensive review of various mechanical drilling techniques and the best practices for achieving accurate and undamaged holes. A study by Yuksel et al[33] found that when using a 3 mm diameter drill, there was a drilling affected region of approximately 2 mm around the edge of the hole and that measurements needed to be taken away from this area to avoid machining induced errors in the results.

The hole-drilling technique offers an unmatched insight into the multi-axis through-thickness variation in residual stress in composite laminates. Traditionally, the large amounts of computation required and extensive time-consuming testing limited this techniques popularity. However, more recently this is much less of an obstacle to overcome and the technique has become more popular. The primary shortcoming of hole-drilling is that it relies on surface measurements of strains that propagates through the thickness of a laminate from the point of relieved stress. Thus, there is an inherent reduction in the accuracy of the results as the distance between the cutting and measurement surfaces increases, making it particularly unsuitable for very thick composites. However, one new technology that might be able to overcome this shortcoming is digital volumetric speckle photography (DVSP). DVSP uses x-ray computed tomographic (CT) images to reconstruct a 3D volume image of a composite. Various internal markers in the CT image such as fibers and fiber interfaces can then be tracked (without the need for additional contrasting particles) using DIC and a 3D quantitative strain map can then be developed. The use of this technique for quantitatively measuring strain in woven laminated fiber reinforced composites was first applied by Mao and Chiang[34] where they investigated internal strains in a beam in bending. Presently, this technique has not been used to quantify residual stress in fiber reinforced laminates. However, it is the view of the authors that this technique could be used in conjunction with a variety of the techniques outlined in this review, and particularly with hole-drilling, to overcome surface measurement errors.

2.3 | Ring-core method

The ring-core method operates on a similar principle to the hole-drilling technique. However, instead of a hole being drilled, an annular groove is cut and the elastic response is measured by the strain gauge rosette placed in the center of the groove, as can be seen in Figure 2. This technique was first developed by Gunnert[35] to investigate the residual welding stress in metallic plates and has since been widely adopted in the determination of residual stress in metallic structures. This method has not seen widespread adoption in the measurement of residual stress in fiber reinforced composites despite a number of benefits that the ring-core method has over the more common hole-drilling technique. The ring-core method allows for a greater strain response to be measured as more stress is relaxed during the trepanning process which should reduce measurement errors. This technique also reduces the stress concentration around the machined area which

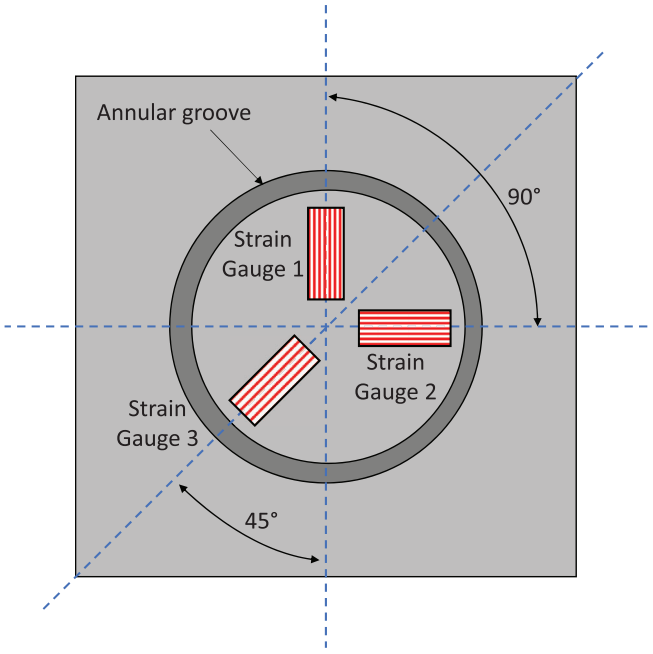

FIGURE 2 The ring-core method [Color figure can be viewed at wileyonlinelibrary.com]

means, compared to the hole-drilling technique, larger residual stresses can be measured without exceeding the yield stress of the material.[16]

The ring-core method has been combined with interferometric strain/slope rosettes[36, 37] and 3D DIC[38] with both techniques finding good corroboration with theoretical predictions. These noncontact global measurement techniques offer a more robust measurement solution as they do not rely on the accurate placement of strain gauges or suffer from the difficulties of cable management that traditional strain gauges do during trepanning. Baldi[39] suggested that it would be possible to use noncontact interferometry methods to restart the ring-core technique at multiple depths throughout a components thickness. This could be achieved by removing the core left by the ring-core method when an appropriate depth is reached and reapplying the virtual strain gauge to the new surface and then continuing to trepan at a greater depth. This could be very advantageous as with an increase in distance from the surface where strain is being measured to where the strain is being released causes an increase in error. If this distance could be reset at appropriate points the depth of accurate measurement could be vastly improved. However, these techniques still seem to be confined to homogenous and isotropic materials and have not been used in anisotropic, inhomogeneous fiber reinforced laminates.

Korsunsky et al[40] investigated the use of focused ion beams to create a micro-scale ringed groove, citing this technique's ability to measure strains on a much smaller scale and being much less destructive to the sample being tested. Work by Lunt et al[41] reviews the applicability of using focused ion beams in conjunction with DIC to determine the spatially resolved strains. Due to the high resolution and accuracy that ion beams afford it is possible to measure strains on the micron scale with nano-scale precision. With a few modifications it is possible to use focused ion beams on nonconductive materials like most common polymer matrices. Therefore, in theory it is possible for this technique to be applied to fiber reinforced composites and even has the potential for examining micro-scale residual stress interactions between fiber and matrix. However, current efforts in this area have been limited in depth of cut to around 0.3 μm[42] making it difficult to apply this technique effectively to composites where fiber diameters are on the order of 5 to 7 μm.

