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Review of hybrid composites fatigue

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ABSTRACT

Hybrid composites become popular and are today used in a large number of contemporary structural applications. When compared to non-hybrid composites, hybridization offers additional benefits since the mixing of cheaper, low-quality fibers, with more expensive fibers of higher quality can improve the properties of a composite without significantly affecting the cost. Among of improvements resulted from the hybridization is the fatigue behavior, although this has not yet been thoroughly investigated for a wide range of hybrid composites. This review article summarizes and discusses the existing works on the fatigue behavior of synthetic and natural fiber reinforced (FRP) hybrid composites, as well as fiber metal laminates (FMLs).

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1. Introduction

Fiber reinforced polymeric (FRP) composites have been used since the last 6 to 7 decades in a wide range of applications including aerospace, marine, civil engineering, sports, wind energy automotive, medicine, electronics and other scientific domains. Synthetic fibers such as glass, carbon and Kevlar, reinforced with polymeric resins are used in light-weight designs, offering better specific stiffness, specific strength, and fatigue life when compared to conventional materials such as steel and concrete [1-4]. The concept is very simple and goes back in time; combining a strong material (the fiber) and a soft material (the resin/-matrix) to produce a composite material with properties limited between those of the constituents. Although this approach brings several advantages, it also has disadvantages. Fiber reinforced composites exhibit linear behavior until the peak load and fails abruptly in a brittle manner without any prior failure indication. On top of this, low-cost composites (e.g., glass fiber reinforced polyesters) have certain property limitations, whereas composites with higher quality and better properties are very expensive for certain applications. To overcome these and other disadvantages, the concept of "composite-composites" has been invented in the late 1970 s based on the hybridization of different fiber types in the same resin [5-8]. Usually two different types of fibers are used, and with a proper design, the synergetic effects of strength, stiffness and toughness of both can be achieved. This positive effect of hybridization is usually known as the "hybrid effect" [7,9,10]. Hybrids are produced, attempting to reduce the cost of composites with expensive reinforcements by incorporating a proportion of cheaper, low-quality fibers without significantly reducing the pristine composite properties. On the other hand, hybrids are implemented in structures in order to improve the properties of a composite by judiciously placing the high quality fibers, without significantly affecting the cost [9]. The reinforcement fibers can be similar or dissimilar. Similar fibers are those of the same material but with different sizes and properties, e.g., high and low stiffness carbon fibers used in [9], while dissimilar fibers are those made from different materials, e.g., glass fibers with carbon fibers shown in [11]. Typical structural examples showing the usefulness of hybrid composites are the contemporary, (very) long wind turbine rotor blades, reaching >100 m [12] and reaching 50 tons [13,14] of weight. To reduce the weight of such massive structures and keep the cost in reasonable limits, carbon fibers were locally reinforced with glass fibers in the hybrid composite blades [12]. In other applications, Kevlar fibers are combined with carbon fibers to increase the toughness and the damage tolerance. Recent development in nano-materials advances the hybridization scale from the micro to the nano level offering outstanding material properties [15,16]. In these type of composites, micro/nano veils or mats are introduced in composite interlayers for better interlaminar fracture toughness, a critical material property to resist delamination [7,10,17-19].

Most of the applications using hybrid composites are operating under fatigue loading and subjected to a high number of fatigue cycles during their lifetime. Actually, it is well documented that the most common failure mechanism in typical engineering components is fatigue or other fatigue related mechanisms [20-23]. Fatigue of hybrid composites has been investigated, although not consistently, since their appearance in the early 1970s. Initial investigations, e.g. [7,24-27], attempted to reveal whether fatigue behavior of hybrid composites was better than a linear mixture of the constituent materials' fatigue behavior. In general, it was found that a careful material architecture design can produce hybrid composites with improved fatigue properties compared to their constituents [27]. A benefit in fatigue life can be achieved if fibers with different failure strains are combined as the less stiff fibers, preventing further rapid crack extension from the stiffer fibers and this leads to a slower fatigue damage growth and enhances fatigue life [9].

However, the fatigue response of hybrid composites was not extensively investigated yet, as several specific topics have been overlooked in the past. As shown in the review of fiber-reinforced polymer composite laminate fatigue presented in [20], the evolution of the fatigue stiffness of composites, adhesively bonded composite joints, and structural adhesives, and that of the hysteresis loop area, have attracted the attention of several researches in the past, e.g., [28-32], although received much less attention for hybrids [21]. The same holds true for the investigation of the fatigue failure modes. Failure of composite materials is a gradual process involving different damage mechanisms that can interact with each other [33]. This damage development becomes more complicated for hybrid composites [21]. In addition, the fatigue behavior of pseudo-ductile hybrid composites has not been sufficiently explored yet, although first reports, e.g., [9,34] shown that catastrophic fatigue failure can be avoided by hybridization.

Only a limited number of works exist on the fatigue performance of hybrid composites in the literature and to the authors' knowledge, no review article exists on this topic. This review article summarizes the literature on the pseudo-ductility, quasi-static and fatigue performance of fiber reinforced (FRP) hybrid composites and fiber metal laminates (FMLs) and presents the effects of different hybridization types, processing techniques and environmental loadings on hybrid composites' performance. Experimental data from several independent research groups are also congregated and compared for facilitating material design process.

2. Pseudo-ductile behavior of hybrid FRPs

In this section, the importance of Pseudo-ductility of hybrid composites, the mechanism and the associated terminologies are briefly described. Hybrid composites (HCs) generally exhibit a "Pseudo-ductile" [9,35-45] behavior, showing a gradual failure development in contrast to the catastrophic failure, usually observed in non-hybrid composites. Pseudo-ductility can be achieved by designing the hybrid composites with proper proportion of low strain fibers (LSF) and high strain fibers (HSF). Improper design could lead to premature failure of HCs resulting lower strength than their pristine counter-parts. The mechanical behavior of pristine and hybrid composites and the corresponding failure mechanism is briefly described in Fig. 1. The black dashed line, 'a' shows the tensile behavior of a high strength and stiffness, brittle unidirectional fiber reinforced composite that fails catastrophically at a very low strain. The green dashed line, 'c' shows the behavior of a high strain fiber reinforced composite that possess low stiffness but high failure strain. The blue solid line, 'b' refers to a typical pseudo-ductile behavior of hybrid composite. The initial linear behavior of the hybrid composites can be described by the initial modulus (E_i) where the load transfer occurs between low strain fibers (LSF) and high strain fibers (HSFs) until the pseudo yield point, b_1. The corresponding stress and strain values of point b_1 are known as pseudo yield strain (ε_{py}) and pseudo yield stress (σ_{py}). After b_1, a slight drop in the stress shows the fragmentation of LSFs at multiple sites (some designs can have stress plateau region in between b_1 and b_2) and further loading leads to stable delamination of the LSFs from the HSFs. In case of higher strain rate loading, the second rising region (b_3) can be noticed [46]. Finally, the pull out of LSF leads to a complete failure of the composite at b_4. Pseudo-ductile strain (ε_{pd}) is measured as a strain range between the extended initial slope from b_1 and the final failure strain at b_4. Improvement of any of the above discussed properties is part of the hybridization objectives. As vivid from Fig. 1, hybrid composites can benefit from the advantages of both high strength/stiffness and low strength/stiffness composite constituents.

Carbon fiber reinforced polymer composites (CFRP) often fail catastrophically without any warning leaving less or no time for repair and maintenance. The hybrid composites offer pseudo ductility

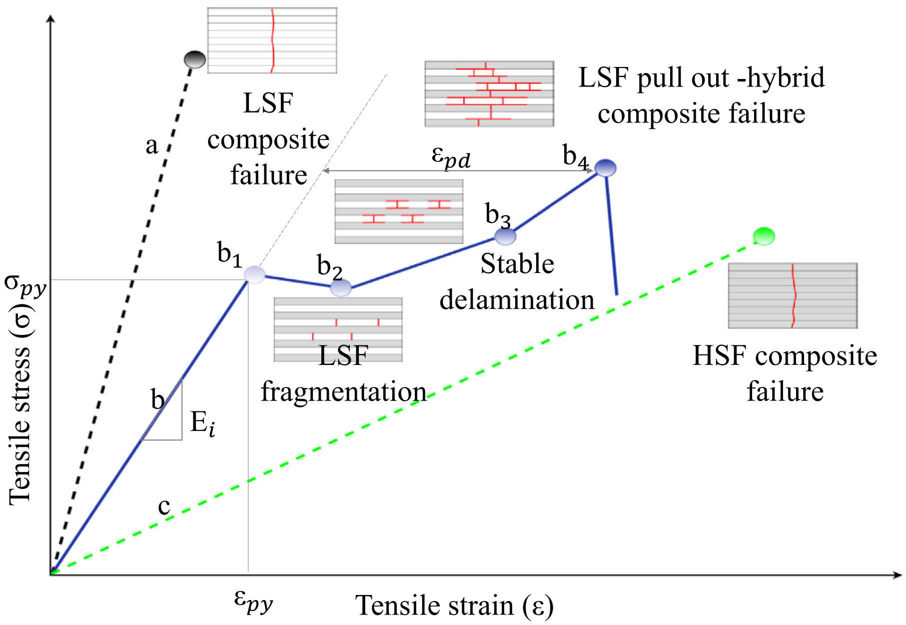


Fig. 1. Typical tensile behavior of pristine and hybrid fiber reinforced polymeric composites.

