Prestressed Fibre-Reinforced Polymer Matrix Composites

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Composite materials are developed by combining materials offering unique properties that cannot be achieved individually by the constituent materials. To produce a fibre-reinforced polymer composite, fibres of various configurations and stiffness are embedded into a polymer matrix of lower stiffness. While the fibre is responsible for carrying the load and offering much needed strength and stiffness, the polymer matrix is responsible for the mobility of the load to other parts of the fibre by providing the required binding forces. The matrices also prevent the reinforced fibres from absorbing moisture, propagating micro-cracking due to microbial and chemical attacks.

polymer composite fibre-prestressing residual stresses

1. Introduction

Composite materials are developed by combining materials offering unique properties that cannot be achieved individually by the constituent materials. Because of their excellent strength to weight ratio, they have increasingly been used as engineering materials for many applications, that include automotive and aerospace parts, construction materials, electrical parts and other consumer products [1]. The growth of composite materials for extended use, particularly in the aerospace and automobile industries, has necessitated continuous research for developing improved composites with excellent mechanical properties [2]. The constituents of composites are classified into matrix and reinforcement. While the matrix can be made of polymers, metals or ceramics, reinforcement includes fibres, whiskers and particulate fillers that exist in natural (lignocellulose, animal fibres and minerals) or synthetic form (carbon, aramid, boron, nylon, polyethylene) [3].

To produce a fibre-reinforced polymer composite, fibres of various configurations and stiffness are embedded into a polymer matrix of lower stiffness. While the fibre is responsible for carrying the load and offering much needed strength and stiffness, the polymer matrix is responsible for the mobility of the load to other parts of the fibre by providing the required binding forces [3]. The matrices also prevent the reinforced fibres from absorbing moisture, propagating micro-cracking due to microbial and chemical attacks. Polymer matrices can be either thermoplastic or thermoset. Thermoplastic polymers undergo a physical change when heated and can be softened and reformed. Some thermoplastics commonly used in composites include polyetheretherketone (PEEK), polyetherketoneketone (PEKK), polyphenylene sulphide, polyethylenimine (PEI) and polycarbonates (PC) [4]. On the other hand, thermoset polymers undergo a chemical change in the presence of a crosslinking agent (hardener) to form a three-dimensional structure. Thermosets include epoxies, phenolics, polyimides, polyester, vinyl ester, bismaleimide, melamine and silicone [4]. Thermoplastic composites offer great potential due to less processing time. However, significant drawbacks, which include a high processing temperature (the polymers must be heated to melting point to incorporate the fibre), a high tendency for the buckling of fibres in the polymer matrices, and solvent and fluid resistance features, have reduced their adoption as a substitute for thermoset in fibre-reinforced polymer composites [5].

Both tensile and compressive stresses are generated in polymer composite structures during the manufacturing process, and their occurrence in a composite can result from differences in physical and mechanical properties, a contraction of the polymer matrices before curing, manufacturing techniques and moisture absorption from the environment [6]. However, while compressive stresses have positive influences on the mechanical properties of the composite material, the tensile stresses have a detrimental effect on the manufactured polymer composite by causing distortion, dimensional instability and matrix cracking [7]. Fibre-prestressing offers a low-cost means of reducing the influence of tensile residual stresses, thereby improving the mechanical properties without increasing the mass or dimension of the composite [8]. It is important to know that fibre-prestressing can only reduce residual stress in polymer composites if applied to a certain level [9].

2. Source of Residual Stresses in a Composite

In the absence of external forces, residual stresses are forms of stress that bring about the deformation of a composite material [7]. There are two primary sources of residual stresses in a composite material; (i) residual stresses generated due to differences in deformation-related properties of the materials, and (ii) production processes that induce residual stresses [9]. Moisture absorption, the chemical shrinkage of the matrix and a variation in the coefficient of thermal expansion induce residual stresses in polymer composites. Researchers have also shown that residual stresses can initiate failure in a composite material due to matrix cracking [10]. The influence of matrix cracking can lead to a dangerous failure, especially when the material is under loading conditions. Both compressive and tensile residual stresses are generated in composite materials. However, while compressive residual stresses help prevent cracks from spreading throughout the matrices, tensile residual stresses assist in the opening of micro-cracks in the polymer matrix [11]. Other defects such as fibre waviness, delamination, warping and dimensional imbalance are also due to residual stresses [12].

