REVIEW PAPER

An Assessment on the Residual Stress Measurement in FRP Composites Using Relaxation Techniques

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Abstract: *Residual stress measurement is of utmost importance for the safety and reliability of engineering components and has been an active area of scientific research. Relaxation techniques such as hole drilling, slitting and ring core method are widely applied semi destructive techniques for residual stress measurements in polymer composites. This article reviews the recent literature on the measurement of residual stress in polymer composite by employing the above-mentioned relaxation techniques. This article summarizes the categories of residual stresses, causes of formation, techniques of measurements and also briefly outlines the chronological developments of the Hole drilling and slitting method. The article also provides a comparative summary of these relaxation methods.*

Keywords: *Residual stresses, Hole drilling, Slitting Method and Ring core method*

1. INTRODUCTION

Fiber reinforced polymer (FRP) composites have emerged as materials deemed to meet the modern world requirements, materials with high strength, high modulus, lightweight, better fatigue and corrosion resistance are need of the hour. FRP composites have found application in aircraft, automobile, marine, domestic industries and also in civil infrastructure. As modern engineering structures become less conservative, it is important to understand the different factors that affect the behavior of these materials to get the very best out of them. An important factor that needs an investigation is the impact of the manufacturing process applied on the overall behavior of the composites. Residual stresses creep into composites during their manufacturing, which is usually carried at elevated temperatures and pressure.

Residual stresses can add up to the applied load and may critically degrade the strength and integrity of the composite structure. These stresses are particularly tricky as they satisfy equilibrium and offer no external indication of their presence. These stresses may also contribute to delamination, premature failure, warpage and matrix cracking. As the residual stresses significantly affect the behavior of composites and their almost universal presence, knowledge of these stresses is very crucial for any structure where sizeable safety factors are impractical [1-5].

2. DEFINITION, CAUSES OF DEVELOPMENT AND CLASSIFICATION OF RESIDUAL STRESSES

Residual stresses can be defined as stresses which are present in the material even before they are externally loaded. The polymer composites are usually processed at elevated temperatures and pressure, the sources of residual stress development in the laminates composites are; the thermal expansion coefficient mismatch between the fibers and matrix, different expansion coefficient in the transverse and longitudinal direction of the lamina, the chemical shrinkage of the matrix and difference in contraction and expansion of successive laminas due to their sequential arrangement.

Residual stresses developed in polymer composites are categorized into three different levels; primary, secondary and tertiary levels of stresses [6-7].

The residual stresses which are formed between individual fibers within a lamina come under the primary level of residual stresses which are also referred to as micro stresses. The second level of residual stresses also referred to as macro stresses are formed at a ply-to-ply scale in multi-axial laminates due to the differential CTE of the individual laminas in different directions. The third level of stresses are formed due to different thermal histories of different parts of a laminate during the curing process.

2.1. Classification of residual stress measuring techniques

The detailed classification of residual stress measurement techniques is shown in Figure 1, the classification is based on whether the damage will be done to the specimen or not as destructive/semi destructive ("relaxation") and nondestructive techniques [8-9]. Semi destructive techniques are based on the principle of relaxation, the strains are relieved by partially removing material from the component where stresses need to be determined. Measurement of deformation/strain can be accomplished by using strain gauges, holography, Moire interferometry, laser speckle interferometry and/or digital image correlation (DIC). Semi destructive techniques include the hole-drilling, crack compliance, sectioning, ring core, and layer removal method.

One of the major challenges in the relaxation technique is the complicated mathematical calculation, as the material removed is from one region (material machining) and corresponding relaxed strains are measured away from the machined portion in another region [1,8-9,63-66]. Non-destructive techniques use changes in material structure to measure residual stresses induced in a material. X-ray diffraction, magnetic, ultrasonic and Raman method of residual stress measurement techniques comes under the non-destructive techniques. These techniques have the advantage of specimen preservation and have found application in product quality control, failure monitoring and continuous health monitoring of structures. These methods require a detailed calibration of samples to obtain the required computational data.

