

Fibre prestressed polymer-matrix composites: a review

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Abstract

This article reviews the literature studies based on improving the mechanical properties of fibre-reinforced composites using fibre-prestressing method. The idea is characterized by pretensioning the fibres either elastically or viscoelastically prior matrix curing. The beginnings of the studies in this field were focused on reducing fibre waviness and breaking the weaker fibres by pretensioning the fibres to a relatively high stress level prior moulding process. In the last three decades, the concept of fibre prestressing had been developed to include its ability to reduce the effect of undesired residual stresses existence accompanying manufacturing process of fibre-reinforced composites. The main advantage of fibre prestressing method is to generate a desired and controlled residual stress state within the matrix in order to obstruct the initiation and propagation of cracks. Various techniques of fibre prestressing have been reviewed to show their scope of applications, developments and limitations. Therefore, the findings drawn from this review can be used for further studies in the field of fibre prestressed composites in order to select the most suitable methodology and develop it to fit the manufacturing process requirements towards a production of high-performance composites without a considerable additional cost.

Keywords

Fibre pretension, polymeric matrix composites, prestressing method, microcracks, residual stresses

Introduction

Nowadays, using of composite materials in aerospace, automotive and marine industries is increasing day by day, leading to increase in the demand for developing the manufacturing techniques, which can improve the mechanical performance of such advanced materials.^{1–3} Although currently available composites have superior mechanical properties compared with conventional metallic materials, the improvements are still on-going. In fact, the cost of producing more reliable composite component needs either additive materials and/or improved fabrication techniques. It is generally believed that when manufacturing of the composite materials, residual stresses are generated within the structure.^{4–6} These residual stresses can be developed in composite materials due to several reasons such as chemical shrinkage of polymer matrix, different thermomechanical properties of the constitutions and humidity absorption.^{6–12} Residual stresses results from chemical shrinkage occurred during the polymerization process of the resin where the resin has changed its phase from liquid to

solid state.^{4,6} The mismatch in coefficient of thermal expansion between the fibre and the matrix could produce residual stresses in composite when it cooled from its curing temperature.^{4,6,7,13–16} Whereas, moisture absorption by the polymeric matrix and fibre leads the composite constituents to deform and expand at different levels depending on the swelling permeability.¹⁷ Manufacturing process such as the filament winding fabrication technique can add another source of induced

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residual in the final composite product due to tensioning the fibre during the fabrication processes.^{18–23} The residual stresses produced by resin chemical shrinkage and the mismatch in thermal expansion between fibre and matrix materials have a negative effect on the final mechanical performance of composites because they accompanied with a generation of tensile residual stress within the matrix of the composite. Fibre pretension (prestressing) method could be one of the best available options for enhancing the properties of polymeric matrix composites (PMCs) without increasing section dimensions, mass and can be performed without a considerable additional cost to the final composite products.

Fibre pretension during matrix curing has generally a positive effect on the composite mechanical performance as it generates a compressive residual stresses within the matrix (the weaker phase). It is important to mention that fibre pretension has this beneficiary effect only if it is applied to limited level or range.^{6,7,14,24} In particular, the existence of tensile residual stresses in the composites could reduce the resistance to matrix microcracking. The presence of residual stresses and waviness of fibre might have a detrimental effect on the mechanical properties of composite structures and this could decrease the service life of a composite structures.^{5,7} Therefore, it is of most importance to minimize the magnitude of unfavourable residual stresses and waviness of fibre.

Obviously, the cost of composites is shared between materials and its fabrication, for instance the cost of glass fibre-reinforced polymer is approximately 60% of materials and 40% of fabrication.²⁵ Therefore, the focus on improving the fabrication techniques is still reasonable if they can enhance the mechanical performance of composites.²⁶ Improvement in the mechanical properties of composite materials would be of great benefit for the many pending requirements of future applications.^{27,28} Therefore, the effort of improving the mechanical properties of composites is still ongoing by means of either developing the materials used to fabricate the composites or by improving the associated manufacturing techniques.

This paper reviews the most studies that focused on elastically and viscoelastically fibre prestressed composites. The main mechanisms attributed to the improving of composite performance by the fibre pretension method were explained in detail. The various methodologies used to perform the fibre prestressing method were also listed. Moreover, the reported methodologies and type of prestressing methods were compared and assessed.

Matrix microcracking damage in composite materials

In general, the strength of a composite material is commonly defined in terms of how much load it can sustain

before complete failure takes place. The stress at which the matrix shows catastrophic failure and the fibre undergoes breakage is known as the ultimate strength. However, before this ultimate strength is attained, the composite reaches a stress level where the matrix has begun to initiate microcracks spreading throughout the matrix. At this stage, the composite has not completely failed yet, but the breakdown process has started. Good studies in the field of deformation prediction and failure strength of fibre reinforced composite structures under different types of loadings can be found in exercise book by Hinton et al.²⁹ Moreover, toughness and adhesive properties of the resin type affect the strain that can cause microcracking.³⁰ For brittle resins, particularly polyester, this point takes place in early stage before the failure of a whole composite.

On the other hand, in an environment where the composite is exposed to water or humid air, the microcracked composite structure will absorb much more water than an uncracked one. First, this will lead to an increase in the composite weight. Second, moisture will attack fibre, resin and fibre-matrix interface leading to a degradation in the mechanical properties with time.³¹ Although matrix microcracking does not cause structural failure by itself, it can lead to a significant decline in material stiffness and can also encourage more severe forms of damage such as fiber breakage, delamination and give paths for entry of fluids.³² Therefore, minimizing and/or delaying the initiation and propagation of these cracks will be the destination goal for designing a good composite structure.

Residual stresses in composite materials

Residual stresses can be defined as those stresses that remain in a solid structure after the original cause of the stresses has been removed.⁴ The main sources to develop the residual stresses in composites are the properties of constituent materials that are related to the deformation behaviour and the processing that the part undergoes.³³ Many reasons can arise for the residual stresses in composites, such as the mismatch between the thermal expansion coefficients, yield stresses, rigidities or phase changes of different constituents.⁴

In the processing of fibre-reinforced composite, the fabrication is usually accompanied with resin heating.³⁴ Therefore, the curing stage is mostly performed at elevated temperatures. The need for elevated temperatures in the curing stage results in generation of residual stresses in the final composite product.³⁵ These residual stresses are developed due to the change in volume induced by the mismatch in thermal expansion of the constituents, and chemical shrinkage of polymer due to polymerization reaction.⁶ The measurement and

representation of these stresses are complex.³⁶ Other resources of residual stresses in composites include moisture, ageing, elevated post-cure temperature, differences in fibre volume across the matrix and non-uniform degree of cure.^{4,5} In general, residual stresses that developed within the fibre-reinforced composites could be divided into longitudinal (parallel) and radial (orthogonal) to fibre longitudinal axis. The longitudinal residual stress has a detrimental effect while the radial residual stress has a beneficial effect on the composite performance.^{13,37}

Effects of residual stresses on composite performance

Composite materials failures are mainly associated with tensile residual stresses.^{4,8} When the residual stresses in the material are compressive, it definitely helps to obstruct the cracks to propagate throughout the matrix easily. So that, to get a fracture by crack propagation of the initially existed crack, the external tensile stress should overcome the compressive residual stress at the crack tip. The residual stresses in fibre-reinforced polymer composites extremely influences fibre-matrix debonding and pullout.^{38–40} Residual stress in composite material has also been proven to impact some other characteristics, such as matrix cracking,⁴¹ yield strength^{42–44} and dimensional instability.^{45–48} The presence of compressive residual stress close to the surface has been proven to lengthen fatigue life and prevent stress corrosion cracking.³³ Fibre waviness, cracking, delamination, warpage and dimensional instability are some defect examples caused by residual stresses.⁴⁹

During the manufacturing of a composite lamina, fibres will be subject to compressive axial loads due to thermal residual stresses. Since the matrix cannot afford any transverse support, the fibres will deform in a micro-scale (buckling), leading to what is called waviness.⁷ The existence of fibre waviness in a composite material can reduce the strength of the structure.⁵ Figure 1 shows fibre waviness in composites.

However, if the thermal residual stresses are greater than the yield strength of the resin, cracks in composite materials will form. Cracks can grow into the matrix when the fibre-matrix interface bond is strong. However, when the interface is weak, the cracks will spread along the interface as shown in Figure 2.^{5,50}

Many researchers have used several techniques to decrease the formation of residual stresses that generated during the cure process. The optimization of dwell temperature, dwell time, number of dwells and cool-down rate during the cure cycle can minimize the generation of residual stresses during the fabrication process.^{35,52–54} Another technique is by using the electron beam curing instead of the traditional thermally curing.^{55,56}

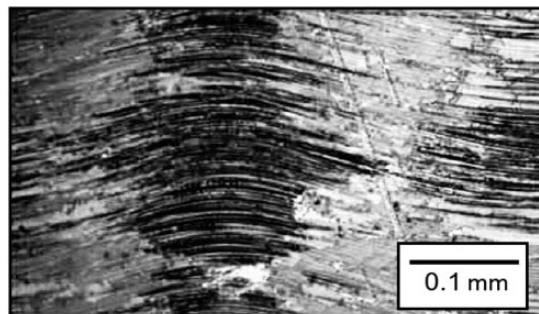


Figure 1. Micrograph of a composite laminate showing fibre waviness.⁵

The benefit drawn from this method was signified by its ability to cure the resin speedily at an ambient temperature.⁵⁷ Moreover, some studies have addressed the use of expanding monomers to reduce the glass transition temperature of the resin, thereby reducing the residual stresses induced by the cool-down cycle shrinkage from glass transition temperature to ambient temperature.^{58–60} However, this method has a disadvantage represented by increasing the transverse crack growth rate because of increasing matrix brittleness.⁶¹ Another method, but to a less extent, attempted to use shape memory alloy to reduce thermal residual stress.^{62–65} Psarras et al.⁶² used shaped memory alloy wires embedded into aramid/epoxy composites, and the stress distributions in the fibres were obtained using laser Raman's sensor. They have shown that by adding of these wires into the composite, thermal residual stresses reduced by 76% in aramid fibres. According to Parthenios et al.,⁶⁵ the main disadvantage of using shaped memory alloy wires in composite materials was their ability to motivate fibre misalignment. On the other hand, shape memory alloy tends to increase the non-uniformity of stresses distribution within the entire hybrid composite and raise stress concentration. With regard to complexity, relatively higher cost and/or drawbacks of the previously mentioned techniques, fibre prestressing method seems comparatively more adequate.

Types of Fibre prestressing method

Recently, the design of engineering components have become less conservative, prompting to increase the interest into how residual stress affects the mechanical properties of composites. These residual stresses play a significant role in failure of composite materials.^{4,5} As it is well-known, improving composite material performance is usually accompanied with increasing its production cost.⁶⁶ Because of the constituent materials and their fabrication share, the total production cost of composites,²⁵ focusing on improving the manufacturing method, is still reasonable and effective. Researchers have

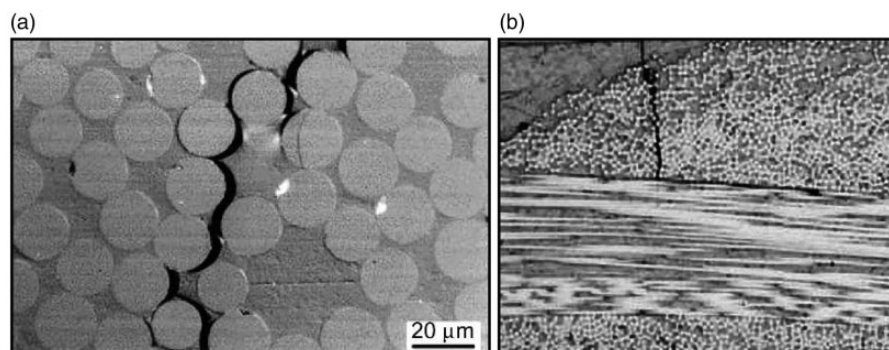


Figure 2. Cracked composites.⁵¹ (a) Crack initiation along fibre-matrix interfaces, (b) transverse cracks in weft tow in 3D non-crimp orthogonal woven composite.

confirmed theoretically and experimentally that fibre prestension can be used as an active method for reducing the detrimental effects of residual stresses that existed in composite components during manufacturing processes. The method of fibre prestressing can be divided into two generic types, which are elastically and viscoelastically prestressed PMCs. The elastically prestressing method is performed by applying tension loading in the fibres and maintaining it during matrix curing.^{1,67,68} After the composite is cured well and cooled down to room temperature, the pretension load will be released. As a result, the pretensioned fibres will tend to recover to their original length and therefore inducing compressive stresses in the matrix, which will minimize or relieve the tensile residual stresses produced by curing process and chemical shrinkage. However, the second prestressing method is performed by applying the pretension load to the fibres for a certain time, to induce creep strain, prior to incorporating them into the matrix.^{69–71} Each one of the two reported types of fibre prestressing has advantages and its limitations as well.

The proposed governing mechanisms associated with prestressing

Many researchers have shown that the method of fibre prestressing can improve the mechanical properties of fibre-reinforced composites. During the last four decades, several mechanisms that contribute to this improvement have been reported. Therefore, providing a good background about the advantages acquired from using the prestressing method and their justifications is very important to understand the method viewpoint. These mechanisms are

1. Breaking the weaker fibres before inserting them into the matrix

In the earlier stages, fibre pretension method was used to identify the weaker fibres before fabricating the

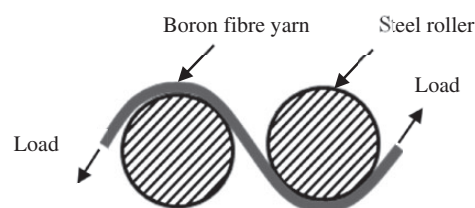


Figure 3. Schematic representation of a fibre undergoes bending.

composite. By doing this, these fibres were broken prior to moulding them into the matrix and hence reducing the defects in the final composite products. Mills and Dauksys⁷² studied the effect of fibre pretension on the composite strength of a system fabricated from a prepreg of boron/epoxy. The tensile load was applied by bending the prepreg tape over 25 steel rollers (Figure 3). The purpose of prestressing the tape was to break the weaker fibres prior composite fabrication. This was accomplished by bending the tape over a sharp radius, thereby applying a tensile load greater than the strength of the local weak regions. This method had increased the average fibre strength and hence improved the properties of the composite component to ~20% by eliminating the defected parts and considering only the defect-free parts of a composite structure.