Many techniques have reportedly been used to reduce the effect of residual stresses in polymer composites. Process optimisation of cure cycle parameters such as dwell time, dwell temperature, dwell cycle and cooling rate can minimise residual stress during production [13][14][15]. Shape memory alloys (SMAs) also reduce stress concentration in FRP matrices. SMAs are novel metallic materials that can undergo reversible solid to solid change in a phase when subjected to thermal or mechanical loading that can cause sizeable inelastic strain [16]. They are generally available in the form of a wire with a diameter below 200 µm [17] and can be embedded in various configurations, as shown in **Figure 1**. SMAs offer other vital properties such as impact damage control, crack closure and shape morphing. Nevertheless, SMAs induce fibre misalignment and can create an uneven stress distribution in a composite [17].

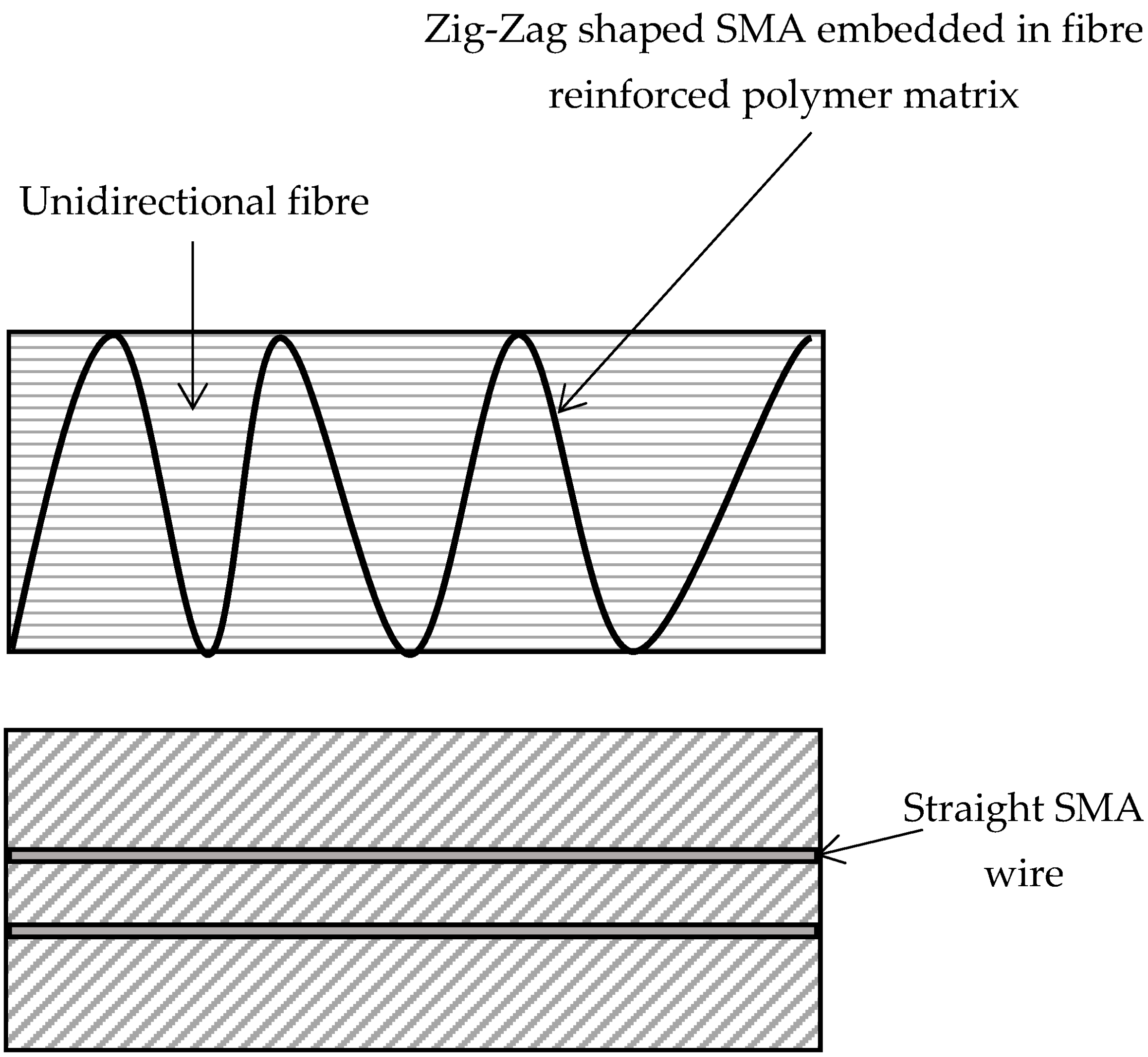

Figure 1. Integration of SMA into a Fibre-Reinforced Polymer Composite.

Similarly, the electron beam curing technique composite can also reduce stress concentration [18]. The technique involves generating free radicals from a high-energy electron accelerator that propagates the polymerisation and crosslinking reaction at room temperature. Since the curing temperature is kept below the traditional thermal curing process temperature, the residual stress generated using an electron beam will be lowered [19]. Moreover, high processing electron beam curing results in an increased production rate and low shrinkage compared to that of conventional thermally cured composites [20]. To utilise the electron beam curing process, cationic initiators are required. Hence, the initiators—that are primarily Lewis or Bronsted acids—react when exposed to high energy electron irradiation. However, a high initiator concentration can lead to a thermal degradation of the polymer matrix, while excess irradiation can damage the fibre strength [21].

