PARAMETRIC STUDY OF THE TENSILE BEHAVIOUR OF UNIDIRECTIONAL HYBRID CARBON/GLASS COMPOSITES

Y. Swolfs[a*], R.M. McMeeking[b,c,d], L. Gorbatikh[a], I. Verpoest[a]

[a]*Department of Metallurgy and Materials Engineering, KU Leuven, Kasteelpark Arenberg 44, B-3001 Leuven*
[b]*Department of Mechanical Engineering, University of California, Santa Barbara, CA 93106, USA*
[c]*Materials Department, University of California, Santa Barbara, CA 93106, USA*
[d]*School of Engineering, University of Aberdeen, King's College, Aberdeen AB24 3UE, Scotland, UK*

**yentl.swolfs@mtm.kuleuven.be*

Keywords: hybrid composites, unidirectional composites, strength model, carbon fibres

Abstract

The hybrid effect, which is the apparent failure strain enhancement of brittle fibres in a hybrid composite, was analysed for unidirectional carbon/glass hybrid composites. The hybrid effect strongly depended on the hybrid volume fraction and was found to be up to 36%. This was explained based on a reduction of the number of pathways for break cluster growth, and a delay in break cluster development to larger strains. The critical cluster size of hybrid composites also positively deviates from the linear rule-of-mixtures, contributing to the hybrid effect. Similarly, increased fibre dispersion decreased the number of pathways for break cluster growth, delayed break cluster development and increased the hybrid effect. The critical break cluster size was not affected by the dispersion. These results provide new insight into the failure development of hybrid composites and can help in their further optimisation.

1. Introduction

Carbon fibre-reinforced composites offer excellent mechanical properties, but often suffer from lack of toughness and low failure strain. While there are many strategies to improve toughness, it remains challenging to increase the failure strain. The most promising strategy to increase the failure strain of carbon fibre composites without changing the type of fibre, is fibre-hybridisation. This means that two fibre types are combined in a single matrix.

To understand how this can increase the failure strain, one first needs to understand failure development in unidirectional non-hybrid composites. When such a composite is increasingly strained in the fibre direction, individual fibre failures occur in a stochastic fashion. Each broken fibre locally loses its stress transfer capability and sheds its load to nearby fibres. This causes stress concentrations in the nearby fibres [1, 2], which are now more likely to fail. At higher applied strains, this eventually leads to the formation of break clusters [3]. When such a cluster of breaks reaches the critical size, it will propagate unstably and lead to final failure.

This failure development can be altered by introducing a second fibre type with a higher failure strain. This affects the failure development in 4 different ways. Firstly, the stress concentrations are modified [4, 5]. Secondly, the development of break clusters can be affected, as the second fibre type can bridge the cracks created by the broken carbon fibres. Thirdly, the critical break cluster size may be larger, as a consequence of the crack bridging effect. Finally, a size effect can occur, as some carbon fibres are replaced by the second fibre type, so that there are fewer carbon fibres in the composite. According to the well-known size scaling effect of composite strength [6], this is expected to increase the apparent failure strain of the carbon fibres.

It is, however, unclear how these 4 different ways contribute to the failure strain enhancement of the hybrid composite, compared to the all-carbon fibre composite, an enhancement that is known as the hybrid effect. This phenomenon has been investigated by many researchers, with most of the available data coming from experiments rather than modelling predictions. The results show that the hybrid effect increases with decreased carbon fibre fraction, as convincingly proven by Kretsis' review of experimental data [7]. The hybrid effect also seems to increase with better dispersion of the fibres [7-10]. However, evidence for this influence from modelling is rather limited, as most of the early efforts [4, 11, 12] used a fixed dispersion. Fukunaga et al. [13] was the first to demonstrate this influence.

This paper presents a new model for unidirectional hybrid composites capable of tracking break cluster development. This will aid in the understanding of the failure development in hybrid composites and how this is affected by various parameters, such as hybrid volume fraction and fibre dispersion. The model will be applied to carbon/glass/epoxy hybrid composites with epoxy matrices, but can easily be extended to other combinations.