A recent study, comparing the ring-core, hole-drilling and slitting methods (see below), was conducted by Ghaedamini et al[43] where glass fiber fabrics were used to create symmetrical and balanced cross-ply laminates through the use of hand layup. It was found that the slitting method had the largest strain response followed by the ring-core method and then the hole-drilling method. Nevertheless, it was concluded that the ring-core method was preferred as it released the most residual stress out of any of the processes which was said to increase the methods accuracy. However, few repeats were conducted in this study meaning the experimental error was not determined for all cases, therefore it was not possible to validate this claim rigorously through experimental analysis. Currently, the hole-drilling technique seems to be preferred over the ring-core method in academia due to its generally easier implementation, without the need for special strain gauge wiring or annular drill bits. But it is clear that the ring-core method still offers some unique benefits, particularly at the micro-scale, and more research needs to be done in this area to explore its full potential.

2.4 | The slitting method

The slitting method can be found in literature under a number of different names such as "crack compliance," "compliance," and "incremental slitting." However, they are all fundamentally the same and, in this review, we will refer to the "slitting method." A small slit or slot is made in a prestressed sample and the resulting deformation normal to the direction of the slot caused by force equilibrium being restored is measured. This process is repeated at increasing depths, thus residual stress through the thickness of the part can be determined. This method is similar

in application to that of the hole-drilling method. However, only the average stress along the width (*y*-direction in Figure 3) can be determined as all of this material is removed per increment.

This method was developed for measuring hoop stresses in homogeneous metallic cylinders by Cheng and Finnie[44] and good agreement with hole-drilling and x-ray results was found. The major advantage of this method found in the study was cited as its "simple experimental and computational procedures" making it ideal for rapid testing. These experiments implemented strain gauges perpendicular to the slot to measure the induced deformation after each cut is made. Today, strain gauges remain common when conducting slitting method testing due to their ease of implementation. The positioning of the strain gauge can be adjusted to best capture specific stresses. Placing a strain gauge on the back face, opposite the slot of the sample allows for detection of residual stress through the full thickness of the sample while placing a strain gauge on the front face of the sample will give higher resolution close to the surface but is unable to resolve cuts of high depth. Therefore, it is common to use multiple strain gauges to get a more detailed picture of the residual stress distributions within a sample. One such arrangement is shown in Figure 3.

Ersoy and Vardar[14] went on to extend this technique to layered orthotropic composites and compared their findings to the layer removal method (see below) and finite element modeling. They found high levels of scatter in the data when using layer removal and found the experimental procedure to be impractical. However, the slitting method offered lower result scatter, easier implementation, and good agreement with the model used.

Various other methods for measuring the resulting displacements have been explored such as moiré interferometry[45] and micrograph DIC.[42, 46] The latter of which has been used to investigate residual stress on a nanoscale in thin films. Recently, Salehi et al[47] applied 2D DIC with incremental slitting to investigate the macro scale residual stress in a cross-ply sample. It was found that shear effects and rigid body motion was high for some of the slitting increments. However, these were able to be removed mathematically due to the large amount of data captured with DIC. It was found that there was acceptable agreement between results obtained via a traditional strain gauge and those found with DIC and it was suggested that this full-field technique can be extended to smaller scales.

Various methods for creating the slit have been used from the basic approach of using a thin saw blade[14, 48–52] to using focused ion beams[42, 46, 53, 54] and an electron discharge machine (EDM).[45, 55] One obvious problem of using a saw, a mill or any other abrasive method is that it will invariably introduce additional stresses into the specimen being tested. This can be mitigated through the use of lubrication and careful control of cutting parameters, but the introduction of some stress is intrinsic to the process. This is particularly true when measuring strains on the "front face" of the specimen when surface residual stresses are under investigation. When using a "back face" strain gauge it was found that this measurement is reasonably insensitive to cutting stresses.[56] Ion beams have been shown to be effective as they can be used on a very small scale and thus used to measure stress at high through-thickness resolutions. However, their application is currently limited to less than a thickness of a single ply. Thus, they cannot easily be used for gaining an understanding of the macro-scale interlaminar residual stress within a laminate but could lend an unmatched level of resolution for the intralaminar stresses. EDM has the advantage of imparting very low stresses into the sample during the slitting process due to the inherent nature of the material cutting process and the thin wire used. The laminate is also usually placed in a bath of deionized water which has the side-effect of acting as a mechanism for removing heat away from the part, again reducing unwanted stress. However, EDM only works on conducting materials such as metals and carbon, it will therefore not work on composite systems based on glass for example. There is also the potential influence of moisture on the laminate during the submersion in water and it has been shown that an increase in moisture content increases the relaxation of residual stress.[57]