Brown⁷³ studied the method of fibre pretension to detect the defective or weak fibres and prebreak them prior resin curing. The graphite/epoxy prepreg was pretensioned by pulling it under constant tensile load at a low temperature-curing environment. The tension mechanism of the prepreg, shown in Figure 4, was performed using different stressing roller diameters to break the weak fibres prior the fabrication process of the prepreg system. The reported data indicated an improvement in some mechanical properties due to prestressing process. The increase in the tensile strength was about 17%; however, the elastic modulus seemed

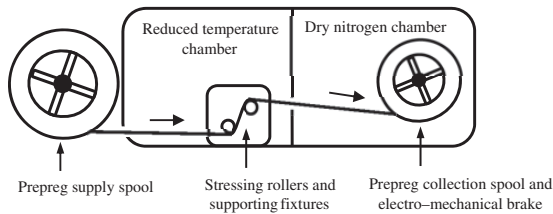


Figure 4. Prestressing equipment used by Brown⁷³ (redraw).

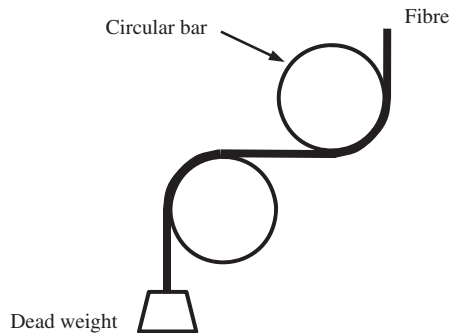


Figure 5. A schematic view of fibre prestressing by bending used by Chi and Chou⁷⁴ (redraw).

approximately unaffected by the prestressing process. Moreover, there was a significant reduction in the data scattering when compared with the non-prestressed composite counterparts.

Chi and Chou⁷⁴ studied the effect of fibre prestressing on the mean strength of the unidirectional carbon fibre/epoxy composite system. The carbon fibre strands were prestressed, before being impregnated with the matrix resin, by passing them over a pair of circular bars to induce bending stresses as shown in Figure 5. Different levels of bending stress, ranged from 0.511 to 2.21 GPa, were performed by only changing the diameter of the bars, while the tensile force (dead weight) was kept constant at 30 g. The authors claimed that by prebreaking the weak fibres, the variation in composite strength was reduced significantly due to increasing the uniformity in the mechanical properties of remaining non-defected fibres. Another significant conclusion was represented by the existence of optimum level of fibre prestressing, which leads to maximized strength enhancement. In their study, 25% improvement in the strength was attained.

II. Improving the architecture of reinforcement phase

A very clear physical mechanism related to the fibre architecture improvement such as its waviness (misalignment and undulation) and packing density has been reported to be one of the advantages drawn from employing fibre pretension. Fibre misalignment has detrimental effects on the overall composite

integrity. The waviness of fibre can appear in-plane, out-of-plane or both within the volume of a composite structure. There are many reasons for the raise in waviness of fibres within the composite, such as bad lay-up process, excessive feeding of resin, low viscosity of the resin, trapped air, mismatch in the thermomechanical properties between composite constituents and the mould and over-pressurized during fabrication process.^{7,75} Figure 6 shows some patterns of fibre waviness.⁷⁶ Increasing the straightness of the fibre yarns means the fibres within the composite can carry the transferred load from the matrix instantly and simultaneously.^{6,14,77} In 2D plain-weave fabric, the fabric pretension could reduce the crimp percentage of the interlacing yarns; therefore, reducing the stresses concentration at the cross-over sites.^{1,68} Numerous studies have indicated a reduction of fibre waviness and an improvement in the fibre packing density of fibre-reinforced composites due to using fibre prestressing method.^{1,6,7,14,24,77–89}

III. Generating compressive residual stresses within the matrix

One of the most important benefits drawn from using fibre prestressing method is by generating compressive residual stresses within the matrix. These stresses are imparted due to releasing fibre pretension load after matrix resin has been cured either elastically or viscoelastically. This kind of residual stress is characterized by its ability to impede crack propagation. Therefore, its function can be characterized as a delaying and obstructing mechanism against the formation of microcracks within the composite structure. Subsequently, the strength of the prestressed composite could enhance to some degrees. Many researchers have reported the advantages of employing fibre prestressing method on the mechanical performance of composite materials.^{4,6,7,13,14,19,24,67–70,77,80–82,85,87,89–106} The scheme shown in Figure 7 illustrates the positive effect of the compressive residual stress existence within the matrix. Applying fibre prestressing method can decrease the generation and propagation of cracks within the matrix by reducing the magnitude of existing tensile residual stresses.

IV. Adapting the interfacial region to absorb more energy against transverse fracture

Once the fibre-reinforced composite is subjected to transverse impact loading, the expected fracture mode is mostly defined by propagating the crack transversely on the fibre lengthwise. During impact events, the weakest sites (lower strength regions) within the composite structure will be the preferred path(s) for

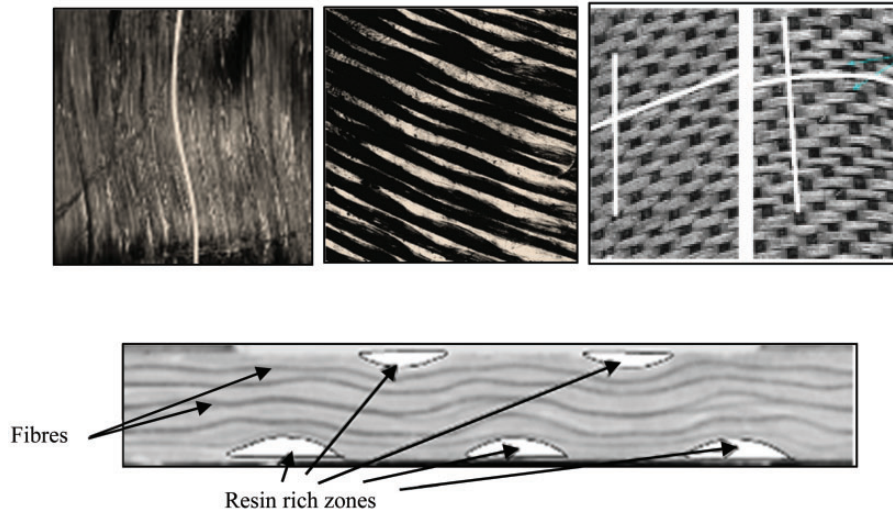


Figure 6. In-plane and out-of-plane waviness examples.⁷⁶

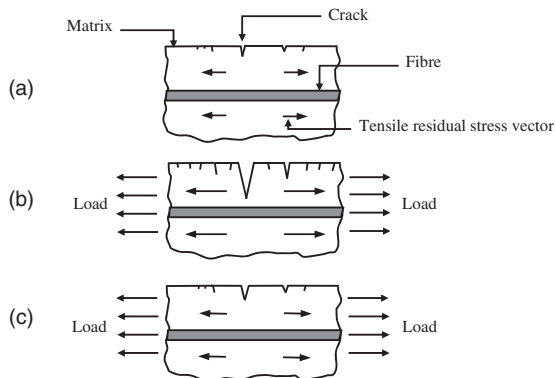


Figure 7. Effect of residual stresses in composites failure by crack propagation. (a) As fabricated without external tensile load, (b) as fabricated with external tensile load and (c) fibre-prestressed with external tensile load.

growing the crack(s).^{107,108} Therefore, when the crack tip has reached the reinforcement phase, characterized by its comparatively stronger strength, two scenarios are expected for absorbing the energy. The first scenario is propagating the crack throughout shearing the fibre. This kind of fracture is not a desirable one as it may lead the composite structure to lose its strength and stiffness dramatically with low energy absorbance. However, the second scenario of crack propagation is characterized by changing the crack propagation towards the fibre/matrix interfacial region. Therefore, the reinforcement phase within the composite will not suffer from a severe damage if it was compared with first scenario. The absorbed energy by interfacial debonding mechanism is accompanied with generating a comparatively larger surface area than by cutting the fibre at its cross-sectional area. Therefore, more energy

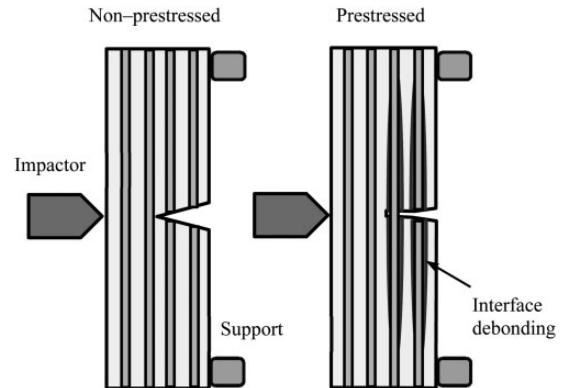


Figure 8. Schemes of fracture by impact in non-prestressed and prestressed composite samples.

is expected to absorb by adapting the second scenario of failure. The mechanism that controls which scenario is predominated can be related to the adhesion bond strength (interface shear strength). Strong adhesion bonding contributes to the incidence of first scenario; however, a relatively weak bonding will lead the composite to damage by the second scenario. Figure 8 shows the effect of fibre prestressing on the bonding strength between fibres and the matrix when the composite is subjected to impact.

The fibre prestressing method can increase the induced residual stress in fibre/matrix interface layer, thereby debonding can happen at a lower level of stress than the non-prestressed counterparts.⁹⁷ The same behaviour has been indicated for a composite reinforced by viscoelastically prestressed nylon fibres.^{69,70,90–92,98,109,110} Cao and Cameron⁸² have reported an increase in the impact properties of silica particle modified glass/epoxy composite with fibre

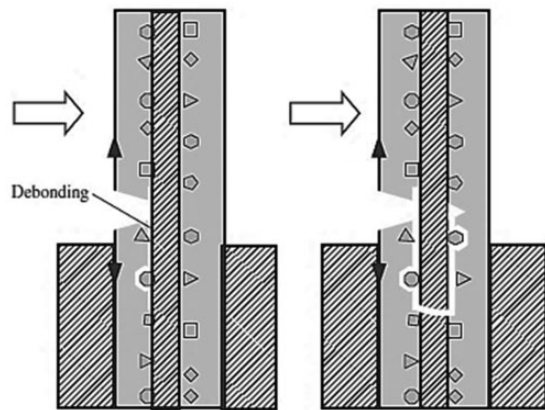


Figure 9. Schematic diagram of the crack developing in the silica-modified glass fibre-reinforced epoxy composite by Cao and Cameron.⁸²

prestressing. The schematic illustration examined in Cao and Cameron⁸² is shown in Figure 9.

V. Creating a transverse force opposite to bending load

It is well-known that the slope of bending load-deflection curve represents the flexural stiffness of the beam. The more the loading required for deflecting the beam, more is the stiffness acquired. Therefore, any inherent load opposite to the direction of the bending load will provide a resistance action against flexure deformation, thereby increasing the stiffness of the beam.

Fibre prestressing method can support the idea of increasing flexural stiffness and strength of the fibre-reinforced composite by two ways. First, the remaining tension force, saying F_r , within the fibres creates a vertical force component that is opposite to the direction of applied bending load.^{1,6,14,96} Second, the neutral axis of the beam cross-section tend to shift from its usual position (centroid) towards the part of the beam section that carrying a tensile flexural stress due to the presence of the compressive residual stress within the matrix. Therefore, the moment arm in the tensioned sectional part of the prestressed composite beam has become shorter and this leading to decrease the amount of tensile flexural stress in the beam.⁹⁶ Mechanism V is illustrated schematically in Figure 10.¹

Fibre prestressing concepts

To the best of the author's knowledge, the concept of fibre prestressing appeared approximately half century ago. Zhigun¹¹¹ was the first researcher who investigated experimentally the effect of pretensioning a woven fabric during the moulding process. The composite was fabricated from plain-weave glass fabric/phenol-

formaldehyde-based resin. The maximum increase in the elastic modulus was about 23% when yarns were equally pretensioned in both warp and fill directions. The interpretation of this behaviour was related to the increase of fibre straightness. Unfortunately, there was a missing information related directly to the value of a prestress level. Figure 11 shows the apparatus used by Zhigun¹¹¹ to apply the pretension load to the fabric.

In the period between 1973 and 1984, the fibre prestressing method was used for breaking the weaker fibres in order to detect the defective fibres before moulding them into the resin or curing the prepreg tape. Mills and Dauksys,⁷² Brown⁷³ and Manders and Chou¹¹² considered this concept. At the end of the eighth decade of the last century, a new concept was defined by Tuttle.⁶⁷ This concept is associated with reducing the tensile residual stresses in composites using the method of fibre prestressing. Since that time, numerous researchers have been enriching the field of advanced composites manufacturing using fibre-prestressing method. The emphasis was on exploiting the compressive residual stresses induced within the cured matrix due to releasing the pretension load in impeding the propagation of cracks. Many studies have been focused on the mechanical properties of the prestressed composites using different mechanisms for applying prestressing load to the reinforcement phase. Therefore, it is important to view the methodologies used in the previous studies in order to make it a guideline for the future related studies and research directions.