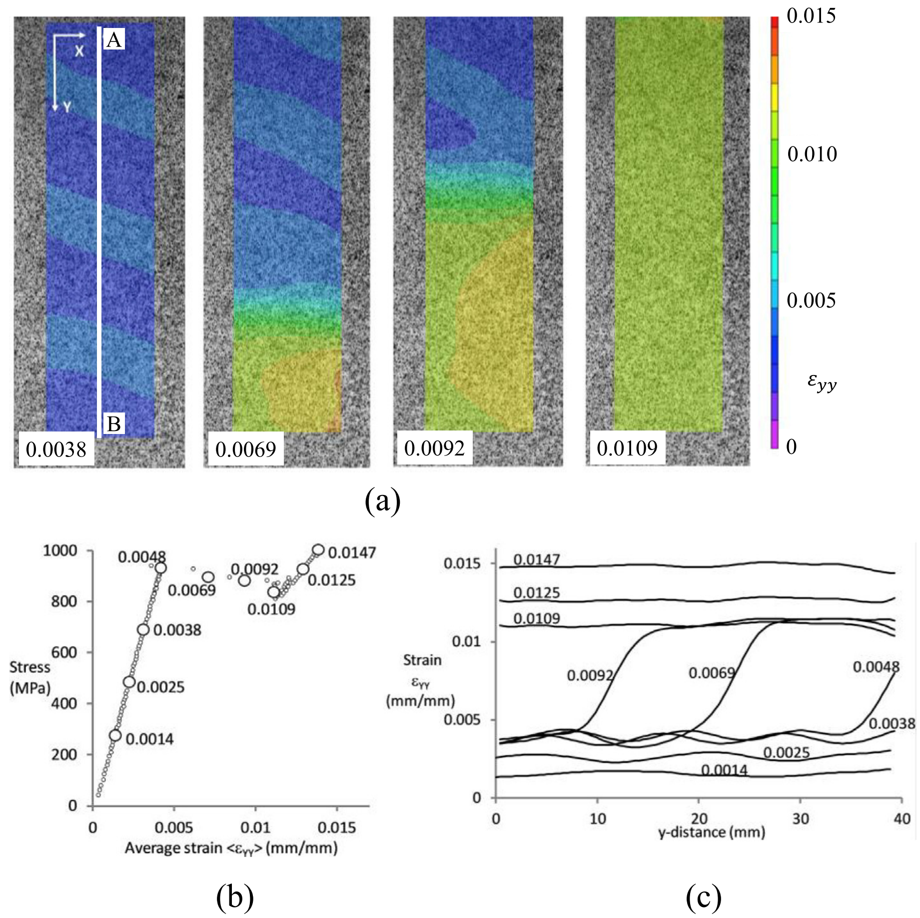
however, a major drop in load can be noticed post LSF fragmentation [47]. This can be overcome with thin-ply hybrid composites made by similar fibers with different diameter or modulus [39,47,48], resulting to more stable fragmentation and delamination of high modulus (HM) fibers in the hybrid composites. A plateau of the stress strain curve followed by a higher pseudo yield stress (like in metals) and further rise in stress before final failure can be observed [47]. Czel et al. [9,39,48] investigated the behavior of a pseudo-ductile all-carbon/epoxy unidirectional hybrid composite in which the central high modulus carbon plies fragmented and delaminated steadily from the outer high strength carbon plies under uniaxial tensile loading. Although the initial modulus, E_i was increased between 12% and 71%, the pseudo stress (from 990 MPa to 1400 MPa) and pseudo strain (from 0.4% to 0.83%) decreased in a quadratic manner. Prato et al. [49] conducted low velocity impact and indentation tests in angle- thin ply hybrid CFRP composites. Further tensile loading of the impact and indentation damaged composites revealed that their local pseudo-ductility can be retained. Fig. 2(a) shows surface digital image correlation (DIC) full-field strain results for a $[T_2/D/T_2]_2$ laminate where the pseudo-ductility resulting from the stable delamination of D layer [35]. The T-layer is a high modulus T800, carbon prepreg whereas the D-layer is a low modulus DIALEAD prepreg – an ultra-high modulus pitch-based carbon fiber. Fig. 2(b) shows the stress–strain curve marked with discrete average strain values corresponding to the DIC images. The variation of the axial strain, ε_{YY} along the center line (refer line AB in Fig. 2(a), $|AB| = 39$, $y = 0$ at the point A) can be seen in Fig. 2(c). The pale green and yellow colored region in the full-field strain (ε_{YY}) distribution images (Fig. 2(a)) shows the transition of elastic behavior into pseudo-ductile (in between 0.0048 mm/mm and 0.0109 mm/mm).

3. Hybridization methods in FRPs and FMLs

Hybrid composites can be derived by combining similar or dissimilar fibers with different modulus and/or diameter, with those been made by using dissimilar fibers, such as a combination of glass/carbon, Kevlar/carbon and natural fibers/glass been the most popular hybrids. Apart from the fiber material, the fiber type (continuous, short and woven) and placement (interlayer, intralayer and intra-yarn) is also considered in hybridization procedures. In addition to the polymeric composite layers, metallic layers or foils can be cured with or without adhesives, to form the so-called fiber-metal laminates (FMLs). The different hybridization types and hybrid material configurations based on the reinforcement material, type and arrangement are illustrated in Fig. 3(a). Hybridization can be realized by placing the different forms of fibers in the interply (as discrete lamina) or intraply/intrayarn [50] (in the same layer) or intermingled region where the fibers are intimately mixed (refer Fig. 3(b)).

Different types of hybrid composites were developed in the past by combining different fibers such as glass/carbon [34,52-56], Kevlar/carbon [57-60], Kevlar/glass [61-66], synthetic/natural fibers [67-77] to improve the material properties and/or reduce the cost. Jute, kenaf, hemp, bamboo, flax, basalt, sisal, palm and coir fibers were commonly reinforced with glass fibers to improve the strength and stiffness of natural fiber reinforced composites. Table 1 lists the tensile strength and failure strain of structural synthetic fibers that could assist the selection of the right combination of LSF and HSF, according to the required hybrid properties.

Use of light-weight materials, like high strength aluminum alloys and FRPs can improve the cost effectiveness of a structure. However, aluminum alloys have poorer fatigue crack resistance compared to FRPs, while on the contrary, polymeric composites possess poor impact and residual strength properties [79]. Certain disadvantages of these individual materials can be overcome however, by forming hybrid fiber-metal laminate (FML) materials. FMLs offer high strength, impact and fatigue resistance and therefore they are commonly used in modern aircraft components such as wings, fuselage skins and in sandwich structures as face sheets. Generally, thin sheets of aluminum alloy are used in FMLs along with glass, Kevlar or carbon fibers. They are accordingly known as GLARE (Glass ALuminum Reinforced Laminates), ARALL, (ARamid-fiber-reinforced-polymer/ALuminum Laminates) and CARALL, (CArbon Reinforced ALuminum Laminates). The thin metal sheets laminated with adhesives could offer a better crack growth resistance than a thick monolithic sheet. The major drawback of the FMLs is the long processing time to cure the epoxy in the composite. Alternatively, thermo-forming process is a one-step adhesion of thermoplastic composite with metallic layers that reduces the curing cycle time without any penalty in the quality [80].



(a)

(b)

(c)

Fig. 2. $[T_2/D/T_2]_2$ hybrid composite under tension: (a) DIC images showing the transition of elastic behavior into pseudo-ductile, (b) stress–strain diagram and (c) Variation of the axial strain, ε_{YY} [35].

4. Quasi-static performance of hybrid composites

In this section, the effect of interply, intraply and intermingled hybridization on the quasi-static performance of synthetic and natural fiber composites is reviewed. Finally, the tensile strength and tensile modulus data collected from different studies is plotted for aiding material selection process.

4.1. Interply hybrid composites

Interply or interlayer hybrid composites consist of layers, where two or more homogenous reinforcements are stacked as individual laminae. Interply hybridization is a relatively simple technique of manufacturing hybrid composites and the resulting properties depend on various parameters such as fiber volume fraction of low strain fiber, bonding interface, lay-up configuration and the processing conditions. Thanks to the simplicity in manufacturing, interply hybridization realized by hand lay-up was used in civil engineering applications [9,45,81]. The bonding interface between the different fiber layers is critical in stabilizing the delamination post pseudo-yielding, as weak bonding interface can lead to a sudden load drop after the pseudo-yield point as observed in carbon/glass hybrid composites [6]. Hassani et al. [82] managed to achieve pseudo-ductile behavior in glass fiber reinforced polypropylene composites through self-reinforced polypropylene (SRPP) plies with different hybrid fiber volume ratio. SRPP plies stacked in the outer surfaces showed more stable failure behavior and higher tensile strength than inner stacking that can be explained by the presence of curing induced compressive thermal residual stresses. All the hybrid designs failed at a lower load than SRPP composites due to higher volume of SRPP plies (>80%). Additionally, Belgacem et al. [83] reported that increasing the volume of glass fibers in the interply hybrid laminates (glass/carbon/epoxy) decreases the mechanical performance. Similarly, other researchers [54,84,85], also substantiated the effect of stacking sequences and hybrid fiber volume in glass/carbon composites and for various loading conditions. For example, hybrid composites having carbon plies in the surface provide higher bending stiffness and flexural strength whereas the alternating carbon/glass lay-up withstands higher compressive loads. Taketa et al. [86] enhanced the impregnation quality of interply hybrid composites with carbon fiber reinforced polypropylene and SRPP that increased the tensile strength by 7 % to 18%.