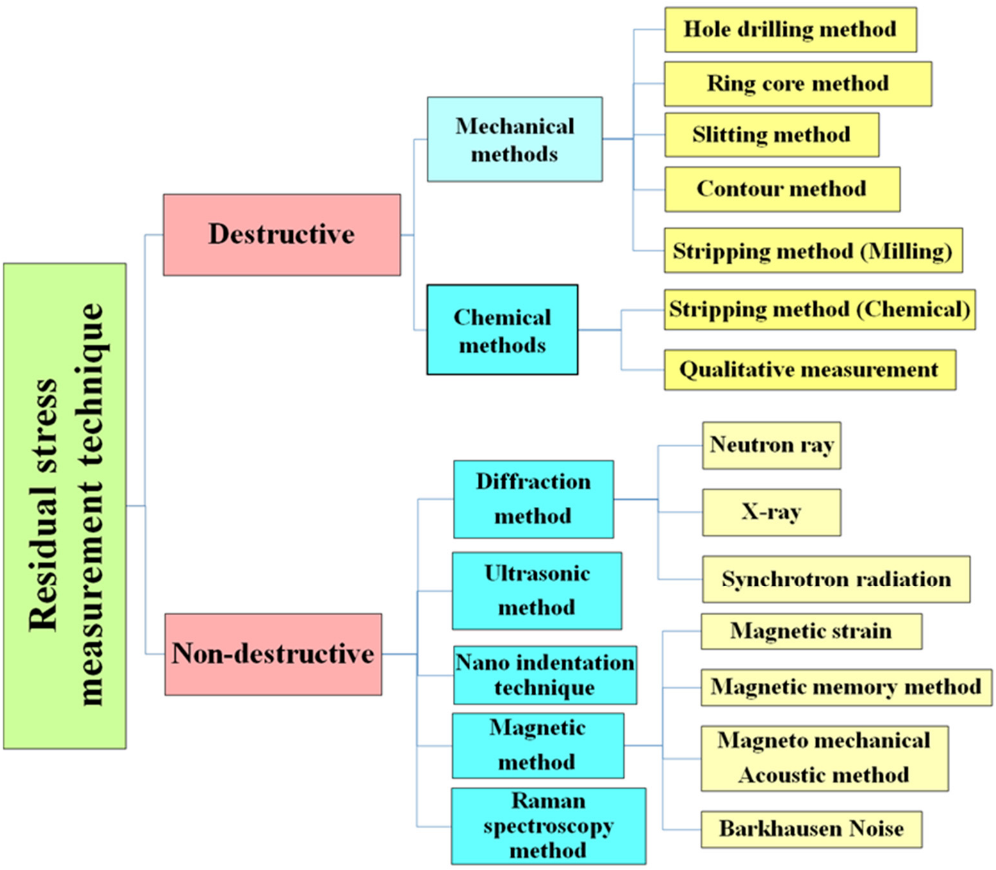

Fig. 1. Classification of the residual stress measurement technique

However destructive techniques make use of not so significant calibration as they measure basic quantities such as displacement or strains and hence have found wide application areas. Figure 2 summarizes the residual stress measurement techniques in terms of their ability to measure residual stresses through-thickness of the specimen. Factors that need to be considered while selecting the residual stress measurement technique are; Objectives of measurement, specimen material (Crystalline/ amorphous), the magnitude of damage to the specimen, specimen shape and dimension, environment of measurement, accuracy and spatial resolution, cost, duration of the test. This paper reviews and summarizes the recent work done on the determination of residual stresses in polymer composite by applying HDM, ring core and slitting methods.

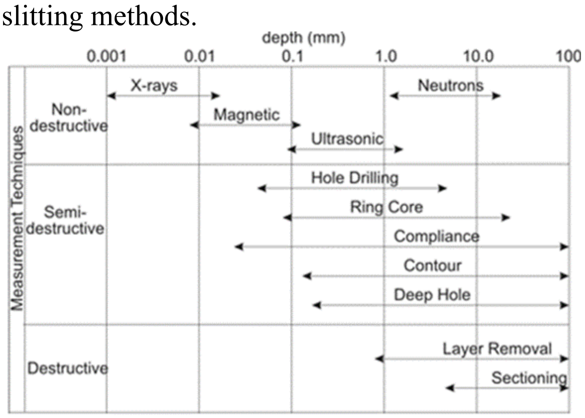

Fig. 2. Comparison of several residual stress measurement techniques and their respective depth of penetration [36].

3. HOLE DRILLING METHOD

HDM is the most widely used semi-destructive technique for residual stress determination. The method was first proposed by Mathar [10] in the 1930s. This method has grown and has been developed substantially with the integration of cutting-edge drilling techniques, precise displacement/strain measuring methods, and modern computational techniques. The methodology of residual stress measurement and its estimation using hole drilling technique has been well established by the ASTM E837 [11]. HDM using strain gauges is recommended as per ASTM standards. In the last few decades, optical methods such as Moiré, Electronic Speckle Pattern Interferometry (ESPI), and DIC have been applied to measure the released displacements (or strains) with hole drilling to determine residual stresses.

3.1. Basic concept of HDM

HDM compromises drilling a small hole at the center of a strain gauge rosette, which causes relaxation of localized strains around the hole as shown in Figure 3. These relaxed strains will be used to derive the residual stresses locked-up in the material. Various computational methods have been developed to derive the residual stresses from the relaxed strains. The timeline of the inception of HDM and its subsequent development is shown in Figure 4.