Application mechanisms of Fibre prestressing methods

In order to manufacture fibre prestressed composites, a suitable loading mechanism is needed to apply the required preload and take advantage of stored strain in the fibres to be imparted to the matrix later. Several methods with different mechanical arrangements have been used to achieve the required task. Each method has its advantages and limitations as well. In general, there are two basic types of fibre prestressing, namely elastic and viscoelastic, which depend mainly on the material behaviour.

Elastically fibre prestressed PMCs

The elastically prestressed fibre composites are produced by applying a predefined load lower than the elastic limit of the fibre materials and maintaining it during the curing cycle of the resin. Once the resin is cured well, the preload is released. Subsequently, the elastically strained fibre tends to return to its original length, but its good bonding with the cured matrix will induce compressive strain within the surrounding matrix. Many

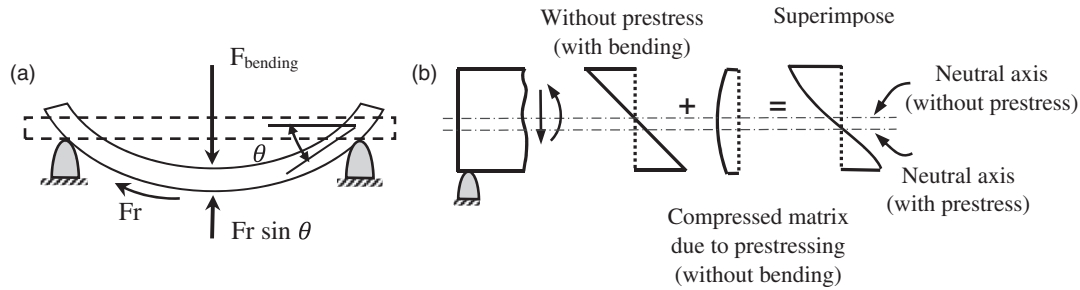


Figure 10. Schematic diagram of the flexural properties improving mechanism in the prestressed composites.¹ (a) Remaining tension force effect, (b) shifting of a neutral axis.

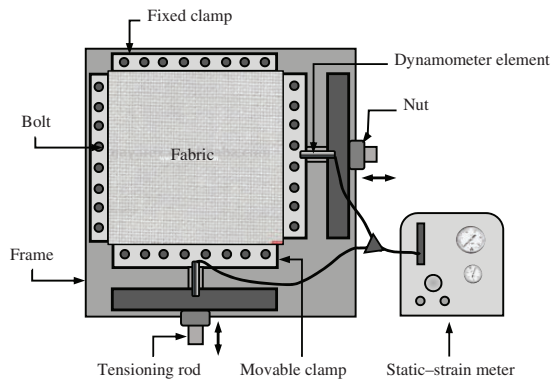


Figure 11. The apparatus used by Zhigun¹¹¹ (redraw).

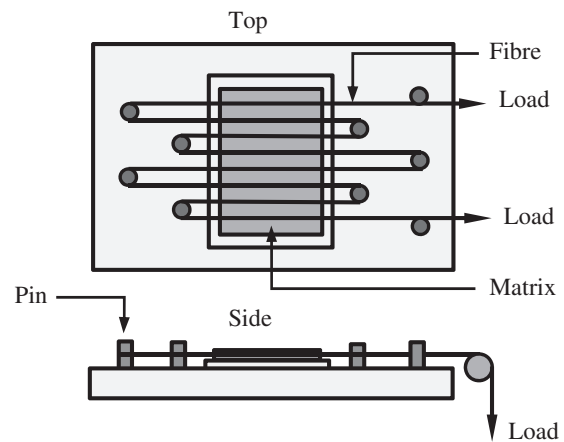


Figure 12. The rig used by Jorge et al.¹¹³ to fabricate the prestressed composite plates (redraw).

techniques have been used to implement elastic prestressed fibre composites, which are discussed below.

Dead-weight. The dead-weight is considered the simplest technique to perform fibre prestressing in composite. Several investigators have used it in their works to improve the composite performance. Jorge et al.¹¹³ used E-glass fibre with unsaturated polyester resin to manufacture the prestressed unidirectional fibre-reinforced composites. In their experiments, the prestressing load was applied using known weights with several pins arranged on the roving boundary. The roving was performed using two steel combs arranged as shown in Figure 12. The distance between any adjacent pins is ~ 2 mm and each roving consists of six to eight parallel paths of fibres to get good prestressing uniformity.

The same general prestressing techniques was used by Sadiq¹⁰⁴ and Schlichting et al.¹⁰⁵ as shown in Figure 13. The former used unidirectional E-glass fibre with epoxy resin; however, the latter used S-glass with two types of special dental resin namely Quixfil and Adoro. The dead-weight method was also used effectively by Nishi et al.¹¹⁴

The main disadvantages of using this prestressing technique are the difficulty to obtain a uniform fibre preloading in case of roving the yarn around the pins,

limited to a small size of composite samples, need for a relatively large space and its difficulty to perform with prepreg tape materials.

V-slot. The V-slot fibre prestressing technique is considered relatively easy to perform. Schulte and Marissen¹⁰⁶ have used this technique for manufacturing the hybrid prestressed cross-ply laminate $[0, 90, 90, 0]$ made from carbon- aramid/epoxy system. The rig used to apply fibre prestress is shown in Figure 14. The prepreg system was fixed well at its ends by bolted-clamps and several V-shaped bars were laid into the slots that bring the tape to stretch.

Clearly, the main disadvantages of using such technique are its limitation to apply a specified level of prestressing, the problem of sharp corners that may lead to kink and/or break the fibres and last one is the possibility of attaining non-uniform prestressing level through the reinforcement thickness.

Pressure forming mould. Pressure forming mould technique offers a good solution to perform fibre prestressing method in manufacturing composite components

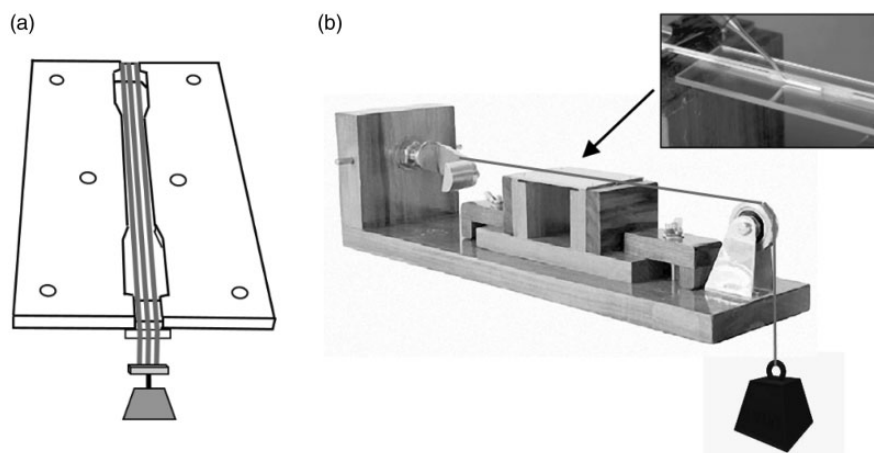


Figure 13. The dead-weight prestressing rig used (a) by Sadiq¹⁰⁴ and (b) by Schlichting et al.¹⁰⁵

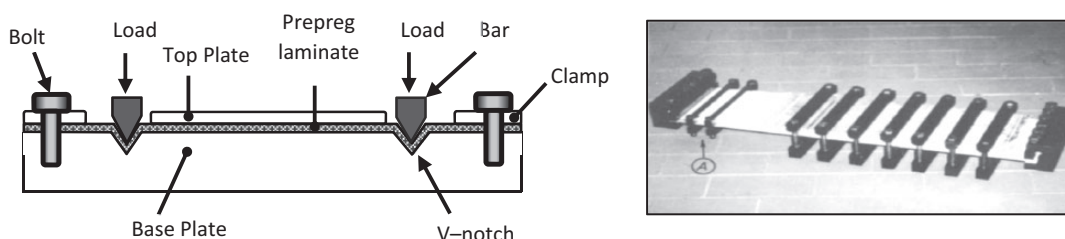


Figure 14. The prestressing device with V-shaped slots used by Schulte and Marissen.¹⁰⁶

with complex profile.⁶⁸ Bekampiene et al.⁸⁰ investigated experimentally the effect of fibre pretension of the woven fabric composites on improving the strength and quality of formed composite parts. Two types of fabric materials that consisted of cotton and E-glass woven fabrics were used individually with unsaturated polyester resin as a matrix to fabricate the prestressed composites with single layer of fabric. Two types of forming moulds were used, particularly hemispherical and frustum cones, to apply the pretension in the fabric as shown in Figure 15. The authors pointed out that in the case of using glass fabric, the fabric exhibited a shear deformation mode during shaping inside the mould. Moreover, the wrinkle failure regions and structural failure integrity were observed in the glass fabric, particularly in the bias direction. Whereas, cotton fabric showed its ability of shaping in the principal fibre directions beside the bias direction.

Although this technique is very effective in forming shaped prestressed composite parts, the more consideration is required to avoid the wrinkle and yarn shearing (sliding) defects, which alternated with a type of fabric material and its weaving.

Filament winding. Hadi and Ashton¹⁰² have used the filament winding to produce a prestressed composite as

shown in Figure 16. The yarns were pulled at known loading levels and then impregnated in the resin path before they have been warped on the mandrel. They used a unidirectional E-glass fibre with epoxy resin to fabricate the prestressed composite. To predict the influence of fibre prestressing on composite performance, different levels of prestressing were applied prior and during the matrix cure.

By using this technique, the first fibre winding is the best controlled one and next accumulative warp has lower advantage due to compressing the former underneath layer and squeezing out the resin. Therefore, it is difficult to control the manufacturing process with equal fibre volume fraction throughout the thickness. Moreover, the level of fibre pretension in the final composite component is affected by the stiffness of the mandrel.⁸⁴

Hydraulic cylinder. Tuttle et al.¹⁰³ used a hydraulic system, shown in Figure 17, to apply the required prestressing level in fibres. The hydraulic cylinder was installed horizontally and in parallel to the fibre alignment. The prepreg layers were rolled up around the movable loading rod. The pretension was applied and controlled by means of a hydraulic cylinder. The pressure gauge was used to measure the pressure level inside

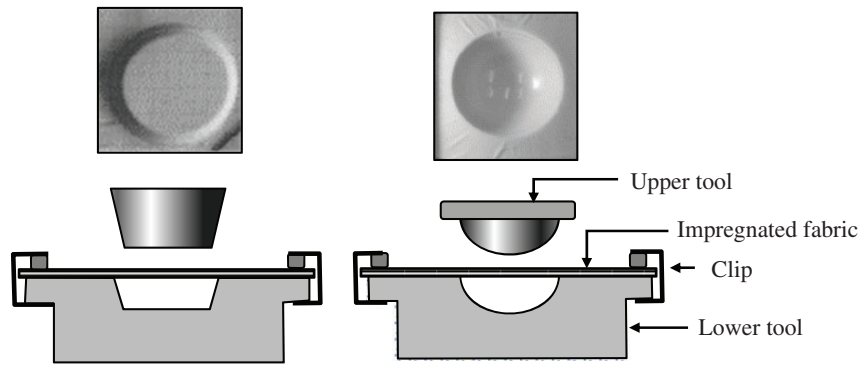


Figure 15. The schematic representation of pressure-forming moulds, Bekampiene et al.⁸⁰ (redraw).

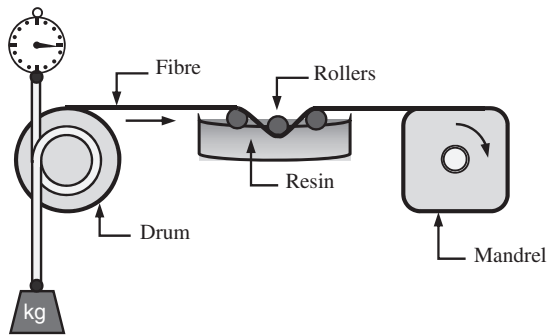


Figure 16. Schematic drawing of the pretensioning device by Hadi and Ashton¹⁰² (redraw).

the hydraulic cylinder; therefore, the fibre prestressing level was identified. The prepreg laminate was exposed to heating source using hot platens in order to cure the prepreg.

By using this technique, prestressed composites could be fabricated with different prestressing levels. However, lamina slippage was indicated at relatively higher levels of fibre prestressing. Another issue in using this technique is that tension load can be applied only in one direction.

Horizontal tensiometer machine. Motahhari and Cameron^{14,97,115} have adopted the horizontal tensiometer machine that is shown in Figure 18 to prepare a prestressed composite panel. Different prestressing levels were achieved by using this technique. An electrical motor was used to provide the required energy to rotate the drum, which put fibres under tensile load. The preload level was measured by using a load cell. The rig is also capable to provide heating source to cure the composite panel. This technique seemed simple and effective with only one restriction which was represented by applying the tension load to unidirectional fibres only.

Fibre-stretching frame. Zhao and Cameron⁸⁹ have used what was called *fibre-stretching frame*, shown in Figure 19, to provide pretension load at different levels. The preloads were applied on co-mingled polypropylene/glass fiber roving system. First, the fibres were wound onto the steel frame and then the rig was fixed at the tensile test machine to provide the required level of pretension. Subsequently, the locking nut was tightened and the rig taken out from the tensile machine for performing moulding process. The composite constituents were heated at 205°C for 3 minutes in order to melt the polypropylene fibres to form the matrix phase. The same prestressing technique, depending on tightening a screw or nut to provide the tension load, was used by Zaidi et al.⁷⁷ for a composite system that consisted of flax spun yarn/polyester resin.