2. Model description

2.1. Approach

The model is based on the chain-of-bundles approach of Rosen [14]. It uses very local load sharing on a hexagonal fibre packing with 2000 fibres, as shown in Figure 1. This means that the stress of an isolated broken fibre is shed equally to the 6 nearest neighbours. To simplify the model, it is assumed that the carbon and glass fibres have the same fibre radius, which allows an overall fibre volume fraction of 50%. The fibre types are assigned in various ways to investigate the influence of dispersion. To avoid preferential failure at the edge of the model, 276 dummy fibres are placed at the perimeter. These fibres cannot break and are not used in the averaging of composite stress. Each fibre is divided into 300 elements along its length, and each of those elements is assigned a strength consistent with a Weibull distribution. The longitudinal strain in the model is gradually incremented, and the stress in the fibre elements is updated accordingly. The model checks in each strain increment whether the stress in any element has exceeded its strength. If this is the case, then that element is broken and break clusters are updated. Updating of element stresses is then performed through an adaptation of the stress concentration factors (SCFs), described in the next section.

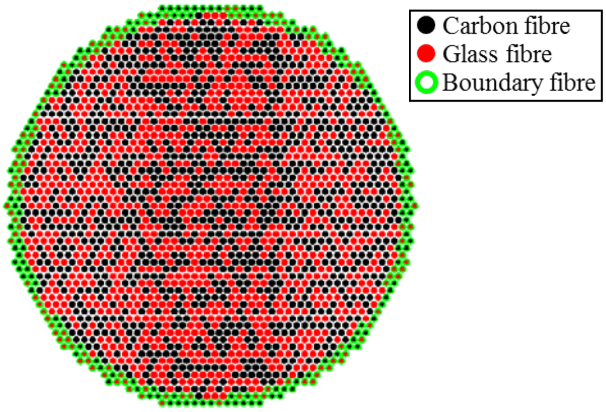


Figure 1. A randomly dispersed packing at a hybrid volume fraction of 50%.

Since the stress concentrations can lead to new elements breaking, this procedure is repeated until no new fibre elements break within the same strain increment. The strain is then incremented and the entire procedure repeated until failure of the entire composite is detected. This detection is based on an exponential increase in the number of broken elements. For each of the studied configurations, 10 simulations were run. For accurately determining the average critical break cluster size, an additional 40 simulations were used.

2.2. Stress redistribution

Applying to correct SCFs in hybrid composites is a challenging task, and some simplifications are unavoidable. A linear stress recovery profile in the broken fibre was assumed, which corresponds to the Kelly-Tyson model [15]. The ineffective length, in which the fibre stress is less than 90% of the nominal fibre level, was calculated from the finite element models described in [1]. It was found to be 14.9 and 7.3 times the fibre radius for carbon and glass fibre respectively.

For the SCFs around a single broken fibre, the information in Swolfs et al. [5] was used. In non-hybrid composites, the very local load sharing rule means that each of the six nearest neighbours carries an SCF of 7/6. In hybrid composites, this situation is slightly more complex, as carbon and glass have a different stiffness and do not carry the same SCF around a given fibre break. From [5], it can be deduced that the ratio of SCFs for both fibre types is equal to the inverse ratio of their axial stiffness: 70 GPa/230 GPa. Examples of the corresponding SCFs are shown in Figure 2.

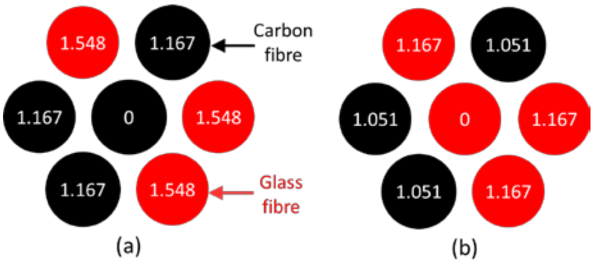


Figure 2. Redistribution of the stress concentration factors in hybrid composites according to the very local load sharing rule: (a) for a broken carbon fibre in the centre, and (b) for a broken glass fibre in the centre.