4.2. Intraply hybrid composites

Intraply or intralayer hybridization is realized by mixing the tows of dissimilar fibers or aligned discontinuous fibers in the same layer. Intraply hybridization yields a better mixture of hybrid fibers as compared to other types, however, it requires advanced weaving techniques [87]. Rajpurohit et al. [88] investigated the effect of interply and intraply hybridization on the tensile and the compressive properties of carbon/glass/epoxy composite laminates. As compared to interply composites, the stiffness of intraply composites was usually higher both in tension and compression – differences of ca. 17% and 9% were reported in Rajpurohit et al. [88] under tensile and compressive loading, respectively. Additionally, the tensile and compressive strength of intraply composites estimated higher than that of interply by 17.8%

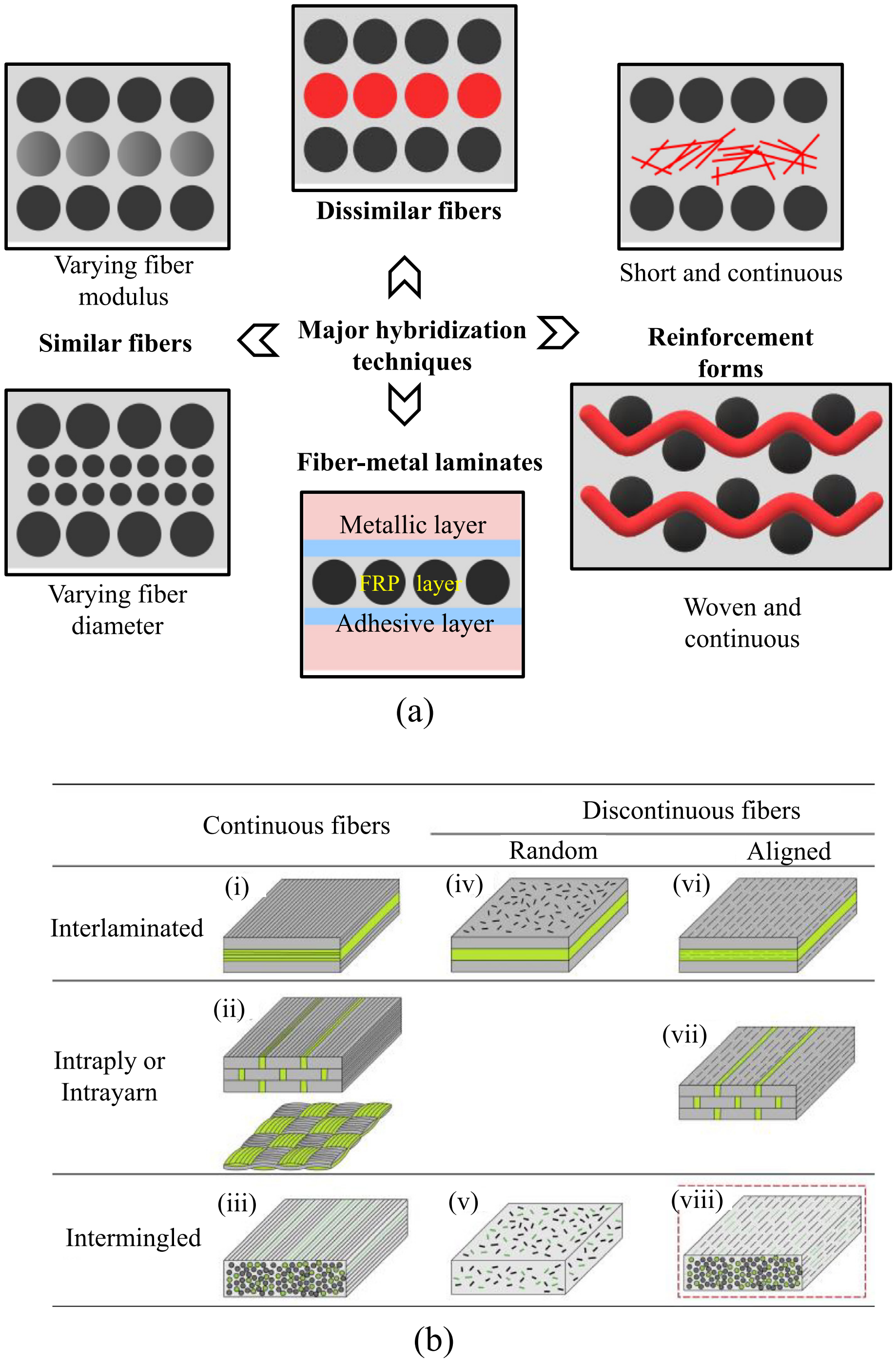


Fig. 3. Hybridization methods: (a) schematic representation of different hybridization methods and (b) based on hybrid fibers form and placement [51].

Table 1
Typical tensile properties of synthetic fibers used in structural applications [78].

Fiber type	Tensile strength (MPa)	Failure strain (%)
High-modulus carbon fiber	3500–5500	0.1–1.0
High-strength carbon fiber	3500–4800	1.5–2.0
S-glass fiber	3500	4.5
E-glass fiber	4600	5.0
Kevlar-49 fiber	3000	2.8

and 39.6%. However, pseudo-ductility was not observed in the stress-–strain behavior of any material configurations.

Similarly, the effect of interply and intraply hybridization in E-glass and poly-vinyl alcohol (PVA) woven fabric composites prepared with different hybrid fiber volume fractions was studied by Pegoretti et al. [89]. By comparing pristine GFRPs, the failure strain of the interply composites (having glass fibers in the middle) can be improved by a maximum of 42.1%, with a small decrease of 5.9% in peak tensile stress. In case of the intraply composites, there was no increase in the tensile load following the initial peak load but showed better impact resistance (charpy) and ductility index as compared with the interply configuration, showing that pseudo ductility was more prevalent in the interply hybridization than in the intraply configuration. The hybrid effect of basalt fibers with carbon and Kevlar fibers was investigated by Pan et al. [90]. The tensile failure strain of carbon/basalt and Kevlar/basalt hybrid composites were increased up to 65% and 80% respectively, that is higher than the failure strain of basalt composite, although no explanation was provided in the study to explain this behavior.

4.3. Intermingled hybrid composites

Intermingled hybrid composites refer to those hybrids having dissimilar continuous or discontinuous fibers, randomly mixed (see Fig. 1(c)). Continuous fibers can be intermingled using air assisted tow spreading and commingling technique where the as-received tows' width was increased by 3 to 4 times before mingling. Hybrid CFRPs comprising T700 and IM7 fibers composites were fabricated using this technique and showed more gradual tensile failure and 14% increase in the failure strain as compared to low-strain fiber reinforced composites [91]. Filament winding technique can be also employed to develop uniformly distributed intermingling hybrid composites with continuous fibers. Gruber et al. [92] used this technique in which the glass and Kevlar filament rovings at different fiber volume ratios were guided through the steel pins. The transverse tensile and shear modulus of composites (as a function of Kevlar fiber volume ratio) were found between the upper and lower bound curves whereas the longitudinal tensile modulus was above the upper bound. No explanation was provided in Taketa et al. [86] to justify this behavior and the tensile strength values were not reported in the study to analyze the hybrid effect on the strength.

Developing randomly distributed hybrid short fiber reinforced composites is relatively simple as it involves only chopping of short fibers with a length of few millimeters and randomly mixing without any alignment. This type of hybrid composites however, cannot be used in primary load carrying structures due to their inferior material properties. For example, short glass and banana fibers mixed with polystyrene resin achieved a maximum tensile strength of 40 MPa and Young's modulus of 1.6 GPa [93]. On the other hand, the discontinuous fibers can be aligned and hybridized with continuous fibers for high performance applications. HaNa Yu et al. [51] developed a technique to align discontinuous fibers also known as "high performance discontinuous fiber (HiPerDiF)". In this technique, discontinuous hybrid fibers were dispersed in water that was sprayed at high speed through a nozzle towards the parallel plates separated at a small distance. Due to a sudden change in the momentum of water, the fibers were aligned transversely and later, the water was removed using a vacuum assisted conveyer belt. Two different hybrid intermingled composite designs such as high strength carbon/glass and high modulus carbon/glass with different relative carbon ratio were developed using the above technique. The latter one having a relative carbon ratio of 0.25 exhibited a maximum pseudo ductile strain of 1.1%, 400 MPa yield stress, 690 MPa failure strength and 110 GPa tensile modulus. The tensile modulus can be increased to 134 GPa (3 times of GFRP) by changing the ratio to 0.4.

Unlike other hybridization techniques, selective placement of micro/nano veils would result a little knock down in the bulk mechanical properties of the parent composite. Micro-veils made up of thermo-plastic nano-fibers such as polyamide (PA66) can be placed in the composite interlayer for enhancing the fracture characteristics of ply including mode I (G_{IC}- initiation, G_{IR}- propogation) and mode II fracture toughness (G_{IIC}) and interlaminar shear strength (ILSS). Table 2 elucidates how the use of PA66 veils could improve the fracture energy of composites along with the corresponding references.

The tensile strength and modulus of several hybrid composites were congregated from the literature and mapped in Fig. 4. The region 1 (between the black dashed lines) and region 2 (between the red dashed lines) show a typical strength and stiffness range of unidirectional CFRPs and GFRPs, respectively. As can be seen in Fig. 3, most of C/G hybrid composites possess better strength and tensile modulus than the pristine GFRPs. Furthermore, it can be concluded that the hybrid composite properties can be increased by incorporating thin ply CFRPs. This pattern verifies the positive hybrid effect in which the strength and stiffness of hybrid composites range between LSF and HSF composites, as seen in Fig. 1, Section 2. It is also established that FMLs have higher strength (>310 MPa) and modulus (>70 MPa) than a typical Al alloy. In contrast to synthetic hybrids and FMLs, the natural fiber reinforced hybrid composites have very low strength and stiffness which could be used in low-cost, non-structural applications.

5. Fatigue and fracture of hybrid composites

Fatigue was first identified as a critical loading pattern even early in 1900s by the scientific community [20,99]. The first reference regarding fatigue can be obtained probably from the book which was written by Jean-Victor Poncelet [100] in 1841, who mentioned that any spring subjected to push–pull force would eventually break under a load far smaller than the static breaking load. Between 1852 and 1870, August Wöhler [101] conducted the first, extended fatigue experimental program with metallic materials (wagon axles) under tensile, bending and torsional loads. The fatigue strength (S) and the number of life cycles (N) were plotted to formulate the first S-N curve, however without any mathematical relation to describe this behavior. It was in 1910, when Basquin [102] proposed a power law equation to define the S-N curve to correlate the (σ_{max}) in terms of the applied stress (σ_0), the number of cycles (N) and the slope of the curve (1/k) as shown in Eq.(1).

$$\sigma_{max} = \sigma_0 N^{-\frac{1}{k}} \tag{1}$$

This is the most commonly used S-N equation for composites and hybrid composite materials, although other formulations have been proposed in the literature over the last several decades [103-105]. In the following subsections from 5.1 to 5.5, the fatigue damage mechanisms of hybrid composites and the fatigue performance of synthetic and natural fiber hybrid composites and different types of FMLs are discussed.