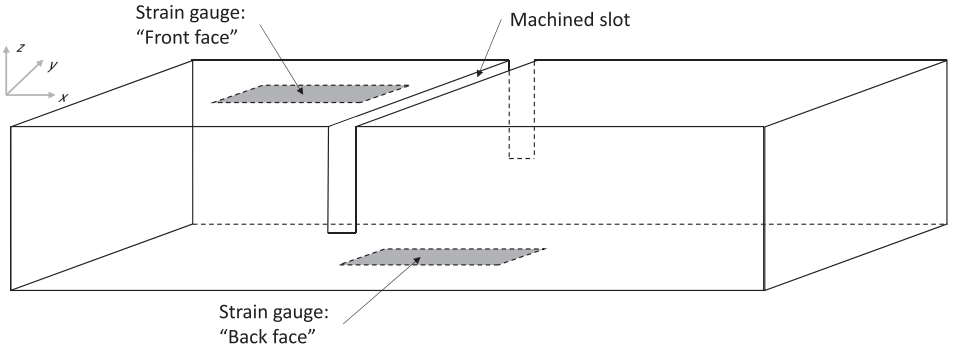

FIGURE 3 The slitting method experimental setup

In a recent study, Salehi and Shokrieh[58] defined a repeated slitting safe distance (RSSD) as the minimum distance between the slitting experiments to exclude the effect of the previous one. In theory this allows for multiple slits to be made in a specimen along its length without subsequent slits affecting the previous ones. Thus, extending the capability of the slitting method to not only determine the residual stress perpendicular to the slit face but to also determine this along the length of a specimen. Using a numerical and empirical approach it was concluded that a RSSD of 2.5 times that of the thickness of the part is sufficient to diminish the experimental error to 1% for laminated composites. Future work proposed by Salehi and Shokrieh is to extend this analysis to hole-drilling, ring-core, and other destructive methods.

2.5 | The contour method

The contour method was first developed in 2001 by Prime[59] as a new method of mapping the two-dimensional residual stress distribution through a cross-section of a prestressed homogeneous specimen. First, the object under inspection is cut in half at the area of interest. This process releases the residual stress from within the object and causes the cut surface to deform a small amount. A detailed topographical map of the cut surface is then created using a coordinate measuring machine. Imposing boundary conditions upon a finite element model of the object under investigation to restore the residual stress induced deformations back to zero then allows for the determination of the original residual stress within the object.

This technique continues to be popular in the nuclear and oil and gas industry[60] for determining residual stress in pressure vessels and welds as it is able to provide high resolution stress maps of stresses normal to the cut surface and has been shown to have a high degree of accuracy.[61] However, this method has a few limitations which has led to it not being applied successfully to fiber reinforced polymer composites. First, it is not possible to use standard mechanical machining for the slot as this process inherently imparts machining stress into the surface of the cut, thereby making the measurement invalid. Therefore, the standard practice for metallic materials is to use EDM to cut the specimen. This induces very little additional residual stress as the process only interacts with the material that is being removed and it is conducted in a bath of dielectric liquid which acts as a large heat sink rendering thermal affects insignificant. However, the EDM process requires that the material being cut is electrically conductive which is not the case for standard polymer matrices and glass/aramid fiber reinforcements. Therefore, this process is limited to carbon, or other electrically conductive fibers, and a metal matrix or a polymer matrix with additives causing it to be conductive. These limitations have resulted in little to no research in this area but it still possible in theory and would offer a unique insight into the distribution of residual stress through a cross-section.

2.6 | The first ply failure method

The first ply failure method can be used to obtain the transverse residual stress found in a cross-ply laminate. The basis of this technique is to compare the transverse tensile strength of an unloaded UD reference specimen to that of an embedded stressed ply within a cross-ply laminate. It is assumed that failure occurs upon initial crack growth within the matrix and this happens at the same stress throughout testing. The difference in failure strengths is then determined and then used to determine the residual stress that caused the disparity in strengths. This approach assumes that it is possible to achieve a perfectly stress-free UD sample which can be used as the reference. While it is possible to have a global residual stress of zero across the laminate this cannot be said to be true on a micromechanical level as there is a series of complex fiber matrix interactions at play at this scale as previously discussed. Therefore, this technique is limited to a macro-scale residual stress measurement.

Kim and Hahn[62] were the first to take significant steps in the development of the first ply failure technique. The approach was based around using strain gauges and acoustic emission to monitor initial cracking within the matrix of the laminate. While strain gauges were found to be effective when the crack occurred underneath the gauge, they were unreliable at detecting cracks in other regions. However, acoustic emissions were found to be very effective at detecting first ply failure. Later, Cowley and Beaumont[63] used this technique to investigate the effect of temperature on residual stress, finding a linearly increasing trend which is consistent with current theory and other experimental techniques. They found the first ply failure technique underpredicted residual stress compared to lamination theory by 5% to 25%. Reasons for the discrepancy were: the transverse strength not remaining constant as assumed; stress relaxation effects; and fibers in other plies of the laminate constraining the transverse ply. This latter point is corroborated by Flaggs and Kural[64] who demonstrated that the transverse tensile strength is not an intrinsic property of the ply and is affected by neighboring plies. Strengths of up to 2.5 times that of a UD ply were found in laminates with transverse shear strength being found to be strongly dependent upon laminate thickness and neighboring ply orientations. Thus, the assumption that neighboring plies have no effect on the strength of the ply under investigation is false.

There have been suggestions[16] that this method could be used in the longitudinal direction to measure the micro-scale residual stress aligned with the fibers. However, the problems previously stated also hold true in the longitudinal direction and it is therefore not possible to determine micromechanical residual stress using this method.

3 | NONDESTRUCTIVE METHODS

3.1 | Raman spectroscopy

Micro-Raman Spectroscopy is a commonly used method in the micro-electronics industry for determining areas of local mechanical stress in silicon circuit board parts.[65] Raman spectroscopy uses the scattering of light to investigate the vibrational energy of the chemical bonds of a crystalline structure. The scattered light is detected and characteristic Raman peaks can be observed. The position of these peaks is altered by any externally applied strain.[66] Therefore, it is possible to quantify the applied strain by measuring the differences in the Raman peak position between a stressed and unstressed sample.