For the SCFs around multiple broken fibres, a superposition principle is needed. Linear superposition of the SCFs around a single broken fibre is the most straightforward approach. This approach, however, does not maintain force equilibrium, as illustrated in Figure 3a for non-hybrid composites. This is caused by neglecting the SCFs that the broken fibres exert on each other. An enhanced linear superposition is proposed, which redistributes those neglected SCFs onto the intact fibres. This redistribution is done proportionally to the solution of linear superposition, as illustrated in Figure 3b.

Figure 3. Illustration of superposition principles in non-hybrid composites: (a) standard linear superposition, and (b) enhanced linear superposition.

Break clusters are tracked at every strain increment. Two broken elements in nearest neighbour fibres are part of the same cluster if they are within 10 fibre radii of each other in the axial direction.

2.4. Material parameters

The Weibull fibre strength is assigned based on:

$$P = 1 - \exp\left[-\left(\frac{L}{L_0}\right)^{\alpha} \cdot \left(\frac{\sigma_f}{\sigma_0}\right)^{m}\right] \tag{1}$$

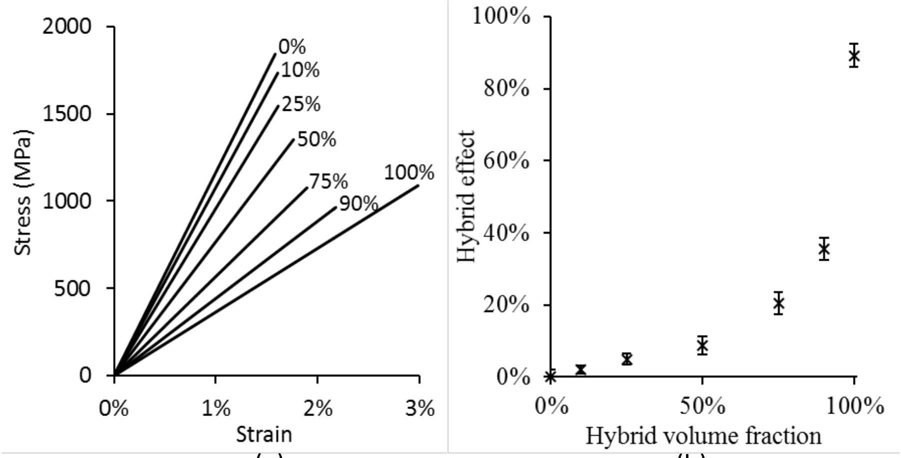
where P is the probability that a fibre element of length L will fail when an axial stress σ_f is applied to it, σ_0 is the Weibull strength scale parameter, m is the Weibull shape parameter, and L_0 is the reference gauge length. The exponent α is introduced to capture the gauge length dependency of the Weibull distribution [16]. Data from Beyerlein et al. [17] are used for AS4 carbon fibre, having $\sigma_0 = 4493MPa$, $L_0 = 10mm$, $m = 4.8$ and $\alpha = 0.6$. For glass fibres, the standard Weibull equation with $\alpha = 1$ is more common: $\sigma_0 = 1550MPa$, $L_0 = 24mm$, $m = 6.34$ and $\alpha = 1$ [18].

3. Results

3.1. Effect of hybrid volume fraction

The hybrid volume fraction is defined as the relative volume fraction of glass fibres over the overall fibre volume fraction. From literature, it is known that this has a major influence on the hybrid effect. To investigate how this affects failure development, the hybrid volume fraction was varied between 0% and 100%. This is done for a randomly dispersed packing, and such an example at a hybrid fibre volume fraction of 50% is shown in Figure 1.

The resulting stress-strain diagrams are shown in Figure 4a. Adding glass fibres decreases the strength, but also gradually increases failure strain. This failure strain enhancement compared to the all-carbon fibre composite is called the hybrid effect and summarised in Figure 4b. Hybrid effects of up to 36% were predicted. The data point at 100% hybrid volume fraction does not represent a hybrid composite as it is purely a glass fibre one.



