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Fibre hybridisation in polymer composites: a review

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Abstract

Fibre-reinforced composites are rapidly gaining market share in structural applications, but further growth is limited by their lack of toughness. Fibre hybridisation is a promising strategy to toughen composite materials. By combining two or more fibre types, these hybrid composites offer a better balance in mechanical properties than non-hybrid composites. Predicting their mechanical properties is challenging due to the synergistic effects between both fibres. This review aims to explain basic mechanisms of these hybrid effects and describes the state-of-the-art models to predict them. An overview of the tensile, flexural, impact and fatigue properties of hybrid composites is presented to aid in optimal design of hybrid composites. Finally, some current trends in fibre hybridisation, such as pseudo-ductility, are described.

Keywords: A. Carbon fibre; A. Hybrid; A. Polymer-matrix composites (PMCs); B. Mechanical properties.

1 Introduction

Lightweight design is becoming increasingly important in various industries, particularly in aerospace, wind energy and automotive applications. Fibre-reinforced composites are attracting more interest for these weight-sensitive applications as their excellent stiffness and strength are combined with a low density. Unfortunately, the high stiffness and strength of these composites come at the expense of their limited toughness. Like most materials, fibre-reinforced composites also face the strength versus toughness dilemma.

Over the years, toughening of fibre-reinforced polymer composites has been a highly active research area. Many different strategies have been proposed to make these materials more damage resistant and less brittle. One of the most researched strategy is toughening of the polymer matrix by tuning the polymer chemistry or by rubbers, thermoplastics or nano-scale reinforcements. In this strategy, the increased matrix toughness has a beneficial effect on the matrix-dominated composite properties [1-3]. In search of new toughening mechanisms, there has been an increasing interest in structure-property relations of biological composites that are exceptionally resilient to failure [4-6].

The failure strain and toughness can be dramatically increased if brittle fibres are replaced by ductile fibres. In this respect, metal fibres have the potential of high stiffness and large failure strain, but they are hampered by their high densities. Polymer fibres, on the other hand, do have low densities and can be ductile, but are limited by their low stiffness and limited temperature resistance.

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Because of the drawbacks of these toughening strategies and the strong need for new lightweight materials with improved toughness, the research interest in “hybridization”, is reviving. The term ‘hybrid composite’ is generally used to describe a matrix containing at least two types of reinforcements, but this review is restricted to hybrid composites containing two types of reinforcing fibres. Such composites are also called ‘fibre hybrids’ or ‘fibre hybrid composites’. This review focuses on polymer matrix composites, though some references to hybrid composites with ceramic or metal matrices will be made.

Research on fibre hybrid composites started several decades ago. After the invention of carbon fibres in the sixties [7, 8], the high price was their main drawback. In an attempt to reduce the price, while still exploiting the exceptional properties of carbon fibre, hybridization became a highly active research area in the seventies and eighties. Afterwards, the price dropped [9] and the focus shifted towards production technologies and understanding the mechanical behaviour of non-hybrid composites.

The last review paper on hybrid composites was written in 1987 by Kretsis [10]. Since then, a much wider range of materials is available and several processing technologies have been invented and improved. This resulted in a renewed interest in hybrid composites as a possible strategy for toughening fibre-reinforced composites.

In general, the purpose of bringing two fibre types in a single composite is to maintain the advantages of both fibres and alleviate some disadvantages. For instance, replacing carbon fibres in the middle of a laminate by cheaper glass fibres can significantly reduce the cost, while the flexural properties remain almost unaffected. If a hybrid composite is loaded in the fibre direction in tension, then the more brittle fibres will fail before the more ductile fibres. This fracture behaviour can be used for health monitoring purposes [12] or as a warning sign before final failure [13].

The two fibre types are typically referred to as low elongation (LE) and high elongation (HE) fibres. The first fibre to fail is normally the LE fibre. The HE fibre does not necessarily have a large failure strain, but it is always larger than the one of the LE fibre. This is also the reason why the terminology brittle/ductile fibres instead of LE/HE fibres can lead to confusion.

The LE and HE fibres can be combined in many different configurations. The three most important configurations are visualised in Fig. 1. In the interlayer configuration, see Fig. 1a, the layers of two fibre types are stacked onto each other. This is the simplest and cheapest method for producing a hybrid composite. In the intralayer hybrid, the two fibre types are mixed within the layers. This is illustrated in Fig. 1b, where different yarns are co-woven into a fabric. Other intralayer configurations such as parallel bundles are also possible. The two fibre types can also be mixed or co-mingled on the fibre level, resulting in an intrayarn hybrid (see Fig. 1c). More complex configurations can be obtained by combining two of these three configurations. For example, an intrayarn hybrid can be woven together with a homogeneous yarn.

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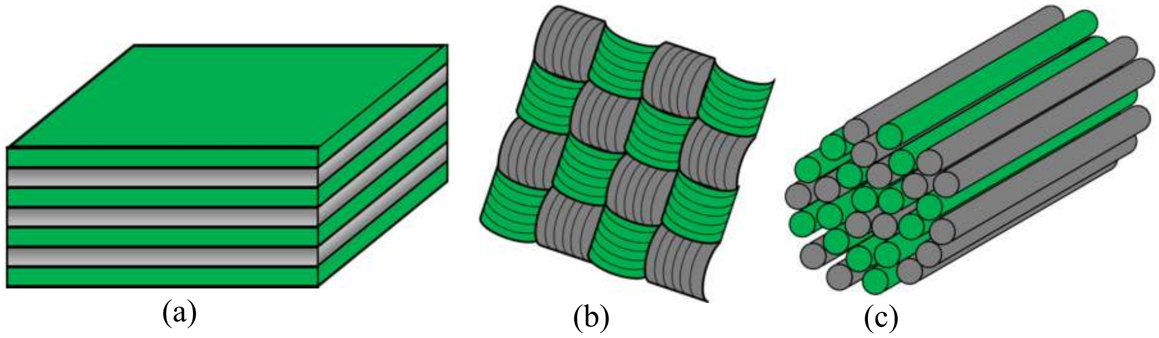

Figure 1: The three main hybrid configurations: (a) interlayer or layer-by-layer, (b) intralayer or yarn-by-yarn, and (c) intrayarn or fibre-by-fibre.

A crucial aspect in hybrid composites is the dispersion of the two fibre types. This is a measure for how well the two fibre types are mixed and is defined as the reciprocal of the smallest repeat length [10, 14]. Fig. 2 schematically illustrates the degree of dispersion. Fig. 2a shows a hybrid with a low degree of dispersion, as the two fibre types are in two distinct layers. This can be improved by increasing the number of layers or decreasing the layer thickness, as illustrated in Fig. 2b. Another way to increase the dispersion is by hybridising on the fibre bundle level, see Fig. 2c. The best dispersion is achieved if the two fibre types are completely randomly distributed, as in Fig. 2d.

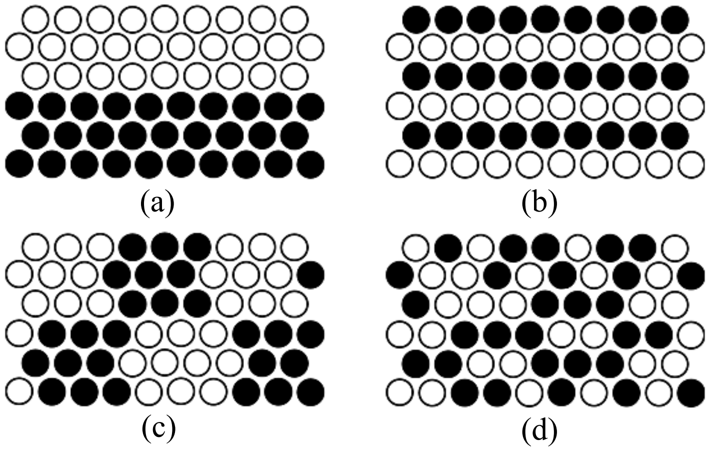

Figure 2: Illustration of the various degrees of dispersion (a) two layers, (b) alternating layers, (c) bundle-by-bundle dispersion, and (d) completely random dispersion.

The present paper is split up into six sections, of which the first one is this introduction. In the second section, the synergy between the two fibres, the so-called hybrid effect, will be discussed. The third section reviews the existing models for the hybrid effect and failure development of UD hybrid composites and provides suggestions for future model developments. The fourth section describes the mechanical properties of composites and how they can be improved by fibre hybridisation. The fifth section gives an overview of the most recent trends in fibre hybridisation. The final section gives conclusions as well as recommendations for future work.

2 The hybrid effect

2.1 Introduction

In 1972, Hayashi [15] reported that the failure strain of the carbon fibre layers in a carbon/glass hybrid composite was 40% higher than in the reference carbon fibre composite. As will be shown in "4.1.2 Failure strain", typical values for this remarkable synergistic effect are typically in the range 10% to 50%. Various definitions have been coined for this hybrid effect. The most basic definition of the hybrid effect is the apparent failure strain enhancement of the LE fibre in a hybrid composite compared to the failure strain of a LE fibre-reinforced non-hybrid composite. This definition is schematically illustrated in Fig. 3a and corresponds to Hayashi's observations [15]. This definition requires an accurate determination of the failure strain of the reference carbon fibre composite. This baseline failure strain is often affected by stress concentrations at the grips, while this effect is smaller in hybrid composites. This may cause overestimations of the hybrid effect. It should also be emphasised that calculating the hybrid effect based on the ultimate failure strain of the hybrid composite is not correct. Such improvements in ultimate failure strain may be useful to report, but the terminology of hybrid effect should be avoided.

Another definition of the hybrid effect, which is able to capture more features, is a deviation from the simple rule of mixtures [16, 17]. The advantage of the latter definition is that it can also be applied to mechanical properties other than failure strain, see Fig. 3b. It is, however, not straightforward to apply this definition for three reasons. Firstly, the rule of mixtures is not necessarily linear for all properties. For the tensile strength, the rule of mixtures is bilinear [10, 14], while a constant value would be expected for the failure strain of the LE fibre. Secondly, each rule of mixtures needs a certain composition parameter and, as Phillips [18, 19] and Kretsis [10] pointed out, it is vital that the right one is chosen. The relative volume fractions of the LE and HE composites are a good choice, but are not always easy to determine experimentally. Finally, even though the second definition is more general, it still does not work for all mechanical properties. For example, if the inner layers of a carbon fibre composite are replaced by glass fibre layers, then the flexural modulus would remain almost unaffected. Clearly, simple rules of mixtures would not apply to bending conditions. More advanced theories, such as classical laminate theory, are needed to determine whether a hybrid effect in bending is present or not. This severely complicates the prediction of the hybrid effect, as predictions of the strength and failure strain are difficult in these complex loading conditions.

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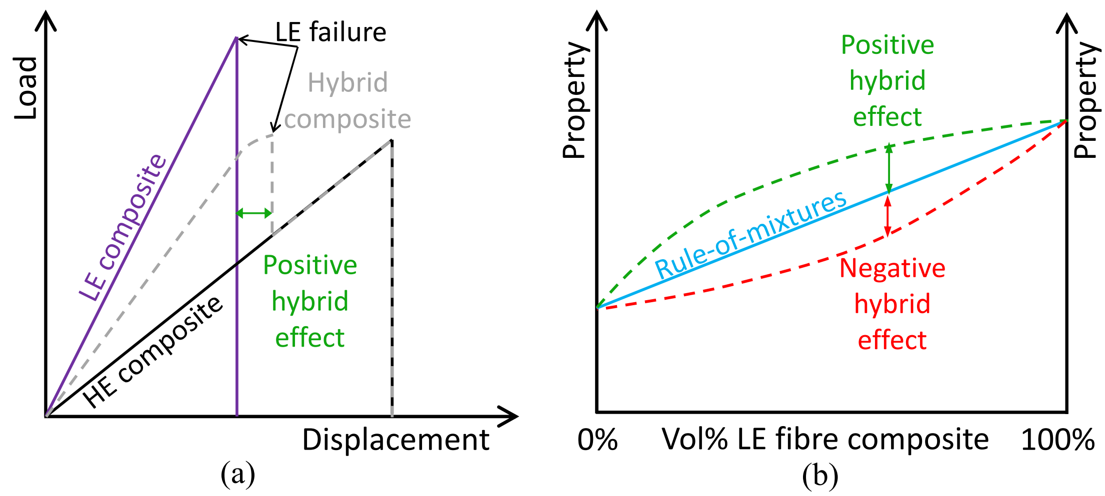

Figure 3: Illustration of the definitions of the hybrid effect: (a) the apparent failure strain enhancement of the LE fibres, under the assumption that relative volume fraction is 50/50 and that the hybrid composite is twice as thick as the reference composites, and (b) a deviation from the rule of mixtures.