Bannister et al[67] successfully applied micro-Raman spectroscopy in the analysis of fiber stress during pull-out in an aramid/epoxy composite. Fiber strains were able to be measured along the length of the fiber during pull-out and thus allowed for determination of the interfacial strength of the fiber/matrix bond. Thomsen and Pyrz[68] were also able to use this technique to measure creep in fibers in a carbon/polypropylene composite. Measurements along the length of the fiber at 20 μm increments were used to a develop a stress map along the axis of the fiber.

It is also possible to measure the strain in the amorphous polymer matrix by determining the distribution of molecular orientations in the polymer. This is achieved through measuring the angular variation in Raman peaks which relates to the applied strain.[69, 70] However, Raman peaks for amorphous materials like thermosetting polymers or glass are quite wide and irregular in nature. Whereas the Raman peaks for crystalline polymer structures like thermoplastics are much more well defined.[71] Therefore, this technique is most suitable for examining micro-scale strain within crystalline fibers, such as carbon, or for use on a macro-scale with crystalline matrices such as thermoplastics but offers poorer resolution for amorphous materials like thermosetting polymers.

3.2 | Warpage of asymmetric laminates

Arguably one of the simplest methods for determining residual stress is the evaluation of the warpage of asymmetric laminates. First imagine two perpendicular plies, a [0/90] UD laminate, which are allowed to slide over each other and do not interact. Each ply will experience less shrinkage along the direction of the fibers than in the transverse direction as the fibers will constrain the matrix's movement. Therefore, if the coordinate system in Figure 4 is used, it can be seen that the 90° plies will shrink much more than the 0° plies along the x-axis as demonstrated in Figure 4A. Now imagine the real case where the plies are bonded together, as shown in Figure 4B, the difference in contraction between the upper and lower (90° and 0°) plies will cause the laminate to warp out of plane in the positive z-direction and a tension-bending couple has been formed. Thus, it is the chemical shrinkage of the matrix that causes warpage in an asymmetric laminate during cure. During cool-down the thermal effects due to the variation in CTE between matrix and fiber then come into play as previously discussed. This warpage can then be measured and compared to a theoretical model to determine the residual stress.

This analysis works on the assumption that the residual stress induced during the curing process can be relieved through the out-of-plane bending of the laminate.[63] By using an asymmetric laminate of $[0_4/90_4]$ Kim and Hahn[72] were some of the first to apply this technique successfully to composites. A simple elastic analysis was utilized to relate measured deformation to residual stress; however, it should be noted that constrained residual stress at the micro-scale was not accounted for in this analysis. Nairn and Zoller[73] later showed this technique's applicability to both thermoplastics and thermosets. Additionally, thermoplastics experience an increase in matrix density upon cooldown due to the crystallization of the polymer structure, thereby increasing residual stress.

Gigliottia et al[74] used fringe projection on thin [0/90] plates to measure the stress induced by hydrothermal loads. This allowed for a full-field view of the displacement, thereby allowing the authors to more robustly capture the nonlinear behavior seen during their experiments. The use of fringe projection also allowed for the detection of anticlastic deformations (saddling) in the composites which is indicative of an additional bending moment being present in the laminate. This would not have been possible using a nonfull-field approach.

These previous studies were not able to monitor the in-situ build-up of residual deformation during the cure cycle as they were conducted in closed ovens. The samples were also cured on flat plates which introduced anticlastic deformations in the samples which were caused by bending and torsion moments combining, thus resulting in transverse curvature of the plate. A pair of

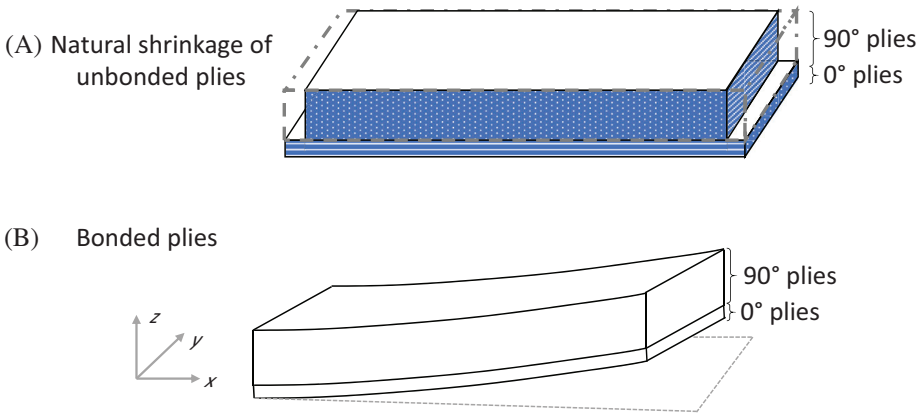

FIGURE 4 A, Unconstrained shrinkage and B, constrained shrinkage and warpage of asymmetric laminates [Color figure can be viewed at wileyonlinelibrary.com]

studies by Kravchenko et al[75, 76] expand on previous studies by implementing both an asymmetric and unbalanced laminate with the latter being used to exaggerate the deformations seen. The setup also utilized a cantilever-beam mounted sample to avoid any tool/part effects and to also measure deformation due to self-weight. Finally, image tracking was carried out on the sample during cure by observing the curvature development of the sample through a window in the curing oven. These data were then combined with knowledge of the cure kinetics of the resin, CTE, and chemical shrinkage with respect to degree of cure and the resins storage modulus to predict residual deformations. While these experiments did not predict residual stress, they were able to predict end-deflection with reasonable accuracy. It is suggested by the authors that residual stress could be modeled using similar techniques.