5.1. Fatigue damage mechanisms

Although composite materials offer higher fatigue resistance as compared to metals, they are still prone to fatigue damage. For both hybrid and non-hybrid composites, the fatigue damage mechanisms are different than those under static loading conditions. The fatigue damage mechanisms of non-hybrid composites comprise a sequence

Table 2
Hybridization of composites with PA66 veils and their effect on CFRP fracture properties.

Composite	Functional material	Property	Improvement	Reference
CFRP	40 μm PA66	G_{IC}, G_{IR}	137%, 124%	[94]
	1 gsm PA66	G_{IC}, G_{IR}	49%, 50%	[95]
	9 gsm PA66	G_{IC}, G_{II}	173%, 54%	[96]
	12 gsm PA66	G_{IC}	340%	[97]
	50 gsm PA66	ILSS, G_{IC},G_{IR}	25%, 349%, 718%	[98]

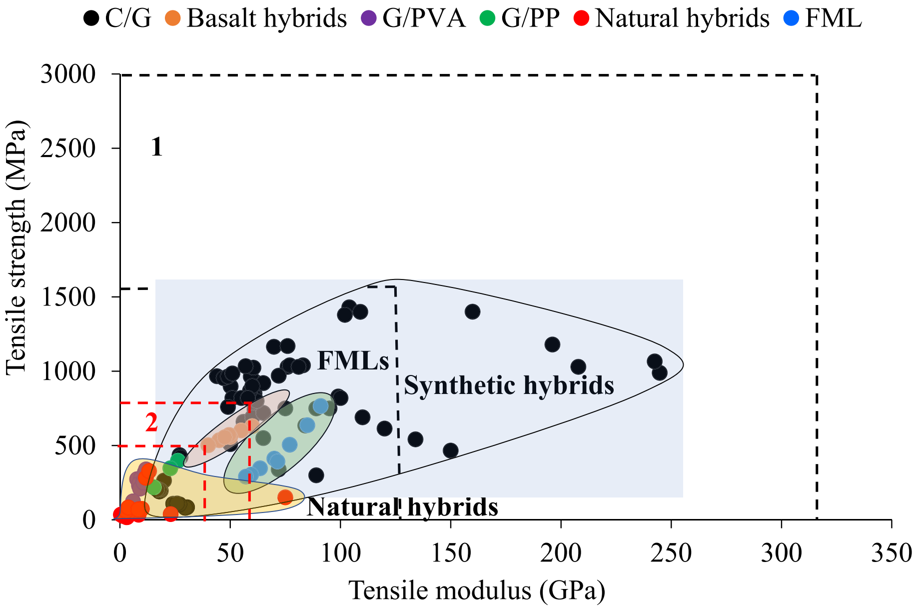


Fig. 4. Tensile strength vs. tensile modulus based on synthetic hybrids, natural hybrids and FMLs (C- carbon, G-glass, PVA- polyvinyl alcohol, PP- polypropylene fibers).

of events that have been investigated and described extensively in the past [106-115]. Considering hybrid composites, the failure mechanism is altered in several ways [9,116] as they are designed with two or more fiber types. It was shown in [117] that a (glass/carbon) hybrid material exhibits a lower S-N slope than the slopes of pure GFRP and pure CFRP for a range of fatigue load levels. Unidirectional hybrid composites made of high-performance polyethylene (HP-PE) and carbon fiber intermingled tow hybrids with a high degree of dispersion showed also a flatter S-N curve as compared with the pure CFRP. Therefore, it brings our attention to the general fatigue behavior and damage mechanisms of hybrid composites. Fig. 5a shows a schematic representation of typical fatigue behavior of hybrid FRP composites along with low strain fiber (LSF) and high strain fiber (HSF) composites. The fatigue lifetime of hybrid composites can be increased as

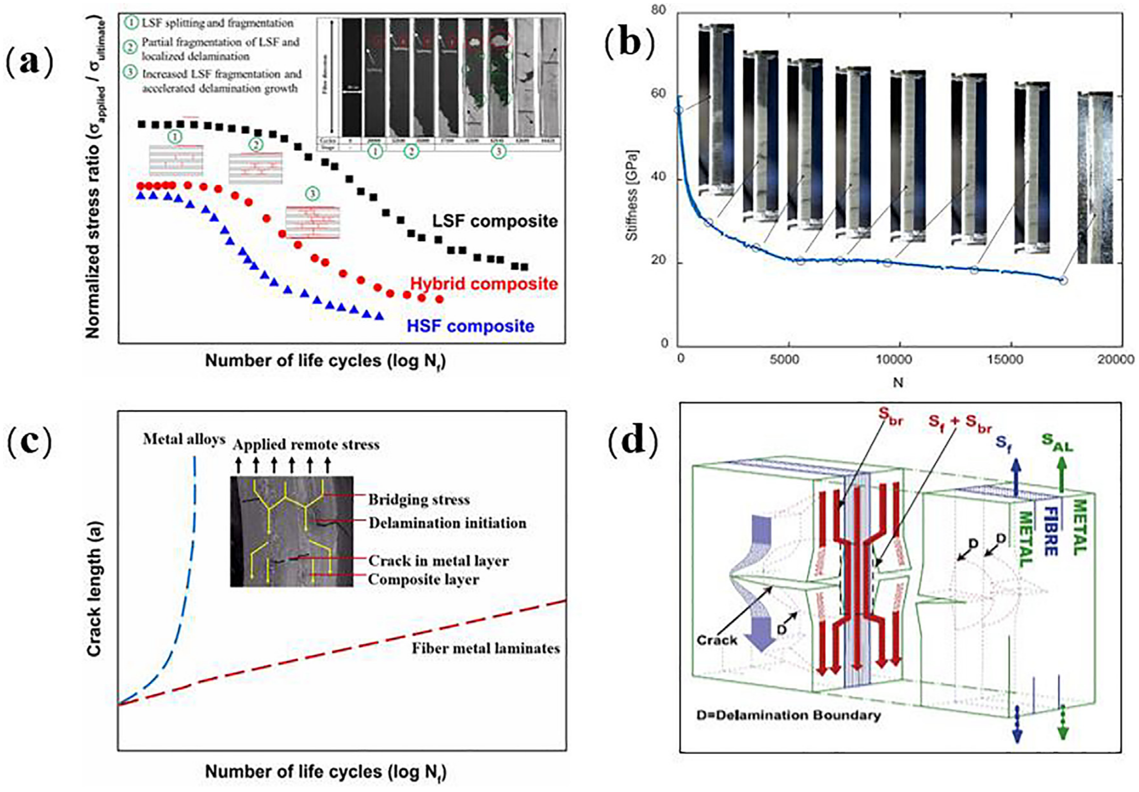


Fig. 5. Typical fatigue behavior of hybrid composites: (a) FRPs [137,138], (b) damage and stiffness degradation at lowest maximum stress level [9], (c) comparison of crack growth resistance in metals and FMLs and (d) Crack bridging of the fibers and delamination of the layers in FMLs[127-136].

compared to HSF composites as the cracks from LSF were delayed by the presence of the HSF, thus decreasing the likelihood of further HSF failure and increasing the fatigue lifetime of the hybrid composites. Furthermore, the tensile fatigue resistance of hybrid composites can be enhanced by improving the dispersion between the LSF and HSF fibers as well as ensuring proper adhesion between them by means of surface treatments. The sequence of fatigue damage mechanisms and the corresponding stiffness degradation in a carbon/glass hybrid composite laminate are presented in Fig. 5b [9]. The damage events follow a sequence starting with limited number of cracks that develop splitting and fragmentation in the LSF layer, followed by development of the fragmentation in the same layer and the derivation of localized delamination, and ended with extended fragmentation and delamination until the failure of the hybrid composite. The stiffness drop was more evident in the first stages of the fatigue life until the completion of the delamination. During the remaining fatigue life, a moderate stiffness decrease was observed.

Similar to hybrid FRPs, FMLs also have a complex damage progression during fatigue loading. FMLs have higher fatigue resistance than metals [118-125]. Although both metals and composites show a similar sequence of damage mechanisms consisting of a distinguishable crack initiation, stable crack growth phase and final failure phases, the number and position of cracks in the two media differs significantly. Fatigue damage in metals often starts from the initiation of a single crack and progresses to catastrophic failure with little warning. In comparison, composite materials accumulate damage at multiple locations, and failure usually does not occur by the propagation of a single microscopic crack. Moreover, in composite materials, the micro-mechanics of damage accumulation includes fiber fracture, matrix cracking, debonding, and transverse ply cracking, and delamination. These mechanisms may occur independently or simultaneously, depending on the material variables and loading conditions [126].

A typical fatigue behavior of FMLs is illustrated in the schematic diagram (see Fig. 5c) showing the crack growth versus number life cycles. In detail, cracks are usually initiated in the metal layers of the FMLs under fatigue loading conditions. The fibers in the wake of the fatigue crack remain intact resulting delamination between the composite and metal layers. In this scenario, the applied far-field stress is transmitted to the undamaged composite layers, also called as bridging stress. This fiber-bridging mechanism plays an important role in crack growth resistance of FMLs under fatigue loading [127-136]. The effectiveness of the crack growth reduction depends on the amount of fibers in the crack wake and the effective length of these fibers. The effective fiber length is determined by the delamination shape, i.e., the distance over which the intact fibers are delaminated from the metal layers. In principle, the delamination growth and crack growth are balanced and coupled phenomena that significantly influence each other. During constant amplitude *(CA)* loading, the balance between the delamination growth and crack growth is achieved after a certain crack extension, resulting in constant crack growth rates (see Fig. 5d) [127-136].