Controversy and considerable confusion arose in the composites community after Hayashi's report of the hybrid effect for failure strain first appeared [15]. As explained by Phillips [20], some researchers [16, 21] did not believe Hayashi's results and thought that the rule of mixtures still applied. The confusion grew by several reports of errors in the way the hybrid effect was determined. Qiu and Schwartz [22] reported that Phillips' baseline for hybrid fatigue resistance [20] was dubious. The failure strain enhancement of 100%, reported by Aveston and Sillwood [23], is quoted by Manders and Bader [14] to be caused by a wrong definition for the failure strain of the hybrid composite. This type of discussions in the seventies and early eighties are well illustrated by Phillips [18, 20] and the letter by Marom and Wagner, with corresponding reply by Phillips [19].

The belief in the surprising failure strain enhancement of the LE fibre gradually increased when more experimental data became available as well as more convincing theoretical hypotheses followed [24-27]. Three different hypotheses for the hybrid effect have been coined by now: (1) residual stresses, (2) changes in the damage development leading to final failure of the hybrid composite, and (3) dynamic stress concentrations. Most hypotheses have been applied to unidirectional hybrid composites in either the intrayarn or interlayer configuration. These hypotheses can be extended to multidirectional composites, as their failure, although more complex, still coincides with failure of fibres in the loading direction. Therefore, almost all models in literature predict the hybrid effect for unidirectional rather than for multidirectional hybrid composites. The next sections discuss the three possible hypotheses for the hybrid effect for failure strain in unidirectional hybrid composites.

2.2 Residual stresses

In the first hypothesis, the hybrid effect is attributed to residual shrinkage stresses due to differences in the thermal contraction of the two fibre types. Let's consider the classic combination of carbon fibres and glass fibres in an epoxy matrix. After impregnation of the fibres, the temperature is raised to cure the epoxy. Both fibres will have the tendency to change their length due to their coefficient of thermal expansion (CTE). The CTE of carbon fibre is typically between -1 and +1 K^{-1} [14, 28, 29], while the CTE of glass fibre is 5-10 K^{-1} [14, 30]. This causes the glass fibres to increase their length upon heating, while carbon fibres will more or less maintain their length. This does not yet result in stress build up, as the resin is still liquid.

After the resin is cured and the composite is cooled down, the glass fibres will shrink, while the carbon fibres will more or less maintain their length. This can only occur in a situation without constraints. In reality, the cured resin connects the layers reinforced with different fibre types and prevents them from having a different length. A force equilibrium is established, putting compressive stresses on the carbon fibres and tensile stresses on the glass fibres. These compressive stresses counteract the applied stress and increase the apparent failure strain of the carbon fibres. In contrast, the apparent failure strain of the glass fibres is reduced.

While the thermal effect can contribute to the hybrid effect, it is insufficient to explain the full hybrid effect. This was pointed out by Zweben [24], Manders and Bader [14], and Bunsell and Harris [31]. Zweben hybridised carbon fibres with aramid fibres. The CTE of aramid fibre is smaller than the CTE of carbon fibre, resulting in residual tensile strains in the carbon fibres. Nevertheless, a positive hybrid effect for the failure strain of the carbon fibres was observed [24]. In all three works [14, 24, 31], it is mentioned that the thermal effect can only account for a hybrid effect of 10%, while hybrid effects of up to 50% have been reported [10]. Soon, it became clear that other effects are more important.

2.3 Failure development

The second hypothesis for the hybrid effect is related to changes in the way failure develops. This can be dealt with in a statistical or a fracture mechanics approach, as explained by Manders and Bader [32]. The fracture mechanics approach deals with a structure that contains a pre-existing crack and determines when it is energetically favourable for that crack to grow. The structural inhomogeneity and anisotropy of fibre-reinforced composites however, make it difficult to use this approach for modelling of the composite strength. Consequently, the statistical approach has received more attention than the fracture mechanics approach.

Consecutive failure of fibres with their stochastically distributed flaws is an intrinsic statistical problem. Fibre strength is indeed not a single, unique value, but is a stochastic variable. Often it is assumed that fibre failure is determined by the weakest link, which makes the Weibull distribution an appropriate choice to characterise fibre strength.

The failure development in unidirectional composites is shown in Fig. 4. If all fibres are intact, then the stress is the same in all fibres, see Fig. 4a. If the strain is further increased, the first fibre will break and locally lose its load carrying capacity. However, this does not lead to composite failure, see Fig. 4b [33]. After the first fibre break, the surrounding matrix is loaded in shear and transfers stress back onto the broken fibre, which will recover its full load carrying capacity a certain distance from the fracture location. Moreover, the neighbouring fibres will be subjected to stress concentrations and locally take over the additional load caused by the broken fibre [34, 35]. These stress concentrations on neighbouring fibres are typically in the range of 5% to 15% [36, 37] in the plane of the fibre break, but rapidly decrease with increased distance from this fibre break plane.

The stress concentrations lead to an increased failure probability in the neighbouring fibres. When the strain is further increased, this increased probability will lead to the development of clusters of broken fibres (see Fig. 4c) [38]. If one of these clusters grows large enough and reaches a certain critical size, then that cluster will grow in an unstable manner and lead to final failure (see Fig. 4d) [39].

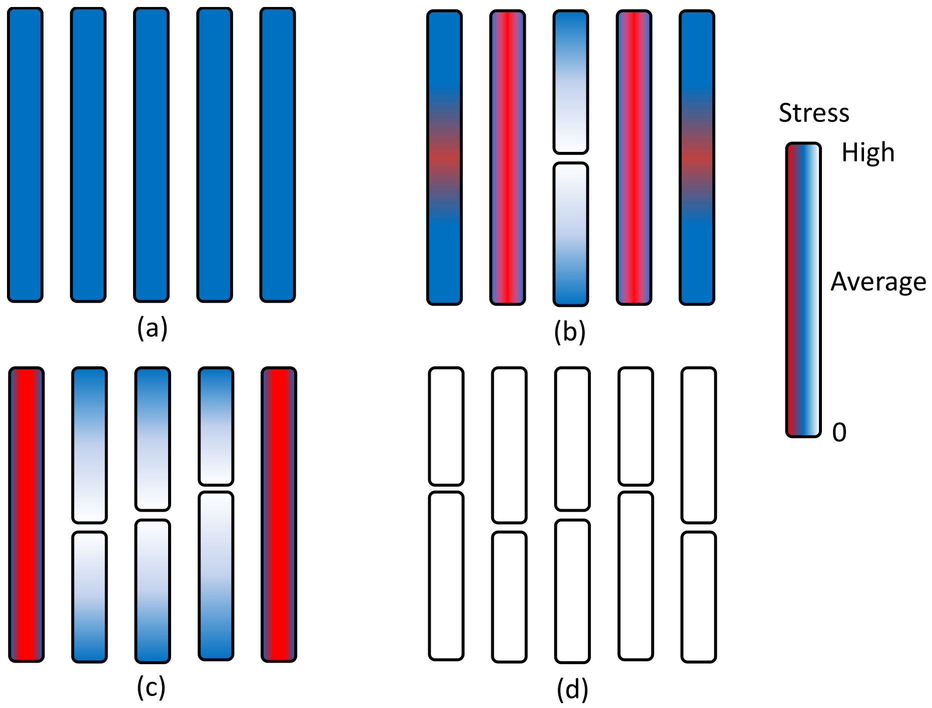

Figure 4: Schematic representation of the failure development in unidirectional non-hybrid composites: (a) all fibres intact, (b) one broken fibre, with the surrounding fibres subjected to stress concentrations, (c) development of a broken fibre cluster, and (d) crack propagation and final failure.

Hybrid composites can interfere with this damage development process at several stages. Firstly, the stress concentrations in the intact fibres as well as the stress recovery in the broken fibre can be altered if the LE and HE fibre have a different stiffness or diameter [24, 40]. This interferes with the cluster development. Secondly, the broken LE fibres can be bridged by the HE fibres [10, 41], which does not only hinder the development of the clusters, but can also increase the critical cluster size. The remaining LE fibre fragments will have a higher failure strain, as their weakest link just got eliminated [41]. Thirdly, a size scaling effect can occur. It is now well established that the failure strain of non-hybrid composites increases with decreasing sample size [42, 43]. This effect can also increase the apparent failure strain of hybrid composites compared to the reference LE composite. More specifically, if a LE/HE fibre hybrid composite is compared with a LE fibre composite of the same volume, then the volume of LE fibres is lower in the hybrid composite, and hence its failure probability is lower.

2.4 Dynamic stress concentrations

Some authors have also stressed the importance of dynamic stress concentrations in the failure of unidirectional composites. When a fibre breaks, the load on that fibre is locally relaxed and the fibre springs back. This creates a stress wave travelling along each fibre, causing a temporary increase in the stress concentration. This was first pointed out by Hedgepeth in 1961 [44], and later confirmed by Ji et al. [45]. Hedgepeth used a shear lag approach to prove that the dynamic stress concentrations are 15% to 27% higher than the static stress concentrations. Hedgepeth mentions the limitations of the shear lag approach to study these dynamic phenomena. Matrix plasticity and deviations from unidirectionality are mentioned to reduce the dynamic stress concentrations. Ji et al. [45] further extended Hedgepeth's work to dynamic stress concentrations along the fibres, rather than just at the plane of the fibre break.

Xia and Ruiz [46] predicted the dynamic stress concentration factors to be 20% higher in glass fibre composites than in carbon fibre composites. This indicates that these two fibre types behave differently under dynamic loading. An explanation for this was not provided by Xia et al., but is most likely caused by the higher longitudinal modulus of carbon fibre. It cannot be attributed to the anisotropy of carbon fibres compared to the isotropy of glass fibres, as this was not taken into account in the model.

An extension towards hybrid composites was done by Xing et al. [47]. These authors considered hybrid composites composed of one row of LE and one row of HE fibres. Their theoretical model demonstrated that two independent stress waves develop and propagate through the hybrid composite when an LE fibre breaks in a hybrid composite. The first wave propagated in the LE layer, while the second one propagated in the HE layer. Both waves were always out-of-phase, which led to lower stress concentrations in LE/HE fibre-reinforced hybrid composites compared to those in LE fibre-reinforced composites. From this point of view, a positive hybrid effect for failure strain can always be expected.

Unfortunately, this hypothesis for the hybrid effect remains poorly investigated. This topic has received no attention at all in the past 2 decades. More refined models are required to advance the understanding in this area.

2.5 Conclusion

After the early discussions more than thirty years ago, the existence of the hybrid effect for failure strain is now well established, but not thoroughly understood. Three explanations have been coined by various researchers to explain this hybrid effect. The thermal effect is easy to understand and predict, but is limited in magnitude. Dynamic stress concentrations have only rarely been investigated, but may have an important contribution to the hybrid effect and hence merit more attention.The statistical effect is expected to be the largest effect, but is more complex to predict. The next section will explain the statistical models that were developed to advance the understanding of the hybrid effect for failure strain.

3 Statistical models

3.1 Zweben's model

In 1961, Hedgepeth [44] was the first to develop a shear lag model for non-hybrid fibre-reinforced composites, by assuming that the fibres carry all the axial load and that the matrix carries only the shear load. Hedgepeth calculated the stress concentration factor when one or more fibres are broken in a 1D fibre packing, which is an infinite row of fibres, see Fig. 5a. Rosen [33] and Harlow and Phoenix [48] later extended this approach with the statistical distribution of fibre strength to obtain a strength model for non-hybrid composites.

Modelling strength of hybrid composites is more complex than of non-hybrid composites. When a single fibre breaks in a unidirectional composite, the broken fibre locally loses its load transfer capacity over a certain length, called the ineffective length. Simultaneously, the nearby fibres take over the load of the broken fibre and are hence subject to stress concentrations. Both the stress concentrations and ineffective length depend on the type of the nearby fibres. This additional geometrical complexity makes modelling hybrid composites a challenging task.

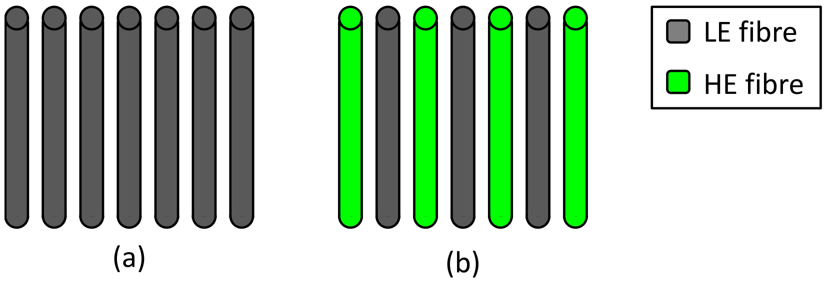

Figure 5: Schematical representation of 1D fibre packings: (a) only LE fibres, and (b) alternating LE and HE fibres.