It seems that a major drawback appeared by using this prestressing technique and was not considered in the work of Zhao and Cameron. The issue is represented by the inaccurate estimation of the final fibre pretension level. This inaccuracy is associated with the methodology and the matrix material used, where fibre prestressing was initially provided to both glass and polypropylene fibres. Subsequently, a process of providing an elevated temperature was used to melt only the polypropylene fibres to form the matrix. Therefore, the pretension that was carried by polypropylene fibres would be transferred to the glass fibres instead.

Flat-bed prestressing rig. Krishnamurthy⁷ used the flat-bed prestressing equipment such as the one shown in Figure 20. The prepreg lamina was fixed by the clamps with four bolts for each clamp. The tension load was provided by using loaded screw. The level of loading was measured via a load cell and the applied prestressing level was reached up to 150 MPa. The ends of the prepreg laminates (16 layers) were tabbed by hot-pressed cure to fix them well by the clamps; however, the rest of pretensioned part of the prepared composite panel was cured using an autoclave. Daynes et al.^{46,47}

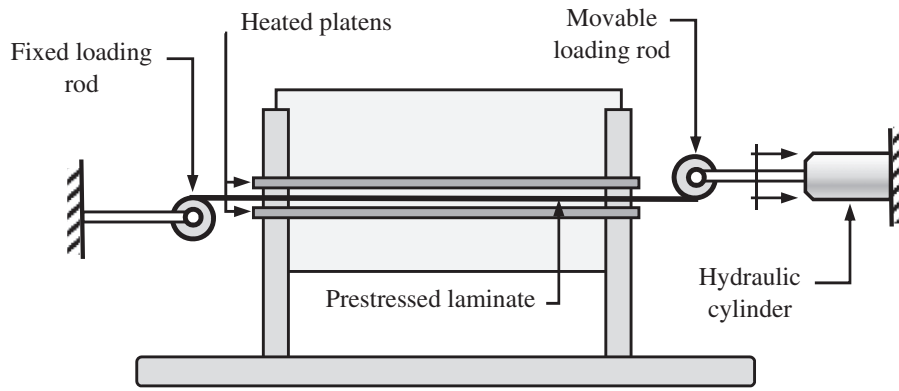


Figure 17. Schematic drawing of the hydraulic cylinder-prestressing device by Tuttle et al.¹⁰³ (redraw).

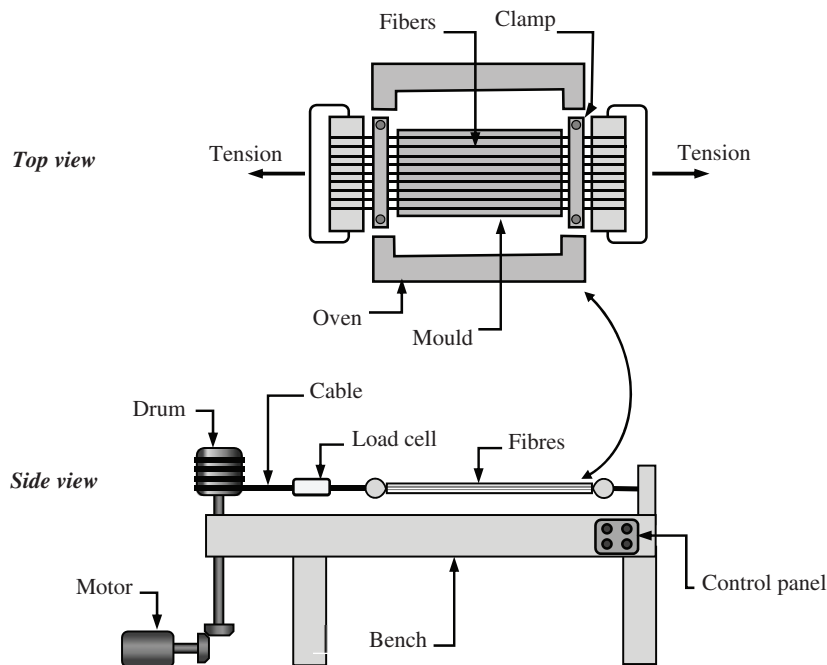


Figure 18. Schematic drawing of horizontal tensiometer machine device by Motahhari and Cameron^{14,97,115} (redraw).

used the same equipment to fabricate prestressed laminated composite samples with bistable behaviour.

Although this technique looks perfect at the first time, some issues accompanied the prestressing process. As mentioned before, the ends of the prepreg have been cured (hot-pressed) before subjecting it to the pretension loading in order to clamp the tabbed ends of the composite. This process might make the composite panel to cure at different temperatures. Therefore, fibre misalignment has been raised close to the end-tab region as shown in Figure 21. The designer has also reported another issue related to the hot-press curing of ended tabs. During the hot-press tabbing, fibres were instigated to move and distort leading to increase in the misalignment problem.

Biaxial loading frame. Jevons²⁴ designed a new rig to apply the fibre prestressing in biaxial directions as shown in Figure 22. The rig was made from C-channel steel section with four fixtures along the internal perimeter of the rig to fix the prepreg lamina using seven bolts at each clamp. The fibre prestressing was provided by two means. First, by thermal expansion of the equipment and taking advantage of the different thermomechanical properties between the steel frame and the prepreg fibre when inserted in the autoclave at elevated temperatures. Second, by using tensile test machine to provide comparatively higher levels of prestressing load. The former was provided a maximum prestressing level of 40 MPa; however, the later was used for increasing the prestressing level up to 100 MPa.

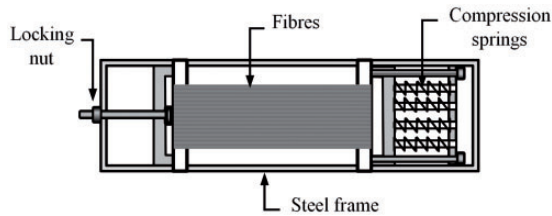


Figure 19. The fibre-stretching frame used by Zhao and Cameron⁸⁹ (redraw).

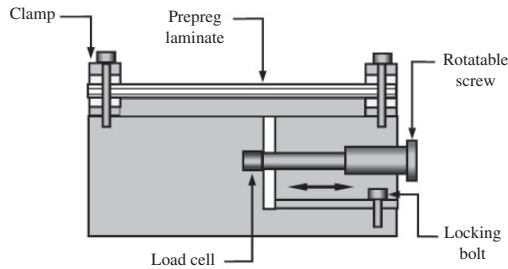


Figure 20. The fibre-stretching frame used by Krishnamurthy⁷ and Daynes et al.^{46,47} (redraw).

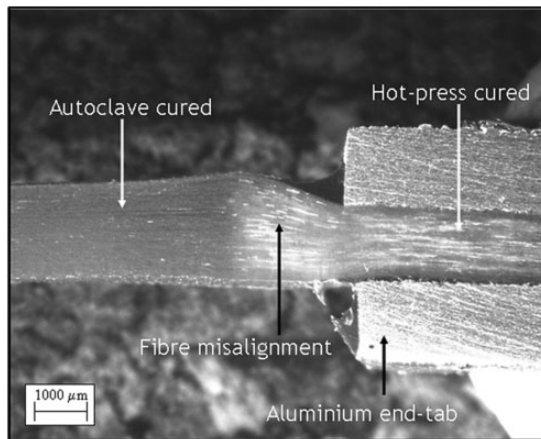


Figure 21. Fibre misalignment near end-tab region by Krishnamurthy.⁷

By using this equipment, some issues are associated with the sharp corners of the frame, which might make the vacuum bagging relatively difficult to perform. Moreover, the need for tensile machine to provide the required load is a critical issue due to the limitation of the available distance between the fixed and the movable jaws (maximum gauge length) required for inserting the prestressing frame within the machine. The latter issue was fixed by using hydraulic cylinders instead of the tensile machine to provide the required

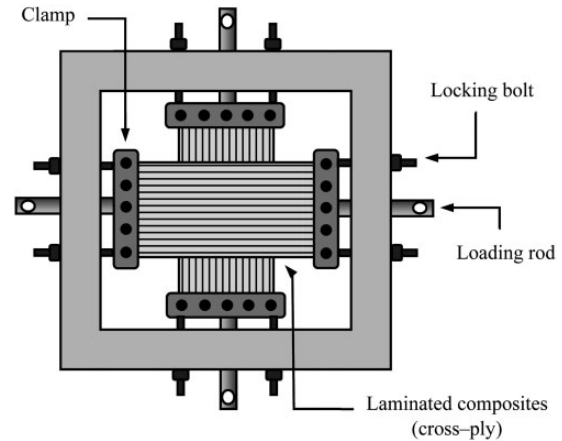


Figure 22. Biaxial fibre prestressing frame (redraw) used by Jevons²⁴ (redraw).

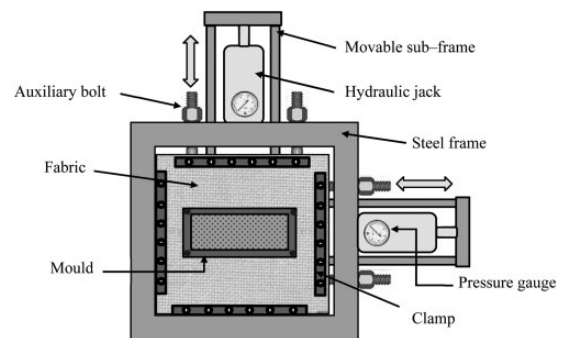


Figure 23. The plan-view of the biaxially fabric prestressing rig.^{1,68}

preload in the plain-weave fabric as shown in Figure 23.^{1,68}

Viscoelastically fibre prestressed PMCs

Studies on viscoelastically fibre prestressed PMCs (VEFPPMCs) were started in 2000 by Fancey.⁹⁸ The focus will be on prestressing the fibre that exhibit viscoelastic properties. This mechanism involves applying a tension load in the fibre for a certain time to induce creep and releasing it before moulding the fibres into the matrix. After the matrix has attained a solid phase, the fibre attempts to recover the viscoelastic strain and this can lead to impart compressive residual stresses into the surrounding matrix. This prestressing technique permits to stretch and mould the fibres in detached processes. Therefore, it can be considered more flexible than elastically prestressed composites in fabricating complex structural components, but it is limited to the materials characterized by a viscoelastic behaviour.

Several studies have investigated the effectiveness of viscoelastically fibre prestressed method on the mechanical performance of composite materials. The reported results indicated considerable enhancements in tensile, flexural and impact properties of composites reinforced by nylon 6,6 or ultra-high-molecular-weight polyethylene (UHMWPE) fibres.^{70,71,90,91,93–96,98,100,109} Recently, bistable VEFPPMCs was successfully achieved by Wang and Fancey.¹¹⁶

Overview of fibre prestressing studies

In the previous sections, the effect of residual stresses on the performance of PMCs was covered. Moreover, the main prestressed governing mechanisms of improving the mechanical performance of fibre-reinforced composites were reviewed. Fibre prestressing method was implemented during the last five decades and several mechanisms have been attributed the enhancement of PMCs. To provide the matrix by compressive residual stresses, either elastic or viscoelastic prestressing type have been adopted. Elastically fibre prestressed PMC (EFPPMC) is achieved by applying the pretension load prior and during curing process; however, VEFPPMCs is applied by pretensioning the fibres for a certain timescale to induce creep strain prior to moulding them into the matrix. Both of the two prestressing types have proven their worthiness over other improving techniques due to relatively low cost and the ability to perform without increasing the mass and volume of composite components.

Table 1 provides the available studies related to fibre pretension method from its first appearance at 1968 by Zhigun¹¹¹ to the date of writing this paper. For better and easier follow-up, the previous studies are listed here in the chronological order.

Potential applications and future trend of fibre prestressing

The reviewed studies in the field of fibre prestressed PMCs demonstrated the positive effects on the structural performance under different types of loadings. It is, therefore, important to explore the areas that fibre prestressing method may find applications. Up to now, filament winding is the most successful and practical way to exploit advantages drawn from using this method. According to Parlevliet et al.¹²¹ and Kannan et al.,¹²² thick composite laminates such as wind turbine blades, pressure vessels, parts in aircrafts, bridges can be manufactured with filament winding. Many studies have shown that fibre pretension level has an important effect on the performance of composite structures fabricated by filament winding technique, such as pressure pipes and vessels,^{21,22,123–126}

submersible cylindrical bodies^{84,127} and cylindrical shells.¹²⁸ Another application of using prestressed fibres was found by Suvorov and Dvorak¹¹⁸ in improving the protective efficiency of ceramic armor plates by using laminated plates that encapsulate the ceramic layer and supported by prestressed fibers. Bistable composite components, usually used in the aerodynamic control of an aircraft and wind turbine blade that have received increasing interest in the few recent years, could be successfully fabricated using prestressed fibres.^{46,47,116} In addition, the fibre prestressing methods exhibited its ability to apply not only for synthetic fibres but also for natural fibres like flax, cotton and bamboo. This ability can offer to produce more durable green composite materials as these fibres are eco-friendly, have low cost, low density, are abundant and renewable.¹²⁹ Since improvements in structural properties can be accomplished without the need to increase mass or section size of component, fibre prestressed composites may provide benefits for transportation (reduced fuel consumption and/or improved crashworthiness), sports or safety applications (lightweight impact/blast protection), military, aerospace and pressure vessels. Future trend will focus on alternative fibre materials, process optimization and the applicability of fibre prestressing method with lower cost.