Despite their positive influences, electron beam cured composites cannot replicate some of the characteristics of thermally cured composites (high fracture toughness and inter-laminar shear strength) [20]. Similarly, expanding monomers have reportedly been used as anti-shrinkage in composite materials [22]. The polymerisation reaction of the polymer matrices results in a volumetric shrinkage of the matrices during the curing stage. The addition of the expanding polymer gives rise to volumetric expansion, thereby reducing volumetric shrinkage and residual stress [23][24]. The expanding monomers can also reduce the modulus and initiate the transverse cracking of composite materials [9]. Compared to the techniques mentioned above concerning the cost and simplicity, fibre-prestressing is relatively more acceptable.

3. Fibre-Prestressing Technique

There has been growing interest in improving the mechanical performance of FRP composites by minimising the induced stress without increasing the mass or dimension of the composite [8]. Since improving the composite performance increases the production cost, improving the production technique of composites through fibre-prestressing is a possible way of mitigating the cost [9]. Fibre-prestressing has been discovered by researchers as a productive method of reducing the effect of residual stresses in composite materials during production [25][26][27].

Fibre-prestressing can be achieved elastically or viscoelastically. The elastically prestressed polymer matrix composite (EPPMC) is achieved by subjecting the fibre material to the applied load and maintaining the load throughout the curing cycle of the polymer composite [28][29]. The load is released after the cooling and solidification of the composite at ambient temperature. Subsequently, the prestressed fibres tend to return to their initial length, generating compressive stresses in the matrix. These compressive stresses reduce the detrimental effect of the tensile residual stresses induced during the curing process [29]. In addition, the viscoelastically prestressed polymer matrix composite (VPPMC) is formed by subjecting polymeric fibres to a tension load, which introduces creep stress, and then removing the load before moulding the fibre to the polymer matrix. After the curing stage, prestressed fibres tend to return to their initial length, thereby creating compressive stresses that counterbalance the effect of induced tensile residual stresses [28].