In 1977, Zweben [24] was the first author to extend shear lag models for unidirectional composites to hybrid composites and model the hybrid effect for failure strain. Zweben modelled one dimensional fibre packings, consisting of a single row of LE fibres, see Fig. 5a. This was modelled and compared to a similar packing with alternating LE and HE fibres, as illustrated in Fig. 5b. This type of packing has been used by many other authors [26, 49-51], as it is the most straightforward way to simplify the geometrical complexity of hybrid composites. Zweben derived analytical expressions for the strain concentrations and ineffective length in both packings. The strain concentration factor k was defined as the ratio of the strain in a fibre next to a single broken fibre over the applied strain. Since all fractures were assumed to occur in a single plane, this parameter was only defined in the plane of fibre break. The strain concentration factor for hybrid composites k_h only depends on ρ, which is the ratio of normalised stiffnesses of both fibre types:

$$\rho = \frac{E_{LE} \cdot A_{LE}}{E_{HE} \cdot A_{HE}} , \quad (1)$$

in which E_{LE} and E_{HE} are the Young's moduli of the LE and HE fibres, respectively, and A_{LE} and A_{HE} are the cross-sectional areas of the LE and HE fibres, respectively. For the exact relationship between k_h and ρ, the reader is referred to Zweben [24]. The factor k_h monotonically increases with ρ and is larger than k for ρ-values above 1.

The ineffective length δ_h for the hybrid composite can be calculated as:

$$\delta_h = F . \sqrt{\frac{E_{LE} \cdot A_{LE} \cdot d}{G \cdot h}} , \quad (2)$$

in which d and h are the width and thickness of the matrix region between the fibres, G is the matrix shear modulus, and F is a factor which solely depends on ρ. The strain concentration factor k and ineffective length δ for a composite containing a single type of fibres are achieved by setting ρ equal to 1.

Zweben assumed that composite failure occurs when the first HE fibre breaks, resulting in a lower bound for the composite strength. This led to the derivation of an expression for the hybrid effect R. This is a dimensionless parameter, which is defined as the ratio of the failure strain of the hybrid composite $\bar{\varepsilon}_{h,\mathrm{c}}$ over the failure strain of the LE fibre-reinforced composite $\bar{\varepsilon}_{\mathrm{LE,c}}$. Please note that this definition does not completely correspond to the definitions given in Fig. 3, as Zweben defined failure to coincide with the first failure of a HE fibre next to a broken LE fibre. Zweben however assumes that this first HE failure will trigger unstable failure of all the other LE fibres. With these assumptions, Zweben's definition does conform to the definition in Fig. 3a. Combining equation (1) and (2) with the Weibull distributions for fibre strength yields equation (3) for the hybrid effect R:

$$R = \frac{\bar{\varepsilon}_{h,c}}{\bar{\varepsilon}_{\mathrm{LE},c}} = \sqrt{\frac{\bar{\varepsilon}_{\mathrm{HE,f}}}{\bar{\varepsilon}_{LE,\mathrm{f}}}} \cdot \left[\frac{\delta_h \cdot \left(k_h^q - 1\right)}{2 \cdot \delta \cdot \left(k^q - 1\right)} \right]^{-1/2\cdot q}, \tag{3}$$

in which $\bar{\varepsilon}_{LE,\mathrm{f}}$ and $\bar{\varepsilon}_{HE,\mathrm{f}}$ are the mean failure strains of the LE and HE fibres at the tested gauge length, respectively, and q is the Weibull shape parameter of both fibres. Note that Zweben assumed both fibres to have the same Weibull shape parameters to simplify the equations.

Zweben also compared their model predictions to experimental data. Zweben's model predicted a hybrid effect of 22% for unidirectional carbon/aramid hybrids. This is significantly higher than the 4% found in their experiments. Zweben also compared this prediction with a multidirectional carbon/aramid composite, which showed a hybrid effect of 31%. This is closer to the predicted value of 22%, but questions arise whether this model can be applied to the more complex situation of multidirectional hybrids.

If Zweben's equations (1-3) are further analysed and interpreted, then several important conclusions can be drawn:

- The strain concentration factor depends only on the ratio ρ of the normalised stiffnesses of the two fibre types. In the rare occasion of a hybrid composite with two fibre types of the same stiffness, the strain concentrations are the same in the hybrid and non-hybrid composite.
- The most crucial parameter in Zweben's model is the ratio of the failure strains. If this ratio is larger, then the hybrid effect will be larger. Therefore, hybridisation with very high elongation fibres should be very effective.
- The exponent $-1/2q$ is typically very small, as most Weibull moduli are between 3 and 10. This means that, according to Zweben's model, the ineffective length and stress concentration factor only have a small influence on the magnitude of the hybrid effect.
- Although this was not mentioned by Zweben, fibres with small Weibull shape parameters should yield a larger hybrid effect. This means that a large spread on the fibre strength is beneficial for the hybrid effect. This was later confirmed by Fukunaga et al. [52] and is one of the reasons why natural fibres are promising fibres to hybridise, as they typically demonstrate a large variability in fibre strength.

3.2 Later improvements

Zweben's model is powerful, as it is simple and allows for an easy interpretation. The simplified fibre packing leads to three limitations. Firstly, the fibre packing is a one-dimensional row of fibres, which leads to overestimations of the stress concentrations compared to the more realistic 2D packings [34]. Secondly, the LE and HE fibres are arranged in an alternating manner, leading to the highest possible dispersion for the fixed 50/50 ratio of LE/HE fibres. A broken LE fibre is always shielded from the next LE fibre by the HE fibre in between. It does not allow to investigate the influence of dispersion. Finally, the packing leads to a fixed ratio of LE over HE fibres, which means it cannot investigate the influence of the LE fibre volume fraction. This fractionwas proven to be a key parameter for maximising the hybrid effect [10].

Fukuda [49] pointed out three other intrinsic shortcomings of Zweben's model [24], which he improved in his own model. Firstly, Zweben used the first failure of a HE fibre near a broken LE fibre as failure criterion, which may not be a realistic criterion for hybrid composites and does not conform to the definition given in Fig. 3a. Secondly, Zweben [24] mentions calculating a lower bound for the failure strain of hybrid composites by assuming failure occurs when an HE fibre next to a broken LE fibre fails. In hybrid composites, however, a broken LE fibre typically leads to failure of the adjacent LE fibres instead of the adjacent HE fibre. This surrounds an HE fibre by two broken LE fibres and leads to larger stress concentrations than predicted by Zweben. Finally, Zweben's approximate method [24, 53] predicts stress concentration factors smaller than Hedgepeth's solution. Fukuda [49] mentions that this may lead to an overestimation of the composite strength. The latter argument may not be a valid one, as other authors, such as Nedele and Wisnom [36] and Zhou and Wagner [54] later demonstrated that Hedgepeth's approach [34, 44] overestimates the stress concentrations.

Addressing these three shortcomings, Fukuda [49] obtained equation (4) for the enhancement of the LE composite failure strain.

$$R = \left[\frac{\delta_h \cdot \left(k_h^q - 1\right)}{2 \cdot \delta \cdot \left(k^q - 1\right)} \right]^{-1/2 \cdot q} \tag{4}$$

This equation is similar to equation (3), but with two important differences. Firstly, the ratio of failure strains of both fibres is not included in this model anymore. This would mean that the failure strain of the HE fibres does not affect the hybrid effect. Secondly, the stress concentrations and ineffective lengths were calculated more accurately. Fukuda's equation results in a better correlation with the experimental results of Zweben [24] and Bunsell and Harris [31].

Fukuda and Chou [25] extended Hedgepeth's approach [44] to calculate the stress concentrations adjacent to a group of broken fibres. Their results indicate that hybrid composites with high and low modulus fibres display lower stress concentrations on the high modulus fibre than composites with only high modulus fibres. This effect leads to an increased failure strain of the high modulus fibres and hence, a positive hybrid effect. Their terminology may be confusing, as in their work high and low modulus fibres are the LE and HE fibres, respectively. Zeng [55] confirmed the conclusion that the stress concentrations on LE fibres decrease if HE fibres, which have a lower modulus, are added. Fukunaga et al. [56]

later showed that the stress concentrations could also be higher in hybrid composites if the number of adjacent LE fibres increases. Their model was, however, based on a single row of only 4 adjacent fibres.

Fukuda and Chou [25], Zeng [55], and Fukunaga et al. [56] all used 1D fibre packings. This was in recent years refined to more realistic packings by Swolfs et al. [40]. By using the finite element method, Swolfs et al. [40] proved that the stress concentrations on the LE fibres are hardly affected by the relative fraction of both fibres. This is shown in Fig. 6 for a carbon/glass hybrid composites for 4 different relative fractions. This conclusion was also validated for carbon/aramid hybrid composites.

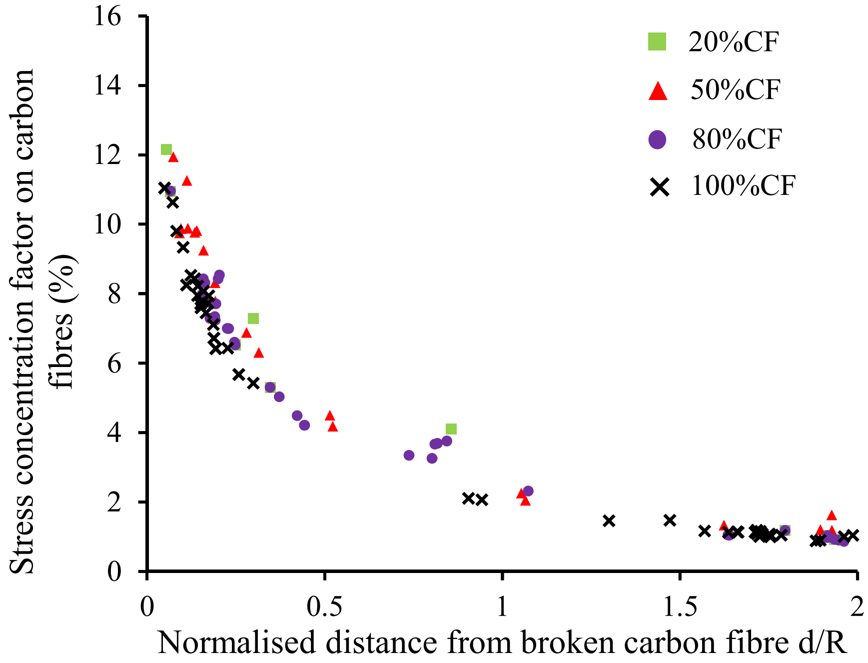

Figure 6: Stress concentration factors on the intact carbon fibres in a carbon/glass hybrid composite as a function of the distance from the broken carbon fibre. The legend indicates the volume fraction of carbon fibres over the total volume of fibres (reprinted from [40], with permission from Elsevier).

The previous paragraphs focused on the hybrid effect for failure strain. The damage development, however, can also be altered by hybridisation. Using a Monte Carlo approach, Fukuda and Chou [57] demonstrated that the initial fibre failures occurred at the same strain in hybrid and non-hybrid composites, but that hybrid composites failed more gradually, leading to a higher ultimate failure strain. This feature may be caused by a slower cluster development and a larger critical cluster size. Zeng's model for hybrid composites [55] reached a similar conclusion after observing a change in the failure mode of the LE fibres. Zeng demonstrated that the stress perturbation around a broken LE fibre is more localised in hybrid composites and therefore have a tendency to break at multiple, independent locations along their gauge length.

The model of Harlow [26] demonstrated that HE fibres act as crack arresters in hybrid composites. Since HE fibres have a higher failure strain, they can bridge the cracks formed by the broken LE fibres. This understanding is vital, as it also helps to explain why the hybrid effect is more pronounced at lower LE fibre content and higher degrees of dispersion. In both cases, the crack arresting effect is more pronounced. The low LE fibre content argument was confirmed by Kretsis [10], by reviewing the experimental results of other authors. Fukunaga et al. [56] confirmed this with their model. The higher hybrid effect with better dispersion has not only been observed experimentally, as will be shown in "4.1.2 Failure strain", but was also confirmed by the models of Fukunaga et al. [52], Pan et al. [58], Fariborz et al. [50, 59] and Harlow [60].