Discussion

Although the concept of prestressed concrete has been widely used in civil constructions such as the prestressed concrete for its benefits, using it in fibre-reinforced composites seems comparatively more recent and less convenient. Unfortunately, the formation of residual stresses within fibre-reinforced composite components was commonly generated during fabrication processes. The chemical and thermal shrinkages of different constituent properties, that a composite is fabricated from, attributed to generate these stresses. Nevertheless, several methods were performed to overcome the drawbacks related to the existence of residual stresses within the matrix. One method, which the present literature focused on, is by taking advantage of applying elastic or viscoelastic pretension to the fibres. In this method, the continuous fibres play a role of strain energy storage when pretensioned. Therefore, removing the pretension after curing the matrix leads to release the energy into the surrounding matrix material according to spring-back behaviour. The energy released from fibres is imparted to the surrounding matrix as a compressive strain. Thereby, the new state of residual stresses in the matrix will offer more resistance to crack initiation and propagation.

Table 2 shows an overview of the discussed methods categorized according to the used prestressing

technique. It is easy to indicate that although there are various techniques of applying the prestressing in the fibre, each one has particular restrictions. The more complicated the fibre prestressing technique, the more accurate and wider range of prestressing level could be achieved. On the other hand, Table 3 lists the most

obvious positive and negative aspects of the two types of prestressing methods used to improve the structural performance of the PMCs. Clearly, up to now some restrictions still appeared difficult to be overcome.

Table 4 indicates the contributions of fibre prestressing on the mechanical performance of fibre-reinforced

Table 1. Literature review on prestressed PMCs.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Zhigun ¹¹¹	Tension and compression test (EFPPMCs)	Tightening nuts on the ends of the tensioning rods	Plain-weave glass fabric/phenol-formaldehyde resin	<ul style="list-style-type: none"> ■ Elastic properties were improved up to 31% ■ The enhancement in the mechanical properties is attributed to the increase in the straightness of the warp fibres.
Mills and Dauksys ⁷²	Tensile strength (EFPPMCs)	Prebending the prepreg tape over steel rollers to break the weaker fibres	Unidirectional boron fibre/epoxy prepreg tape	<ul style="list-style-type: none"> ■ Tensile strength improved up to 20% ■ Pretensioning can be used to indicate the defective parts within composites
Brown ⁷³	Tensile strength Elastic modulus (EFPPMCs)	Prebending the prepreg tape over steel rollers to break the weaker fibres	Unidirectional graphite/epoxy prepreg tape	<ul style="list-style-type: none"> ■ Tensile strength improved up to 17% ■ Elastic modulus seemed unaffected ■ Significant reduction in the data scattering
Chi and Chou ⁷⁴	Tensile strength (EFPPMCs)	Prebending the fibres over a pair of circular bars to break the weaker fibres	Unidirectional carbon fibre/epoxy resin	<ul style="list-style-type: none"> ■ Enhancement of the composite tensile strength is reported up to 25% ■ There is an optimum level of fibre prestressing ■ Higher survivability is achieved by prestressing the fibres
Tuttle ⁶⁷	Mechanical/ thermal analysis of prestressed composites laminates (EFPPMCs)	Not specified clearly, but he assumed the fibre preload was applied prior to and during matrix cure	Unidirectional carbon fibre/epoxy composite Fibre $V_f = 60\%$	<ul style="list-style-type: none"> ■ Prestressing could reduce matrix residual stresses considerably
Jorge et al. ¹¹³	Tensile properties (EFPPMCs)	Dead weight	Unidirectional E-glass fibre/unsaturated polyester resin Fibre $V_f = 56\%$	<ul style="list-style-type: none"> ■ Tensile strength and modulus increased with increasing prestressing, up to a certain prestress level ranged from 60 to 80 MPa. The maximum increase in tensile strength and tensile modulus was $\sim 15\%$ and $\sim 18\%$, respectively

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Scherf and Wagner ⁸⁶	Tensile properties (EFPPMCs)	Dead weight	Single carbon filament/ epoxy resin The diameter of the fibre was 9.9 μm	<ul style="list-style-type: none"> ■ Interfacial shear stress increased with increasing fibre pretension ■ Increasing fibre pretension could increase the number of fibre fragments when the composite undergoes tensile stress
Schulte and Marissen ¹⁰⁶	Tension properties and transverse crack density (VEFPPMCs)	V-slot (Notched bar)	Hybrid cross-ply laminate of structure [0,90 ₂ ,0] was produced from carbon/ epoxy and aramid/ epoxy prepreg systems	<ul style="list-style-type: none"> ■ Prestressing increased average ultimate stress and strain by $\sim 2.9\%$ and $\sim 3.4\%$ respectively ■ The formation of the cracks was delayed by 0.2%. ■ No change has been seen in tensile modulus
Sui et al. ¹¹⁷	Tensile properties (EFPPMCs)	Not mentioned	Vynlon (PVA, poly-vinyl alcohol) fibre/ epoxy layer and aluminium sheets (VIRALL) Fibre $V_f = \sim 32\%$ Aluminium $V_f = \sim 57\%$	<ul style="list-style-type: none"> ■ Tensile strengthened effect for Vynlon fibres due to prestressing (work hardening) ■ More fibre is forced to align to the direction of tension load with increasing the preload ■ The prestressing could induce compressive stress in the aluminium lamina and thereby delaying it to reach the elastic limit ■ Increasing fibre prestressing led to increase VIRALL modulus ($\sim 6.6\%$), yield strength ($\sim 37\%$), elastic limit strength ($\sim 44\%$) and strain ($\sim 34\%$), and failure strength ($\sim 15\%$) when the range of fibre prestressing is increased to 300 MPa
Sui et al. ¹⁰¹	Fatigue properties (EFPPMCs)	Not mentioned	Vynlon (poly-vinyl alcohol, PVA) fibre / epoxy layer and aluminium sheets (VIRALL)	<ul style="list-style-type: none"> ■ The tensile residual stresses induced in the aluminium sheet after VIRALL laminate has been cured is not favorable ■ Fatigue strength was increased with increasing the prestrain especially at a relatively low stress levels ■ Prestraining the VIRALL laminate to a level that can cause permanent deformation within the aluminium sheet and this can induce compressive residual stresses in the aluminium sheet when the prestrain has been released

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Tuttle et al. ¹⁰³	Tensile properties, curvature and transverse cracking (EFPPMCs)	Hydraulic cylinder	Graphite fibre/epoxy resin, unsymmetric [0/90] _T laminates Fibre $V_f = 56\%$	<ul style="list-style-type: none"> ■ Warping or buckling was reduced by employing fibre prestressing especially if the prestress is applied in the 0° layer ■ Transverse cracks and curvature were reduced by prestressing ■ The optimum level of fibre prestressing is 241 MPa (equal to ~28% of composite laminates ultimate strength)
Motahhari and Cameron ¹¹⁵ 1997	Measurement of residual stresses due to fibre prestressing (EFPPMCs)	Horizontal tensiometer machine (drawing bench)	Unidirectional E-glass fibre/epoxy resin Fibre $V_f = 40\%$	<ul style="list-style-type: none"> ■ Fibre prestressing prior and during the curing process could reduce the effect of tensile residual stress within the matrix ■ Two opposite effects could be occurred with fibre prestressing. It could enhance the composite strength by impeding crack propagation and at the same time it could reduce the strength by weakening the bonding between the fibres and the matrix
Motahhari and Cameron ⁹⁷	Impact properties (Charpy) (EFPPMCs)	Horizontal tensiometer machine (drawing bench)	Unidirectional E-glass fibre/epoxy resin Fibre $V_f = 40\%$	<ul style="list-style-type: none"> ■ Impact strength improvement was up to 33% ■ The increase in the fibre prestressing level could increase the impact strength up to a particular level of prestressing ■ After the optimum level was reached (~60 MPa), the properties have been decreased gradually ■ The strength alteration of fibre-matrix interface due to prestressing played the main role of improvement
Hadi and Ashton ¹⁰²	Tensile properties (EFPPMCs)	Filament winding	Unidirectional E-glass fibre/epoxy resin Fibre $V_f = 30, 45$ and 60%	<ul style="list-style-type: none"> ■ Improvement in the tensile modulus up to ~45% and strength up to ~20% with increasing prestressing level and fibre volume fraction
Zhao and Cameron ⁸⁹	Tensile, flexural properties and interlaminar shear strength (EFPPMCs)	Fibre-stretching frame	Unidirectional glass fibre/polypropylene matrix Fibre $V_f = 34.2\%$	<ul style="list-style-type: none"> ■ The properties were increased with increasing prestressing level up to a certain level ■ Fibre prestressing method improved tensile strength, flexural strength and ILSS of composites by 19%, 22% and 9%, respectively

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Motahhari and Cameron ¹⁴	Flexural properties (EFPPMCs)	Horizontal tensiometer machine (drawing bench)	Unidirectional E-glass fibre/epoxy resin Fibre $V_f = 40\%$	<ul style="list-style-type: none"> ■ Flexural strength and modulus increased by 33% by prestressing ■ The optimum prestressing level depended on the curing temperature; increasing the curing temperature could increase the optimum prestressing level
Fancey ⁶⁹	Impact properties (Charpy) (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/polyester resin Fibre $V_f = 3 \sim 4\%$	<ul style="list-style-type: none"> ■ Viscoelastic prestressing of nylon fibre could induce compressive stress in the matrix due to recovery mechanism ■ The increase in the absorbed impact energy was up to 25%
Dvorak and Suvorov ^{85,2000}	Damage envelope (first ply failure) (EFPPMCs)	Not mentioned (analytical)	Unidirectional S-glass/epoxy prepreg symmetric laminates Fibre $V_f = 50\%$	<ul style="list-style-type: none"> ■ Fibre prestressing could reduce the thermal residual stresses developed in the composite due to temperature changes ■ Fibre prestressing could delay the onset of first layer failure to higher stress level
Suvorov and Dvorak ¹¹⁸	Free edge stresses in the composite laminates and the plies (EFPPMCs)	Not mentioned (analytical)	Unidirectional S-glass/epoxy prepreg symmetric laminates Fibre $V_f = 50\%$	<ul style="list-style-type: none"> ■ The stress distribution in the individual plies and at the free edges could be minimized to remain within acceptable limits
Jevons et al. ¹¹⁹	Low velocity impact (dropped weight) (EFPPMCs)	Biaxial loading frame	E-glass fibre/Epoxy resin cross-ply laminates $[0^\circ/90^\circ_2/0^\circ_2/90^\circ/0^\circ/90^\circ]_s$ Fibre $V_f = 56\%$	<ul style="list-style-type: none"> ■ The study indicated a small improvement in low velocity impact properties of composites due to fibre prestressing
Jevons ²⁴	Low and high velocity impact (EFPPMCs)	Biaxial loading frame	E-glass fibre/Epoxy resin cross-ply laminates $[0^\circ/90^\circ_2/0^\circ_2/90^\circ/0^\circ/90^\circ]_s$ Fibre $V_f = 56\%$	<ul style="list-style-type: none"> ■ The study indicated an improvement in low velocity impact performance of composites due to fibre prestressing up to $\sim 25\%$ ■ The prestressing level of 60 MPa was the level that gave the least amount of damage by delamination; however, it could be considered the worst level for the composite laminates to absorb the impact energy ■ Prestressing has no recognized effect on high velocity impact ■ Finite elements could not perform the prestressed composite and the failure mechanism accurately

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Krishnamurthy ^{7,120}	Tensile, compressive and fatigue (experimental and analytical) (EFPPMCs)	Flat-bed	Unidirectional E-glass fibre/epoxy prepreg [0] ₁₆ Fibre $V_f = 58.2\%$	<ul style="list-style-type: none"> ■ Fibre alignment improved with increasing prestressing level ■ The resistance to the onset of damage was increased due to the induced compressive residual stresses within the matrix ■ Tensile modulus improved up to $\sim 9\%$ at 51 MPa prestressing level ■ Compressive strength and modulus were increased by 9% at prestressing level of 80 MPa ■ Fatigue life prolonged up to 75% (tension-tension) and over 200% (tension-compression) at prestressing level of 51 MPa in the region of low stress levels
Cao and Cameron ⁸²	Impact properties (Izod) (EFPPMCs)	Hounsfield Tensometer	Hybrid unidirectional E-glass fibre-silica particle/epoxy resin Fibre $V_f = 20$ and 29%	<ul style="list-style-type: none"> ■ Adding silica particles without fibre prestressing has no measurable effect on absorbed impact energy ■ The energy absorbed by the clean samples (without silica particles) was increased up to $\sim 62\%$ by prestressing the fibre to 15 MPa ■ The energy absorbed by the silica particle modified glass fibre samples was increased up to $\sim 100\%$ (with 15 MPa Prestressing) when compared with non-prestressed clean samples ■ The fibre-matrix interface bonding strength can absorb larger amount of impact energy in an optimum fibre prestressing level
Cao and Cameron ⁸¹	Flexural and Shear Properties (EFPPMCs)	Hounsfield Tensometer	Hybrid unidirectional E-glass fibre-silica particle/epoxy resin Fibre $V_f = 20$ and 30%	<ul style="list-style-type: none"> ■ The flexural properties of the samples without silica particles could increase by $\sim 10\%$ due to 15 MPa of fibre prestressing level; however, shear modulus increased by only $\sim 29\%$ due to a level of fibre prestressing of 10 MPa ■ The improvements in the flexural and shear properties by the silica particle modified glass fibre samples were $\sim 75\%$ (with 15 MPa prestressing level) and 50%, respectively, when compared with non-prestressed clean samples
Pang and Fancey ⁹⁵	Impact properties (Charpy) long-term viscoelastic recover of nylon 6,6 fibres (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/polyester resin Fibre $V_f = 3 \sim 4\%$	<ul style="list-style-type: none"> ■ No significant decline in the improved impact properties ($\sim 30\%$ improvement) of viscoelastically prestressed composite up to 100 years at 20°C (accelerated aging) has been detected