5.2. Fatigue of synthetic fiber hybrid composites

Synthetic fibers such as glass, carbon, Kevlar, basalt and polypropylene can be hybridized among them to improve the fatigue performance of structural components. Synthetic fiber hybrids are the most common hybrid composites. The fatigue behavior of FRPs or hybrid FRPs is influenced by various factors such as the reinforcing material, the fiber orientation, the selected matrix system, the achieved fiber volume fraction, the operating temperature and humidity, the processing methods, the residual stresses, the boundary conditions, and the type of applied load. Already in the early 1970s, several authors investigated the effect of hybridization in composite materials under fatigue loading conditions [21,25,139]. The effect of these parameters on the fatigue performance is discussed in the following subsections.

5.2.1. Effect of fiber type

Phillips [10] showed a proportional to the quantity of carbon fibers increase of the tensile fatigue strength of carbon/glass hybrid composites when compared to all glass fiber reinforced composites. However, in accordance to another relevant study, it still proved unidirectional carbon-glass hybrids displayed a positive deviation from the rule of mixtures in terms of both fatigue stress and fatigue ratio [117] when compared with non-hybrids. On the contrary, Bach [140] did not observe any positive effect of replacement of 30% glass by carbon fibers in glass fiber reinforced polyesters, while Bortolotti et al. [141] tested hybrid, pure glass and pure carbon composites and concluded that the longest tensile fatigue lifetime, and the highest stiffness was observed for the pure carbon fibers, for all load ratios, although there was very larger scattering of results for tension–compression loading, while the fatigue of the hybrid composites was longer than that of the glass fiber ones, and increased markedly with the carbon fiber content as was also reported in Hofer et al. [21]. Nevertheless, the experimental results presented by Hofer et al. [21] showed that although the pure glass and pure carbon fiber composites exhibited a classical fatigue behavior – the glass/epoxy composite showing a smooth decreasing curved S-N curve, while the carbon/epoxy composite showing a very flat response until 5 million cycles, the hybrid UD composites showed a mixed behavior with the best performance shown by 2:1 carbon-to-glass ratio. Actually, the 2:1 performance was better than 1:1 or 3:1 performance and almost as good as the pure graphite/epoxy performance. The reason for this, as explained in Hofer et al. [21], is probably the good stacking sequencing of the carbon and glass in the laminate with a rather uniform distribution of glass and carbon plies, thus producing a minimum of shear transfer problems at the interfaces of the glass and carbon plies. A hybrid effect was observed however, only for the examined quasi-isotropic glass/carbon hybrid laminates. In that case, the hybrid composites showed a considerably better fatigue performance that the one shown by the pure carbon/epoxy material.

A series of publications investigated the fatigue behavior of other synthetic fiber reinforced composites besides carbon/glass hybrid composites. Hashim et al. [142] concluded that the tensile-tensile fatigue behavior of carbon/aramid fiber hybrid composites was mainly influenced by the modulus of the used fibers while Marom et al. [143] reported that the aramid/carbon fiber reinforced sandwich structure composites exhibited a positive hybrid effect on their fatigue behavior. Harel et al. [144] investigated the flexural fatigue performance of aramid/carbon/aramid hybrids and showed a far better fatigue performance when compared to carbon/aramid/carbon composites and their aramid parent composites. The authors attributed the different fatigue performance of the two configurations to the different rate dependences of the compressive and tensile properties (essentially the strength) of the parent carbon and aramid composites. Although carbon fiber reinforced composites possess high specific strength/stiffness and long-term fatigue resistance, they still face the challenge of brittle nature. One concept to overcome the brittle nature of carbon fiber reinforced composites is hybridization with high performance polyethylene (HP-PE) fibers. Peijs et al. [145] studied the quasi-static and fatigue behavior of high performance polyethylene (HP-PE) fiber/carbon fiber hybrid composite systems and concluded that the tensile behavior of HP-PE/carbon hybrids under both monotonic and fatigue loading can be interpreted adopting the conventional “constant strain model” for hybrid composites. Deviations from this constant strain model, so-called hybrid effects, were observed. The results indicated that the existence of synergistic or hybrid effects depends on both the hybrid design and the interfacial bond strength of the HP-PE fibers. According to the authors, obviously, the possibility of crack arrest due to the presence of HP-PE fibers, preventing rapid crack extension from initially failed carbon fibers, diminishes when these fibers are not highly dispersed throughout the carbon fiber composite. Synergistic effects under fatigue loading conditions, i.e., positive deviations from the expected fatigue behaviors based on this constant strain model were observed for the intermingled hybrids with treated PE fibers. These hybrids also showed the lowest level of fatigue damage monitored by ultrasonic C-scan and acoustic emission. A modeling approach of the fatigue damage mechanisms in glass/carbon hybrid composites performed in [137] showed an improvement in the fatigue lifetime of hybrid composites compared to pure glass fiber composites. This improvement was attributed to the delay of the crack propagation when moving from the lower strain carbon fibers to the higher strain glass fibers as was also shown experimentally for another glass/carbon hybrid system in [9]. According to the modeling work [137], higher degree of fiber dispersion could improve the hybrid's fatigue damage resistance.

The tension–tension fatigue performance of hybrids is reported to fall close to the rule of mixtures prediction, with slight benefit from mixing low strain with high strain fibers since this can delay the crack propagation and cause a kind of pseudo-ductility under tension–tension fatigue loading. The positive hybrid effect that was observed in some cases under flexural fatigue loading was attributed to the strain rate dependency of the involved materials' stiffness. Nevertheless, the fatigue behavior of hybrid composites is affected significantly by other factors, such as the fiber volume fraction, the fiber placement, the fiber orientation and the processing conditions, then the material type, as discussed in the following paragraph.

5.2.2. Effect of fiber volume/fraction, placement, orientation and processing methods

In the work of Shan et al. [52], the tension–tension fatigue life of the interply carbon/glass hybrid composite was reported to increase linearly with the increase of volume ratio of carbon fibers. This effect was also confirmed by the work of Dai et al. [137] who observed that the higher fractions of carbon fibers in carbon/glass fiber hybrid composites is beneficial for the fatigue lifetime under tension–tension cyclic loading. However, additional testing under different loading conditions showed that higher carbon fiber fractions might have negative effect on the fatigue lifetime under compression-compression loading while have mixed effect for the tension–compression cyclic loading. It was observed in Dai et al. [137] that while the fiber misalignment has some potential for increasing the fracture toughness of the hybrid composites, it speeds up the fiber damage and leads to the shortening of fatigue life.

Belingardi et al. [53] investigated the tension–tension bending fatigue behavior of a hybrid glass–carbon fiber reinforced epoxy matrix composite, characterized by the presence of intraply biaxial glass–carbon laminae as well as biaxial glass laminae and biaxial carbon laminae. The specimens were subjected to different fatigue loading, with the maximum load level up to 85% of the material ultimate flexural strength. Early damage was observed after a few hundred loading cycles causing degradation of material stiffness with cycling. The amount of stiffness reduction was observed to be a function of the magnitude of applied fatigue loading on the specimen. Similar behavior is described in Ribeiro et al. [9] after investigating the tension–tension fatigue behavior of a glass/ultrahigh modulus carbon UD hybrid composite laminate. The fatigue stiffness variation with fatigue cycles was minimal at high stress levels, but pronounced for low stress levels when more distributed damage was accumulated in the specimen volume.

The effect of the stacking sequence and the fiber orientation was also investigated in the past. Already in 1978, Hofer et al. [21] studied the effect of the stacking sequence of (0°), $(\pm 45^{\circ})$ and $(0^{\circ}, \pm 45^{\circ})$ carbon-glass hybrid laminates, showing that interplay hybridization with alternating carbon-glass plies was superior to sandwich hybrids. As discussed in the previous paragraph, an obvious hybrid effect was observed only for the quasi-isotropic (0/90/45) configuration. Shahzad et al. [146] investigated the effect of the stacking sequence on hemp/glass reinforced polyester composites using compression molding. The results of fatigue tests showed that placing hemp fibers as the peripheral layer and glass fiber as the innermost layer improved the fatigue strength of the composites as compared to inner layer of hemp fibers and two outer layers of glass fibers.

Belingardi et al. [147] reported that the cross-ply laminates were accumulating more damage than angle-ply laminates, specifically at high fatigue loading levels. This argument was supported by another study on bi-axial intraply C/G hybrid composites [53]. The role of fiber mixing on the fatigue behavior was investigated numerically and it was proved to be significant [137], while it was suggested that the interlayer hybrids show the best fatigue behavior among all types of hybrid composites. Hashim et al. [142] systematically studied the effect of fiber direction on the fatigue life of intraply carbon/Kevlar fabric/epoxy hybrid composites and concluded that a slower degradation rate of fatigue linear regression lines was found in the Kevlar loading direction when compared to the carbon loading directions.

The quality of the hybrid composites depends on the processing techniques and affects the fatigue performance as well. For example, Cavatorta et al. [148] fabricated C/G hybrid composites via RTM and hand lay-up techniques. The fatigue and post-fatigue performance of RTM specimens was inferior to that of hand lay-up specimens regardless of the fiber orientation, in which the resin rich areas acted as crack initiation sites.