Fukunaga et al. [56] proved that a hybrid effect only exists if the LE fibres have a spread on the strength. This was also indicated by Manders [61], who stated that: "*the hybrid effect arises from a failure to realise the full potential strength of the fibres in all-carbon fibre composites, rather than from an enhancement of their strength in the hybrids*". If all LE fibres have the same strength, then they will already realise their full potential in non-hybrid composites and no hybrid effect can exist.

3.3 Influencing parameters

The previous sections described various aspects of understanding the failure of hybrid composites. This section aims to give an overview of the many different parameters affecting the hybrid effect, and to assess which parameters are the most important ones. The focus is put on the hybrid effect for failure strain, as most available data is concerned with this specific hybrid effect.

3.3.1 Relative amount of fibres

The relative amount of both fibres is a crucial parameter for the hybrid effect. As illustrated by Kretsis [10], a larger hybrid effect for failure strain of the LE fibre composite is found in experiments if the relative volume of LE fibres over the volume of all fibres is lower. The corresponding modelling evidence is limited, as most models are limited to alternating packings, and hence a 50/50 volume ratio, as in Fig. 5b. Some authors were not limited by this type of packing and did prove the importance of the relative amount of both fibres. First, Fukunaga et al. [56] determined that the hybrid effect is maximised at low LE fibre content. Later, this was confirmed by the model of Jones and Dibenedetto [62], who showed an increase in the apparent breaking strength of carbon fibre by 92% if the carbon fibres were isolated from each other by the addition of many glass fibres.

3.3.2 Elastic properties of the fibres

The elastic properties of the two fibres are important, as they affect (1) the static stress concentrations [24, 25, 40, 49], (2) the ineffective length [24, 25, 40, 49], (3) the dynamic stress concentrations [47]. It should be noted that Zweben's model predicted only a small influence of the first two parameters, but his conclusions need to be verified with more refined models. If the coefficients of thermal expansion remain the same, but the stiffness changes, then the thermal effect will also be influenced. Therefore, all three hypotheses for the hybrid effect are affected.

3.3.3 Failure strain ratio

The ratio of the average failure strains of both fibre types was indicated by Zweben's model [24] to play a crucial role in the hybrid effect. His definition of the hybrid effect was based on fracture of a HE fibre near a broken LE fibre. In contrast, Fukuda [49] defined the hybrid effect based on fracture of a LE fibre near a broken LE fibre. In that case, the ratio of the failure strains has no effect on the hybrid effect. Both Zweben's and Fukuda's model are simplified and require several assumptions, which probably means the reality lies somewhere in the middle. If the HE fibre failure strain is close to the LE fibre failure strain, then some

HE fibres will break prior to full failure of the LE fibres. This should reduce the hybrid effect. By contrast, if the HE fibre failure strain is much larger than LE fibre failure strain, then the two fibres act independently and a larger hybrid effect can be expected. This was also pointed out by Fariborz et al. [50]. More work is needed to establish how important the ratio of average fibre failure strains is in determining the hybrid effect for composite failure strain.

3.3.4 Fibre strength distribution

The fibre strength distribution also plays an important role. Fukunaga et al. [56] revealed that the hybrid effect is zero when there is no scatter on the LE fibre strength. If the strength of the LE fibres has a large scatter, or alternatively a small Weibull shape parameter, then the hybrid effect is expected to be larger. This can also be derived from the models of Zweben [24] and Fukuda [49].

3.3.5 Degree of dispersion

The degree of dispersion is yet another important parameter. Some of the early models were not able to model this, as they used the simplified 1D packing with alternating LE and HE fibres [24, 25, 49, 58]. Some authors have claimed to find an increase in the hybrid effect for failure strain with increased dispersion, but they simultaneously changed the relative volume fractions of both fibre types. This was for example the case in Harlow [60]. Fukunaga et al. [56] were the first ones to prove that the hybrid effect increases when the bundle size decreases from four fibres to a single fibre, while keeping the relative volume fractions constant. Fukunaga et al. did not mention how large the increase was, but from their figures an increase in the strength by about 10% can be estimated. A recent study by Mishnaevsky and Dai [63] showed that a finer dispersion leads to slower development of internal damage. This was only true for displacement-controlled models, while a faster damage development was found for load-controlled models. Displacement-controlled models are, however, more relevant for hybrid composites.

Due to the overwhelming amount of experimental data confirming the importance of dispersion [14, 64-68], there is no doubt that this is one of the most critical parameters. In these experiments, additional improvements of about 20% in failure strain by increasing the dispersion have been reported by several authors [65, 67, 68].

3.3.6 Matrix properties

Finally, the matrix properties also affect the hybrid effect, through their influence on the stress concentrations and ineffective length. The influence of the matrix on the ineffective length is determined by its shear modulus G, as can be seen in equation 2. Zweben's equations [24] for the stress concentration are only affected by the fibre moduli and cross-sections. This is due to the assumptions of the shear lag theory, which assumes that the matrix does not carry axial loads. As Pan and Postle [58] showed in their models, an increased matrix shear yield strength can also increase the hybrid effect, but only at a high fraction of LE fibres. The matrix properties are hence expected to have only a secondary effect.

3.3.7 Other parameters

There are several other parameters, such as fibre-matrix interface strength, interlaminar strength and interlaminar fracture toughness, which may also influence the hybrid effect. So far, none of the models take into account these properties and it is therefore difficult to judge their importance. More advanced models are required to establish the importance of these parameters.

3.4 Conclusion

In the seventies and eighties, several models for hybrid composites were developed. In the past two decades, however, hybrid models ground to a halt, while the state-of-the-art models for non-hybrid composites have advanced significantly. Currently, the models for hybrid composites are lagging behind.

While the initial fibre failures occur at the same strain, the failure development in hybrid composites is more gradual than in non-hybrid composites. Predicting this failure development remains a challenging task, as it is a complex interplay of many parameters. The additional geometric complexity compared to non-hybrid composites makes the currently available models limited to qualitative statements. This gap between experiments and models was also confirmed by Jawaid et al. [69]. To increase the use of hybrid composites, there is a strong need for quantitative predictions of not only the initial failure of the LE fibres, but also on the final failure of hybrid composites.

4 Mechanical properties of hybrid composites

The next sections review the collected data on mechanical properties of hybrid composites and provide an extensive discussion on which configurations yield the best properties. The investigated mechanical properties are tensile, flexural, impact and fatigue resistance. Other properties, such as shear or compression, will not be investigated, as those remain smaller sub-fields within hybrid composite research.

4.1 Tensile properties

4.1.1 Tensile modulus

The longitudinal tensile modulus of hybrid composites has been shown to obey a linear rule of mixtures, according to many researchers [10, 15, 16, 20, 21, 31, 70]. Values deviating from this behaviour can in most cases be attributed to variations in the fibre volume fraction or fibre orientation. This is for example the case in Ren et al. [64], who reported a higher modulus for intralayer than for interlayer unidirectional carbon fibre/carbon fibre hybrids. It can be expected that the small reported deviations are due to crimp, fibre misorientations or measurement inaccuracies in the fibre volume fraction.

Alternatively, as reported by Phillips [18, 19], some deviations can also be explained by an incorrect use of the rule of mixtures [18, 19]. The relative volume fractions of both constituent fibres should be used as composition parameter, but these are often difficult to measure separately in hybrid composites. Estimates based on ply fraction or tow fraction are easier to obtain, but they do not necessarily depend linearly on the fibre volume fraction, meaning that the rule of mixtures would not be linear either.

Hybrid effects may not be expected for the longitudinal tensile modulus, but can still occur in the transverse direction, where rule of mixtures are not linear and often less accurate. In his PhD. thesis, Taketa [71] demonstrated that the tensile modulus in the transverse direction of unidirectional carbon fibre-reinforced polypropylene (PP) hybridized with woven self-reinforced PP displays a positive hybrid effect. This is explained based on the high Poisson's ratio of the self-reinforced PP, which means it has a high tendency to shrink in the transverse direction during a tensile test. This transverse direction coincides with the stiff carbon fibres, which counteract the Poisson's contraction. As a consequence of the additional constraints, the composite as a whole behaves stiffer than expected from the linear rule of mixtures.

4.1.2 Failure strain

The first definition of the hybrid effect, given in "2.1 Introduction", was based on the apparent failure strain enhancement of the LE fibre in a hybrid composite compared to the failure strain of a LE fibre-reinforced non-hybrid composite. This hybrid effect has been extensively studied in the past and was also the subject of the first report of a hybrid effect in 1972 [15]. As explained in section "2.1 Introduction", this hybrid effect was the subject of scientific discussion in the seventies and eighties. Currently, the failure strain enhancement is well established in literature. In a review paper, Kretsis [10] analysed literature data prior to 1987 and clearly demonstrated that the hybrid effect increased with decreasing LE fibre content. An overview of the hybrid effect reported in literature can be found in Fig. 7 and Table 1 [14, 15, 23, 24, 31, 41, 72-79].

A typical range of the hybrid effect for failure strain is 10-50%, although some outliers have been reported. Based on the data reported in Chamis et al. [76], Kretsis [10] calculated negative hybrid effects down to -66%. These results were discarded as unrealistic values. Aveston and Sillwood [23] reported a hybrid effect of +116% in carbon/glass interlayer hybrids, but this is mainly due to an unreasonably low failure strain for their carbon fibre reference composite.

A vital caveat for interpreting the literature data that Kretsis [10] gathered is that this data is more than 25 years old. At that time, carbon fibre had a lower failure strain, sometimes even below 1% [15, 23], and a higher scatter on the fibre strength [9]. As pointed out in "3.3 Influencing parameters", both these changes in carbon fibre properties have an influence on the hybrid effect. Firstly, a lower failure strain for the LE fibres results in a higher ratio of the composite failure strains, which can be seen in equation 3, and will increase the hybrid effect. Secondly, Fukunaga et al. [56] proved that the scatter on the LE fibre strength, or equivalently LE fibre failure strain, is a vital parameter for the hybrid effect. If the fibre strength was a deterministic value, then the hybrid effect would be zero. Therefore, even though this remains unproven, it seems to be reasonable to conclude that a larger scatter on fibre strength results in a larger hybrid effect. The low cost carbon fibres that are expected to come on the market for automotive applications in the next years [80] will most likely have a larger scatter on fibre strength than the current state-of-the-art carbon fibres. Hence, they are expected to bear potential for a large hybrid effect.

Based on the previous arguments, it can be expected that the hybrid effect in hybrid composites with the current carbon fibres is smaller than in the early reports. Diao et al. [75] recently reported a failure strain decrease of 8% in co-mingled T700-IM7 carbon fibre/carbon fibre hybrid composite compared to the reference IM7 carbon fibre composite. This decrease was attributed to surface damage introduced by the co-mingling process. The small difference in the failure strains of both fibre types may explain the lack of a positive hybrid effect.

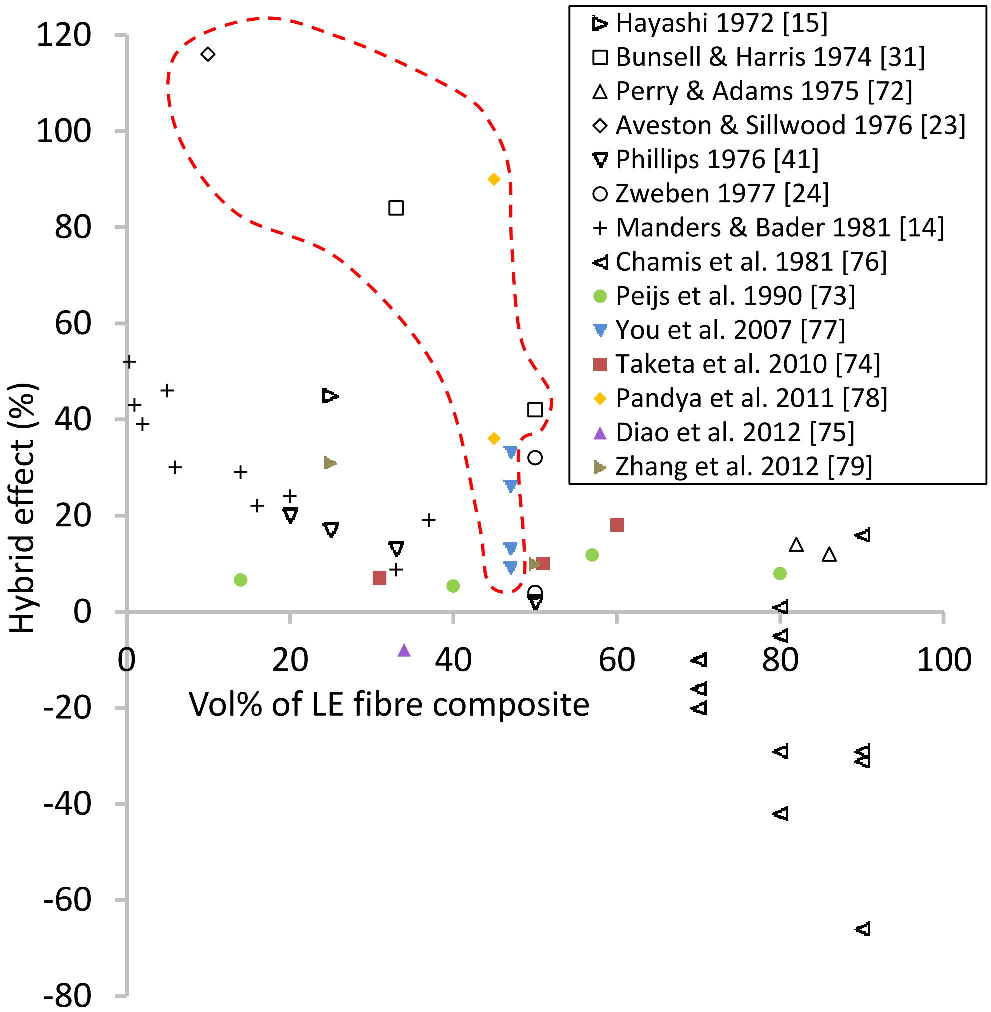

Figure 7: The hybrid effect for tensile failure strain as a function of the volume percentage of the LE fibre composite. Data from before Kretsis' review in 1987 are in black, while the others are coloured. Data which has to be interpreted with care can be found within the red dashed region.

