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Flat glass fibres: The influence of fibre cross section shape on composite micromechanics and composite strength

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A R T I C L E I N F O

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A B S T R A C T

Many of the fibres used in composite reinforcement have a non-circular cross section and recently non-circular glass fibre products have become commercially available. This paper explores the potential effects that such non-circular fibre shapes may have on the micro-mechanics of stress transfer at the fibre–matrix interface and the resulting changes in composite strength performance. Analytical modelling is used to show how the critical fibre length in composites with non-circular fibres is always less when compared to circular fibres with an equal cross sectional area. This can result in significant changes to the strength performance of discontinuous fibre reinforced composites. Additionally it is shown that non-circularity in fibre cross section can have important consequences for the use of single fibre micromechanical tests in the characterisation of interfacial strength.

1. Introduction

Glass fibre has been particularly successful as the reinforcement of choice in the rapidly expanding fibre reinforced polymer composites market. Today glass fibre products account for more than 95% of fibre reinforcements used in the composites industry, primarily due to of their highly attractive performance to price ratio [1,2]. Since the development of the mass production of glass fibres at Owens-Corning in the 1930s glass fibre cross-sectional geometry has remained almost exclusively circular. However, recently there have been a number of developments from glass fibre manufacturers in the production of non-circular cross section glass fibres and these "flat" glass fibres are now widely available for use in composite applications. Although a relatively new commercial development for glass fibres, reinforcements of many different shapes have been available and studied extensively. For instance it is well known that many of the currently available carbon fibres do not have true circular cross sections [3–7]. The majority of these papers focus on effects in unidirectional reinforced carbon fibre composites with high fibre volume fractions since this continues to be the main type of polymer composite produced with carbon fibres. Hsueh extensively studied the elastic stress transfer of various shaped inclusions in the case of ceramic composites [8]. His results for aligned ellipsoidal particle reinforced ceramics indicated that interfacial stress transfer increases with the increase in the aspect ratio of the inclusion when the Young's modulus of the inclusion is greater than that of the matrix.

More recently there has also been an upsurge in interest in composite reinforcement using natural fibres which are presented as having a better sustainability profile than many man-made fibres [9–17]. These natural fibres exhibit many different fibre cross section shapes which may well vary from fibre to fibre and along any one individual fibre [9–17]. In a recent series of papers we noted how the commonly used assumption of circularity in determining the cross sectional area of natural fibres could lead to large errors in the values obtained for fibre strength [15,16]. Similar observations were made by Virk et al in their paper which also referenced the common practice of using an erroneous "diameter" value for the estimation or measurement of fibre strength and modulus [17]. Consequently, non-circular cross section fibres are now widely available and used in many composite applications. This prompts the question as to whether all of the micromechanical analysis that we know and love is fully compatible with the reinforcement potential of these non-circular fibres. Interestingly many of the considerations of composite micromechanics make use of the assumption, or approximation, that the fibres under consideration have a circular cross section. This is understandable since at the time of the development of these concepts most reinforcement fibres, such as glass fibres, often did have a predominantly circular cross section.

The development of the micromechanics of composite materials has played an important role in studying and understanding the performance of fibre reinforced composites. Many of the concepts and equations developed to predict composite micromechanical performance have been developed early in the history of the development of fibre

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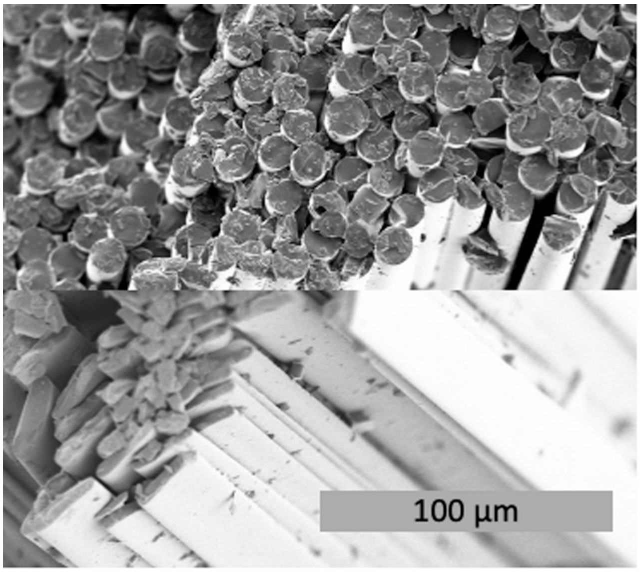

Fig. 1. SEM of circular and flat cross-section glass fibres. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