(a) (b)

Figure 4. (a) Stress-strain diagrams, and (b) the hybrid effect for randomly dispersed packings at various hybrid volume fractions. The hybrid volume fraction corresponds to the fraction of glass fibres.

Next, failure development is analysed, for which two markers were chosen. The first marker is the evolution of 3-plets, i.e. clusters of 3 broken fibres, see Figure 5a. With increased hybrid volume fraction, 3-plet development is delayed. This delay is believed to be caused by the additional glass fibres reducing the number of possible pathways for break cluster growth. Evidence of the glass fibres bridging cracks formed by clusters of broken carbon fibres were not detected in the simulation.

The second marker is the critical break cluster size. Figure 5b demonstrates that the critical cluster size is larger for carbon fibre composites than for glass fibre composites. This contrast is caused by the difference in fibre strength scatter, in this case larger for the carbon fibres. The critical break cluster sizes of hybrid composites, however, show a positive deviation from the linear rule-of-mixtures. This is the first proof that changes in the critical cluster size contribute to the magnitude of the hybrid effect.

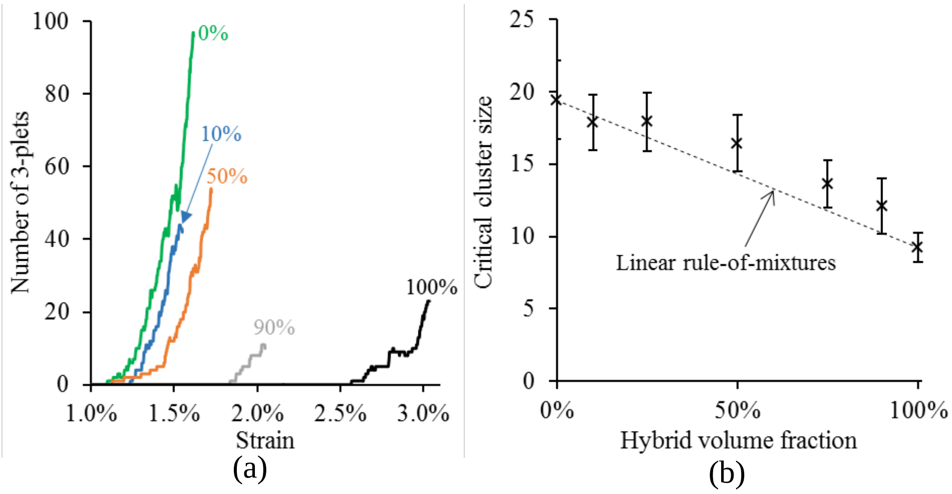


Figure 5. (a) The evolution of 3-plets as a function of strain for randomly dispersed hybrid composites, and (b) critical break cluster size as a function of hybrid volume fraction. Results for hybrid volume fractions of 25% and 75% have been omitted from the figure for the sake of clarity.

3.2. Effect of degree of dispersion

The effect of the degree of dispersion on the hybrid effect has been often investigated experimentally. Modelling work in this area has been lagging. Therefore, models were created with various degrees of dispersion, as illustrated in Figure 6.