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Sadiq ¹⁰⁴	Tensile, flexural and interfacial shear properties (EFPPMCs)	Dead weight	E-glass fibre yarns/ epoxy Fibre $V_f = 30\%$	<ul style="list-style-type: none"> ■ The tensile strength, tensile modulus, and tensile failure strain were increased by 70%, 60% and 45%, respectively, at 20 MPa of fibre prestressing level ■ The flexural strength and flexural modulus were increased by 67% and 26%, respectively, at 20 MPa of fibre prestressing level ■ Increasing the prestressing level could increase the residual shear stress at fibre-matrix interfacial considerably
Pang and Fancey ⁹⁴	Tensile properties (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/epoxy resin Fibre $V_f = 16, 28, 41$ and 53%	<ul style="list-style-type: none"> ■ Tensile modulus and strength improved by $\sim 31\%$ and $\sim 15\%$, respectively ■ Strain-limited toughness (0.25% strain) increased between 24 and 42% ■ The maximum increase in the properties due to viscoelastic prestressing occurred at a volume ratio between 35 and 40%
Daynes et al. ^{46,47}	Bi-stable prestressed buckled laminates analytical, experimental and numerical (EFPPMCs)	Flat-bed	Hexcel 8552/IM7 (unidirectional carbon fibre/epoxy prepreg) and Hexcel 913 (unidirectional glass fibre/epoxy prepreg) symmetric cross-play $[0/90/90/0]_T$ laminates, the prestrain was applied only to the 0° aligned fibres	<ul style="list-style-type: none"> ■ Bistable behaviour can be induced by applying a prestress to selected fibres in prestressing the fibre prior to and during matrix curing ■ Snap-through load of prestressed symmetric laminate was much higher than the non-stressed $[0_n/90_n]_T$ equivalent
Pang and Fancey ⁹⁶	Flexural properties (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/epoxy and polyester resins Fibre $V_f = 8, 12,$ and 16%	<ul style="list-style-type: none"> ■ Flexural modulus was increased by 50% compared with non-prestressed counterparts
Schlichting et al. ¹⁰⁵	Flexural properties (EFPPMCs)	Dead weight stretching machine	Unidirectional S-glass/composite resins (Quixfil and Adoro) Fibre $V_f = \sim 12\%$	<ul style="list-style-type: none"> ■ With a fibre pretension load of 73.5% of its tensile strength, the flexural strength could improve by 33% (Quixfil) and 28% (Adoro)
Fancey ¹⁰⁹	Impact properties (Charpy) (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/polyester resin Fibre $V_f = 2-3\%$.	<ul style="list-style-type: none"> ■ No significant decline in the improved impact properties (30% improvement) of viscoelastically prestressed composite up to 20 years at 40°C (accelerated aging) has been detected
Bekampiene et al. ⁸⁰	Tensile properties (EFPPMCs)	Pressure forming mould	Plain-weave fabric (cotton and E-glass)/polyester resin Fibre $V_f = 32\%$ for cotton and 27% for glass	<ul style="list-style-type: none"> ■ Tensile strength of the pretensioned composite samples increased $\sim 12\%$ in warp direction, in $\sim 58\%$ in weft direction and in $\sim 39\%$ in bias direction with cotton reinforcement; however, the improvement was $\sim 135\%$ in the bias direction with glass reinforcement ■ The method of pretension was not performed well in case of glass fabric at warp and weft directions since the mode of deformation was shear only

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Cui et al. ¹⁰⁰	Flexural properties (VEFPPMCs)	Not mentioned	Bamboo slivers-poplar veneer strands (weight ratio 1:4) / phenol formaldehyde resin (Parallel Strand Lumber, PSL) Resin content = 15%	<ul style="list-style-type: none"> ■ The modulus of rupture and modulus of elasticity of prestressed bamboo slivers reinforced PSL increased by 7.84% and 11.76%, respectively ■ Flexural toughness index was increased by 27.55% in comparison with unprestressed counterparts
Fazal and Fancey ⁹²	Impact properties (Charpy) (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/polyester resin Fibre $V_f = 3.3, 10$ and 16.6%	<ul style="list-style-type: none"> ■ The energy absorbed by the prestressed samples could improve up to 40% ■ More energy could be absorbed by increasing the fibre content ■ Increasing the span of tested samples from 24 to 60 mm could reduce the percentage of improvement in absorbed energy drawn from prestressing due to decreasing the induced-shear stress
Fazal and Fancey ⁹³	Flexural properties (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional ultra-high molecular weight polyethylene fibres/polyester resin Fibre $V_f = 3.6$ and 7.2%	<ul style="list-style-type: none"> ■ Flexural stiffness increased by 40 and 23% at 3.6 and 7.2% volume fraction due to viscoelastic fibre prestressing, respectively No deterioration in the acquired improvement has been detected over a timescale of 2016 hours at room temperature
Širvaitienė et al. ⁸⁷	Tensile and flexural properties (EFPPMCs)	Not mentioned	Flax (68 tex.) and cotton (70 tex.) yarns/biodegradable poly(lactic acid) resin Fibre $V_f =$ not specified	<ul style="list-style-type: none"> ■ By only prestressing the vegetable fibres 50–70% of their tensile strength, the tensile and flexural strength of composites could increase considerably ■ The main factors attributed to the strength improvement were related to the increase in the fibres alignment and bulk integrity with increasing the pre-tension ■ The tensile and flexural strengths of the flax composite samples increased by ~140 and ~39%, respectively, due to prestressing the fibre 40% of its ultimate tensile strength; however, cotton composite samples increased by ~120 and ~19%, respectively, due to prestressing the fibres to 45% of fibre ultimate tensile strength ■ After the optimum level of fibre prestressing, the properties reached, they have declined due to fibre rupture
Nishi et al. ¹¹⁴	Impact properties (Charpy) (EFPPMCs)	Dead weight	Unidirectional carbon fibre/epoxy Fibre $V_f = 50\%$	<ul style="list-style-type: none"> ■ Prestressing improved the Charpy impact value by 30% (at 17.6 MPa prestressing)
Fazal and Fancey ⁹¹	Impact properties (Charpy) (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional ultra-high molecular weight polyethylene fibres/polyester resin Fibre $V_f = 3.6\%$	<ul style="list-style-type: none"> ■ The energy absorbed by viscoelastically prestressed samples was increased by 20%, with some samples reaching 30–40% ■ Debonding occurred at fibre-matrix interface and skin-core within fibres interface played the main role of energy absorption

(Continued)

Table 1. Continued.

Reference	Research area	Prestress technique	Materials	Main finding(s)
Fazal and Fancey ⁷⁰	Impact (Charpy) and flexural properties (VEFPPMCs)	Bespoke vertical stretching rig (only for nylon fibre)	Hybrid unidirectional nylon 6,6 and Kevlar-29 fibres/polyester resin Fibre $V_f = 4.5\%$ (3.3% nylon with 1.2% Kevlar fibres)	<ul style="list-style-type: none"> ■ The absorbed impact energy was increased up to 33% ■ The increase in the flexural modulus was ~40%
Fancey and Fazal ⁷⁰	Impact properties (Charpy) (VEFPPMCs)	Bespoke vertical stretching rig	Unidirectional nylon 6,6 fibre/polyester resin Fibre $V_f = 2.2\%$	<ul style="list-style-type: none"> ■ The increase in the absorbed impact energy was ~40% No deterioration in the acquired improvement was detected over a time-scale of ~25 years at 50°C
Zaidi et al. ⁷⁷	Tensile and flexural properties (EFPPMCs)	Screw tensioning frame	Flax yarn/polyester resin Fibre $W_f = 50\%$	<ul style="list-style-type: none"> ■ Fibre pretension could increase fibre-backing density and improve fibre alignment ■ Tensile strength and tensile modulus improved by 15% and 36% due to applying 0.03 prestrain, respectively ■ Flexural strength and flexural modulus improved by 34% and 26% due to applying 0.03 prestrain, respectively
Mostafa et al. ¹	Flexural properties (EFPPMCs)	Biaxial loading frame with hydraulic cylinder	Plain-weave E-glass fabric/polyester resin Fibreweight fraction Fibre $W_f = 16\%$	<ul style="list-style-type: none"> ■ Prestressing improved the flexural properties by ~16% (at 50 MPa optimum equibiaxial fabric prestressing) ■ Testing the samples at different off-axis orientation angles exhibited a reduction in the percentage improvement with increasing the fabric orientation angle towards the bias direction ■ A relatively low regression, less than 6%, in the flexural properties of the prestressed composite was indicated after 3 months of composite lifetime due to matrix creep
Mostafa et al. ⁶⁸	Tensile and fatigue properties (EFPPMCs)	Biaxial loading frame with hydraulic cylinder	Plain-weave E-glass fabric/polyester resin Fibre $V_f = 11\%$	<ul style="list-style-type: none"> ■ The optimum level of equibiaxial fabric prestress was 50 MPa when testing the samples under quasi-static tensile and tension-tension fatigue loading ■ Maximum increase in the fatigue life of the prestressed samples was 43% when compared with non-prestressed counterparts ■ The prestressed samples showed an improvement in their fatigue life when subjected to low or intermediate stress fatigue loading ■ The advantages of employing fabric prestressing was decreased gradually with increasing the off-axis fabric orientation angle from 0 to 45° relative to warp direction

PMC: polymeric matrix composite; EFPPMC: elastically fibre prestressed PMC; VEFPPMCs: viscoelastically fibre prestressed PMCs; V_f : volume fraction; W_f : weight fraction.

Table 2. Prestressing techniques and their limitations.

Prestressing techniques	Limitations
Dead weight	<ul style="list-style-type: none"> ■ Need for large scale weights
Notched bar (V-slot)	<ul style="list-style-type: none"> ■ Space limitations ■ Unknown level of pretension
Hydraulic cylinder	<ul style="list-style-type: none"> ■ Problems of fibre fracture ■ Problem of pressure drop caused by oil leakage for prolonged usage
Tensile testing machine	<ul style="list-style-type: none"> ■ Space limitations ■ Problems of split units
Filament winding	<ul style="list-style-type: none"> ■ Space limitations ■ Uncontrolled fibre volume fraction problem relative to fibre pretension
Forming moulds	<ul style="list-style-type: none"> ■ Mandrel thermal properties affect the level of fibre prestressing ■ Fibre shear deformation and wrinkle
Loaded screw	<ul style="list-style-type: none"> ■ Unknown prestressing level ■ The prestress level is not measured directly ■ Need for electronic facilities to analyze the electrical signal if using load cell; thereby wiring obstructions may arise

composites and the non-performed tests (pending). It is noteworthy to point out that the degree of improvements in the prestressed composite performance was also associated with the type and direction of loading. The list of the mechanical structural tests indicates there are some pending subjects that need to be investigated; however, some completed tests need more validations in order to be considered reliable.

The pie chart, shown in Figure 24, indicates the percent of all performed tests related to fibre prestressed composites. Tensile test seems clearly in the lead with ~32% of the total tests due to its importance to enrich many valuable mechanical properties. The slice denoted by "other" represents the collection of various studies and tests related to interlaminar shear strength, interface shear strength, shear properties, instability, free edge stresses, fatigue and compression.

Conclusions

This review article attempted to cover most studies related to fibre prestressing method and its developments. Initially, the fibre pretension method was used to decrease the fibre waviness and then after to detect and break the weak fibres before moulding it into the resin. Therefore, the structural properties of the final product were enhanced by eliminating the negative effect of weak fibre's existence. Subsequently, the idea of the fibre pretension was extended to include its benefits for obstructing the matrix cracking and its development. The focus was related directly to minimize the generated residual stresses during fabrication processes. The existence of tensile residual stress affects the composite structural performance directly and becomes

more detrimental when the composites are subjected to external loading than the unloaded ones during service life.

The interest in the subject began since 1968, which included structural properties like tensile modulus, tensile strength, flexural modulus, flexural strength, compressive modulus, compressive strength, fatigue and impact toughness. The overall effects of fibre pre-stressing on these structural properties were positive. Several mechanisms were attributed to enhance the PMC's structural properties. These mechanisms are (i) generating compressive residual stresses within the matrix upon releasing the fibre pretension and this makes the matrix more resistant to cracks initiation and propagation, (ii) improving the architecture of the yarns to become straighter and tighter, thereby the load is instantaneously transferred from matrix to the fibre, (iii) breaking the weaker fibres prior moulding process, (iv) adapting the composite to absorb more impact energy by increasing the fibre-matrix debonding damage and (v) creating a transverse force opposite to bending load. For various composite systems used in the previous studies, a maximum increase in the structural properties was recorded to range up to 10–60% (tensile modulus) and 15–140% (tensile strength), 10–50% (flexural modulus) and 10–67% (flexural strength), ~9% (compressive strength), 25–62% (impact strength) and 43–200% (fatigue life). Although fibre prestressing can significantly improve structural properties, there are potential disadvantages. In case of EFPPMCs type, the main disadvantages or restrictions are its complexity to apply for non-flat constructions, the applied prestress value is a function of plies number that formed the composite, need for

Table 3. The positive and negative aspects of elastically and viscoelastically prestressing method.

Prestressing type	Positive aspects	Negative aspects
EFPPMCs	<ul style="list-style-type: none"> ■ Can be performed to all commercially available types of fibres (synthetic and natural) ■ Can be applied in pre-impregnated composite fibres ■ Curing at elevated temperature is applicable 	<ul style="list-style-type: none"> ■ Restriction in fibre orientation ■ Applicable for only continuous fibres ■ Optimum fibre pretension depends on type of exerted loading and constituent materials of the composite ■ The products are not tested after a long period of service (viability) ■ Product geometry constraints ■ This type of prestressing comparatively seemed more complex
VEFPPMCs	<ul style="list-style-type: none"> ■ No geometrical constraints ■ Can be used for both continuous and chopped fibres. ■ The fibre prestressing and moulding stages are decoupled ■ Long fibre recovery time means long viability 	<ul style="list-style-type: none"> ■ Only fibres with viscoelastic behaviour can be used ■ Not suitable for applications at relatively high temperatures ■ To satisfy certain mechanical properties, comingled or hybrid fibre system may be used ■ The recovery force in viscoelastic fibre may be not enough, particularly for hard resin, to overcome the tensile residual stresses within the matrix

PMC: polymeric matrix composite; EFPPMC: elastically fibre prestressed PMC; VEFPPMCs: viscoelastically fibre prestressed PMCs.