Pandya et al. [78] reports a hybrid effect of +36% and +90% for a carbon/glass hybrid composite. Since the relative content of carbon fibre was 47% and the degree of dispersion was low, these results are surprisingly higher than the trends predicted by Kretsis [10]. Moreover, the hybrid effect was increased from +36% to +90% by putting the carbon fibre layers as inner plies rather than outer plies. Their tensile diagrams do not display a vertical drop, which would coincide with failure of the carbon fibre plies. Instead, Pandya et al. [78] achieved a gradual failure, but still used the ultimate failure strain to calculate the hybrid effect. This does not conform to the definition of hybrid effect based on the apparent failure strain enhancement of the LE fibre composite. From their data, it was not possible to deduce the hybrid effect using the proper definition.

You et al. [77] reported a hybrid effect of 9-33% in unidirectional carbon/glass hybrids. The highest hybrid effect was achieved when the fibres were well dispersed. You et al. obtained a failure strain of only 1.25% for unidirectional T700 carbon fibre composites. In our opinion, this surprisingly low failure strain for their reference T700 composites might be partially due to the testing conditions. This would mean that the reported effect may be partially caused by the fact that the hybrid composite is less sensitive to the testing conditions. Their results therefore need to be interpreted with care. Moreover, You et al. used the ultimate failure strain to calculate the hybrid effect and do not mention whether this coincides with failure of the carbon fibres. Again, it was not possible to deduce the hybrid effect according to the proper definition.

Table 1: Overview of the hybrid effect for failure strain. The column UD/MD indicates whether the composites were unidirectional (UD) or multidirectional (MD). The hybrid effect is calculated as the relative failure strain enhancement of the carbon fibres in the hybrid composites compared to their failure strain in an all-carbon fibre composite.

Ref.	Year	Fibres	Configuration	UD/MD	V_f ratio	Hybrid effect (%)	Remarks
Hayashi [9]	1972	Carbon/glass	Interlayer	UD	25/75	+45	
Bunsell & Harris [25]	1974	Carbon/glass	Interlayer	UD	33/67 to 50/50	+42 to +84	Very low failure strain for LE fibres measured, and short gauge lengths used (50mm)
Aveston & Sillwood [17]	1976	Carbon/glass	Interlayer	UD	10/90	+116	Ultimate failure strain was used to calculate the hybrid effect
Perry and Adams [66]	1975	Carbon/glass	Interlayer	UD/MD	86/14	+12	HE fibre was under 45°
		Carbon/kevlar			82/18	+14	
Phillips [35]	1976	Carbon/glass	Intralayer	UD	20/80	+20	
					25/75	+17	
					33/67	+13	
					50/50	+2	
Zweben [18]	1977	Carbon/kevlar	Interlayer	UD	50/50	+4	
			Interlayer	MD	50/50	+32	
Manders & Bader [8]	1981	Carbon/glass	Interlayer	UD	5/95 to 50/50	+6 to +46	
			Intralayer	UD	6/94 to 0.4/99.6	+30 to +52	0.4/99.6 was achieved by a carbon tow in between HE layers
Chamis et al. [70]	1981	Carbon/glass	Intralayer	UD	70/30 to 90/10	-42 to +16	High fractions of LE fibre
		Carbon/kevlar	Intralayer	UD	70/30 to 90/10	-66 to +10	
Peijs et al. [67]	1991	Carbon/PE	Intralayer	UD	20/80 to 80/20	+5 to +12	
You et al. [71]	2007	Carbon/glass	Intralayer	UD	47/53	+9 to +27	Ultimate failure strain was used to calculate the hybrid effect
			Intrayarn	UD	47/53	+14 to +33	
Taketa et al. [68]	2010	Carbon/PP	Interlayer	MD	31/69 to 60/40	+7 to +18	
Pandya et al. [72]	2011	Carbon/glass	Interlayer	MD	45/55	+36 to +90	Ultimate failure strain was used to calculate the hybrid effect
Diao et al. [69]	2012	Carbon/carbon	Intrayarn	UD	34/66	-8	Carbon fibres with different failure strains. Negative effect attributed to process-induced damage
Zhang et al. [73]	2012	Carbon/glass	Interlayer	MD	25/75 to 50/50	+10 to +32	

Zhang et al. [79] hybridised woven glass and carbon fibre and found improvements in failure strain, ranging between 10% and 31%. The failure of the carbon fibre layers coincided with final failure of the hybrid composite and no further load carrying by the glass fibre layers was observed. This remaining load carrying capacity was observed by several other authors, e.g. [13, 15, 31]. It is unclear which parameters are exactly required to maintain this load carrying capacity after the carbon fibre failure, though interlaminar bonding [31] and dispersion [13] have been proven to play a crucial role.

All the described data are also summarised in Fig. 7 and Table 1. In general, most of the reported values are positive. The values of Bunsell and Harris [31], Aveston and Sillwood [23], Pandya et al. [78], You et al. [77] are found within the red dashed line in Fig. 7. These values have to be interpreted with care, as they may be affected by improper testing of the reference composites or an improper definition of the hybrid effect. From Fig. 7, it cannot be concluded that the hybrid effect has decreased compared to before 1987, even though this was expected based on theoretical considerations.

4.1.3 Tensile strength

According to many authors, the hybrid effect for tensile strength is based on a bilinear rule of mixtures, see Fig. 8a [10, 14, 81, 82]. This prediction is based on a displacement controlled test, in which iso-strain is assumed for both the LE and HE fibres. For simplicity of this explanation, the contribution of the matrix is neglected.

Based on their failure strains, the LE fibres fail first, followed by the HE fibres. After the LE fibres have failed, they are assumed to fully debond or delaminate from the HE fibres. The LE fibre hence stop carrying stress, leaving only the HE fibres as load-carrying elements. As would be the case in a regular tensile test, the initial cross-sectional area would still be used to convert load into stress. Depending on whether the fraction of HE fibres is high or low, two possibilities arise after the LE fibre failure. At high fractions of HE fibres, the stress is able to reach levels higher than the stress at the failure strain of the LE fibres, as illustrated in Fig. 8b. The strength will hence be dominated by the stress contribution of HE fibres at their failure strain, which is represented by the line ACE. At low fractions of HE fibres, these fibres also continue to carry stress, but in this case, the stress at HE failure does not exceed the stress at the failure strain of the LE fibres. This is illustrated in Fig. 8d. The strength in this region is hence determined by the line BCD, which represents the stress in the hybrid when the LE fibres break. The minimum in this bi-linear rule of mixtures occurs when both peaks in the tensile diagram have the same height, as displayed in Fig. 8c.

Fig. 8 also contains experimental data points for carbon/glass hybrid composites from Shan and Liao [83], showing that the bilinear rule of mixtures does not yield a satisfactory prediction. A similar positive deviation from the bilinear rule of mixtures was found in Peijs et al. [73].

If both fibres are linearly elastic, then the tensile modulus follows a linear rule of mixtures in the fibre direction. If one observes experimentally that the failure strain is enhanced, then the tensile strength should also be enhanced. This is not as straightforward as it seems. The reason for the failure strain enhancement is often a more gradual failure, meaning that the last part of the tensile diagram is not linear anymore. In some cases, the tensile diagram even has a plateau near the end [13, 75].

Zhang et al. [70] found that the ultimate tensile strength of unidirectional glass/flax composites increased by 15% if the dispersion was improved. Ren et al. [64] observed a small but negative hybrid effect by combining two different types of carbon fibres in a single composite. The tensile strength for intralayer hybrids was slightly higher than for interlayer hybrids, demonstrating that increased dispersion leads to better mechanical performance in hybrid composites.

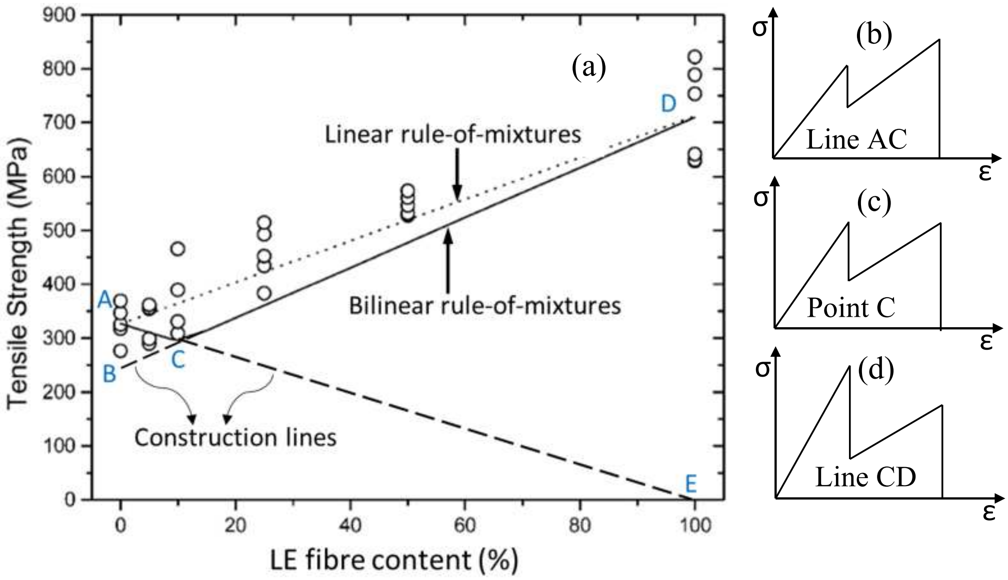

Figure 8: (a) Illustration of the bilinear rule of mixtures for the tensile strength of carbon/glass hybrid composites (adapted from Shan and Liao [83], with permission from Elsevier), and corresponding tensile diagrams of hybrid composites for (b) line AC, (c) point C, and (d) line CD.

4.1.4 Conclusion

Accurately measuring the hybrid effect requires very precise tensile tests on the hybrid composite as well as on the reference carbon fibre composite. Most of the reported hybrid effects were found in unidirectional composites, which are even more difficult to test than multidirectional composites. Therefore, the baseline strength or failure strain of the carbon fibre reference composites is doubtful in several publications. It has been pointed out that stress concentrations at the grips may be less detrimental in hybrid composites than in non-hybrid composites [13]. This could lead to an overestimation of the hybrid effect. This protective effect of the glass layers can also be exploited for a more reliable measurements of the baseline failure strain of UD carbon fibre composites. The carbon fibre layers however have to be sufficiently thick to avoid any hybrid effects. The minimal layer thickness in this case should be supported by modelling evidence.

Special care should be taken in the sample preparation and the tensile testing setup to ensure a suitable failure away from the grips. The authors strongly recommend researchers to provide an accurate description of the tensile testing procedure and the observed failure mechanisms. This is required to allow a proper interpretation of the reported test data and advance the state of the art.

4.2 Flexural properties

Flexural properties of hybrid composites are highly dependent on the layup, as the longitudinal stress at the neutral line is zero, but increases when moving away from that line. Hybrid composites yield additional possibilities to optimise the mechanical performance by not only changing the ply angles, but also by changing the material type of each ply. This also makes the flexural properties of hybrid composites more difficult to interpret than the tensile properties. Just like the tensile modulus, the flexural modulus can be predicted rather well. While simple rule of mixtures apply to tensile moduli, the classical laminate theory is commonly used to predict flexural moduli. This part of the review will therefore focus on flexural strength rather than modulus.