5.2.3. Environmental effects

The operating environment is, in addition to the fatigue loading, affecting the fatigue performance of composite materials and should be considered while investigating their service-life. Moisture in any form is detrimental to polymeric composites and often results to degradation of the mechanical properties. Such effects are more pronounced when they are combined with temperature loadings, generally referred as "hygro-thermal loading". The effects of various moisture conditions on the fatigue behavior of composites/adhesives/joints have been investigated in previous publications. For example, Habibi et al. [149] found a consecutive decrease of the fatigue modulus under moisture conditions based on nonwoven flax epoxy composites. Moreover, Costa et al. [150] presented an overview of investigations regarding the environmental effect on the fatigue degradation of adhesive joints performed in the past several decades. Regarding the effect of the environmental conditions on the fatigue behavior of hybrid composites, EI-Baky et al. [151] investigated the flexural fatigue performance of PP/G hybrid composites with different stacking sequences, (i.e., intraply, inter-intraply and plies stacking sequences), and they reported a deleterious role in the fatigue endurance strength. In detail, PP-Glass fiber- reinforced epoxy composites show a considerable reduction in fatigue life after the preconditioning in distilled water for 350 days. Generally, water immersion technique is used to introduce moisture in the test samples. Shan et al. [52] conducted environmental cyclic testing of GFRP and G/C hybrid composites in a distilled water bath at 75 °C. The moisture decreased the fatigue lives of both composites, however, adding sufficient volume of carbon fibers into the GFRP showed a better fatigue life retention when compared with GFRP composites themselves [52,152]. Furthermore, the intra-ply hybrid composites seem to have better fatigue life under environmental loading condition than interply hybrid composites. In fact, intraply composites can mix fibers with a single layer and this can reduce mismatches of fibers. In comparison, interply composites are laminated together with distinct layers of fibers and this process may lead to different fatigue behaviors in different layers. Although environmental factors such as temperature and moisture usually lead to the degradation of fatigue performance[153,154], McBagonluri et al. [155] still argued that the temperature effect on fatigue response did not depend on the presence or absence of fresh or salt water. Additionally, they pointed out that the fatigue damage evolution and the subsequent failure of fiber reinforced composites were found to be independent of moisture content or moisture regime in the short term although the authors also found the influence of long-term aging and moisture on the detrimental fatigue performance of the composite materials.

5.2.4. Methods to enhance fatigue performance

As discussed above, delamination is a critical fatigue failure mode in hybrid composites that can be suppressed by various techniques such as stitching, z-anchoring, z-pinning or weaving. Fan et al. [156] investigated the flexural fatigue behavior of the 3D orthogonal C/G hybrid composites and compared with C/G hybrid composites, shown that the z-direction reinforcement can delay the delamination. The reduction of the interface stress concentrations altered the damage mechanism from delamination to fiber breakage, resulting higher fatigue life. A novel 3D textile self-healing composite showed an unique combination of high resistance to mode I and mode II interlaminar fatigue cracking and in-situ repairability of fatigue-induced delamination crack [157]. The composite containing carbon (0.35%) and poly [ethylene-co-methacrylic acid] (EMAA) (1.6%) z-binders exhibited an increase in threshold strain energy release rate range to initiate fatigue cracking by ~ 800% and ~ 200% under mode I and mode II, respectively. The polymeric composite interfaces can be modified with PA66 fibers or thermoplastic layers to improve the fatigue life and crack growth resistance. For example, adding a 40 μm thick PA66 nano fibers (diameter of 520 ± 100 nm) in CFRP interface reduced the crack growth rate up to 30 times. The cracks were bounced between the toughened PA66 nano-modified layer and the carbon fibers, propagated in different planes (width and thickness directions) requiring higher energy for further propagation [95]. Similar results have been shown by Shivakumar et al. [158] that observed a significant delay in the delamination onset for PA66 nano-modified specimens under fatigue loading condition. By interleaving the carbon nano-fibers, the axial fatigue life (tension, compression, tension dominated) can be increased in between 150 % and 670% as result of increased interface density and the damage shielding effect of the nano-fibers [159].

5.2.5. Special applications of synthetic fiber hybrid composites

Several years ago, it was suggested in [160] to replace the steel cable core in overhead conductors by a unidirectional hybrid (carbon/glass fiber) composite rod. Such overhead conductors typically experience crosswinds, which in certain conditions can result in galloping and Aeolian vibration, inducing dynamic tensile and flexural stresses [161]. Flexural fatigue tests were performed by Kar et al. [161] in order to investigate the long-term performance, the durability, and the failure mechanisms of unidirectional hybrid composite rods having a carbon fiber core and a glass fiber shell. This study showed that no damage is initiated in the material if the cyclic deflection remains low, in the ranges of the cyclic deflection due to wind loading and Aeolian vibrations in actual operating conditions. At higher deflections, damage initiated by the formation of microscopic transverse matrix cracks on the GF tensile surface, followed by both fiber bundle failures and matrix crack propagation that played an interactive role in the progression of damage and reduction in stiffness. A distinctive failure pattern was observed, as radial and circumferential cracks made up layer like formations that saturated along the CF/GF interface. Because damage did not extend into the CF core however, the static mechanical properties were retained to ~85% or more.

The use of unbalanced composite laminates in wind turbine blades is of high interest for creating passively adaptive (smart) blades. Unbalanced laminates incorporate off-axis ply orientations which promote bend-twist and extension-shear couplings that provoke the blade to twist due to applied bending loads [162]. The potential of the use of unbalanced laminates in the spar flanges to resist the bending moments induced by the oncoming wind has been presented in several research articles [163-166]. The spar flanges are thick laminates composed of many layers of reinforced fibers usually oriented to 0 deg and ± 45 deg angles with respect to the blade span direction. The 0 deg fibers provide the blade with bending stiffness while the ± 45 deg (biaxial) plies provide torsional support and resist buckling. In large blades for multimegawatt machines, 0 deg carbon fiber plies are used resulting in stiffer and lighter structures than only glass fiber blades. These hybrid laminates typically have a symmetric layup schedule with ply layers alternating between ± 45 deg glass and 0 deg carbon through the thickness. The flexural fatigue performance of a glass-carbon unbalanced hybrid laminate showing a bend-twist coupling ($[45\ _g/-45\ _g/24_c/24_c]_s$) has been investigated by Cox et al. [162]. The flexural loads led to stiffness reductions from matrix cracking and small regions of delamination in the glass plies loaded in tension, while the compression side of the laminate was nearly undamaged after cycling. Ultimate failure of the specimens occurred by delamination between the glass and carbon plies loaded in tension after which shear failure and fiber rupture occurred in the carbon plies. The failure mode and progression of damage in the laminates was independent of the load magnitude and the number of cycles. The influence of interlaminar shear stresses were more evident on the stiffness degradation of the laminates than the induced torsional deflections or the bend-twist coupling [162].

5.3. Fatigue of natural fiber hybrid composites

Natural fibers provide many advantages over synthetic fibers, including low density, reasonable mechanical properties, and environmental benefits (including sustainability and a lower carbon footprint) [167]. Regarding fatigue of natural fiber hybrid composites, there are many researches in previous publications to show the benefits of hybridizing natural fibers with synthetic fibers. For example, Liao et al. [168] prepared glass/bamboo fiber reinforced polymer sandwich composites and they found the hybridization of bamboo and glass fibers can improve the fatigue life of the composites when compared to non-hybridization. Seghini et al. [169] proved that hybridization of flax and basalt fibers can produce a positive effect on the fatigue resistance of basalt laminates and a better normalized fatigue resistance was obtained for the hybrid composites in comparison with the 100% basalt fiber laminates. Asim and Isaac [170] examined the life span of fatigue in tension–tension mode based on hemp fiber and glass fiber reinforced composites, they recommend hemp fiber as a suitable alternate for glass fiber under fatigue loading condition to reduce fatigue sensitivity as compared with only glass fibers. Similarly, Mostfa et al. [171] reported that inclusion of jute fibers in woven glass/jute/epoxy composites can also reduce the fatigue sensitivity of hybrid composites. In terms of manufacturing configurations, Sharba et al. [172] studied the hybrid effect of woven, UD and non-woven kenaf fibers on the fatigue life. The fatigue degradation coefficient of the hybrid composites was increased by 6.2 % and 6.4 % for woven and UD kenaf fibers, respectively, compared with 7.9 % for non-woven fibers. The failure surface of hybrid composites shows fiber pull-out and fiber breakage as fibers are mainly carrying the loads [146]. In another study, nonwoven, random hemp fibers (H) were sandwiched (as TPP/TPP/PP/H/PP/H/PP/TPP/TPP) between the Twintex TPP (woven mat of polypropylene (PP) reinforced with E-glass fibers at a fiber volume fraction of 33.4%) layers. They showed better specific flexural fatigue strength than Twintex TPP composites. At relatively higher stress levels, the fiber breakage was noticed due to compressive stress in both Twintex TPP and hemp hybrid composites. As the stress level was reduced, the delamination occurred in Twintex TPP whereas the rupture of PP and hemp fibers in hemp hybrid composites [173]. Given the fiber waviness, intrinsic defects due to manufacturing, poor moisture resistance and random orientation of the fibers, natural hybrid composites for fatigue applications could not be justified. Table 3 summarizes typical S-N curve slope values for different hybrid FRPs. The sensitivity to fatigue loading can be estimated

Table 3
Summary of typical S-N curve slope values for different hybrid composites. T-tension, C-compression and TPB- three-point bending.