Table 4. The accomplished and pending tests related to prestressed PMCs.

Type of fibre prestressing	Contributions of fibre prestressing on mechanical performance						
	Tensile	Compressive	Flexural	Impact and Toughness	Fatigue	Buckling	Wear
EFPPMCs	I ^a	I	I	I	I	Y	Y
VEFPPMCs	I	Y ^b	I	I	Y	Y	Y

PMC: polymeric matrix composite; EFPPMC: elastically fibre prestressed PMC; VEFPPMCs: viscoelastically fibre prestressed PMCs.

^aImproved.

^bYet unknown effect.

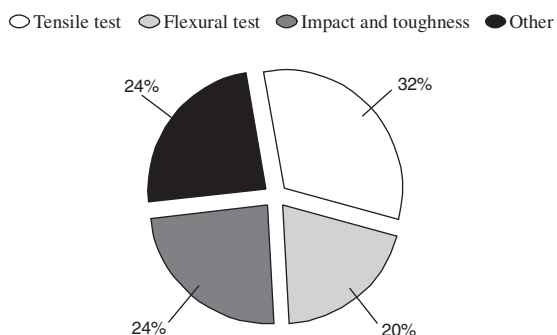


Figure 24. The percent ratios of performed tests of prestressed PMCs.

maintaining fibres stretched as the matrix cures and prestress effect could decline with time because of localised matrix creep effects near the fibre-matrix interface. On the other hand, the production of VEFPPMCs is not without drawbacks like the limitation of fibre materials offering viscoelastic behaviour and the viscoelastic recovery mechanism is highly affected by exposure temperature.

Different methodologies of fibre prestressing have been used during a half century to improve the structural performance of PMCs. Two basic mechanisms of fibre prestressing, elastically and viscoelastically, were adopted to improve the composite performance. Although the mentioned two mechanisms seem somewhat different in procedure, the objective is still the

same, which is a method for minimizing or removing the tensile residual stresses within the matrix.

In spite of the restrictions accompanied with the manufacturing processes of composites, the method of fibre prestressing seems comparatively less costed and offers a considerable enhancement in most structural properties of composites. Summarizing, this literature review illustrates the need for a few pending experimental tests to wind up the laboratory tests and moving toward modern composites manufacturing.

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References

- Mostafa NH, Ismarrubie ZN, Sapuan SM, et al. The influence of equi-biaxially fabric prestressing on the flexural performance of woven E-glass/polyester-reinforced composites. *J Compos Mater* 2015. DOI: 10.1177/0021998315620478.
- Andersson F, Hagqvist A, Sundin E, et al. Design for manufacturing of composite structures for commercial aircraft – the development of a DFM strategy at SAAB aerostructures. In: *Procedia CIRP, variety management in manufacturing - proceedings of the 47th CIRP conference on manufacturing systems*. Elsevier B.V., 2014, pp.362–367.
- Khan LA, Mahmood AH, Hassan B, et al. Cost-effective manufacturing process for the development of automotive from energy efficient composite materials and sandwich structures. *Polym Compos* 2014; 35: 97–104.
- Shokrieh M. *Residual stresses in composite materials*. Cambridge: Woodhead Publishing Limited, 2014.
- Parlevliet PP, Bersee HEN and Beukers A. Residual stresses in thermoplastic composites - a study of the literature. Part III: effects of thermal residual stresses. *Compos Part A Appl Sci Manuf* 2007; 38: 1581–1596.
- Motahhari S. *Fiber prestressed composites: a study of the influences of fibre prestressing on the mechanical properties of polymer matrix composites*. PhD Thesis, Queen's University, Kingston, Ontario, Canada, 1998.
- Krishnamurthy S. *Prestressed advanced fibre reinforced composites: fabrication and mechanical performance*. PhD Thesis, Engineering System Department, Defence College of Management and Technology, Cranfield University, UK, 2006.
- Zhao LG, Warrior NA and Long AC. A micromechanical study of residual stress and its effect on transverse failure in polymer–matrix composites. *Int J Solids Struct* 2006; 43: 5449–5467.
- Zhao L, Warrior NA and Long AC. Analysis of residual stress in fiber-reinforced polymer composite. In: *16th international conference on composite materials: a giant step towards environmental awareness: from Green Composites to Aerospace* (eds Kageyama K, Ishikawa T, Takeda N, et al.), Kyoto, Japan: Japan Society for Composite Materials (JSCM) and Japan Aerospace Exploration Agency (JAXA), 2007, pp.1–9.
- Abou Msallem Y, Jacquemin F and Poitou A. Residual stresses formation during the manufacturing process of epoxy matrix composites: resin yield stress and anisotropic chemical shrinkage. *Int J Mater Form* 2010; 3: 1363–1372.
- Mazumdar S. *Composites manufacturing: materials, product, and process engineering*. Boca Raton, FL, USA: CRC Press (Taylor & Francis Group, LLC), 2002.
- Kravchenko OG, Kravchenko SG and Byron PR. Residual cure stress buildup in thermosetting composites: modeling and experimental validation. In: *Proceedings of the American Society for Composites 2015 - thirtieth technical conference on composite materials* (eds Xiao X (Sharon), Loos A and Liu D). Lancaster, Pennsylvania, USA: DEStech Publications, Inc, 2015, pp.725–741.
- Cao Y and Cameron J. The effect of curing conditions on the properties of silica modified glass fiber reinforced epoxy composite. *J Reinf Plast Compos* 2007; 26: 41–50.
- Motahhari S and Cameron J. Fibre prestressed composites: improvement of flexural properties through fibre prestressing. *J Reinf Plast Compos* 1999; 18: 279–288.
- Fletcher AJ and Oakeshott JL. Thermal residual microstress generation during the processing of unidirectional carbon fibre/epoxy resin composites: random fibre arrays. *Composites* 1994; 25: 806–813.
- Fletcher AJ and Oakeshott JL. Thermal residual microstress generation during the processing of unidirectional carbon fibre/epoxy resin composites: regular fibre arrays. *Composites* 1994; 25: 797–805.
- Li M. *Temperature and moisture effects on composite materials for wind turbine blades*. MSc Thesis, Montana State University-Bozeman, Bozeman, Montana, USA, 2000.
- Knight CE. Orthotropic photoelastic analysis of residual stresses in filament-wound rings. *Exp Mech* 1972; 12: 107–112.
- Binienda WK and Wang Y. Residual stresses reduction in filament wound composite tubes. *J Reinf Plast Compos* 1999; 18: 684–701.
- Gabrys CW and Bakis CE. Simplified analysis of residual stresses in in-situ cured hoop-wound rings. *J Compos Mater* 1998; 32: 1325–1343.
- Mertiny P and Ellyin F. Influence of the filament winding tension on physical and mechanical properties of reinforced composites. *Compos Part A Appl Sci Manuf* 2002; 33: 1615–1622.
- Cohen D. Influence of filament winding parameters on composite vessel quality and strength. *Compos Part A Appl Sci Manuf* 1997; 28: 1035–1047.

23. Tabuchi D, Sajima T, Doi T, et al. Residual stress of hoop-wound CFRP composites manufactured with simultaneous heating. *Sensors Mater* 2012; 24: 99–111.
24. Jevons MP. *The effects of fibre pre-stressing on the impact performance of composite laminates*. PhD Thesis, Engineering Systems Department, College of Defence Technology, Cranfield University, UK, 2004.
25. Ashby MF and Jones DRH. *Engineering materials 1: an introduction to properties, applications, and design*, 4th ed. Oxford, UK: Elsevier Ltd, 2012.
26. Advani S and Hsiao K-T. *Manufacturing techniques for polymer matrix composites (PMCs)*, 1st ed. Cambridge, UK: Woodhead Publishing Limited, 2012.
27. Davis DC, Wilkerson JW, Zhu J, et al. A strategy for improving mechanical properties of a fiber reinforced epoxy composite using functionalized carbon nanotubes. *Compos Sci Technol* 2011; 71: 1089–1097.
28. Williams JC and Starke EA. Progress in structural materials for aerospace systems. *Acta Mater* 2003; 51: 5775–5799.
29. Hinton MJ, Kaddour AS and Soden PD (eds). *Failure criteria in fibre reinforced polymer composites: the worldwide failure exercise*. ELSEVIER B. The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK, 2004.
30. Ja Nairn. Matrix microcracking in composites. In: Talreja R and Manson JA (eds). *Polymer matrix composites*. Oxford: Elsevier Science Ltd, 2000, pp.403–432.
31. Myers DG. *Method for measurement of residual stress and coefficient of thermal expansion of laminated composites*. University of Florida, USA, 2004.
32. Talreja R and Singh CV. *Damage and failure of composite materials*, 1st ed. NY, USA: Cambridge University Press, 2012.
33. Cheng W and Finnie I. *Residual stress measurement and the slitting method*. New York, NY 10013, USA: Springer Science + Business Media, LLC, 2007.
34. Reinhart TJ. Overview of composite materials. In: Peters ST (ed.) *Handbook of composites*. Tonbridge, England: Springer Science + Business Media Donlrecht, 1998, pp.21–33.
35. White SR and Hahn HT. Cure cycle optimization for the reduction of processing-induced residual stresses in composite materials. *J Compos Mater* 1993; 27: 1352–1378.
36. Liu S-C. *Residual stress characterization for laminated composites*. PhD dissertation, University of Florida, 1999.
37. Hull D and Clyne TW. *An introduction to composite materials*, 2nd ed. NY, USA: Cambridge University Press, 1996.
38. Liu H. On steady-state fibre pull-out: II computer simulation. *Compos Sci Technol* 1999; 59: 2191–2199.
39. Warriar SG, Rangaswamy P, Bourke MaM, et al. Assessment of the fiber/matrix interface bond strength in SiC/Ti-6Al-4V composites. *Mater Sci Eng A* 1999; 259: 220–227.
40. Nath RB, Fenner DN and Galiotis C. Progressional approach to interfacial failure in carbon reinforced composites: Elasto-plastic finite element modelling of interface cracks. *Compos Part A Appl Sci Manuf* 2000; 31: 929–943.
41. Deve HE and Maloney MJ. On the toughening of intermetallics with ductile fibers: Role of interfaces. *Acta Metall Mater* 1991; 39: 2275–2284.
42. Nakamura T and Suresh S. Effects of thermal residual stresses and fiber packing on deformation of metal-matrix composites. *Acta Metall Mater* 1993; 41: 1665–1681.
43. Tsai J-L and Chi Y-K. Investigating thermal residual stress effect on mechanical behaviors of fiber composites with different fiber arrays. *Compos Part B Eng* 2008; 39: 714–721.
44. Huang ZM. Strength formulae of unidirectional composites including thermal residual stresses. *Mater Lett* 2000; 43: 36–42.
45. Jain LK and Mai Y-W. On residual stress induced distortions during fabrication of composite shells. *J Reinf Plast Compos* 1996; 15: 793–805.
46. Daynes S, Potter KD and Weaver PM. Bistable prestressed buckled laminates. *Compos Sci Technol* 2008; 68: 3431–3437.
47. Daynes S, Diaconu CG, Potter KD, et al. Bistable prestressed symmetric laminates. *J Compos Mater* 2010; 44: 1119–1137.
48. Ge C, Wang B and Fancey KS. Techniques to investigate viscoelastically generated prestress in polymeric composites. In: *10th international conference on composite science and technology, ICCST/10* (eds Araújo AL, Correia JR, Mota Soares CM), Lisbon, Portugal, 2015, pp.1–11.
49. Stamatoopoulos K. *Measurement of residual stresses in composite materials with the incremental hole drilling method*. Diploma Thesis, National Technical University of Athens, Greece, 2011.
50. Filiou C and Galiotis C. In situ monitoring of the fibre strain distribution in carbon-fibre thermoplastic composites, 1. Application of a tensile stress field. *Compos Sci Technol* 1999; 59: 2149–2161.
51. Talreja R. Fatigue damage mechanisms. In: Talreja R and Varna J (eds). *Modeling damage, fatigue and failure of composite materials*. Cambridge, UK: Woodhead Publishing, 2016, pp.25–39.
52. Madhukar MS, Genidy MS and Russell JD. A new method to reduce cure-induced stresses in thermoset polymer composites, part I: test method. *J Compos Mater* 2000; 34: 1882–1904.
53. Gopal AK, Adali S and Verijenko VE. Optimal temperature profiles for minimum residual stress in the cure process of polymer composites. *Compos Struct* 2000; 48: 99–106.
54. Kessler MR. *Advanced topics in characterization of composites*. Victoria, BC, Canada: Trafford Publishing, 2004.
55. Singh A. Radiation processing of carbon fibre-reinforced advanced composites B. *Nucl Instruments Methods Phys Res* 2001; 185: 50–54.
56. Korenev S. Electron beam curing of composites. *Vacuum* 2001; 62: 233–236.
57. Goodman D and Palmese G. Curing and bonding of composites using electron beam processing. In: Kulshreshtha AK and Vasile C (eds). *Handbook of polymer blends and composites, volume 1*. Shawbury, UK: Rapra Technology Ltd, 2002, pp.459–499.