4.2.1 Basic effects

The ratio of compressive strength over tensile strength is different for carbon and glass fibre composites. Wonderly et al. [84] for example reported this ratio as 0.73 for glass fibre composites, while it was only 0.34 for carbon fibre composites due to the anisotropic nature of carbon fibres. These values may not be generally applicable though. They are known to strongly depend on the carbon fibre type [85] and how well the fibres are supported against buckling. Nevertheless, it may be possible to increase the flexural strength of a composite by replacing carbon fibres in the outer ply on the compressive side by glass fibres. This can potentially lead to large hybrid effects.

Flexural tests do have the advantage over tensile tests that they are not influenced by gripping artefacts. Flexural strength may however be affected by other artefacts, such as stress concentrations at the rollers and difficulties in accurately measuring stresses [86, 87]. Size effects are also known to be significant in flexural strength of non-hybrid composites [88, 89]. Wisnom et al. [88] pointed out that the strain or stress gradients may be the main contributor to the size effect in flexure. The underlying assumption is that large stress or strain gradients provide larger support of the outer layers by the inner layers. The distribution of stress gradients in hybrid composites can be rather complex in hybrid composites due to the different stiffness of the layers. The literature on hybrid composites has not given any attention to these phenomena. It is therefore unclear how important they are in determining the hybrid effect.

4.2.2 Experimental results

Dong et al. [90] obtained experimental flexural strengths for carbon/glass intralayer hybrids, which are 40% and 9% higher than the full carbon and full glass reference composites. The achieved strength for the hybrids was higher than the values predicted by both finite element analysis and classical laminate theory.

Similarly, Giancaspro et al. [91] noticed that glass fibre composites failed on the tension side, while carbon fibre composites failed mainly on the compression side. Adding carbon fibres on the tension side of glass fibre composites increased the flexural strength, while this was not the case when they were added on the compressive side. In the latter case, the failure mode was changed from failure in the tension side to crushing on the compression side. Davies et al. [92] demonstrated that replacing 12.5 vol% of carbon fibres on the compression side by silicon carbide fibres increased the flexural strength by 22%. It is suggested that silicon carbide fibres have a compressive-to-tensile strength ratio similar to glass fibres and hence, higher than that for carbon fibres.

According to Giancaspro et al. [91] and Dong et al. [93], an optimal level of glass fibre exists to achieve maximum flexural strength. Dong et al. [93] stated that the highest flexural strength in carbon/glass hybrids was achieved at a relative content of 12.5% of glass fibres, all of which are placed on the compressive side. A symmetric layup is hence not the optimal design for a hybrid composite that will be subjected to flexural loads [90, 93]. A further optimisation showed that the flexural strength can be further improved if the fibre volume fraction within the glass fibre layers is higher than in the carbon fibre layers.

Many authors have investigated the flexural behaviour of hybrid composites with natural fibres. These authors often limited themselves to improving the mechanical and physical properties of the natural fibres. As expected, hybridisation mostly leads to performance in between the performance of both fibre types, but most research in this area lacks a clear assessment of the hybrid effects and the intrinsic mechanisms controlling it. Some authors reported lower than expected flexural properties due to problems with adhesion and lack of good interface quality [94-96]. Improving the adhesion by surface treatments improved flexural strength in coir/silk hybrid composites [96], in banana/glass fibre hybrid composites [97].

4.3 Impact resistance

Impact resistance of hybrid composites has been extensively investigated, as toughening is one of the key reasons for fibre hybridisation and impact resistance is strongly related to toughness. Impact resistance can be characterised in three ways: energy absorbed during a penetration impact, damaged area after a non-penetration impact event and residual properties after impact. These three properties are governed by different mechanisms and hybridisation will have a different effect on each of them. Hence, it will always be indicated which type of impact was performed on the described hybrids.

In hybrid composites, the layup is closely linked with the dispersion and determines the positioning of the layers, both of which are known to be important parameters for impact. In the most common configuration, namely interlayer, the dispersion is completely determined by the layup. Therefore, this section is split up according to these two parameters: positioning of layers and dispersion.

4.3.1 Positioning

The positioning of the layers in an interlayer hybrid composite is crucial, as this will change the flexural stiffness and strength, as well as the damage mechanisms. An overview of how various impact properties are affected by the positioning of the layers in symmetric layups is given in Table 2. The corresponding information for asymmetric layups is summarised in Table 3.

Sayer et al. [98] made asymmetric interlayer hybrids of carbon and glass fibres. By this asymmetric layup, it becomes possible to test the glass side as well as the carbon side on the same layup. If the carbon layers are on the impacted side, the penetration impact resistance was increased by 30%. Park and Jang [99] did similar tests on asymmetric aramid/carbon hybrids, and found a higher penetration impact resistance if the carbon was on the impact side. This allowed the aramid layers, which are on the tensile side of the sample, to absorb more energy. This improvement largely disappeared when the aramid fibres were surface treated to improve adhesion. Park and Jang mentioned that most energy was absorbed through delamination in the aramid layers, although there is no direct evidence to back up this statement.

Jang et al. [100] investigated asymmetric aramid/carbon fibre hybrids with only two layers and did not find a significant improvement depending on which layer was on the impacted side. This was attributed to the similar impact behaviour of both reference composites, which seems surprising for such dissimilar fibre types. Replacing the carbon fibres with polyethylene (PE) fibres did result in an influence. Putting the more ductile PE fibres on the impact side increased the impact resistance by about 50% compared to when they were on the other side. Similar results were achieved for carbon with polyester terephthalate (PET) fibres. These results suggest that putting the HE fibres on the impact side is beneficial. This can be attributed to a difference in damage mechanisms. Since the impact face is loaded in compression and the other face is loaded in tension, the damage mechanisms can be different. Surprisingly, the conclusions of Jang et al. [100] seem to contradict with the conclusions of Sayer et al. [98] and Park and Jang [99]. This is most likely caused by differences in the damage mechanisms, which are triggered by differences in the materials and their interfaces. Understanding this relationship is challenging, but crucial for optimising hybrid composites for impact loading.

Enfedaque et al. [101] and Sevkat et al. [102] found that symmetric carbon/glass hybrids had a better penetration impact resistance if the glass was put on the outside rather than on the inside. Both authors attributed this to the higher failure strain of the glass fibres, which delays the onset of damage. Another confirmation was given by Sevkat et al. [11], who found that damage accumulation after repeated impact tests in carbon fibre-reinforced composites is slowed down by adding glass fibres and especially when they are added as outside layers. Similar improvements in carbon/glass hybrids were found for penetration impact resistance by Onal and Adanur [103]. Sevkat et al. [102] reported that the damaged area in their carbon/glass fibre hybrids was higher than in both reference composites. This was attributed to a greater susceptibility to delaminations due to the incompatibility of the layers.

De Cuyper [104] hybridised steel fibres with self-reinforced polymers, both of which have a failure strain of 15-20%, and investigated their penetration impact resistance. It is one of the only works that combined two fibres with such high ductility. It was found that putting the steel fibres on the outside improved the penetration impact resistance, as these fibres reach higher stresses for the same failure strain.

Naik et al. [105] reported that the compression-after-impact strength of carbon/glass hybrids was higher than that of both reference composites. Interestingly, the highest values were reported for the hybrids where the carbon was on the outside. This confirms the results of Kowsika and Mantena [106], who concluded that hybrids with carbon on the outside perform better in compression after impact based on the failure index parameter that they defined. Their parameter was defined as the relative ratio of energy required for damage initiation to the total absorbed energy. Their initiation energy is based on the first significant deviation from linearity in the force-displacement diagram. This initiation energy is lower if the carbon fibres are put on the outside, as they have a lower failure strain combined with a higher modulus compared to the glass fibres. This results in a higher failure index, which led the authors to believe that carbon on the outside is bad for the penetration impact resistance of the hybrid composites.

All these data are summarised in Table 2 for symmetric layups and Table 3 for asymmetric layups. Table 2 shows that penetration impact resistance can be improved by placing the LE fibres in the middle of symmetric layups. For the other properties, the conclusions are less clear, as there are either conflicting or insufficient data in literature. As is clear from Table 3, no clear conclusion on the influence of positioning of the layers in asymmetric hybrid composites on the penetration impact resistance has been reached in literature.

Table 2: Overview of how various impact parameters are affected by placing the LE fibre more towards the middle layers in symmetric layups. Empty cells indicate that the property was not characterised.

Ref.	Year	Fibres	Penetration impact resistance	Damaged area	Repeated impact	Compression after impact
Kowsika & Mantena [95]	1999	Carbon/glass	improved			deteriorated
Naik et al. [94]	2001	Carbon/glass	/	deteriorated		deteriorated
Sevkat et al. [91]	2009	Carbon/glass	improved	deteriorated		
Sevkat et al. [5]	2010	Carbon/glass			improved	
Enfedaque et al. [90]	2010	Carbon/glass	improved			
González et al. [151]	2014	Carbon/glass		improved		no effect

Table 3: Overview of how penetration impact resistance is affected by putting the LE fibre closer to the impact side in asymmetric layups.

Ref.	Year	Fibres	Penetration impact resistance
Jang et al. [89]	1989	Carbon/aramid	no effect
Jang et al. [89]	1989	Carbon/PE	deteriorated
Jang et al. [89]	1989	Carbon/PET	deteriorated
Park & Jang [88]	2001	Carbon/glass	improved
Onal & Adanur [92]	2002	Carbon/glass	deteriorated
Sayer et al. [87]	2010	Carbon/glass	improved

The importance of the position of the LE and HE layers has also been investigated and confirmed on hybrid composites without carbon fibres. Pavithran et al. [107] hybridised glass fibres with sisal fibres, in which sisal is the LE fibre and glass the HE fibre. Their results showed that Charpy impact energy decreased when moving the LE fibres to the outside, which confirms the results on carbon/glass hybrids from the previous paragraph. De Rosa et al. [108] confirmed that putting the stronger basalt fibres on the outside improved the post-flexural strength in basalt/glass hybrids. It is, however, difficult to transfer the conclusions from one hybrid to the other, as there is currently no theoretical framework available to assess the importance of the various material parameters.

4.3.2 Dispersion

Sarasini et al. [109] demonstrated that well dispersed glass/basalt hybrid composites showed a smaller damaged area after a non-penetration impact event and a higher post-impact flexural strength than the glass fibre and basalt fibre reference composites. This was attributed to the occurrence of multiple small delaminations in the well dispersed hybrids compared to extensive fibre breaks or delaminations on the compression side in the less dispersed hybrids. The same authors confirmed these results on aramid/basalt fibre hybrids [110].

De Rosa et al. [108] also demonstrated that a well dispersed glass/basalt hybrid possessed a higher post-impact flexural strength, which was mainly attributed to the higher flexural strength prior to the impact event. De Rosa et al., however, also found a disadvantage of well dispersed hybrids: acoustic emission detected a more extensive and complex damage development during post-impact flexural tests.

Park and Jang [111] observed that interlayer aramid/polyethylene (PE) fibre hybrids possessed a higher penetration impact resistance than the corresponding intralayer hybrids. This was attributed to the delaminations which developed easier in the interlayer hybrids than in intralayer hybrids. The intralayer hybrids do have a smaller delaminated area, which should in principle result in better post-impact mechanical properties.

Peijs et al. [112] demonstrated an improvement in penetration impact resistance at higher degrees of dispersion of polyethylene and carbon fibres. In these interlayer hybrid composites, delaminations typically occur at the interfaces between dissimilar layers. Well dispersed interlayer hybrids have more of these interfaces, which can delaminate and thereby absorb more energy. Other authors have therefore investigated thin plies as a way to increase the number of interphases in non-hybrid composites [113-115]. Thin plies have only rarely been used in hybrid composites, even though they are potentially interesting materials [13, 116].

4.3.3 Conclusion

A lot of data are available on the impact performance of hybrid composites and how it is affected by the dispersion and the positioning of the layers. Increased dispersion seems to increase non-penetrating impact resistance and residual properties in hybrid composites. Some evidence has been presented that indicates that penetration impact resistance also increases with dispersion. Positioning the fibres with the highest energy-absorption potential on the outside allows the hybrid composite to absorb more energy.

4.4 Fatigue resistance

Fatigue resistance is a vital property for many composite applications such as aircrafts or wind turbines. As explained in “2 The hybrid effect”, the HE fibres in a hybrid composite can act as crack stoppers for the broken LE fibres [117]. This can be expected to increase the fatigue life of hybrid composites compared to that of non-hybrid composites. While tensile, flexural and impact properties of hybrid composites have been extensively investigated, the fatigue resistance has only been investigated by a limited number of researchers.