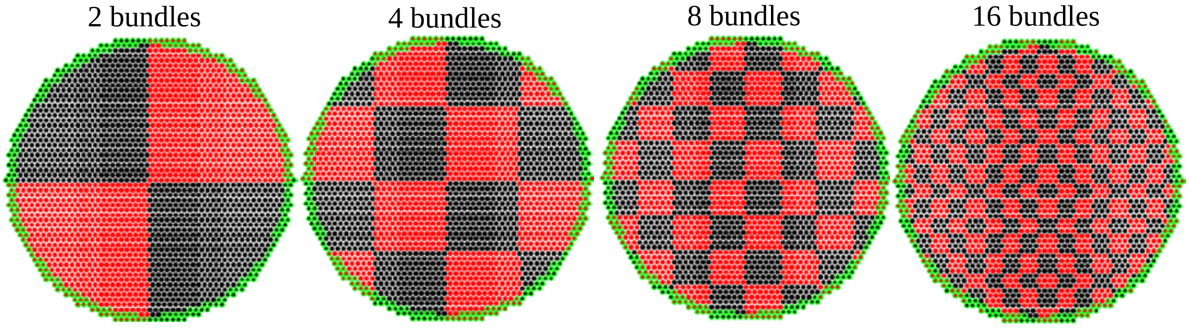
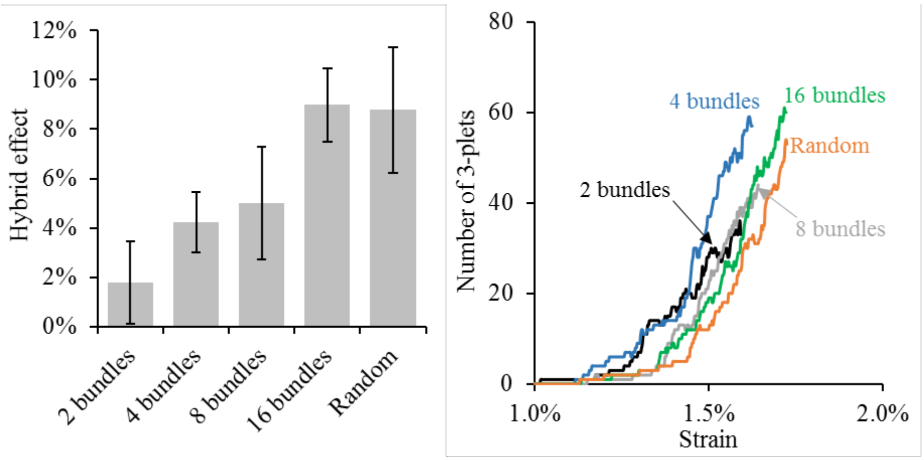


Figure 6. Bundle-by-bundle dispersion, where black circles are carbon fibres and red denotes glass ones.

The corresponding hybrid effects are shown in Figure 7a. While the “2 bundles”-model only has a 2% hybrid effect, this is increased to 9% for the “16 bundles”-model. Interestingly, the hybrid effect of the “16 bundles”-model is just as high as the random dispersion model, even though it seems less dispersed. Figure 7b shows that 3-plet evolution is also delayed with increased dispersion. Due to the sensitivity of the results, this conclusion is not always clear when comparing one dispersion level to another, but is apparent in the overall trend. Finally, the critical break cluster sizes were calculated, but no significant differences were found.

In conclusion, an increased dispersion reduces the number of possible paths for cluster growth. This leads to a delay in 3-plet evolution and a higher hybrid effect. The critical cluster size remains the same, but higher applied strains are required to develop such a large cluster.



(a) (b)

Figure 7. (a) The hybrid effect for bundle-by-bundle fibre dispersion at various bundle sizes, and (b) the evolution of 3-plets (clusters of 3 fibre breaks) as a function of strain. The result for random dispersion was added to facilitate comparisons.

4. Conclusion

A new model for the tensile behaviour of unidirectional hybrid composites was developed based on very local load sharing and applied to carbon/glass hybrids. The effect of hybrid volume fraction and degree of fibre dispersion on failure development was analysed, to elucidate the source of the hybrid effect.

It was shown that the hybrid effect strongly increases with increased glass fibre content. This was explained based on a reduction of the number of paths for break clusters to grow on, leading to a delay in break cluster development. Also, the critical break cluster size was larger than predicted from the linear rule-of-mixture.

The hybrid effect also strongly depends on the degree of fibre dispersion, through similar mechanisms. An increased dispersion delays break cluster development through a reduction of the number of paths for cluster growth. In contrast with the hybrid volume fraction, the degree of dispersion did not affect the critical break cluster size.

These results provide new insights into the failure processes in hybrid composites, allowing further optimisation of the design of hybrid composites. Future work will focus on extending this model to local load sharing instead of very local load sharing. This will increase accuracy and allow a more extensive parametric study.