58. Fu J, Liu W, Liu X, et al. Properties of a new dental photocurable resin based on the expanding monomer and three-component photoinitiator system. *J Wuhan Univ Technol Sci Ed* 2014; 29: 384–390.
59. Alcoutlabi M, Mckenna GB and Simon SL. Analysis of the development of isotropic residual stresses in a bis-maleimide/spiro orthocarbonate thermosetting resin for composite materials. *J Appl Polym Sci* 2003; 88: 227–224.
60. Shimbo M, Ochi M, Inamura T, et al. Internal stress of epoxide resin modified with spiro ortho-ester type resin. *J Mater Sci* 1985; 20: 2965–2972.
61. Vizzini A and Orso J. The effects of an expanding monomer on the tensile properties of graphite/epoxy. *J Compos Technol Res* 1994; 16: 270–274.
62. Psarras GC, Parthenios J and Galiotis C. Adaptive composites incorporating shape memory alloy wires, Part I: Probing the internal stress and temperature distributions with a laser Raman sensor. *J Mater Sci* 2001; 36: 535–546.
63. Murasawa G, Tohgo K and Ishii H. Deformation behavior of NiTi/polymer shape memory alloy composites - experimental verifications. *J Compos Mater* 2004; 38: 399–416.
64. Naghashian S, Fox BL and Barnett MR. Actuation curvature limits for a composite beam with embedded shape memory alloy wires. *Smart Mater Struct* 2014; 23: 1–10.
65. Parthenios J, Psarras GC and Galiotis C. Adaptive composites incorporating shape memory alloy wires. Part 2: development of internal recovery stresses as a function of activation temperature. *Compos Part A Appl Sci Manuf* 2001; 32: 1735–1747.
66. Potter K. *Introduction to composite products - design, development and manufacture*, 1st ed. London, UK: Chapman & Hall, 1997.
67. Tuttle ME. A mechanical/thermal analysis of prestressed composite laminates. *J Compos Mater* 1988; 22: 780–792.
68. Mostafa NH, Ismarrubie ZN, Sapuan SM, et al. Effect of fabric biaxial prestress on the fatigue of woven E-glass/polyester composites. *Mater Des* 2016; 92: 579–589.
69. Fancey KS. Prestressed polymeric composites produced by viscoelastically strained nylon 6,6 fibre reinforcement. *J Reinf Plast Compos* 2000; 19: 1251–1266.
70. Fancey KS and Fazal A. Prestressed polymeric matrix composites: longevity aspects. *Polym Compos* 2015. DOI: 10.1002/pc.23387.
71. Fancey KS. Prestressed polymeric composites: an alternative approach. In: *10th international conference on composite science and technology, ICCST/10* (eds Araújo AL, Correia JR and Mota Soares CM), 2015, pp.1–12.
72. Mills GJ and Dauksys RJ. Effects of prestressing boron/epoxy prepreg on composite strength properties. *AIAA J* 1973; 11: 1459–1460.
73. Brown G. *Development of prestressed graphite processing techniques*. USA: Space Division, North American Rockwell, 1976.
74. Chi Z and Chou T. An experimental study of the effect of prestressed loose carbon strands on composite strength. *J Compos Mater* 1983; 17: 196–209.
75. Piggott MR. The effect of fibre waviness on the mechanical properties of unidirectional fibre composites: a review. *Compos Sci Technol* 1995; 53: 201–205.
76. Potter K, Khan B, Wisnom M, et al. Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures. *Compos Part A Appl Sci Manuf* 2008; 39: 1343–1354.
77. Zaidi BM, Magniez K and Miao M. Prestressed natural fibre spun yarn reinforced polymer-matrix composites. *Compos Part A Appl Sci Manuf* 2015; 75: 68–76.
78. Pan N. Analysis of woven fabric strengths: prediction of fabric strength under uniaxial and biaxial extensions. *Compos Sci Technol* 1996; 56: 311–327.
79. Potluri P and Thammandra VS. Influence of uniaxial and biaxial tension on meso-scale geometry and strain fields in a woven composite. *Compos Struct* 2007; 77: 405–418.
80. Bekampienė P, Domskienė J and Širvaitienė A. The effect of pre-tension on deformation behaviour of natural fabric reinforced composite. *Mater Sci* 2011; 17: 56–61.
81. Cao Y and Cameron J. Flexural and shear properties of silica particle modified glass fiber reinforced epoxy composite. *J Reinf Plast Compos* 2006; 25: 347–359.
82. Cao Y and Cameron J. Impact properties of silica particle modified glass fiber reinforced epoxy composite. *J Reinf Plast Compos* 2006; 25: 761–769.
83. Dvorak GJ and Prochazka P. Thick-walled composite cylinders with optimal fiber prestress. *Compos Part B Eng* 1996; 27: 643–649.
84. Srinivas MV, Dvorak GJ and Prochazka P. Design and fabrication of submerged cylindrical laminates-II. effect of fiber pre-stress. *Int J Solids Struct* 1999; 36: 3917–3943.
85. Dvorak GJ and Suvorov AP. The effect of fiber pre-stress on residual stresses and the onset of damage in symmetric laminates. *Compos Sci Technol* 2000; 60: 1129–1139.
86. Scherf J and Wagner HD. Interpretation of fiber fragmentation in carbon/epoxy single fiber composites: possible fiber pre-tension effects. *Polym Eng Sci* 1992; 32: 298–304.
87. Širvaitienė A, Jankauskaitė V, Bekampienė P, et al. Vegetable fiber pre-tensioning influence on the composites reinforcement. *Polym Compos* 2013; 34: 1533–1537.
88. Širvaitienė A, Jankauskaitė V, Bekampienė P, et al. Influence of natural fibre treatment on interfacial adhesion in biocomposites. *Fibres Text East Eur* 2013; 100: 123–129.
89. Zhao J and Cameron J. Polypropylene matrix composites reinforced with pre-stressed glass fibers. *Polym Compos* 1998; 19: 218–224.
90. Fazal A and Fancey KS. Performance enhancement of nylon/kevlar fiber composites through viscoelastically generated pre-stress. *Polym Compos* 2014; 35: 931–938.
91. Fazal A and Fancey KS. UHMWPE fibre-based composites: prestress-induced enhancement of impact properties. *Compos Part B Eng* 2014; 66: 1–6.
92. Fazal A and Fancey KS. Viscoelastically prestressed polymeric matrix composites – effects of test span and fibre volume fraction on Charpy impact characteristics. *Compos Part B Eng* 2013; 44: 472–479.
93. Fazal A and Fancey KS. Viscoelastically generated prestress from ultra-high molecular weight polyethylene fibres. *J Mater Sci* 2013; 48: 5559–5570.
94. Pang JWC and Fancey KS. Analysis of the tensile behaviour of viscoelastically prestressed polymeric matrix composites. *Compos Sci Technol* 2008; 68: 1903–1910.

95. Pang JWC and Fancey KS. An investigation into the long-term viscoelastic recovery of Nylon 6,6 fibres through accelerated ageing. *Mater Sci Eng A* 2006; 431: 100–105.
96. Pang JWC and Fancey KS. The flexural stiffness characteristics of viscoelastically prestressed polymeric matrix composites. *Compos Part A Appl Sci Manuf* 2009; 40: 784–790.
97. Motahhari S and Cameron J. Impact strength of fiber pre-stressed composites. *J Reinf Plast Compos* 1998; 17: 123–130.
98. Fancey KS. Investigation into the feasibility of viscoelastically generated pre-stress in polymeric matrix composites. *Mater Sci Eng A* 2000; 279: 36–41.
99. Heckel RW, Zaehring RJ and Cheskis HP. *Optimization of the range of elastic behavior of unidirectional composites by prestraining*. Pittsburgh, PA: Office of Naval Research, 1972.
100. Cui HX, Guan MJ, Zhu YX, et al. The flexural characteristics of prestressed bamboo slivers reinforced parallel strand lumber (PSL). *Key Eng Mater* 2012; 517: 96–100.
101. Sui GX, Yao G and Zhou BL. Effects of prestrain on the fatigue of VIRALL laminate properties. *Compos Sci Technol* 1996; 56: 929–932.
102. Hadi AS and Ashton JN. On the influence of pre-stress on the mechanical properties of a unidirectional GRE composite. *Compos Struct* 1998; 40: 305–311.
103. Tuttle ME, Koehler RT and Keren D. Controlling thermal stresses in composites by means of fiber prestress. *J Compos Mater* 1996; 30: 486–502.
104. Sadiq A. *The effect of fiber pre-tension on the static and dynamic behavior of composite plates*. PhD Thesis, Machines and Equipments Engineering, University of Technology, Iraq, 2007.
105. Schlichting LH, de Andrada MAC, Vieira LCC, et al. Composite resin reinforced with pre-tensioned glass fibers. Influence of prestressing on flexural properties. *Dent Mater* 2010; 26: 118–125.
106. Schulte K and Marissen R. Influence of artificial prestressing during curing of CFRP laminates on interfibre transverse cracking. *Compos Sci Technol* 1992; 44: 361–367.
107. Rohen L, Margem F, Neves A, et al. Izod impact test in epoxy matrix composites reinforced with hemp fiber. In: Carpenter J, Bai C, Escobedo-Diaz J, et al (eds) *Characterization of minerals, metals, and materials 2015*. Walt Disney World, Orlando, FL: John Wiley & Sons, Inc., Hoboken, New Jersey, 2015, pp.557–562.
108. McMahon PE and Ying L. *Effect of fiber/matrix interactions on the properties of graphite/epoxy composites*. USA: National Aeronautics and Space Administration (NASA), Scientific and Technical Information Branch, NASA Contractor Report 3607, 1982.
109. Fancey KS. Viscoelastically prestressed polymeric matrix composites – potential for useful life and impact protection. *Compos Part B Eng* 2010; 41: 454–461.
110. Wang B and Fancey KS. Towards optimisation of load-time conditions for producing viscoelastically prestressed polymeric matrix composites. *Compos Part B Eng* 2015; 87: 336–342.
111. Zhigun IG. Experimental evaluation of the effect of prestressing the fibers in two directions on certain elastic characteristic of woven-glass reinforced plastics. *Polym Mech* 1968; 4: 691–695.
112. Manders PW and Chou T. Enhancement of strength in composites reinforced with previously stressed fibers. *J Compos Mater* 1983; 17: 26–44.
113. Jorge LDA, Marques AT and De Castro PMS. The influence of prestressing on the mechanical behaviour of uni-directional composites. In: *Developments in the science and technology of composite materials, fourth European conference on composite materials*. Füller J, Grüniger G, Schulte K, et al. (eds). Stuttgart, Germany: Springer Netherlands, 1990, pp.897–902.
114. Nishi Y, Okada T, Okada S, et al. Effects of tensile prestress level on impact value of 50 vol% continuous unidirectional 0 degree oriented carbon fiber reinforced epoxy polymer (CFRP). *Mater Trans* 2014; 55: 318–322.
115. Motahhari S and Cameron J. Measurement of micro-residual stresses in fiber-prestressed composites. *J Compos Mater* 1997; 16: 1129–1137.
116. Wang B and Fancey KS. Shape-changing (bistable) composites based on viscoelastically generated prestress. In: *10th international conference on composite science and technology, ICCST/10*. Araújo AL, Correia JR, Mota Soares CM (eds), Lisbon, Portugal, 2015, pp.1–9.
117. Sui GX, Yao G and Zhou BL. Influence of artificial prestressing during the curing of VIRALL on its mechanical properties. *Compos Sci Technol* 1995; 53: 361–364.
118. Suvorov AP and Dvorak GJ. Optimal design of prestressed laminate/ceramic plate assemblies. *Meccanica* 2001; 36: 87–109.
119. Jevons MP, Fernando GF and Kalsi GS. Effect of pre-tensioning on the low velocity impact performance of glass fibre composites. In: *Tenth European conference on composite materials (ECCM-10)*. Brugge, Belgium, 2002.
120. Krishnamurthy S, Badcock RA, Fernando GF, et al. Novel prestress methodology for autoclave processing of composites: fabrication and mechanical performance. In: *50th international symposium, society for the advancement of material and process engineering; SAMPE 2005*. Long Beach, California, USA: New Horizons for Materials and Processing Technologies, 2005, pp.2043–2055.
121. Parlevliet PP, van der Werf WAW, Bersee HEN, et al. Thermal effects on microstructural matrix variations in thick-walled composites. *Compos Sci Technol* 2008; 68: 896–907.
122. Kannan M, Kalaichelvan K and Sornakumar T. Development and mechanical testing of filament wound FRP composite components. *Appl Mech Mater* 2015; 787: 578–582.
123. Schlottermueller M, Schledjewski R and Mitschang P. Influence of process parameters on residual stress in thermoplastic filament-wound parts. *J Mater Des Appl* 2004; 218: 157–164.

124. Schlottermuller M, Lu H, Roth Y, et al. Thermal residual stress simulation in thermoplastic filament winding process. *J Thermoplast Compos Mater* 2003; 16: 497–519.
125. Lu H. Effects of tape tension on residual stress in thermoplastic composite filament winding. *J Thermoplast Compos Mater* 2005; 18: 469–487.
126. Xu J, Miao Y, Qiao M, et al. Tension design of heated-mandrel winding process based on analytical algorithm. *J Reinf Plast Compos* 2014; 33: 1529–1541.
127. Dvorak GJ, Prochazka P and Srinivas MV. Design and fabrication of submerged cylindrical laminates–I. *Int J Solids Struct* 1999; 36: 3917–3943.
128. Suvorov AP and Dvorak GJ. Stress relaxation in prestressed composite laminates. *J Appl Mech* 2002; 69: 459–469.
129. Sapuan SM. *Concurrent engineering for composites*, 1st ed. Selangor: Universiti Putra Malaysia, 2010.