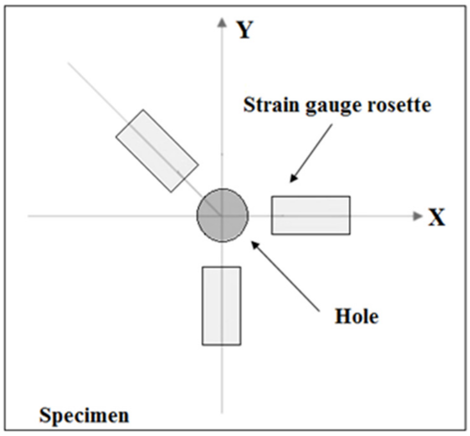

Fig. 3. Residual stress measurement using HDM

The earlier works carried out on the residual stresses measurement in polymer composite laminates using HDM are reviewed in the following segment. The literature has been further divided into subgroups as

i) Residual stress measurements by applying HDM using strain gauges

ii) Residual stress measurements by employing HDM with the aid of optical methods such as Moiré, Electronic Speckle Pattern Interferometry (ESPI), and DIC.

iii) Studies related to effects of experimental parameters on residual stress measurements by using HDM.

3.1.1. Residual stress measurements by applying HDM using strain gauges

Sicot et al. [18] investigated the effects of cooling conditions on the development of residual stresses in $[0_8]$ and $[0_2/90_2]_s$ Carbon/epoxy [CE] composite. The models proposed by Sothe [12] and Lake [15] were used to determine the residual stresses by employing the incremental hole drilling method (IHDM).

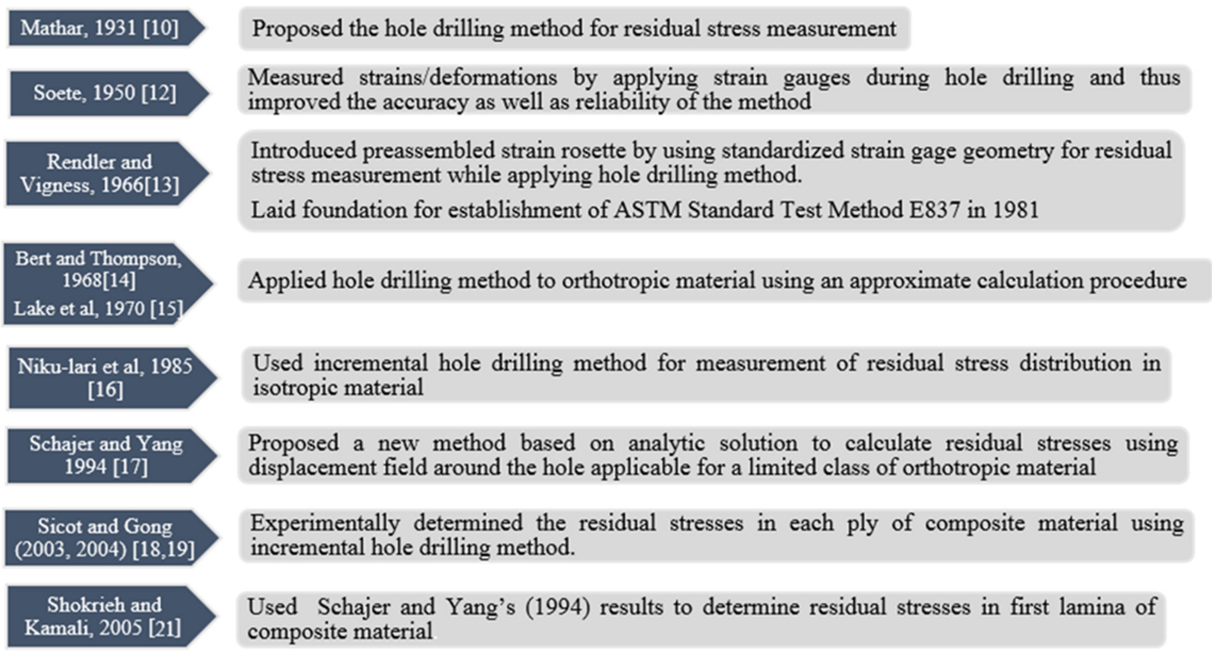

Fig. 4. Timeline of the development of HDM for residual stress measurement

Calibration coefficients required for residual stress determination were obtained using finite element analysis (FEA). The stresses in $[0_8]$ CE composite laminas increased with the depth of increment and a stress increase across the 0/90 boundary was observed. Further, the results obtained were compared with those determined by the Classical lamination theory (CLT) and it was concluded that HDM can be applied for measurement of stress distribution across the entire thickness of the specimen with good accuracy.

Sicot et al. [20] investigated the effects of residual stresses on the mechanical behavior of CE composite subjected to torsion and tensile loads. CE laminates with $[0_4/90_4]_s$, $[0]_{16}$ and $[90]_{16}$ lamina arrangements were prepared under hot press using different cure cycles, the effect of temperature cycles on the development of residual stresses were also studied. The different cure cycles had limited effect (variations in elastic moduli were within 10 %) on longitudinal modulus, transverse modulus and in-plane Poison's coefficient Acoustic emission technique was applied to monitor the initiation of damage and its further development. Higher residual stresses in composites accelerated damage initiation and its propagation.