Fiber types	Material type	Fatigue type	R	Slope 1/k	Reference
Glass/Jute	Hybrid ratio, 55:45	T-T	0.1	−0.112	[171]
	Hybrid ratio, 70:30	T-T	0.1	−0.121	
Carbon/Polyethylene	Sandwich, untreated	T-T	0.1	−0.089	[145]
	Sandwich, treated	T-T	0.1	−0.095	
	Intermingled (untreated)	T-T	0.1	−0.114	
	Intermingled (treated)	T-T	0.1	−0.051	
Carbon/Glass	Hybrid FRP sheet	T-T	0.1	−0.069	[174]
Carbon/Basalt		T-T	0.1	−0.042	
Aramid/Carbon	Hybrid FRP sheet	TPB	0.1	−0.078	[143]
		TPB	0.1	−0.047	
Glass/Kenaf	Woven	T-C	−1	−0.06	[172]
	Non-woven	T-C	−1	−0.08	
	Uni-directional	T-C	−1	−0.06	
Glass/Hemp	Hemp skin-glass core	T-T	0.1	−0.097	[146]
	Glass skin-hemp core	T-T	0.1	−0.115	
Glass/Kevlar	Continuous fibers	TPB	0.4	−0.048	[175]
		TPB (N5)	0.4	−0.053	
		TPB (N10)	0.4	−0.056	

by evaluating the slope of the S-N curve [20], i.e., a measure of the fatigue strength decrease rate with cycles. As shown in Table 3, the fatigue sensitivity of a hybrid composite is affected by the fiber type as well as by the material type.

5.4. Fatigue of fiber metal laminates

As discussed in the previous sections, FMLs offers better fatigue crack growth resistance than solid metals. In addition to that, FMLs also used in impact applications and they were widely reported [136,176-186]. The fatigue of FMLs after impact damage was also extensively investigated [187,188]. Fatigue crack growth (FCG) curves of FMLs[156,189-197] can be described by “Paris law” which was introduced in the 1960 s after the examination of several aluminum alloys and as given in Eq. (2),

$$\frac{da}{dN} = C(\Delta G)^{m} \tag{2}$$

With da/dN denoting the crack growth rate, ΔG the range of the fracture energy and C, m model parameters that need to be estimated by fitting to the experimental data. The faster the rate of crack propagation, the lower the fatigue resistance. Therefore, smaller values of the “Paris law” exponent signify higher material resistance to fatigue crack growth [198]. The “Paris law” has been used in many works about fatigue crack growth of FMLs. Martin and Murri [199] introduced a phenomenological equation that is able to model the FCG behavior over the entire range of applied G, from the first to the third region (not specifically for FMLs). In detail, Region I is the near-threshold region, in which the curve becomes steep and appears to approach an asymptote ΔK_{th}, a lower limiting ΔKvalue below which no crack growth is expected to occur. Region II (intermediate regime) corresponds to a stable macroscopic crack growth whereas region III is associated with a rapid crack growth prior to final failure that is controlled primarily by K_c, the fracture toughness for the material and thickness of interest [200]. The derived model, designated as “total fatigue life model”, expresses the crack growth rate as a function of the maximum cyclic strain energy release rate, G_{max}, the strain energy release rate threshold, G_{th}, and the critical strain energy release rate, G_c. In Homan’s work [201], it was experimentally proven that the fatigue crack initiation in FMLs is determined by the stress cycles in the metal layers only. The internal stresses in the aluminum layers of FMLs are different from the applied stresses on the laminate because of differences in stiffness and in the coefficient of thermal expansion between the metal and fiber layers. Research efforts were also allocated for the characterization and modeling of the fatigue crack growth in FMLs. Austin et al.[202] introduced a technique for in situ strain measurements in a CARALL FML by using fiber-optic Bragg grating sensors. The derived fiber-optic data showed that stress in the bridging fibers is not constant along the length of the crack, neither along the length of the bridging fibers suggesting that a complex combination of damage mechanisms and stress state exist in the delamination zone of even the simplest fiber-metal laminate system. The authors suggested as well as a simplified empirical model to determine an effective stress intensity factor and concluded that this model is adequate to describe the general FCG response of CARALL, although it is not sufficient to describe the detailed response. Shivakumar et al. [203] used the total fatigue life model for characterizing the crack growth rate in glass/vinylester delaminated composite panels subjected to Mode I cyclic loading. Shahverdi et al. [191] introduced a phenomenological total life fatigue model able to consider as well as the effect of the *R*-ratio on the FCG curve. The analytical, experimental and numerical studies on fatigue of GLARE, CARALL and other FMLs are discussed following subsections 5.4.1 to 5.4.3, respectively.

5.4.1. Fatigue of GLARE

The Glass Fiber Reinforced Aluminum Laminates (GLARE) based on the glass fiber reinforced polymer (GFRP) and aluminum alloy are the most prevalent and most investigated type of FMLs although there are some studies focused on Carbon Aluminum Reinforced Laminates (CARALL) to obtain FMLs with better performance, not only in terms of static, but also in terms of fatigue strength [204]. In practice, GLARE is extensively used in large aircraft, especially for the fuselage and wing. The upper fuselage skin structure manufactured with GLARE leads to the 794 kg weight saving of Airbus A380 [120]. The fatigue damage tolerance of GLARE was usually assessed by using notched specimens, as shown for example in [205]. Chlupova et al. [205] tested GLARE specimens with different notch shapes (circular, semi-circular and two-side shallow). The crack was initiated from the notch root of Al layer due to local plastic deformation and simultaneously the delamination was observed as a result of high interfacial shear stresses. It is a coupled phenomenon (crack growth in the metal layers and delamination growth at the fiber-metal interface), balanced under constant amplitude (CA) loading whereas they should be treated independently in variable amplitude (VA) loading condition. In the overloading condition, plasticity induced stress re-distribution may contribute to the delamination shape transition and may not be a dominating one [132,206]. In a relevant work, Alderliesten et al. [207] predicted the fatigue crack growth in GLARE under CA loading using an analytical model having the following assumptions: (a) the crack extension is determined by the stress intensity factor of the crack tip (linear-elastic fracture mechanics) and (b) all the metal layers in the GLARE have same crack length through thickness. This proposed model shows a good correlation between predicted and experimental crack growth rates, crack opening contours and delamination shapes. Similarly, Guo et al. [133] also predicted the crack growth in GLARE under CA loading using the equivalent crack length concept and explained the interaction between the fiber bridging and the delamination growth. The experimental results showed a good agreement with the predicted fatigue life. The fatigue crack initiation life of GLARE could be extended either by intermingling glass and boron fibers or by positioning as inter-ply hybrid layers, under the same loading condition. Shim et al. [208] suggested that the fatigue crack growth behavior in the aluminum layers of GLARE laminates can be predicted using a finite element approach. The predicted fatigue crack growth rates were found to slightly underestimate the experimental values when a power law relationship for the monolithic aluminum sheets from the literature was used, while excellent agreement was seen when a power law relationship calibrated on one of the experimental results was used. However, in this second case (when the model parameters were "calibrated" by using the experimental data) only modeling can be claimed. An overview of the various relevant approaches presented in the literature to predict the crack propagation behavior of fiber metal laminates has been presented by Alderliesten [209] suggesting that neither phenomenological methods nor the analytical methods and the finite element models were able to accurately describe the fatigue crack propagation of GLARE. The phenomenological models fail to perform well due to the complexity of the mechanisms that cannot be described by the simplicity of the proposed methods. On the other hand, the analytical methods and the finite element models describe the occurring mechanisms and approximate the crack growth behavior, but, according to the author they are limited in their current form. The effect of unidirectional glass fiber orientation (θ = 0°, 5°, 10°, 15°, 20°, 30°, 45°, 60° and 90°) in GLARE was studied by Kawai et al. [210,211] at different stress ratios (R = 0.4, 0.1 and −0.2). As the fiber orientation angle was increased from 0° to 90°, the fatigue life of GLARE was decreased as depicted in Fig. 6. The fatigue strength of the GLARE can be characterized by the fatigue failure of glass fibers for the orientation angle range 0° to 30° while the Al alloy failed at higher orientation angle 30° to 90°, which is similar to fiber failure and matrix failure for composite laminates with respect to the fiber angle, as suggested by the Hashin failure criterion [212,213]. In the examined GLARE, the aluminum layers seem to play the role of the matrix in an equivalent system to the non-hybrid composites.

In GLARE [214], the Al alloy protects the inner GFRP from absorbing moisture, however, the intake occurs through the sides in a Fickian manner. The Al alloy layer is susceptible to corrosion which can generally prevented by proper surface treatments. Yucheng Zhong et al. [215] conditioned GLARE specimens with hot-water (80 °C) for a period of up to 4 months and reported significant reduction in the stiffness and the fatigue strength. The formation of hygro-thermal induced cavities was noticeable in the Al alloy layer, forming a source of fatigue crack initiation. In similar work, the authors reported that hygrothermal aging can lead to the degradation of fatigue performance of GLARE [216]. It was observed that the moisture saturation for all specimens occurred after 6 weeks of exposure to temperature and humidity and the diffusion process could be explained by the Fick's second law. In detail, the Fick's second law can be expressed in terms of time (t) and water concentration (c) by the Eq. (3):

$$\frac{\partial \mathrm{c}}{\partial \mathrm{t}} = \frac{\partial}{\partial \mathrm{t}} D_{eff} * \frac{\partial \mathrm{c}}{\partial \mathrm{x}} \tag{3}$$

where, x is the direction transverse to the flow and D_{eff} is the effective diffusion coefficient. This parameter can be estimated considering only the increased weight during the hygro-thermal conditioning, and defining a maximum increase of weight in the specimen instead of an equilibrium value. This coefficient considers all the mechanisms involved in moisture absorption process [216].