Wu et al. [118] investigated the tensile fatigue life of carbon, glass and basalt fibre-reinforced composites and hybrid composites of these fibres. Wu et al. demonstrated that hybrid composites can lower the scatter of the fatigue life. The S-N curves of basalt fibre composites were shifted to higher number of cycles by the addition of carbon fibre. This was explained by the lower longitudinal tensile modulus of basalt fibre compared to carbon fibre. This decreases the stress in the basalt fibre, resulting in a steady development of fatigue damage. It should be noted that the authors expressed S-N curves with the percentage of the static strength as the vertical axis. The interpretation of these data clearly depends on how these data are plotted. Moreover, similar improvements were not observed in carbon/glass hybrids, which was attributed to the smoother surface of glass fibres. The authors suggest that this promotes the development of delaminations, which decreased the fatigue life, but these claims remain unproven.

Peijs and Dekok [65] hybridised PE fibres with carbon fibres and found that it resulted in flatter S-N curves. This means that tensile fatigue damage propagates slower and demonstrates the excellent tensile fatigue resistance of PE/carbon fibre hybrids. Their results also proved that the tensile fatigue resistance can be improved by (1) increasing the dispersion, and (2) increasing the fibre-matrix adhesion of the PE fibres by a surface treatment. Peijs and Dekok also remarked that their hybrids seemed to have a smaller scatter in fatigue life, which confirms [118], but contradicts [119, 120].

Fernando, Dickson and co-workers [119, 120] published a two-part study on the tensile fatigue behaviour of carbon/glass and carbon/aramid hybrids. For carbon/aramid hybrids [120], the fatigue stress level for a given number of cycles to failure was shown to vary linearly with the relative ratio of both fibres. Since the tensile strength does not vary linearly with this ratio, it implies that, in relative terms, a positive hybrid effect for the fatigue resistance at that stress level was achieved. A similar hybrid effect was confirmed for carbon/glass hybrids [119]. The positive hybrid effects were confirmed both for unidirectional and quasi-isotropic layups, although the authors remark that a linear rule of mixtures may not be appropriate for fatigue resistance of hybrids. Another remarkable feature of the carbon/aramid hybrid study [120] was that those hybrids were not weakened in compression-tension fatigue, as could be expected from the low compressive strength of aramid fibres. The carbon fibres seem to have provided additional support, which prevented the compressive failure of the aramid fibres.

Hofer et al. [121] demonstrated that glass/carbon epoxy hybrids performed well in tensile fatigue if the layers are well distributed. Conversely, a sandwich-like construction, with glass fibre layers in the middle and carbon fibre layers on the outside, has a severe modulus mismatch at the interface, leading to high interlaminar shear stresses and promoting earlier failure. The loss in tensile fatigue life by the addition of glass fibres is limited, even if up to 50% of the carbon fibres are replaced by glass fibres. This can be partially attributed to the limited decrease in residual strength and failure strain after fatigue cycling. In a later investigation, Hofer et al. [122] used Wöhler diagrams to demonstrate that unidirectional hybrids were almost as fatigue resistant as the carbon fibre reference composites. For quasi-isotropic layups, the hybrids were even better than the corresponding quasi-isotropic carbon fibre reference. The hybrids with a 2/1 carbon-to-glass ratio performed better than 3/1 hybrids due to a more uniform ply distribution.

Flexural fatigue of carbon/glass intralayer hybrids was investigated by Shan et al. [123] Cyclic loading was applied at 75°C in a water bath and showed that the addition of carbon fibres significantly enhanced the environmental tension-tension fatigue life. This is explained by the higher moisture resistance of carbon fibre composites compared to glass fibre composites. In another study from the same group, these results were confirmed for environmental tension-tension fatigue [83].

Burks et al. [124-126] investigated the fatigue behaviour of carbon/glass hybrid composites used for electricity transportation. Burks et al. did not compare their results with any non-hybrid reference composite, making it difficult to draw any conclusions from their studies.

4.5 Conclusion

This critical review of the mechanical properties of hybrid composites proved that in many cases positive hybrid effects can be achieved, although this is not always the case. For all the examined properties, the degree of dispersion was a crucial parameter. In general, increased dispersion leads to larger hybrid effects and better performance. Some exceptions to this general rule have, however, been described. While the initial focus of hybrid composite research was on the failure strain enhancement of carbon fibre, the focus has now shifted to other mechanical properties.

For the complex loading conditions, such as flexural and impact, some authors report conflicting data for the effect of certain parameters. In these loading conditions, more in-depth investigations as well as more advanced models are required to understand the mechanisms.

5 Current trends

In the early days, the focus of research on hybrid composites was on increasing the failure strain of the LE fibres and reducing the material cost by replacing carbon fibres by cheaper fibres. Significant failure strain enhancements are difficult to achieve and, according to the models, are more likely to be achieved with expensive intrayarn hybrids. While cost reduction remains an important driver, the focus has now shifted to achieving either a better balance in different material properties or properties that are not present in the constituents. Hence, these are the trends found in recent literature: pseudo-ductility, ductile fibre hybrids and natural fibre hybrids. They are further discussed in more detail.

5.1 Pseudo-ductility

Traditional fibre-reinforced composites have excellent mechanical properties combined with a low density. Their failure is abrupt and catastrophic, and comes without a warning, see Fig. 9a. Hidden damage, such as delaminations or matrix cracking, can lead to lower than expected strength of the composite structure. This behaviour leads to large safety factors and sub-optimal use of composites. Hybridisation can be employed to achieve a controlled and more gradual failure in brittle fibre-reinforced composites. This behaviour is termed pseudo-ductility, as it resembles the ductile behaviour typically found in metals. This type of behaviour has already been described in the seventies and eighties by several authors, among which Bunsell and Harris [31] and Manders and Bader [14].

The typical stress-strain diagram of a hybrid composite is shown in Fig. 9b and has a characteristic load drop when the brittle fibres break. By controlling the damage mechanisms, however, it is possible to achieve a more gradual failure and hence pseudo-ductility, as illustrated in Fig. 9c [13, 116].

There is a growing interest in pseudo-ductile material systems. This is driven by a strong need to reduce the safety factor in the design of composites and the corresponding need for increased toughness. Pseudo-ductility can also be achieved by controlling the damage mechanisms in non-hybrid composites [127, 128], but the focus here is on pseudo-ductility in hybrid composites.

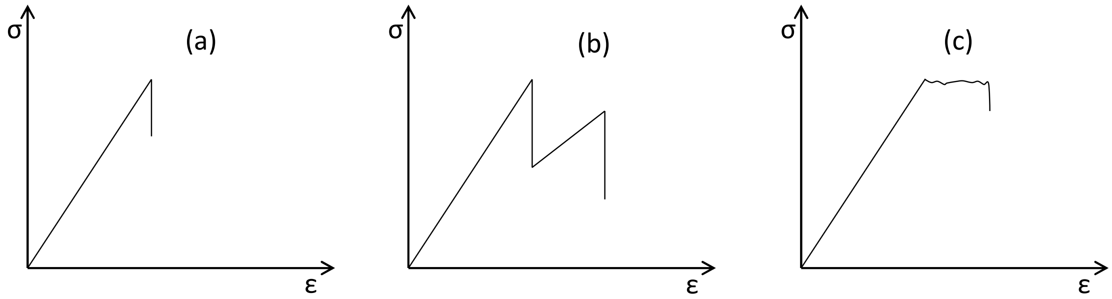

Figure 9: Schematic stress-strain diagrams for (a) non-hybrid composites, (b) typical hybrid composites, and (c) pseudo-ductile hybrid composites.

Czél et al. [13] sandwiched a 29 µm thin layer of unidirectional carbon fibre-epoxy in between thicker layers of glass fibre-epoxy on each side. By making the carbon fibre layer thin enough, a change in the material behaviour was observed. The carbon fibre layer is able to break several times along the length of the sample, before the glass fibre layers break. For their specific material combination, an upper limit of 84 µm for the carbon fibre layer thickness was determined both experimentally and theoretically. Further understanding of this phenomenon was performed by Jalalvand et al. [129], who developed a finite element model for these thin ply hybrid composites. This led to the development of damage mode maps with relative thickness and absolute thickness on x and y-axis (see Fig. 10), showing four quadrants, each of which represent a different failure behaviour of the hybrid composite.

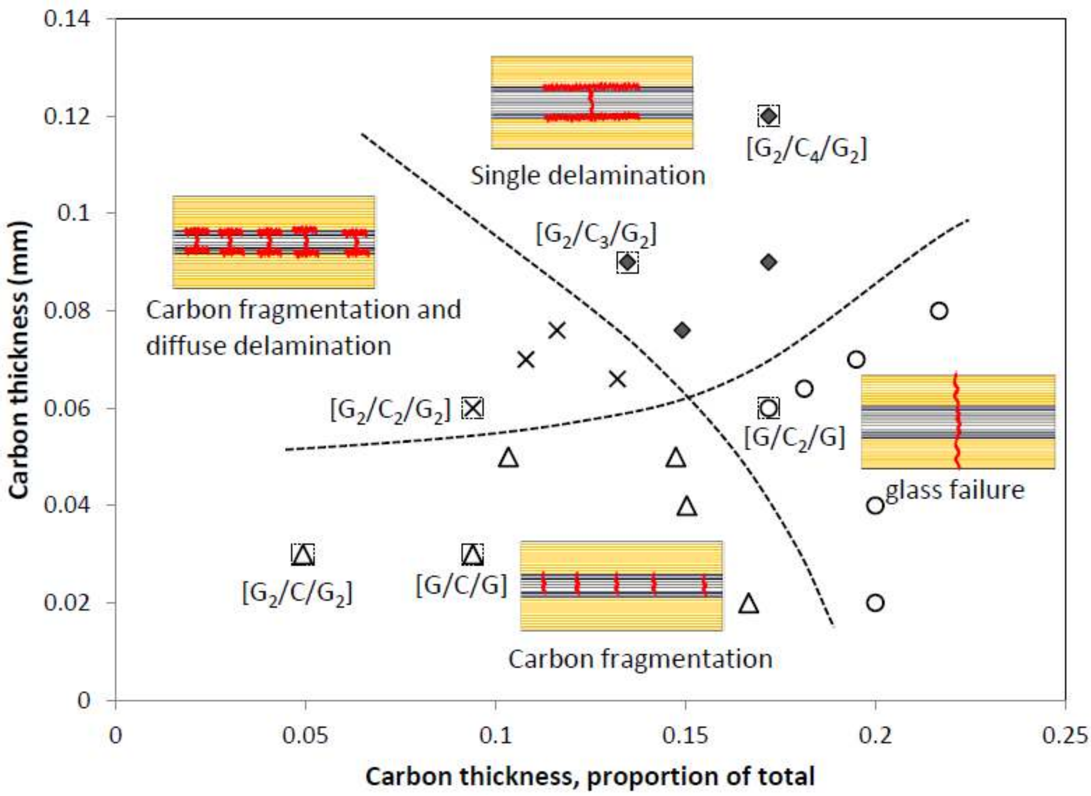

Figure 10: Damage mode map for carbon/glass hybrid composites. The experimental data points are marked with an additional square marker (reprinted from [129], with permission from Elsevier).

Jones and Dibenedetto [62] achieved pseudo-ductile behaviour by finely dispersing carbon fibres with glass or aramid fibres. They calculated an upper limit of 92% improvement in the apparent strength of the carbon fibres if all carbon fibres acted independently from each other. This high value could only be achieved at carbon fibre volume fraction below 6%. The importance of fine dispersion for pseudo-ductility is also shown by Bakis et al. [66] on pultruded rods. Pseudo-ductility was only achieved for their most finely dispersed carbon/glass hybrid, while lower dispersion resulted in two distinct peaks as shown in Fig. 9b.

Somboonsong et al. [130] achieved pseudo-ductility in hybrid bars, by braiding and pultruding carbon and aramid yarns. The various stress drops were attributed to yarns breaking and transferring their stress to the other yarns. Based on their models, Somboonsong et al. could show that the braiding architecture was important in achieving this pseudo-ductility.

Liang et al. [67] demonstrated that carbon/glass rods break at the failure strain of the carbon fibres when the fibres are well dispersed. Some degree of pseudo-ductility is claimed when all the glass fibres were put on the inside. Their tensile diagrams resemble the one in Fig. 9b and therefore should not be called pseudo-ductile. Interestingly, however, the lower dispersion did allow the glass fibres to continue carrying load after the carbon fibre failure. Liang et al. suggest that damage to the glass fibres by the failure of the carbon fibres was limited by the lower dispersion.