Acknowledgements

The work leading to this publication has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under the topic NMP-2009-2.5-1, as part of the project HIVOCOMP (Grant Agreement No. 246389). The authors thank the Agency for Innovation by Science and Technology in Flanders (IWT) for a grant to Y. Swolfs. I. Verpoest holds the Toray Chair in Composite Materials at KU Leuven.

References

[1] Y. Swolfs, L. Gorbatikh, V. Romanov, S. Orlova, S. V. Lomov and I. Verpoest. Stress concentrations in an impregnated fibre bundle with random fibre packing. *Composites Science and Technology*, 74(0):113-120, 2013.

[2] M. R. Nedele and M. R. Wisnom. Three-dimensional finite element analysis of the stress concentration at a single fibre break. *Composites Science and Technology*, 51(4):517-524, 1994.

[3] A. E. Scott, I. Sinclair, S. M. Spearing, A. Thionnet and A. R. Bunsell. Damage accumulation in a carbon/epoxy composite: Comparison between a multiscale model and computed tomography experimental results. *Composites Part A: Applied Science and Manufacturing*, 43(9):1514-1522, 2012.

[4] C. Zweben. Tensile strength of hybrid composites. *Journal of Materials Science*, 12(7):1325-1337, 1977.

[5] Y. Swolfs, L. Gorbatikh and I. Verpoest. Stress concentrations in hybrid unidirectional fibre-reinforced composites with random fibre packings. *Composites Science and Technology*, 85(10-16, 2013.

[6] W. A. Curtin. Size scaling of strength in heterogeneous materials. *Physical Review Letters*, 80(7):1445-1448, 1998.

[7] G. Kretsis. A review of the tensile, compressive, flexural and shear properties of hybrid fibre-reinforced plastics. *Composites*, 18(1):13-23, 1987.

[8] A. Peijs and J. M. M. Dekok. Hybrid composites based on polyethylene and carbon fibres Part 6: Tensile and fatigue behavior. *Composites*, 24(1):19-32, 1993.

[9] C. E. Bakis, A. Nanni, J. A. Terosky and S. W. Koehler. Self-monitoring, pseudo-ductile, hybrid FRP reinforcement rods for concrete applications. *Composites Science and Technology*, 61(6):815-823, 2001.

[10] Y. Liang, C. Sun and F. Ansari. Acoustic emission characterization of damage in hybrid fiber-reinforced polymer rods. *Journal of Composites for Construction*, 8(1):70-78, 2004.

[11] H. Fukuda. An advanced theory of the strength of hybrid composites. *Journal of Materials Science*, 19(3):974-982, 1984.

[12] H. Fukuda and T. W. Chou. Stress concentrations in a hybrid composite sheet. *Journal of Applied Mechanics-Transactions of the Asme*, 50(4A):845-848, 1983.

[13] H. Fukunaga, C. Tsu-Wei and H. Fukuda. Strength of intermingled hybrid composites. *Journal of Reinforced Plastics and Composites*, 3(2):145-160, 1984.

[14] B. W. Rosen. Tensile failure of fibrous composites. *Aiaa Journal*, 2(11):1985-1991, 1964.

[15] A. Kelly and W. R. Tyson. Tensile properties of fibre-reinforced metals - copper/tungsten and copper/molybdenum. *Journal of the Mechanics and Physics of Solids*, 13(6):329-350, 1965.

[16] A. S. Watson and R. L. Smith. An examination of statistical theories for fibrous materials in the light of experimental data. *Journal of Materials Science*, 20(9):3260-3270, 1985.

[17] I. J. Beyerlein and S. L. Phoenix. Statistics for the strength and size effects of microcomposites with four carbon fibers in epoxy resin. *Composites Science and Technology*, 56(1):75-92, 1996.

[18] T. Okabe, N. Takeda, Y. Kamoshida, M. Shimizu and W. A. Curtin. A 3D shear-lag model considering micro-damage and statistical strength prediction of unidirectional fiber-reinforced composites. *Composites Science and Technology*, 61(12):1773-1787, 2001.