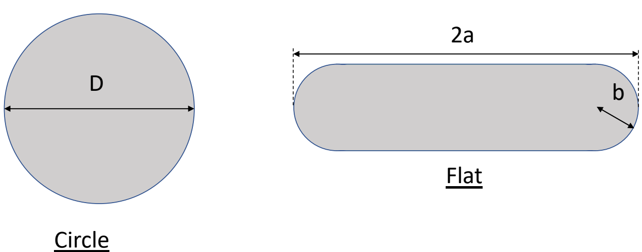

Fig. 2. Model glass fibre cross section shapes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reinforced composites and are unquestioningly embedded in the collective psyche of the composites community. One such concept is that of the role of length to diameter ratio (L/D), which is often found in micromechanical discussions of many composite performance parameters such as modulus, strength and impact resistance [18–20]. This also leads on to the concept of critical fibre length (L_c), which is of particular use when considering the strength of composite materials. From a micromechanics viewpoint the concept of critical fibre length plays an important role in many of the single fibre experimental techniques used for characterising the stress transfer capability of the fibre–matrix interface [21]. In particular the values of interfacial shear strength (IFSS) obtained from the single fragmentation test are related directly to the value of L_c calculated from the experimental data [21–23]. In this paper we consider the effect of non-circularity on the micromechanical stress transfer capability at the fibre–matrix interface and its potential effects on composite performance and the determination of interface strength.

2. Non-circular cross section glass fibres

Since the development of the mass production of glass fibres at Owens-Corning in the 1930s glass fibre cross-sectional geometry has remained almost exclusively circular. However, Gallucci *et al* briefly reported on the effect of experimental bilobal and trilobal fibres from Owens Corning on the properties of fibre reinforced PBT [24]. They reported a reduction in the composite warpage of 20% to 50% when using non-circular glass fibres with equivalent cross section area as circular fibres. Further analysis showed only small variations in other mechanical properties, no significant differences in residual fibre length or fibre orientation. This short report was probably related to a patent which describes a design of bushing plate for the production of such non-circular fibres [25]. Many other glass fibre manufacturers have also issued patents on bushing plate design for the producing non-circular cross-section glass fibres. More recently these same manufacturers have also made composite reinforcement products based on “flat” fibres available [26–28]. Fig. 1 shows an SEM comparison of the traditional circular cross section glass fibres with the more recent flat cross section glass fibres. Fig. 2 illustrates the typical geometry of such flat fibres which can be described as a flattened oval or rounded rectangular cross section with a “flatness” (K) defined as the ratio of major axis (a) to minor axis (b). Commercial flat fibre products currently have a flatness in the range of 2–4 with $K = 4$ being the most common [26–28]. If the flatness is too low, then the fibre behaves like a circular fibre. Conversely, if the flatness is too high, the fibre becomes too fragile to produce or process. It is notable that the current product range of flat glass fibres available are all chopped fibre products for use in extrusion/injection moulding of short fibre reinforced composites.

Despite the availability of flat glass fibres for some years there have been very few published studies of the properties of flat glass fibres and their composites. An extensive search has only turned up five journal papers where the performance of flat glass fibre reinforced composites has been reported. In an early study Deng *et al* investigated the performance of unidirectional continuous fibre reinforced epoxy laminates containing circular or flat glass fibres [29,30]. The flat fibres had a flatness value of $K = 4$ and a cross section area equivalent to that of the 13 µm diameter circular fibres. Their results over a range of mechanical tests showed little significant differences between the performance of the laminates containing the different glass fibres. Tanaka *et al* compared circular and flat glass fibre performance of injection moulded long fibre polypropylene composites [31]. The flat fibres had a flatness value of $K = 4$ and a cross section area equivalent to that of the 17 µm diameter circular fibres. Over the fibre weight range of 20–50% the flat fibre gave consistently lower melt shear viscosity and longer average residual fibre lengths in the moulded composites. Unnotched Charpy impact performance was also consistently higher for flat fibre composites especially at higher fibre contents where circular fibres showed a decreasing performance with increasing fibre content. In a Korean language paper, Heo *et al* reported on the performance of injection moulded short fibre polyphenylene sulphide composites containing circular or flat glass fibres [32]. The flat fibres had a flatness value of $K = 4$ and a cross section area equivalent to that of the 15 µm diameter circular fibres. They found that the tensile strength of flat fibre composites were greater (up to + 20%) at all weight fractions investigated (30–70%) [32]. The average residual fibre lengths in the moulded composites were consistently higher for the flat fibre composites over this fibre content range. Notched Izod impact performance was also consistently higher for flat fibre composites especially at higher fibre contents where circular fibres also showed a decreasing performance with increasing fibre content. In another Korean language paper from the same research group, Kim *et al* reported on the properties of injection moulded short fibre polyethylene terephthalate composites containing the same two glass fibre types [33]. Their results were later published in an English language paper [34]. Similar to the previous paper they found higher composite tensile strength for the flat fibre composites over a 15–45% fibre weight fraction range. However, in this case there was no significant differences in the impact performance of the flat and circular fibre reinforced composites. It is noted that, in none of these referenced studies comparing the performance of flat and circular cross section glass fibres is there any discussion of whether the same sizing was applied to both types of fibre. It is certainly the case that if different sizing were used then differences in fibre–matrix adhesion could be expected [35,36].