5.4.2. Fatigue of CARALL

CARALL has a better fatigue resistance than the conventionally used GLARE composites [204], while the fatigue crack growth rate of CARALL laminates is about 2 orders of magnitude lower than that of 2024-T3 aluminum alloy [217]. Under tension–tension fatigue loading, CARALL laminates display superior fatigue crack growth resistance in the longitudinal orientation, which may be attributed to the bridging effect of intact carbon fibers in the wake of the fatigue crack [218,219]. The authors reported that CARALL's superior crack propagation resistance can be attributed to the restraint of the crack opening imposed by intact fibers in the crack wake. This superior crack

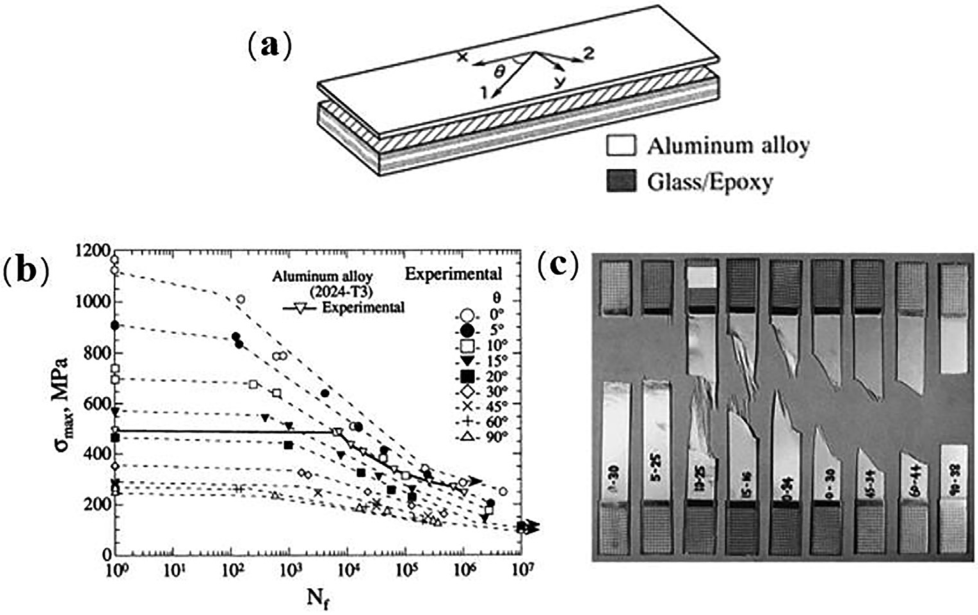


Fig. 6. Effect of glass fiber orientation angle on the fatigue performance of GLARE: (a) sample configuration, (b) maximum stress versus number of fatigue cycles response and (c) failure images of tested samples [210].

propagation resistance can be further improved by introducing compressive residual stresses in the aluminum layer by post-curing stretching the laminate in the plastic region of the aluminum alloy [217]. The growth rate of cyclic delamination between the aluminum sheets and the fiber/epoxy composite core was correlated to the effective strain energy release rate. It has also been shown that the effectiveness of fatigue crack growth reduction increases with the thickness of the carbon fiber/epoxy layer. Stoll et al. [220] investigated the tension–tension fatigue behavior of FMLs with high strength carbon fiber reinforced epoxy face sheets, aluminum 2024-T3 core layer and elastomer interlayer. Carbon fiber reinforced aluminum laminates (CARALL) generally feature a high difference in the constituent's coefficient of thermal expansion (CTE-mismatch) and the possibility of galvanic corrosion. These problems may be solved by integration of elastomer interlayers. The elastomer inhibits corrosion through a high electrical resistance and uses high elastic strains to absorb the CTE-mismatch, while it is desired to increase adhesion. Elastomer interlayers were already used in different laminate structures, with either carbon or glass fibers, to increase damping, adhesion and the resistance to corrosion [221-223]. The experiments were accompanied with infrared thermal measurements and ex-situ CT-scans to assert the validity of the experiments and show the damage during testing. The prominent stiffness drops in the fatigue experiments were correlated with cracks in the aluminum layer, which were detected and located by CT-scans. Additionally, areas of higher temperatures were measured via infrared thermal imaging and it was proven that locating cracks during the experiment was possible.

Damato et al. [224] studied the influence of sea-water and hygrothermal conditioning (water immersion at 70 °C) on the fatigue strength of CARALL composites. Significant moisture absorption (revealed by the increase in weight %) and reduction of fatigue strength were observed in the conditioned specimens, mainly attributed to the carbon fiber-Al alloy interface degradation.

5.4.3. Fatigue of other FMLs

An interesting approach has been presented recently for the hybridization of FMLs by using at least three different materials, see e.g., [220,225-227]. As was shown in [228] through experimental results and analytical and finite element modeling, compared to the GLARE-type laminates used in the aircraft industry, the carbon/glass fiber hybridization is beneficial for the fatigue performance of the FML, when compared to that of the GLARE, although not reaching that of CARALL, therefore the hybridization did not produce and hybrid effect on the fatigue performance.

CFRP/Ti hybrid composites have been proved promising in high speed aerospace applications (military aircrafts) operating at elevated service temperatures up to 177 °C [229]. Previous investigations showed a significant fatigue life improvement by FMLs as compared to Ti alloys. For example, AS4 carbon fiber reinforced PEEK composites bonded with Ti15-3–3–3 alloy foils improved the fatigue life cycles by 50 times in comparison with monolithic Ti alloy. Although increasing CFRP layer thickness exhibited better fatigue performance, the higher delamination and splitting failure mode limits the transverse properties of the laminates [230]. Cortes et al. [231] developed magnesium alloy-CFRP based FML, as the magnesium alloy (Mg) has low density, high corrosion resistance and electro-magnetic shield resistance. The fatigue life was improved by an order of magnitude when compared to the Mg alloy as a result of fiber-bridging. Yamaguchi et al. [232] modelled the complex damages such as transverse cracking, splitting, and interlaminar delamination for CFRP/Ti hybrid laminates using cohesive zone elements. The delamination progressed in the wake of the titanium crack in a triangular shape and the same characteristics were observed in the experiment results. The optimal fatigue damage tolerance of CFRP/Ti composites can be achieved by properly balancing the fiber-bridging effect as well as by controlling the delamination. Through controlling the delamination, the interface strength can be improved. For example, the delamination of the carbon fibers from Ti alloy surface could be effectively suppressed by the alkaline-perborate surface treatment [229]. Annealed austenitic stainless steel SUS316 bonded with different thickness of CFRP layers (3, 6 and 9 plies) showed three different the notched-tensile fatigue failure modes such as fiber breakage, interface delamination and delamination bending. The interface delamination was the primary failure mode and presented in all specimens whereas the first mode was only in 3 plies CFRP- steel laminate. Further, the increase in thickness of CFRP layers improved the fatigue life under the same force loading scenario and vice-versa in the same stress loading condition.

Natural fibers were also used in fabricating FMLs, for example the flax fiber – Al alloy FMLs presented by Kandare et al. [233]. The notch sensitivity of the examined material under fatigue loading was investigated and the authors highlighted the potential for adopting natural fiber FRP composites as material candidates in the design of land transport vehicles including automobiles and rail carriages. Although flax-FML composites exhibit only moderate quasi-static and fatigue resistance as lightweight and sustainable engineering materials, flax-FML composite materials still show the potential to be adopted in the design of land transport vehicles including automobiles and rail carriages. Besides to their green credentials, light-weight composites incorporating plant fibers substantially reduce the vehicle weight, thereby decrease the fuel consumption and the transportation industry carbon footprint.

6. Conclusions

This article examined a considerable number of publications regarding hybrid composites emphasizing on the fatigue behavior investigations. This is an exhaustive literature review covering most of the available literature related to the fatigue performance of laminated hybrid composites and an adequate number of works on FMLs. This review highlights that although the importance of hybrid composites has been appropriately shown in the literature and in relevant practical applications, the research on the performance of these materials, especially the long-term and durability performance, has not received yet sufficient attention from the scientific community.

It is clear that when comparing non-hybrid composite laminates, those made by the most performant material would show the best quasi-static and fatigue behavior. The CFRP laminates possess high specific strength and stiffness, and excellent fatigue resistance, much better than that of GFRP laminates. Nevertheless, carbon fibers are usually brittle and very expensive. Therefore, hybrids were produced, attempting to reduce the cost of composites with expensive reinforcements by incorporating a proportion of cheaper, low-quality fibers without significantly reducing the properties of the initial composite. Alternatively, hybrids were produced to improve the properties of a composite by judiciously placing high quality fibers, without affecting significantly the cost.

Hybridization is expected to provide new materials having a mix of the properties of their constituents, following typical rules of mixtures. However, hybrid composites show very often better properties that those designated by the rule of mixtures, something that is called the "hybrid effect". In rare cases negative hybrid effects were also reported after hybridization. What is important in this context is that by hybridization it is possible to tailor the material parameters aiming to target properties dictated from various applications. The process of creating hybrid composites gives a great degree of freedom in this by the multitude of parameters that affect the final material properties, such as the constituent materials, the type of fiber placement, the manufacturing process, etc.

Currently, natural fiber hybrid composites are receiving more attention, due to the potential benefits, especially their sustainability label. Nevertheless, material properties achieved from natural composites and their hybrids are still low, compared to those of other composite materials. Main limiting factors that were deduced from this review in extending natural fiber hybrid composites use to load-bearing applications are their limited strength, batch-to-batch variability, adhesion problems with certain matrices, and most importantly the limited understanding of their fatigue and durability performance.

The fatigue crack growth behavior of FMLs has been extensively investigated in the literature, mainly because of the commercial success of FMLs, especially in the aerospace. A trend showing attempts to hybridize FMLs is visible in the literature with attempts to produce FMLs with glass and carbon fibers combined with aluminum, or with the implementation of elastomer interlayers in different laminate structures, with either carbon or glass fibers, to increase damping, adhesion and the resistance to corrosion. However, both FMLs and hybrid FMLs are meant to be used in applications operating in harsh environments, and research in this field is very limited in the open literature.

Commonly accepted analytical/numerical/empirical methods for the fatigue life prediction and the description of the fatigue damage progress in hybrid composites and FMLs are not yet in place. Empirical/phenomenological methods are probably not suitable for describing the complicated damage mechanisms occurring in FMLs while analytical and numerical approaches have yet only limited (mainly modeling) capabilities.

CRediT authorship contribution statement

Peiyuan Zuo: Investigation. **Dharun V. Srinivasan:** Investigation. **Anastasios P. Vassilopoulos:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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