3.1. Elastically Prestressed Polymer Matrix Composite (EPPMC)

The fibres are prestressed by subjecting them to a force lower than the elastic limit of the fibre and maintaining this force throughout the curing cycle of the composite. After curing, the force is removed, and the fibres tend to return to their original states. Compressive stresses are developed within the solidified matrix due to the bonding of the prestressed fibre with the polymer matrix [30].

3.2. Viscoelastically Prestressed Polymer Matrix Composite (VPPMC)

The technique involves using polymeric fibres to generate compressive stress in a composite material through the viscoelastic recovery process [31][32]. The fibres are prestressed by applying a load over a while to induce creep. After removal of the load, the fibres undergo a time-dependent elastic recovery. When the prestressed fibres are embedded in the polymer matrix and subjected to curing, the elastic recovery with the surrounding polymer matrix continues, thereby imparting compressive stresses that counterbalance the tensile residual stresses generated in the composite matrix [20]. Because the fibre stretching and moulding operations can be carried out independently, the technique offers flexibility in the geometry of the manufactured composite [33]. Based on previous studies, VPPMC can be classified into cellulose-fibre-based VPPMC (CFVPPMC) and synthetic polymeric fibre-based VPPMC (SPFVPPMC). CFVPPMC contain prestressed cellulose fibres predominantly from natural plants such as kenaf, sisal, flax, bamboo, jute, wheat straw, ramie and eucalyptus. Natural fibres are biodegradable and cheap and have a low density. **Table 1** show physicomechnical properties of some natural and synthetic fibres commonly used in PMC.

Table 1. Physicomechanical properties of some commonly used fibres.

	Fibre	Density (kg/m^3)	Tensile Strength (MPa)	Elongation at Break (%)	Young Modulus (GPa)	References
Natural fibres	Kenaf	1200	295–930	2.7–6.9	53	[34][35]
	Sisal	1200	507–885	1.9–3	9.4–22	[34][35]
	Flax	1380	343–1035	1.2–3	27.6	[34][35]
	Bamboo	800–1400	391–1000	2	11–30	[34][35]
	Banana	1350	529–914	3–10	8–32	[34][35]
	Wheat straw	1600	273	2.7	4.76–6.58	[34][35]
	Hemp	1350	580–1110	1.6–4.5	70	[34][35]
	Jute	1230	187–773	1.5–3.1	13–26.5	[34][35]
	Ramie	1440	400–938	2–4	61.4–128	[34][35]
	Rice straw	1650	449	2.2	1.21–1.25	[34][35]

	Fibre	Density (kg/m^3)	Tensile Strength (MPa)	Elongation at Break (%)	Young Modulus (GPa)	References
Synthetic fibres	E-glass	2500	2000–3000	2.5	70	[36]
	Carbon	1800	4000	1.3	300	[37]
	Kevlar	1400	3600	2.7	130	[37]
	Nylon	1100	950	18	5	[37]

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3.3. Mechanical Properties of Prestressed PMC

Compared to other enhancing techniques, both of the two prestressing methods have shown their significance in improving the mechanical performance of composite material without increasing the mass or section dimension. **Table 2** provides up-to-date findings and results of previous studies on fibre-prestressing techniques.

Table 2. Reviews on fibre-prestressed PMC.

Material	Prestress Technique	Research Area	Results of Findings	References
Glass fibre woven into a fabric Phenol-based formaldehyde resin	Elastically prestressing of the glass fibre using tensioning rod (EPPMC).	Assessment of the compressive and tension characteristics of the composite.	Enhancement of elastic properties up to 31% was recorded due to the straightening of the warp fibres.	[38]
Unidirectional graphite/epoxy prepreg tape	Prepreg tape was subjected to tension by bending over a steel roller (EPPMC).	Tensile and elastic modulus measurement	Up to 17% increase in tensile strength Composite elastic modulus was not affected	[39]
Unidirectional carbon fibre/epoxy composite	The load was applied to fibre	Thermal stress analysis of the	Fibre-prestresses lessen the residual stresses in	[40]