Shokrieh and Kamali [21] experimentally determined the residual stresses in polymer composite using the calibration coefficient calculated based on the method proposed by Schajer and Yang [17]. Results obtained from CLT and the energy method were higher than experimental values. Residual stresses determined using CLT were independent of layup sequence and ply thickness whereas the experimental results were very sensitive to the arrangement of laminas and lamina thickness in the composite. As long as the temperature-dependent properties are not considered, the CLT is adequate for analyzing the residual stresses.

Shokrieh et al. [22] presented a new method to determine the calibration coefficients used to estimate the residual stresses from the relaxed strains obtained during HDM. Calibration coefficients determined by experimental techniques and by simulating HDM using FEA were in good agreement. Residual stresses in composites calculated by these calibration factors as well as those obtained by analytical techniques have shown a very good correlation. The advantage of the simulation method is its ability to determine the calibration coefficients using the different hole and strain gauges geometry using FEA. The non-uniform residual stresses through the entire thickness in an orthotropic material with any degree of orthotropy can be determined.

Akbari et al. [24] applied IHDM to characterize residual stress distribution in a thin-walled filament winded CE ring using an integral method that assumes the stresses to be uniform in each incremental cut. Three components of residual stresses viz hoop stress, axial stress and in-plane shear stress were determined. The hoop stresses obtained were found to be higher than axial and shear stress. Hoop stress across the ring inner surface was 200 MPa and compressive hoop stress of magnitude 140 MPa was found.

Ghasemi et al. [25, 26] assumed the stresses to be discontinuous and used an integral method to determine the non-uniform residual stresses in symmetric, un-symmetric cross-ply and symmetric quasi-isotropic laminates. The ability of the IHDM to evaluate residual stresses in different lay-up arrangements was experimentally studied. Residual stresses obtained matched favorably with those obtained by CLT. In the next set of investigations, the same process was applied to determine residual stresses in each ply of fiber metal composite laminate. The residual stresses determined are in good agreement with theoretically calculated stresses.

Gong et al. [27] studied the effect of ply orientation on the development of residual stresses in CE composite ($[0_2/\theta_2])_s$ {θ = 0°, 30°,45°,60°, 90°} using IHDM and by a novel analytical technique based on the elastic stress-strain model. Calibration coefficients were determined by simulation of IHDM using ABACUS. The residual stresses in composites increased with an increase in angle θ and almost depict a linear correlation with respect to lamina orientation ‘θ’.

Moghadam et al. [28] investigated the effect of CNT agglomeration on the formation of residual stresses in CE composite using IHDM and CLT. Composites loaded with CNT of 0.1 wt. % and 0.5 wt. % with poor and good dispersion were prepared by manual layup technique. An integral method with the assumption of stresses to be uniform in each incremental cut was used to determine calibration coefficients. The residual stresses determined by IHDM are in good agreement with the theoretical residual stresses calculated across each layer of the laminates.

Amir-Ahmadi et al. [29] investigated the effects of MWCNTs and Mandrel material used for curing on the development of residual stresses in CE composite pipes. IHDM using integral inverse solution was applied to determine ply level residual stresses in composite pipes. Composite pipes were manufactured by filament winding technique with 0 and 3 wt. % MWCNTs using steel and aluminum mandrel. An addition of MWCNTs reduced residual stresses in each lamina of the composite. Further residual stresses developed also depended on the mandrel material used for the composite manufacturing.

Khoshrooz et al. [51] investigated the effect of stacking sequence and end cooling conditions on the variation of residual stresses state in Carbon/Glass/Epoxy hybrid composites. Residual stresses in hybrid composites were determined using HDM and compared with the results from CLT and finite element simulation using ABACUS. A 30 % difference in results of HDM and simulation was observed, the errors were attributed to ideal manufacturing conditions assumed during simulation.

Smit and Reid [52] approximated the initial distribution of residual stresses across each lamina of composite by power series expansion functions of Eigen strain. Least-squares error minimization was applied to determine the compliance coefficients. The method was successfully applied to compute the stress profile within the lamina of different orientations and across the lamina interface. The application of Least-squares made the method insensitive to uncertainty in measurements due to noise, the uncertainties were determined by employing Monte Carlo simulations.

3.1.2. Residual stress measurements by employing HDM using optical methods such as Moiré, Electronic Speckle Pattern Interferometry (ESPI), and DIC.

Yuksel et al. [30] determined the transverse residual stresses in a thick pultruded profile of UD Glass/polyester composite using two methods a) HDM with strain gage b) HDM with DIC. The stresses obtained from HDM with strain rosette are in the range of 7.1 - 8.7 MPa, these stresses are were close with those obtained using DIC with the values in the range of 7-10 MPa. The results revealed that the residual stress should be considered into account for using pultruded parts as load-bearing structural units.

Baldi et al. [31] investigated cure-induced stresses in Graphite/Epoxy laminates by applying hole drilling technique using strain rosette and with in-plane speckle interferometry. Displacement fields were measured with speckle interferometry after each drilling step. The obtained displacement fields were numerically differentiated over the strain gage surface to get strain gage type output strains. As per these studies, the results obtained using strain rosette and in-plane speckle interferometry are in good agreement with each other.