Crasto and Kim[77] suggest that it is possible to determine the ratio of residual stress caused by chemical shrinkage to that caused by thermal expansion through the analysis of the stress-free temperature. A warped asymmetric laminate that has been fully cured can be reheated until it flattens again, at which point the stress-free temperature is said to have been reached. This temperature will be above the cure temperature as additional thermal expansion is required to overcome the permanent chemical shrinkage in the fully cured laminate. Later studies[78–81] have found a similar phenomena but are still cautious about heavily relying on this relationship. In general, it seems that there are many different mechanisms at play and as such it is difficult to be certain of the accuracy of this approximation. However, at the very least, it does allow for a qualitative comparison of the contribution of thermal expansion and chemical shrinkage to the build-up of residual stress.

In conclusion, it is possible to model the deformations due to cure of asymmetric laminates with reasonable accuracy if the properties of the matrix are well understood. It is also possible to model the total global-scale residual stress that forms due to chemical shrinkage and thermal expansion which is subsequently relieved due to deformation. However, it is not possible to measure or detect any residual stress which is self-equilibrated between the fibers and the matrix on the micromechanical level as this would not contribute to the curvature of the asymmetric laminate. This technique should be thought of as a way to validate thermomechanical models and not for directly measuring residual stress.

3.3 | Photoelasticity

Photoelasticity relies on the relation between the stress or strain field in a material and the resulting changes in its optical properties. Birefringent materials have two refractive indices and these are dependent upon the stress state of the material. Therefore, through the use of optical measuring devices utilizing polarized light, it is possible to determine the full field stress state of a loaded component that is made of a birefringent material. For a more thorough introduction to photoelasticity refer to Dally and Riley.[82] Photoelasticity has been a preferred technique in academia for a number of decades as it allows the user to get a visual representation of the stress field in a component.

Within composite applications the use of photoelasticity has been for the most part limited to single embedded fibers samples. Experiments performed by Kim and Nairn[74] have shown this technique to be particularly helpful in evaluating fiber debonding in carbon fiber epoxy matrices. This technique has also been shown to work well at a micro-scale by measuring the micro-stress fields around a single fiber. It is also possible to investigate changes in maximum principle stresses at fiber/matrix interfaces while under load and to track these changes over time which allows for the investigation of phenomena like de-bond propagation.[83] Thus, it can be seen that if used correctly photoelasticity allows

for a visual representation of the stress field in composites, which is not possible using most techniques.

However, one of the main limitations of photoelasticity is that it requires light to be able to pass through the material that is being measured. Thus, this technique is limited to composites with very low fiber volume fractions (30%-40%[84]) and UD fibers so as to allow enough light to pass through the sample. If a cross-ply fabric, woven fabric or a fabric with a high fiber density is used, light will not be able to pass through and no measurements can be taken. A lack of transparency is the main reason that photoelasticity is not widely used in composite laminates. To overcome this, Andersson et al[85] investigated the residual stress present in a cross-section of UD fibers. This thin cross-section had sufficient light penetrability through the fiber direction to allow the photoelastic effect to be observed. Good agreement was found between the stress distribution in the modeled and experimental results and they were able to demonstrate the formation of residual stress after cure. It was also found that fiber matrix debonding which occurred during cure caused a reduced light band forming in the matrix making it difficult to analyze the stress distribution in the matrix effectively. They noted that upon the application of 0.5% strain on cured samples, there was hardly any change in the optical pattern. This was in sharp contrast to the modeled results. This led Andersson et al to conclude that "The optical pattern is therefore not an image of existing stresses but rather reflects the stress history."[85] However, this article did not provide sufficient information about the experimental setup of the photoelastic equipment being used for the current authors to be confident about this conclusion. Therefore, it is the opinion of the authors that there is room for further exploration of this technique for the evaluation of residual stress in composites. If this technique can indeed be used, then it could offer a unique view of the formation of residual stress through the thickness of a composite system.

3.4 | Cure reference method

The cure reference method was developed by Ifju et al[86] as a novel noncontact method for determining the build-up of residual stress on the surface of a fiber reinforced polymer laminate. A moiré grating is applied to the surface of an uncured uni-directional laminate in its stress-free state, that is, before the gelation of thermosetting polymers. The part is then cured and the resultant surface displacement is determined using moiré interferometry. This gives a full field strain map of the surface of the laminate from which it is then possible to calculate the theoretical macro/micro-scale residual stress by applying laminate theory. It was also shown that it is possible to apply the same technique to a cross-ply laminate by curing it in parallel to the UD one and calculating the free thermal expansion of the UD laminate.

A similar technique using DIC has been used effectively by Kravchenko et al[87] to determine the chemical shrinkage and thermal expansion of a neat thermosetting resin. Here, an adherent pliable film containing a random speckle pattern was bonded onto the top of gelled resin sample before final curing. The surface deformation during cure was then captured by a camera and a standard DIC postprocessing procedure was carried out of the images. This tracked the strain on the surface of the resin by determining the movement of each speckle between each frame of the video. From these data it was possible to calculate the chemical shrinkage after gelation and the thermal expansion of the resin. This method has not been widely adopted with the exception of a few simple use cases.[88, 89] This is primarily due to the inability of this method to measure the sub-surface strains during cure. Therefore, this technique relies on the assumption that the through-thickness strain is constant which is often not the case, especially when tool-part interactions occur. However, sensors embedded within a laminate can monitor the cure state and build-up of residual strain through the thickness of a laminate.