Material	Prestress Technique	Research Area	Results of Findings	References
with 60% fibre volume fraction	before curing but the nature of assembly was not reported (EPPMC).	composite.	the matrix.	
Unidirectional E-glass fibre/polyester resin with 56% fibre volume fraction	Deadweight (EPPMC)	Tensile properties evaluation	The tensile strength increases with an increase in the level of prestressing (60–80 MPa applied load). The maximum percentage increase in tensile strength and modulus obtained were 15% and 18%, respectively.	[41]
Carbon fibre/epoxy resin cross-ply laminate with 70% fibre volume fraction	Filament winding (EPPMC)	Modelling and experimental study of composite failure	Failure strength of the ply increased by increasing the prestress level up to 690 MPa	[42]
Graphite fibre/epoxy resin, unsymmetric cross-ply laminate with 56% fibre volume fraction	Hydraulic cylinder (EPPMC)	Examination of the tensile strength, curvature and transverse cracking	Fibre-prestressing reduced warping, curvature and transverse crack. Up to 28% increase ultimate strength	[31]
Unidirectional Nylon 6.6 fibre/polyester resin (up 3% fibre volume fraction)	Bespoke vertical stretching rig (VPPMC)	Analysis of the impact energy	Viscoelastically induced compressive stresses.	[43]

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Material	Prestress Technique	Research Area	Results of Findings	References
			Absorption of higher impact energy (25%) by the prestressed sample	
E-glass fibre/epoxy resin cross-ply laminate (56% fibre volume fraction)	Biaxial loading frame (EPPMC)	Effect of low-velocity impact performance	25% increase in impact performance at low velocity due to prestressing	[44]
E-glass fibre/epoxy resin cross ply laminate (56% fibre volume fraction)	Biaxial loading frame (EPPMC)	Effect of high- and low-velocity impact performance	Improvement of impact performance at a low-level velocity	[45]
Unidirectional E-glass fibre/epoxy cross-ply laminates (58.2% fibre volume fraction)	Flatbed (EPPMC)	Tensile, fatigue life and compressive strength measurement	Improved fibre alignment, increase in resistance to onset damage due to induced compressive strength. 9% increase in tensile modulus and compressive strength at prestressing levels of 51 MPa and 80 MPa, respectively.	[46]
Unidirectional Nylon 6.6 fibre/epoxy resin (16, 28, 41) and 53% fibre volume fraction	Bespoke vertical stretching rig	Tensile strength and modulus measurement	30% and 15% tensile modulus and tensile strength, respectively.	[47]
Carbon and glass fibre/Hexcel cross-ply	Flatbed (EPPMC)	Experimental and finite element	Induction of bistable behaviour through	[48]

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Material	Prestress Technique	Research Area	Results of Findings	References
laminates		analysis of bistable prestressed buckled laminate	prestressing.	
Unidirectional Nylon 6.6 fibre/polyester resin (8, 12, 16% fibre volume fraction)	Bespoke vertical stretching rig (VPPMC)	Flexural properties measurement	Up to 50% increase in flexural modulus.	[49]
Unidirectional S-glass fibre/composite resins (Quixfil and Adoro) (12% fibre volume fraction)	Deadweight (EPPMC)	Flexural properties measurement	Increase in flexural strength.	[50]
Unidirectional UHMWPE fibre/polyester resin (3.6% fibre volume fraction)	Bespoke vertical stretching rig (VPPMC)	Impact properties measurement	Prestressing increases impact energy absorption (up to 40% increase in some batches).	[30]
Carbon fibre/epoxy resin (50% fibre volume fraction)	Deadweight (EPPMC)	Impact properties	Increase in strength of composite material.	[51]
Hybrid unidirectional Nylon 6.6 and Kevlar fibres/polyester	Bespoke vertical stretching rig (for Nylon alone) (VPPMC)	Impact and flexural test	33 and 40% rise in absorption energy and flexural modulus.	[30]
Unidirectional Nylon 6.6 fibre/polymer resin	Bespoke vertical stretching rig (VPPMC)	Impact assessment	Impact energy absorbed increased (40%).	[52]