Wu et al. [32] estimated the process-induced stresses in a woven Aramid fiber-reinforced composite using HDM coupled with Moire interferometry. A two-step drilling process was adopted to avoid the delamination across the hole to facilitate the displacement measurement using Moire interferometry. A FEM model based on the actual structure of woven composite was constructed to determine residual stresses. The residual stresses are compressive along with the yarns and tensile perpendicular to them. Shankar et al [33] applied a similar method [32] to determine residual strains in a cross-ply Graphite/Epoxy composite laminate. The results were compared with those computed using CLT. Maximum residual strains obtained by CLT were 3934 με which is 30% higher than those obtained by the experimental method. The differences in results were attributed to material aging, humidity, and theoretical material properties used in CLT for residual strain calculation.

Rief et al. [53] developed an algorithm to take into account various environmental influences on residual stress measurement by employing HDM with 2D DIC. The DIC setup integrated with HDM by a rigid frame was developed to avoid misalignments during the drilling. Experiments for validation of the proposed work are still in progress.

3.1.3. Studies related to effects of experimental parameters on residual stress measurements using HDM

Sicot et al. [19] investigated the influence of experimental parameters namely the incremental depth of cut and the relative position of the strain gauges and the drilled hole on estimated residual stresses in CE composite using HDM. The depth of incremental cut was found to have a significant effect on the stresses determined, the stresses obtained with a single cut per ply were higher than those obtained from two and four incremental cuts per ply. The stresses determined were found to be independent of the geometry of the strain gauges, but are sensitive to the relative position of the hole and strain rosette.

Nobre et al. [23] investigated the effect of drilling parameters applied during IHDM on residual stresses. A numerical model was developed to quantify the effects of hole drilling on the measurement of residual stresses in polymer composite. To calibrate the developed model, Hole drilling was performed using high-speed milling and conventional CNC using the same tool geometry. It is observed that good agreement between the experimental and numerical simulation results after repeatability of the test procedure.

Liu et al. [54] bonded the strain gauge rosette at the top and bottom faces of the specimen and improved the accuracy of the residual stress measurement in IHDM and the calculation algorithms were also changed. CE composite subjected to constant bending was used as a sample to evaluate the accuracy and feasibility of this novel IHDM. Three computational techniques namely, the Tikhonov regularization method, least squares and iteration algorithm were used to obtain the stress distribution profile and the results were compared to the stress profile obtained using FEM.

Babaeeian et al. [55] determined the residual stresses at different times after hole drilling and investigated the effects of time-lapse (Just After drilling, 5 and 30 minutes after drilling) and the hole diameter (2 mm and 4 mm) on the obtained residual stresses by employing HDM with DIC based on the point-wise local least-squares fitting technique. Results showed a significant variation in magnitude and directions of residual stress captured at different times, so the optimal time for capturing the stresses becomes an important parameter to determine the stresses closer to actual values.

4. SLITTING METHOD (CRACK COMPLIANCE METHOD)

The slitting method has emerged as an alternative to HDM for residual stress measurement. The slitting method is also known as the crack compliance method or slotting method. The methodology of strain measurement by slitting method is similar to hole drilling expect the slitting method uses a long slit instead of a hole. HDM can measure a state of residual stresses whereas the slitting method can only measure stresses perpendicular to the machined slit. Vaidya Nathan and Finnie [34] introduced the slitting method in 1971 and its application was delayed due to experimental difficulties until the mid-1980s. Computational advances in later years have facilitated the application of the slitting method to determine the residual stresses. Professor Iain Finnie [35] has been the driving force behind the progress of the slitting method and a detailed review of this method was provided by M. B. Prime [36]. From the literature, it can be found that the slitting method has been applied to both monolithic and orthotropic materials. This method has been applied for the measurement of residual stresses in flat, cylindrical and welded specimens, etc.

4.1. Basic concept of Slitting Method

The fundamental procedure for determining the residual stresses using the slitting method [63-65] can be described with a typical slitting specimen shown in Figure 5. The strain gauges are bonded on the top and bottom face of the specimen as shown in Figure 5. Then a narrow slit is machined nearer to the top gage and exactly opposite to the bottom gage. This method involves the machining of a thin slit starting from the top face of the specimen in incremental cuts along X-direction and the residual strains (Y-direction strains, normal to the slit) relaxed due to machining are measured by strain gages. These measured strains are used to estimate the residual stresses by employing a suitable computational technique.

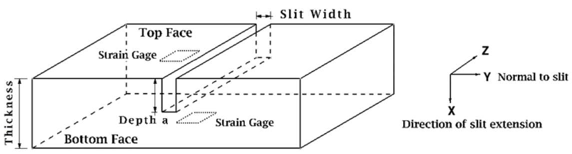

Fig. 5. Typical slitting specimen

A comprehensive review of earlier work in which the slitting method was employed to measure the process-induced residual stresses in polymer composites has been presented in the following section. The literature has been further divided into subgroups as

i. Residual stress measurements by applying slitting method using strain gauges
ii. Residual stress measurements by employing Slitting method using optical methods such as
iii. Moiré, Electronic Speckle Pattern Interferometry (ESPI), and DIC.
iv. Studies related to effects of experimental parameters on residual stress measurements employing the slitting method.