3.5 | Embedded sensors

Residual stress within a composite laminate is primarily caused by the thermal and chemical volumetric changes that occur during cure. Therefore, if these volumetric changes, or strains, could be measured during the curing process it would be possible to calculate the residual strains within the laminate. If a sensor such as a strain gauge or fiber optic sensor is embedded inside the laminate this allows for the calculation of the interlaminar laminar stresses in angle-ply laminates and intralaminar stresses in uni-directional laminates[90] in both the axial and longitudinal directions.[91] It is also possible to use the fiber optic sensor as an embedded temperature sensor by encapsulating a section of grating in a sealed tube to make sure that any expansion or contraction of the fiber optic sensor in that area is purely down to thermal expansion and no other applied strain. This is particularly useful in an embedded composite application as it is often critical to have an accurate temperature reading within the laminate in order to have a good understanding of the cure and material state of the laminate.

The idea of embedding a sensor into a fiber reinforced polymer composite was first developed by Daniels

et al[92] for measuring sub-surface strains in boron/epoxy laminates. Daniels et al were able to show the usefulness of this technique in monitoring the development of sub-surface strain during cure. Kim and Daniel[90] later went on to expand on this work by analyzing various cure cycles and the effect they had on cure-induced strain and comparing this against data gathered with fiber-optic sensors. Measured strain begins to occur after gelation as the matrix strains elastically instead of flowing around the sensor viscously. Past works[93–95] have used both Fiber Bragg Grating (FBG) and Extrinsic Fabry Perot Interferometric (EFPI) fiber optic sensors. However, the latter of the two sensors has since fallen out of common use[4] as they are significantly larger than FBG sensors which causes them to act in similar manner to voids and are therefore common crack initiation sites with some studies finding the cure induced stress alone was enough to cause failures at the sensor interface.[95] More recently, investigations into the use of ferro-magnetic glass-coated microwire inclusions for the monitoring of polymerization by Allue et al[96] have begun. However, this technology is very much still in its infancy and more research is required in this area.

FBG sensors work by passing high-intensity ultraviolet light with wavelength λ, down the length of an optical fiber. This light then interacts with a series of gratings within the fiber that area at a known pitch, Λ and refractive index n. The reflected light has the relationship $\lambda_{\text{ref}} = 2n\Lambda$ and is analyzed by the interrogator unit connected to the end of the optical fiber and the changes in the reflected light spectra are analyzed. If an external axial strain is applied to the fiber the distance between the gratings changes and the wavelength of the reflected light shifts and can be used to determine the applied strain[82] as shown in Figure 5. Caution must be taken when analyzing the raw optical sensor data since factors such as the optical fiber coating, shear-lag affect, and the mechanical properties of the optical fiber itself can cause a misinterpretation of the results. Work by Voet et al[97] investigated the strain transfer between an embedded optical sensor and resin matrix by experimentally determining the response of the sensor to a known transverse load and comparing this to a numerically derived case using finite element simulation. They showed that for their studied case there was good corroboration between experimental and numerical results meaning there was a high degree of strain transfer into the embedded sensor. However, the authors did caution, that similar tests for each individual case would be prudent to validate any experimental data gathered from embedded optical fibers. While this might not be practical for all cases it is evident that some form of validation to the efficacy of the ability of optical fibers to capture accurately the true internal strains must be a part of any rigorous study.

It is also possible for one optical fiber to contain many FBG. This allows for multiplexing which is the ability of the sensor to measure strain at many discrete points along its length to create a quasi-distributed array of sensors.[98] However, it should be noted that a study by Shivakumar and Bhargava[99] found that if a fiber optic

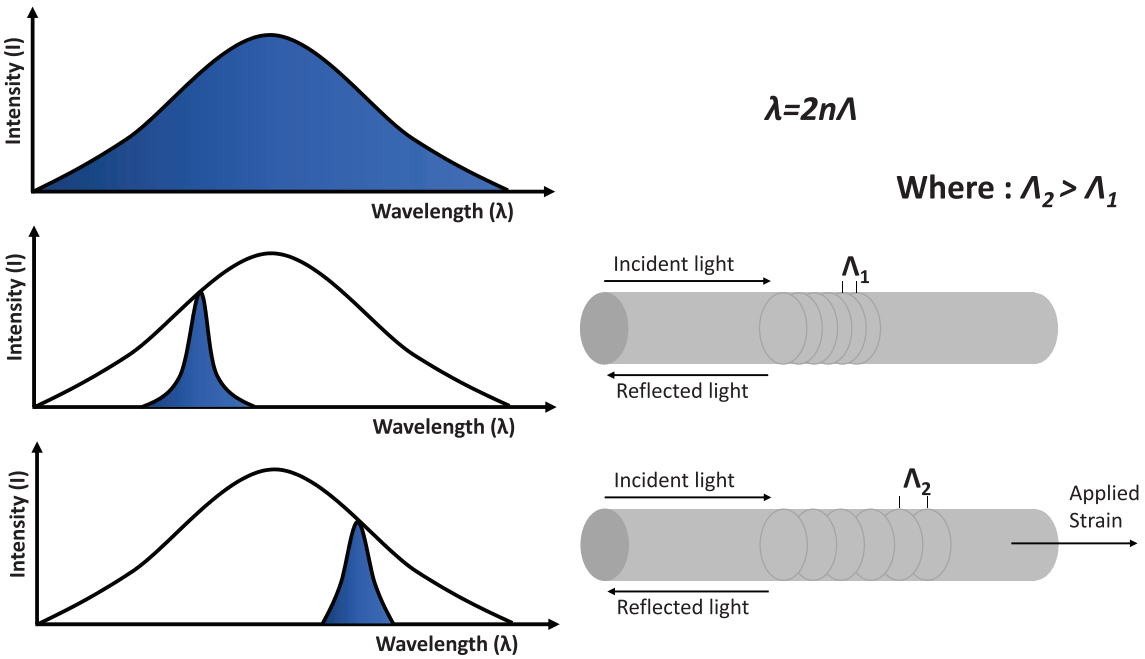

FIGURE 5 FBG response to an applied strain, adapted from ref.[4] [Color figure can be viewed at wileyonlinelibrary.com]