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Material	Prestress Technique	Research Area	Results of Findings	References
(fibre volume fraction 2.2%)				
Flax yarn/polyester resin	Tension frame (EPPMC)	Tensile and flexural assessment	Fibre alignment enhancement. Increased tensile strength and modulus. Increase in flexural strength and modulus.	[26]
Plain weave E-glass fabric/polyester resin (16% fibre weight fraction)	Hydraulic cylinder biaxial loading frame (EPPMC)	Flexural characteristics	Up to 16% increase in flexural strength at 50 MPa optimum prestressing level	[53]
Plain weave E-glass fabric/polyester resin (11% fibre weight fraction)	Hydraulic cylinder biaxial loading frame (EPPMC)	Tensile and fatigue characteristics	Fatigue life increased up to 43% Fatigue life improvement when under low and intermediate stress fatigue load	[54]
Unidirectional E-glass fibre mats/epoxy resin	[56][57] Horizontal testing machine (EPPMC) [58]	Flexural, tensile and compression properties [59]	Reduction in fibre waviness Increase in flexural, tensile and compressive strength	[8]
Nylon 6.6 yarn/polyester cross-ply composite	Bespoke stretching rig (VPPMC)	Impact behaviour	Up to 29% reduction in damage depth	[28]

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… prediction … aterials is … negligible; … than the … fibres to … measure … ill reduce … tresses in … the entire production process or through the observation and measurement of the phenomena resulting in residual stress generation in a material. The latter method can be achieved through destructive and non-destructive testing. **Table 3** highlights the differences between destructive and non-destructive testing techniques. The methods that are

Material	Prestress Technique	Research Area	Results of Findings	References
Unidirectional E-glass fibre/epoxy resin (10% fibre volume fraction)	Deadweight method (EPPMC)	Tensile properties	Increase in maximum strength, percentage elongation and rupture strength by 38.5%,	[55]

Destructive Testing (DT)	Non-Destructive Testing (NDT)
Part of the materials is removed or damaged.	Testing can be done without removing or damaging the material.
Testing cannot be repeated on the same specimen.	Testing can be repeated on the same specimen.
Residual stress measurement is limited to a small area of the material sample.	Residual stresses can be measured within a large surface (e.g., laminate).
Global residual stresses distribution along the plies in a composite can be measured.	They cannot estimate global residual stress distributions along with composite plies.

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It is a common phenomenon to employ ultrasound waves in the detection of faults in engineering materials [60], but they may also be used to quantify applied and residual loads [61]. To effectively assess stress levels in a material, it is necessary to precisely measure the time-of-flight change of an ultrasonic wave travelling between the stressed and unstressed states of the material. To obtain an absolute measurement of stress, the time-of-flight measurement in the stressed material is compared to that in the unstressed material. The method has the advantage of measuring high-magnitude residual stresses. The measuring procedure is fast and tri-axial residual stresses can be measured [61].

Table 4. Common destructive and non-destructive test methods used for the calculation of residual stresses in composites.

Methods	Principle	Material	Shortcomings	References
Layer Removal (DT)	It monitors the elastic response of a laminate to the release of residual stresses	Ceramics Metals	Additional stresses can be imparted to the test sample due to the machining of	[62][63]

Methods	Principle	Material	Shortcomings	References
		Polymers Composites	the composite surfaces. Limited to macro-scale residual stresses	
Hole drilling (SDT)	Drilling of a hole into the stressed object releases the stresses, leading to changes in the surrounding strain field that may be measured and related to the relaxed stresses.	Ceramics Metals Polymers Composites	It requires several assumptions to simplify the result solution. Accurate measurement around the hole, especially in the fibre direction, is very challenging. Limited to macro-scale residual stress measurement	[64][65][66]
Ring-Core Method (SDT)	It follows a principle comparable to the hole-drilling method. However, instead of discharging residual stresses by drilling a hole and measuring the elastic reaction of the surrounding material, the ring-core method discharges stress by cutting an annular groove into the surface of a component that contains residual stress.	Metals Ceramics Polymers	Limited to homogenous and isotropic material.	[67]
Contour Method (DT)	The material is sliced through by a planar surface, releasing residual stresses across the plane. As a result, the surface experiences out-of-plane deformation,	Ceramics Metals	Difficulty in measuring residual stresses close to the	[68]