4.1.1. Residual stress measurements by applying slitting method using strain gauges

Ersoy et al. [37] employed crack compliance and layer removal method to determine cure induced residual stresses in Aromatic Polymer Composite laminate ($[0_{10}/90_{10}]_s$) of thickness 5 mm. The entire thickness was divided into three layers and two 0°/90° boundaries were assumed as borders of these three layers. Compliance coefficients were derived by approximating the initial stress in each lamina using linear Legendre polynomials by finite element simulation. Residual stresses obtained by the layer removal method and compliance method are found to be in close agreement with those determined by the numerical method.

Montay et al. [38] studied the reliability of the compliance method coupled with the FEA to estimate residual stresses in CE composite laminate. The strains released while slitting were measured using a strain gauge and also using an optical technique. Compliance matrix coefficients were obtained by assuming initial residual stress as constant using ABACUS software. The residual stresses obtained from slitting at two different locations on laminate were 15 MPa and 17 MPa whereas stresses obtained from FEM were 30 MPa.

Casari et al. [39] applied the sectioning method and classical equations of solid mechanics to estimate the residual stresses within filament wound R-glass, E-glass, and T-700 CE composite pipes. Several cuts are carried out along the length of pipe, each section had strain gauges bonded on both outer and inner surface. The strains measured during sections of pipe were used to estimate residual stresses, then strains in each layer of the pipe are also measured when cut across the thickness of tubes. It was concluded that residual stress induced during the manufacturing process and/or due to environmental conditions are of notable importance and need to be integrated during the design procedure.

Akbari et al. [42] employed the Slitting method to determine the residual hoop stress distribution in CE composite manufactured by filament winding process. The strains were measured at the inner surface while incremental silt was machined from the outer surface of the ring. Tikhonov regularization was employed as a smoothing technique to stabilize the stress results. As Tikhonov regularization is inappropriate to compute solutions with discontinuities, Tikhonov regularization coupled with the pulse method was applied separately for each lamina of the composite ring.

Shokrieh et al. [43] investigated the effects of carbon nano fibers (CNFs) on the residual stress profile of CE composite. The loading of 0.1 wt. %, 0.5 wt. %, and 1 wt. % CNFs resulted in the reduction of residual stresses in CE hybrid nanocomposites by 4.4 %, 18.8 %, and 25.1 % respectively.

Shorkieh et al. [44] investigated the effects of post-cure duration on the development of residual stresses in a CE composite. Laminates were post cured at 120°C for 6 and 12 hours. An increase in post-cure duration resulted in the reduction of maximum residual stress as well as uniformity in the residual stress distribution in a composite.

Shorkieh et al. [45] determined the cure-induced stresses in Cross-ply and quasi-isotropic CE composite using the slitting method and classical lamination theory (CLT). It was concluded that CLT overestimates the residual stresses in both the composite laminates.

Gower et al. [46] investigated the effects of initial stress distribution across lamina on the residual stresses obtained in CE composite by applying the incremental slitting technique. Initial residual stress profiles were assumed to be constant, linear quadratic across the laminate. The results obtained with constant stress approximation were close to those obtained from the layer removal method and FEA.

Kang et al. [47] proposed a new analytical model to determine the cure-induced residual stresses in a GE composite cylinder by considering stresses due to (i) Chemical shrinkage (ii) Mismatch between the coefficient of thermal expansion of composite constituents (iii) Winding tension. Residual stresses in the composite were also determined experimentally using the slitting method. Slitting was carried out using a hacksaw and the corresponding relaxed bending moment is measured which can be used to determine the residual stresses.

The maximum difference in radial stress obtained from the analytical model and experimental data was 0.4 MPa whereas a variation of 2.6 MPa was observed in hoop stress values. It can be concluded that the new model was successfully applied to study the effects of initial tensions in fiber tows on residual stresses.

Ghasemi et al. [48] studied the effects of layup sequence, thermal fatigue and addition of MWCNTs on residual stresses in GE composite by employing the Slitting method.

The thermal fatigue cycles considerably affect residual stress and an increase in the number of thermal cycles decreases residual stresses. Also, the symmetric lay-up arrangement results in lower residual stresses compared to the unsymmetrical ones.

Umarfarooq et al. [56] determined the residual stresses in GE laminates with the aid of the Slitting method. GE laminates were prepared by hand layup method and post cured at 180°C for 3 hours. The cure-induced stresses determined by applying the pulse method varied between 38.18 MPa and -17.23 MPa.

Umarfarooq et al. [57] investigated the impact of process-induced stresses on mode I delamination resistance of CE laminates. The state of residual stresses in CE composites was varied by post-curing the composite laminates using different cure cycles. The slitting method was used to determine the residual stresses induced in CE laminates. The compressive residual stresses were found to have a beneficial impact on the fracture toughness of CE laminates.