sensor is embedded perpendicular to the direction of the fibers then an eye-shaped resin pocket defect forms with a length 16 times that of the fiber optic radius and a height of double the fiber optic radius. This defect acts as stress concentrator and it was found that under tensile loading, initial failure occurred due to transverse matrix cracking at the defect. Therefore, it is advised that fiber optic sensors are embedded parallel to the fiber direction which causes minimal disruption assuming the fiber optic radius is similar or less than that of the reinforcing fibers.

Work by Okabe et al[100] investigated the effect of optical fiber diameter and coating variants on the, then thought, troublesome splitting of peaks in the reflection spectra, finding that decreasing fiber diameter and coating in polyamide would reduce this splitting. The splitting of peaks in the reflection spectra was attributed to transverse strains being applied to the optical fibers during cooling or in other words the chemical shrinkage of the resin matrix. Figure 6 shows the splitting of the reflection spectra due to unequal transverse strains. Later works by the likes of Sorensen et al[101] found that it was possible to use this peak splitting effect to monitor the build-up of transverse strain during cure and therefore investigate the chemical shrinkage of the resin matrix during cure. This is of particular use when investigating the build-up of residual stress in fiber reinforced composites as it is well-documented that chemical shrinkage is a key contributing factor to residual stress.

The use of embedded fiber optic sensors in laminates is still very prevalent with many examples of this technique being successfully applied to the monitoring of internal strains during cure in thermosets[102–105] and thermoplastics[57, 106, 107] where a higher operating temperature is required. Another key benefit of fiber optic sensors is that they can often be repurposed after cure as condition monitoring devices. Arhant et al[57] demonstrated the ability of embedded fiber optic sensors to measure residual strain during cure and then using the same sensors to monitor the effect of an uptake of moisture within the part during the parts normal operating life without any apparent loss in measurement quality. The idea of having dual functionality of cure monitoring and structural health monitoring is undoubtedly of great interest to those looking to implement this technology in industrial applications.

Recent work by Hu et al[108] has shown the viability of a novel implementation of FBG sensors in laminate by using a "tailed" FBG set. This consists of two parallel FBG sensors with one being shorter than the other. The shear lag effects between the two sensors causes more strain to develop on the long FBG sensor during cure and the difference between these two strains is a function of the modulus of the matrix. Therefore, the gelation point and effective transverse chemical shrinkage can be determined. It is also possible to use the calculated matrix modulus to monitor the degree of cure of the matrix as these two quantities are proportional.

Work by Minakuchi[109] showed the possibility of using fiber optic sensor to characterize the direction-dependent cure shrinkage of thermosetting fiber reinforced composites in-situ during cure. This method relies on a combination of FBG placed in the out-of-plane direction through the thickness of the laminate and sets of short tailed paired sensors embedded in-plane through

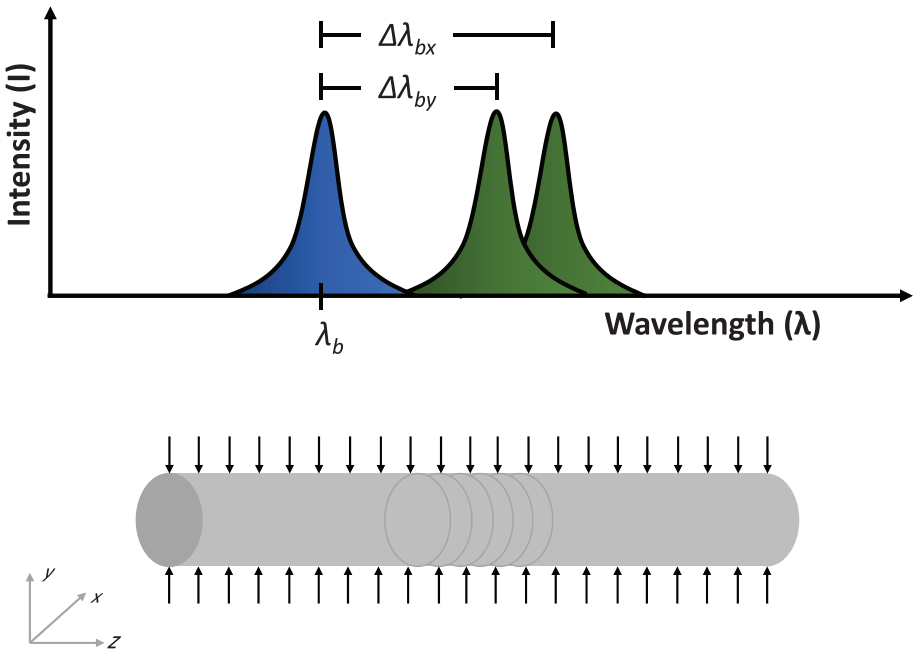

FIGURE 6 FBG response to transverse strain, adapted from ref.[101] [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 A review of all discussed measurement techniques