Pseudo-ductility has so far only been achieved in composites with a low LE fibre volume fraction. Bunsell and Harris [31] and Manders and Bader [14] did succeed in achieving pseudo-ductility at relatively high carbon fibre fractions, but this was mainly due to the weak carbon fibres at that time. The carbon fibre peak in their hybrids was lower than their glass fibre peak, making it easier to achieve pseudo-ductility. With the strength of the state-of-the-art carbon fibres, the easiest way to reduce the height of the carbon fibre peak in a hybrid is to reduce the carbon fibre volume fraction. The major challenge for the pseudo-ductility concept in the future is hence to develop strategies for achieving it at higher volume fraction of the LE fibre.

Bonding in general is seen as a crucial parameter for achieving pseudo-ductility. Bunsell and Harris [31] showed that a minimal bonding strength between carbon and glass layers is required to achieve pseudo-ductility. The importance of the interlaminar fracture toughness was shown in the analytical equation developed by Czél and Wisnom [13]. Similar work in fibre-reinforced concrete also showed that the fibre-matrix adhesion was a crucial parameter to obtain pseudo-ductile concrete [131, 132].

It has not yet been proven that improved tensile behaviour also leads to improvements in other mechanical properties, such as fatigue or impact resistance. So far, the research has focused on tensile behaviour.

5.2 Ductile fibres

An alternative way of achieving higher failure strains in hybrid composites is to combine brittle fibres with ductile fibres. As explained in “3.3 Influencing parameters”, a large difference in failure strain of the fibres may lead to larger hybrid effects. It may also lead to increases in energy absorption. In the early literature on hybrid composites, however, carbon fibres were hybridised with either glass or aramid fibres. While these fibres indeed have a larger failure strain than carbon fibres, it is still relatively low. In the past decades, however, ductile fibres for polymer composites have become increasingly popular. Examples include steel [133, 134], PP [135-137], PE [73, 138], polyamide [139], polyvinyl alcohol (PVA) [140], coir [141-143] and silk [96] fibres.

Pegoretti et al. [140] combined glass with PVA fibres. For their interlayer hybrids, better tensile properties were achieved when the glass fibre layers were put in between the PVA layers. The best tensile properties were achieved with intralayer hybrids. The difference in failure strain of both fibres was, however, relatively small, as the failure strain of the PVA fibre composite is, in relative terms, only 10-30% higher than that of the glass fibre composite.

Fibres with a larger difference in failure strains were used by Taketa et al. [74], who combined carbon fibre-reinforced composites with ductile PP fibres. Hybrid effects of up to 18% for failure strain were achieved, but the load carrying capacity of the PP fibres was destroyed by the sudden and explosive carbon fibre failure. Another example with a large difference in failure strains is found in Hine et al. [144]. Stretch-broken carbon/polyamide yarns were hot compacted into hybrid single polymer composites. Ductility improvements were achieved in bending, but brittle failure persisted in tension.

Large increases in the ultimate failure strain through hybridisation with a ductile fibre were only reported by Swolfs et al. [116, 145]. These increases were achieved by increasing the dispersion compared to the work of Taketa et al. [74]. This was achieved by either interlayer hybrids with a carbon fibre layer thickness of only 100 μm [116] or by intralayer hybrids made through co-weaving of PP tapes with carbon fibre prepregs [145, 146]. In this way, it was possible to maintain the ductility of the PP fibres, even after the sudden energy release due to the carbon fibre failure. These hybrid composites showed a good balance of stiffness and strength, combined with an ultimate failure strain of 20%. The type of tensile diagram displayed by these hybrid composites is shown in Fig. 11. The degree of dispersion was again found to be a crucial parameter [116], as the PP fibre ductility was maintained better at low carbon fibre volume fraction. Multiple cracks of the carbon fibre layers, similar to the ones demonstrated by Czél and Wisnom [13], were observed at low carbon fibre volume fractions. These multiple cracks for both works are compared in Fig. 12.

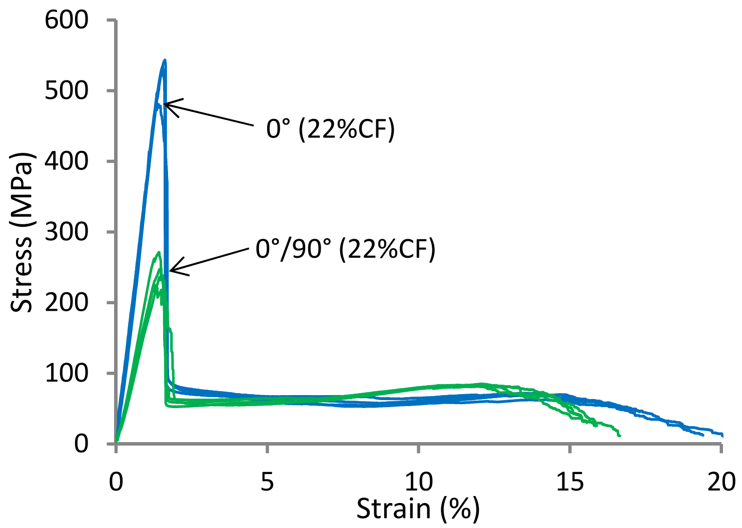

Figure 11: Tensile diagram of intralayer hybrid composites with carbon fibre-reinforced PP and self-reinforced PP. The self-reinforced PP is present in both directions, while the orientation of the carbon fibre PP is indicated by the arrows (reprinted from [145], with permission from Elsevier).

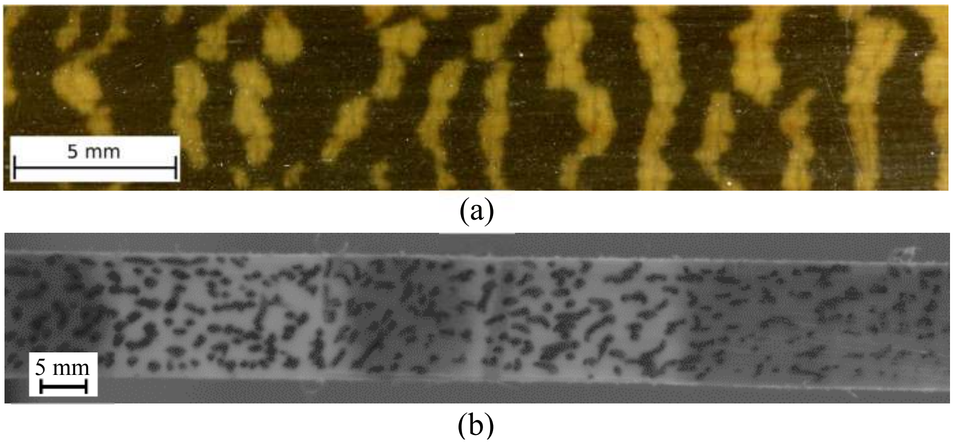

Figure 12: Illustration of the fragmentation of interlayer carbon fibre hybrid composites in a tensile test: (a) multiple cracks in carbon/glass hybrid composites (reprinted from [13], with permission from Elsevier), and (b) two cracks in carbon fibre/self-reinforced hybrid composites [116]. In both cases, the lighter colours indicate locations where the carbon fibre layers are broken and surrounded by delaminations.

While most of the work has been done on hybrid composites with at least one brittle fibre type, the work of De Cuyper [104] investigated the potential of hybrids with two ductile fibre types. De Cuyper hybridised annealed steel fibres with self-reinforced composites in an interlayer fashion. While the tensile strength was according to expectations, the tensile stress was found to be higher than expected at a given strain. This feature was attributed to the large difference in Poisson contraction of both materials, which creates a biaxial stress-strain state and increases the tensile stress at a given strain.

Thysen [134] investigated interlayer hybrid composites of ductile steel fibres and glass fibres. Similar to Czél et al. [13] and Jalalvand et al. [129], Thysen achieved multiple fractures in the LE fibre layers, which are the glass fibres in this case. This only worked when the glass/steel ratio was low. Moreover, a finer dispersion led to smaller delamination lengths, but also to a smaller ultimate failure strain. The same study also investigated the influence of the matrix on the mechanical performance of the hybrid composites. An epoxy matrix led to delaminations, while a similar layup with polyamide matrix showed strain localisation around the location of the broken glass fibre layer. These differences in resistance against delamination led to higher ductility in the epoxy matrix hybrid than in the polyamide matrix hybrid.

By adding ductile fibres, the ductility of brittle fibre composites can be increased. It seems that the larger the difference in failure strains, the more interesting the results are.

5.3 Natural fibre hybrids

The largest boom in hybrid composite publications in the last decade occurred in the field of natural fibre hybrids, mainly driven by environmental concerns. As detailed in the recent review papers by Jawaid and Khalil [69] and Nunna et al. [147], natural fibre hybrid composites are often a combination of a natural fibre with another natural fibre [95, 96, 148-150] or with glass fibre [107, 142, 148, 151-157]. The latter is more common, as it allows larger improvements in mechanical properties. If natural fibres are hybridised with glass fibres, the glass fibres will typically improve most mechanical properties, and at the same time reduce property variability, moisture sensitivity, and increase durability and impact resistance. Reports on natural fibre hybrids with carbon fibres are rare [69]. This is most likely due to (1) the large difference in price and stiffness between natural and carbon fibres, and (2) the higher life cycle cost of carbon fibres compared to glass fibres.

When two natural fibres are combined, then the focus is often on getting a better balance in mechanical, chemical and physical properties, rather than on optimising the hybrid effect. Another reason is that research in natural fibre composites often deals with random mats and short fibres, which make hybrid effects more difficult to find.

The layup of natural fibre hybrids has been extensively investigated [141, 148, 158-160]. In most of these reports, the focus lies on improving the properties with respect to the natural fibre reference composite. This does not necessarily imply that hybrid effects are found, as evidenced from the definitions provided in “2.1 Introduction”. The existence of hybrid effects is focused on less in natural fibre hybrid research. Ahmed and Vijayarangan [158] investigated the influence of the stacking sequence on tensile, shear and flexural properties for woven jute/glass interlayer hybrids. The best flexural properties were found when the glass fibre was positioned at the outer layers, as it has better mechanical properties than the jute fibres. Amico et al. [159] and Khalil et al. [160] reached the same conclusion for interlayer hybrids composed of random mats of sisal/glass and oil palm empty fruit bunch/glass, respectively.

Khalil et al. [160] demonstrated that the impact resistance was higher if the glass fibres were positioned in the middle, although no clear reason for this was given by the authors. Sreekala et al. [156] demonstrated that the Izod impact resistance was higher in hybrid composites than that of the reference glass composites and that of the reference oil palm empty fruit bunch composites.

Ahmed and Vijayarangan [158] found a 10% increase of the tensile strength for woven jute/glass interlayer hybrids by increasing the dispersion. Even though tensile properties are generally not affected by the layup, Jawaid et al. [148] noticed a slightly higher tensile strength if the jute layers were positioned on the outside of the oil palm empty fruit bunch layers.

A common problem in natural fibre hybrids is the adhesion. Investigations of the proper fibre treatments for hybrid composites are common in literature [96, 157, 160-163]. These treatments mainly improve the performance of the natural fibre layers on its own, and do not show synergistic effects.

6 Conclusion and outlook

It can be concluded that the hybrid effect for tensile failure strain is now well established and recognised for traditional hybrid composites such as carbon/glass or carbon/aramid. The three basic mechanisms, namely residual stresses, altered failure development and dynamic effects, have been identified and are qualitatively understood by the use of simple models. Several improvements to Zweben’s model have been made, but they are not yet capable of yielding quantitative predictions of the strength and failure strain of hybrid composites. The current state-of-the-art is lagging behind on models for non-hybrid composites. The increased computational power is expected to facilitate the development of more advanced models for hybrid composites.

Tensile properties of hybrid composites are reasonably well understood. Hybrid effects under more complex loading conditions, such as in flexural, impact and fatigue tests, are not well understood and sometimes even result in apparent contradictions for both the conclusions and mechanisms. More work is needed in this area to clarify the intrinsic mechanisms and to streamline the conclusions.

Despite these issues, hybrid composites are attracting an ever-growing attention from both academia and industry. Fast-growing sub-fields, such as pseudo-ductility, ductile fibres and natural fibre hybrids, are expected to play an important role in the new developments of hybrid composites. These sub-fields are pushed forward by an ever-increasing variety in available materials and processes. More research is needed to fully exploit the potential of metallic and polymer fibres. Processes such as tow spreading and comingling have reached a certain maturity for non-hybrid composites, and open new opportunities for hybrid composites. It is expected that this will further widen the applicability of hybrid composites.

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