Tabatabacian et al. [58] enhanced the mechanical properties of GE composites (4 and 8 layers) by adding MWCNTs (1 wt. %), the parameters for enhancements were residual stress development, delamination damage during hole drilling and weight loss due to thermal cycle fatigue. Residual stresses due to processing were determined by the aid of the Slitting method. The nanoparticles reduced the overall residual stresses and delamination by 30 % and 2.33 % in 8 layers GE composite respectively whereas weight loss decreased by 0.37%.

Shokrieh and Kondori [59] reduced the levels of the residual stresses (11.7%, 14.3% and 16.52%) developed in CE composite laminates by using the Graphene nanofillers in small concentrations (0.1 wt. %, 0.25 wt. % and 0.5 wt. %) during fabrication. The residual stress profile was characterized by the application of the slitting method. The nanoparticles with negative CTE can be used to successfully decrease the magnitudes of stresses in polymer composites.

4.1.2. Residual stress measurements by employing Slitting method using optical methods such as Moiré, Electronic Speckle Pattern Interferometry (ESPI), and DIC.

Sief et al. [40] evaluated residual stresses profile in thin-walled ring of CE and Glass/epoxy (GE) composite by combing slitting method with optical displacement measurement technique. Image processing was used to measure the variations in displacements during the slitting of composite laminates and is used to estimate the locked-up residual stresses (tangential and radial components) in the composites. The variation of radial residual stresses across the thickness behave like a sine wave with zero at the boundaries. The tangential residual stresses have maximum values at the boundaries with compression at the outer diameter and tension at the inner.

Salehi et al. [60] characterized the residual stress profile in cross-ply CE laminates by applying 2D DIC with incremental slitting. The area of interest for stress determination was found by using Eigen strain-based method. The technique utilized the images captured by the optical camera to reduce the effects of the modest deformation sensitivity of the DIC technique on the final results. The results determined from the conventional strain gauge and those obtained with DIC were in close agreement.

4.1.3. Studies related to effects of experimental parameters on residual stress measurements using the slitting method

Shokrieh et al. [41] investigated the effect of various parameters such as order of initial stress approximation, slit width and FEM model (2D or 3D model) applied to obtain the compliance coefficient using simulating of the slitting. These coefficients are pivotal in the estimation of the magnitude and direction of residual stresses. The order of assumed initial residual stress had a significant effect on compliance coefficients, so it is important to choose a proper order of initial stress. The effect of slit width was studied by considering it as a finite dimension and a crack, the slit width had a remarkable effect on coefficients. Hence it is important to use the actual slit width while deriving compliance coefficients. FEM model (2D or 3D model) used for simulating the slitting method do not affect the compliance coefficients. Compliance coefficients are obtained from FEM simulation of slitting technique for isotropic material using 2D model and 3D Model followed the same trend.

Salehi and Shokrieh [61] introduced a new term known as repeated slitting safe distance (RSSD) which defines the minimum distance to be maintained between successive slits to eradicate the effect of an earlier machined slit. RSSD parameters were calculated using the Eigen strain-based method and supplemental stress analysis. The safe distance for experimentation was first confirmed numerically and experimentally verified by employing the slitting method. RSSD obtained for metal and laminated composite was to be 1 and 2.5 times the thickness of the specimen respectively.

Asghari et al. [62] optimized the cure induced stresses in Carbon/CNTs/Epoxy composite cylindrical shells by applying the Taguchi method, three parameters namely the cooling conditions (0°C and 25°C), the radius of the shell (175 and 225 mm) and the mandrel material (Steel and Aluminum) employed were used for optimization. All the three parameters studied individually were found to have a significant effect on the development of residual stresses. Cooling the composite to 25°C was found to induce less stress and the steel mandrel material reduced the tensile and compressive stress magnitudes by 39% and 75%, smaller size shells exhibited higher residual stresses. Among the designs, composites of 225 mm radius manufactured with steel mandrel and cooled to 25 °C exhibited lower residual stresses leading to higher structural strength.

5. RING CORE METHOD

The ring core method is analogous to HDM, in HDM the hole is drilled at the center of the specimen and the deformation around the hole is measured, whereas in the ring core method a circular groove is machined where stresses need to be determined and the deformations at its center are measured. The ring core method is an inside-out version of HDM. The basic methodology of this method is shown in Figure 6. The main feature of the ring core method compared to HDM, is that it relaxes more locked in strain and thus increases the probability of measuring residual stresses closer to actual stresses. But, in this method, the rate of damage inflicted to the specimen is comparatively higher than HDM [64-66].