Technique	Residual stress scale			Comments	References
	Micro	Macro	Global		
Layer removal		[13]	[12]	Low accuracy	[11, 13–16]
Hole-drilling	[19, 27]	[20]	∼	-Potentially global scale if laminate is thin -Bixal stress distribution -Accuracy decreases with depth of cut	[17–34]
Ring-core	[40–42]	[37]	[39]	-Most applicable to micro scale -Potentially relives more residual stress than hole drilling	[16, 35–43]
Slitting method	[53]	[14, 48]	[49]	-Limited to the average stress across a width	[14, 42, 44–46, 48–58]
Contour method	?	?	?	-Has not been done, but has potential	[59–61]
First ply failure		[62]		-Assumes a perfectly stress-free sample is possible	[16, 62–64]
Raman spectroscopy	[67]	∼		-Macro if matrix is crystalline and aramid fibers are used	[65–71]
Asymmetric warpage			[75, 76]	-Only validates model	[63, 72–81]
Photoelasticity	[74]	[85]	[85]	-Only macro and global using a cross section -Matrix must be transparent	[82–85, 112]
Cure referencing	[86]	[86]		-Surface based measurement -Low accuracy	[86–89]
Embedded sensors	[97]	[90, 109]	[90, 98, 109]	-Sub-surface strain measurements allow for no thickness limitations -Possible debonding issues	[4, 57, 82, 90–109]

Note: ?, there is potential but it has not been done to date; ∼, it is possible with some caveats.

the thickness of the laminate. This technique gives a deep insight into the internal build-up of residual strain in three-dimensions during the curing of a composite laminate. It is also able to characterize the through-thickness shear strain of the resin matrix.

Distributed optical sensing (DOS) technology has gained much popularity in recent years for its ability to have continuous real time measurement capabilities along a fiber's entire length, unlike multiplexing which relies on many discrete sensing zones. It works on the principal of coherent Rayleigh optical time domain reflectometry, sending short laser pulses through the fiber and analyzing the reflected laser spectra. It seems that it is currently not possible to measure strains transverse to the optical fibers in DOS as is done with peak splitting in FBG based sensors which means DOS fibers must be placed parallel to the direction of strain measurement. This comes with its own problems with voids and stress concentrations as previously explained. Work by Tsai et al[110] has recently shown the full capability of this technology by combing DOS with cure kinetic, viscosity and glass transition models in thermosetting fiber reinforced laminates to monitor cure strain in both UD laminates and structural cross-ply laminates. It was concluded that "cure shrinkage cannot accurately be measured by the DOS in a laminate where the ply 0° direction is aligned with the sensor" due to the small strain sensitivity parallel to the optical fiber caused restraining reinforcing fibers. This means that for the case of a cross-ply laminate and parallel to the fibers in a UD laminate it was not possible to accurately measure residual strain. However, with all other cases good agreement was found between the recorded results and the results calculated with composite laminate plate theory. This technology shows good potential assuming its limitations are understood as it allows for an unmatched insight into the strain profile along the DOS fiber length.

4 | CONCLUSION

There has been a huge breadth of research that has been undertaken in the numerical modeling of the manufacturing process of fiber reinforced laminates, as Baran et al[3] showed. It is clear that much progress has been made over the past few decades and it is now possible to accurately predict many physical phenomena accurately by choosing and correctly implementing one of the

many models and techniques available. However, as ever, it is crucial that numerical simulations are validated through experimental rigor to have sufficient confidence in a given result. Early works from the likes of Daniel et al,[92] Hahn and Pagano,[111] and Nairn and Zoller[84] paved the way for the current state of the art research in the experimental determination of residual stress. In this article, a variety of the currently most-used experimental techniques have been presented and have been categorized into two groups, destructive and nondestructive techniques. For clarity, a summary outlining applicable measurement scales and the major advantages and disadvantages of each reviewed technique has been given in Table 1. Destructive techniques work off the principle of bulk material removal to induce a relaxation of stress to induce a relaxation of strain which in turn can be measured and analyzed to determine the relaxed stress. Traditionally, these methods have been limited to global or laminate scale stress as their resolution is generally too low to capture the variation of stress through the thickness of a single ply due to inaccuracies in the experimental method; machining, strain measurement, numerical approach. However, recent work like that of Smit and Reid[27] have shown the possibility of using these techniques for the measurement of intraply stresses with the errors being known confidently. This opens up destructive techniques for even wider adoption by those measuring all scales of residual stress. However, nondestructive techniques are still the preferred choice in academia for the analysis of micro-scale intralaminar residual stresses as they do not suffer from the same limits inherent to destructive techniques. With the exception of embedded sensor technologies, nondestructive techniques do not appear to be widely used in industry as they are generally not feasible for end use parts due to limitations like material properties, being permeable to light or having asymmetric lay ups. Embedded sensor technologies have great potential in the analysis of intraply, interply, and laminate residual stresses arising from cure and have the potential to provide condition monitoring data during the operational use of the part.

The aerospace industry is a prime example of an area that greatly benefits from the use of more fiber reinforced polymer composites as the weight and stiffness benefits directly translate to higher efficiencies and subsequently fuel and cost savings. However, high safety factors required by aviation naturally lead to a conservative approach toward new materials.[113] With a better understanding of the process induced residual stress we hope that some of these concerns can be addressed. The methods presented in this review offer the user an insight into the integrity of real-world fiber reinforced composites which would otherwise be poorly understood. This review provides an up to date summary of the advantages and disadvantages of a comprehensive range of experimental approaches to assessing residual stress in fiber reinforced thermosetting composites. Therefore, more certainty can be brought to the aerospace or other similar industries that requires such high levels of confidence in their designs.

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ORCID

Ben Seers https://orcid.org/0000-0003-1297-1480
Rachel Tomlinson https://orcid.org/0000-0003-2786-2439
Patrick Fairclough https://orcid.org/0000-0002-1675-5219

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