Methods	Principle	Material	Shortcomings	References
	which is recorded, and the underlying residual stresses across the cut are calculated using the finite element technique.	Plastics Composites	surface of the material. Not suited for small components.	
Slitting Method (DT)	A tiny slit is cut into a prestressed sample, and the resultant deformation parallel to the slot's direction induced by the restoration of force equilibrium is determined. The repetition of this procedure at increasing depths allows for the determination of residual stress across the component's thickness.	Ceramics Metals Plastics Composites	Macro-scale residual stresses cannot be fully measured. Only average stress along the transverse direction (*y*-axis) can be measured.	[69]
Neutron Diffraction Method (NDT)	Raman spectroscopy employs light scattering to measure the vibrational energy of crystalline chemical bonds. The dispersed light is detected, and typical Raman peaks may be detected. Any externally imposed strain alters the position of these peaks. Consequently, a stressed and unstressed sample's Raman peak position variations may be used to calculate the applied strain.	Metal Ceramics Composites	Resolution is limited, and residual stress changes smaller than 1 mm cannot be measured. Not suitable for amorphous materials	[70]
Raman Spectroscopy Method (NDT)	Stresses are determined by monitoring the frequency of certain luminescence peaks in comparison to those in an unstressed state.	Ceramics Polymers Composites	Limited to macro-scale residual stresses measurement.	[71]
X-ray Diffraction Method (NDT)	When residual stress is determined using X-ray diffraction (XRD), the strain in the crystal lattice is determined and the	Metal Ceramics	Applicable to polycrystalline materials only.	[72]

Methods	Principle	Material	Shortcomings	References
(destructive if used for measuring depth)	related residual stress is calculated using the elastic constants, assuming that the relevant crystal lattice plane exhibits linear elastic deformation.	Composites	The accuracy of this method is affected by the texture and grain size. Measurement is limited to the surface of the material	
Synchrotron X-ray Method (NDT)	Similar to the X-ray diffraction method. However, X-rays are far more intense and have a much greater energy, and their tremendous energy allows them to penetrate much farther into materials.	Metal Ceramics Composites	Applicable to polycrystalline materials only	[73]
Ultrasonic Method (NDT)	The material is subjected to an ultrasonic [75] (acoustic) wave, which is then detected by reflection, transmission or scattering. To determine the magnitude of stresses, the velocity of an ultrasonic wave in some modes is evaluated.	Metals Ceramics Composites	Not suitable for amorphous materials. Limited to macro-scale residual stress [76] measurement. [32]	[74]

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Crashworthiness is an automobile's capacity to protect its occupants from severe injury or death in the event of a given number of collisions. It is a quantitative assessment of a structure's ability to protect its passengers in survivable crashes [77]. It is an essential factor that needs to be considered in selecting the material for vehicular structural assembly [78]. Material crashworthiness is characterised in terms of its energy absorption capacity (EAC). Generally, polymer composites have a high EAC compared to metals, and they can release deformation absorption energy during impact [79]. Prestressed fibres enhance the energy absorption capability of composite materials [52]. Moreover, the application of EPPMC and VPPMC technology in fibre-reinforced concrete development can enhance the resistance to crack propagation in a concrete structure. Bistable composite materials, which are often utilised in the aerodynamic control of aircraft and wind turbine blades, have drawn growing attention in recent years. They can be effectively manufactured utilising prestressed fibre technology [33]. The emerging developments will be toward alternate fibre materials, hybridisation, process optimisation and the use of a cost-effective fibre-prestressing technique.