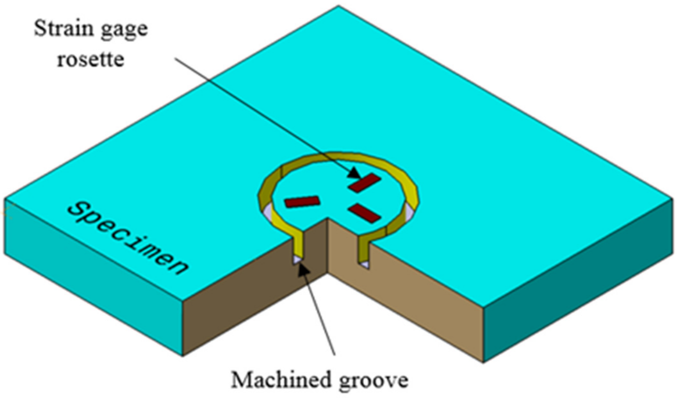

Fig. 6. Schematic of typical ring core method specimen.

Ghaedamini et al. [49] investigated the ability of the incremental ring core method to characterize the non-uniform residual stress distribution across the composite laminate and results were compared with theoretical values. As the machining of the grove relaxes more strains, the results obtained from this method are closer to the actual values.

Ghaedamini et al. [50] employed three relaxation methods namely hole drilling, slitting and ring core method to estimate residual stresses in a Cross-ply GE composite. The relaxed strains measured from all methods demonstrated an increasing trend with an incremental depth of cut. The ring core method due to its methodology is less sensitive to error due to the relative position of the rosette and the tool. The ring core method provides more reliable and stable responses over composite thickness in comparison with other conventional hole-drilling and slitting methods. However the damage to the sample is higher compared to other methods, but this method releases more strains and thus the obtained residual stresses close to actual stresses.

6. COMPARISON OF RELAXATION TECHNIQUES

The comparison of the relaxation techniques in terms of accuracy of measurement and the common sources of error are provided in Table 1.

7. CONCLUSIONS

This paper reviewed the recent works carried out on the measurement of residual stress in polymer composites by employing relaxation techniques namely Hole drilling, Slitting and Ring core method. All three methods can be applied easily to a wide range of materials and geometries with simple experimental setups by using strain gauges with precise machining. These methods have shown the ability of accurate residual stress measurement across the entire thickness of the composite laminate which has been validated with analytical techniques. However the three methods have similar drawbacks: introduction of additional stresses during machining, the relaxed strains are largely dependent on machining parameters (spindle speed, feed and depth of cut), the residual stresses estimated depend on the computational technique employed and the assumed initial residual stress profile. The ring core method releases more strains compared to the other two methods and residual stresses estimated by employing this method are much closer to the actual stress values. The ring core method is also more accurate, stable and reliable compared to the slitting method but inflicts considerable damage on specimen compared to the other two relaxation techniques.

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9. CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

Table 1. Comparison of relaxation techniques

Relaxation technique	Introduction	Common sources of errors during stress determination
Hole Drilling Method	HDM is the most widely used semi-destructive method for residual stress measurement. Incremental HDM has been widely employed for the characterization of non-uniform residual stresses in composite laminates. From the literature A maximum error of 32 % in stress values is observed compared to analytically calculated values in different composite laminates. [25] From the results, higher differences in experimental and analytical values were observed in the plies across the 0/90 boundaries, whereas, a good agreement of results was found for lamina that are not nearer to the boundary. [18]	The causes of error in HDM results may be due to: (i) Addition stresses introduced during drilling of the hole. (ii) The eccentricity between the rosette and the drilled hole highly influences the measured strains. (iii) The influence of temperature variations on strain gauges due to hole drilling. (iv) The effect of radius fillet at the bottom of the hole. (v) Application of a numerical model which takes into account the above errors for analytical calculations. (vi) The effect of finite element model parameters while deriving compliance coefficient matrix.
Slitting Method	Slitting in incremental cuts has been widely used to determine the non-uniform residual stress profile across the entire thickness of composite laminates. From the earlier works A maximum difference of 22 MPa is observed between the experimental and CLT values [45] Residual stresses determined in Glass/epoxy composite by Slitting and Ring core method were in very close agreement with each other.[50]	The sources of the error for the deviation of experimental values from analytical values may be (i) The influence of temperature variation while slitting on strain measurements. (ii) The effect of finite element model parameters while deriving compliance coefficient matrix.
Ring Core Method	The ring core method is analogous to HDM, in HDM the hole is drilled at the center of the specimen and the deformations around the hole are measured, whereas in the ring core method, a circular groove is machined and the deformations at its center are measured. From the earlier works on laminated composites A maximum error of 15 % between the experimental and analytical values was observed. [49] The results of calculating residual stresses showed that the ring core can release 17% more stress compared to the hole-drilling method. [50]	The sources of error during residual stress measurement by the ring core method are (i) Additional stresses introduced while machining of the groove. (ii) The eccentricity between the rosette and the machined ring influences the measured strains. (iii) The influence of temperature variations on strain gauges due to machining of the groove. (iv) The effect of radius fillet at the bottom of ring (v) Application of a numerical model which takes into account the above errors for analytical calculations. (vi) The effect of finite element model parameters while deriving compliance coefficient matrix.

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