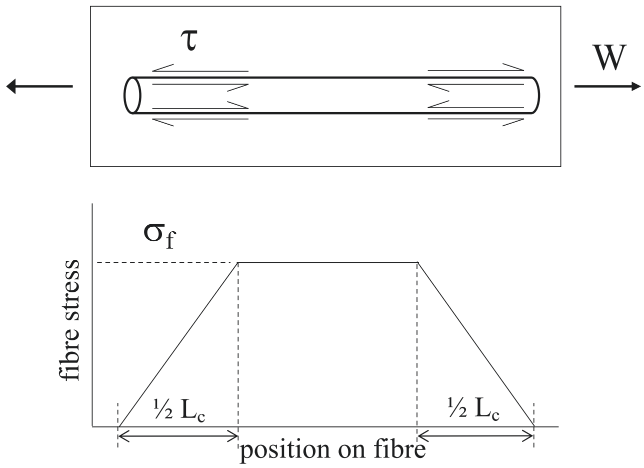

Fig. 3. Schematic of stress transfer in a single discontinuous fibre composite for definition of critical fibre length.

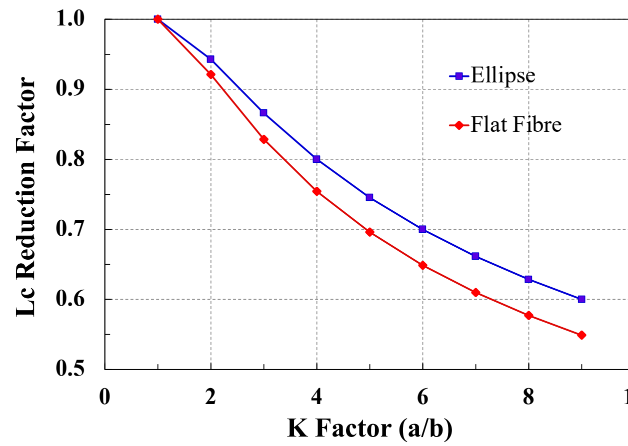

Fig. 4. L_c reduction factors (C) for flat and elliptical fibres versus flat flatness (K). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Critical fibre length

The concept of critical fibre length is well known in composite micromechanics. Thomason has pointed out that it is possible to define a number of "critical" fibre lengths for discontinuous fibre reinforced composites depending on whether modulus, strength or impact performance is under consideration [37]. However, the most common usage of critical fibre length refers to the term in the Kelly-Tyson equation for the calculation of the strength of discontinuous fibre reinforced composites. Considering a single fibre composite (Fig. 3) where the fibre modulus (E_f) is much greater than the matrix modulus (E_m) the external load (W) is transferred across the fibre–matrix interface by shear stress (τ) to the load bearing fibre. The classic approach to defining critical fibre length involves balancing the peak tensile stress (σ_f) transferred to a discontinuous fibre through the shear force (τ) at the interface [21,38–40]. For a fibre with length (L), cross sectional area (A_o), and perimeter (P_o) we obtain:

$$\sigma_f A_o = \tau P_o \frac{L}{2} \tag{1}$$

At critical fibre length (L_c) the peak stress in the fibre reaches the fibre strength and

$$L_c = \frac{A_o}{P_o}\frac{2\sigma_f}{\tau} \tag{2}$$

For the simple geometry of a circular cross section fibre with diameter (D)

$$\frac{A_o}{P_o} = \frac{D}{4} \tag{3}$$

Substituting into equation (2) results in the well-known definition of L_c as

$$L_c = \frac{\sigma_f D}{2\tau} \tag{4}$$

If we now consider the case of a flat fibre shown in Fig. 2 with an equivalent cross sectional area to a circular fibre (A_o), this has a cross sectional area $A_f = A_o$ and

$$A_f = \pi b^2 + 2b(2a - 2b) \tag{5}$$

Since $a = Kb$ then

$$A_f = b^2(\pi + 4(K-1)) \tag{6}$$

Hence

$$b = D\left[\frac{4}{\pi}(\pi + 4(K-1))\right]^{-\frac{1}{2}} \tag{7}$$

The perimeter (P_f) of the flat fibre is given by

$$P_f = 2\pi b + 2(2a - 2b) = b(2\pi + 4(K-1)) \tag{8}$$

Combining equations (7) and (8) gives

$$P_f = D\left[\frac{4}{\pi}(\pi + 4(K-1))\right]^{-\frac{1}{2}}[2\pi + 4(K-1)] \tag{9}$$

And since $P_0 = \pi D$ then

$$P_f = \frac{P_0}{\pi}\left[\frac{4}{\pi}(\pi + 4(K-1))\right]^{-\frac{1}{2}}[2\pi + 4(K-1)] \tag{10}$$

Finally we obtain the area to perimeter ratio of a flat fibre in terms of the area to perimeter ratio of an equivalent cross section area circular fibre as

$$\frac{A_f}{P_f} = \frac{A_o}{P_o}\pi\left[\frac{4}{\pi}(\pi + 4(K-1))\right]^{\frac{1}{2}}[2\pi + 4(K-1)]^{-1} = C_f\frac{A_o}{P_o} \tag{11}$$

Consequently the critical fibre length for a flat fibre with equal cross section, fibre strength and interfacial strength is given by

$$L_{cf} = C_f L_{co} \tag{12}$$

where C_f is the cross section shape factor for flat cross section fibres. Fig. 4 shows values obtained from equation (11) for the C_f parameter for fibres with various degrees of flatness parameter K. It can be seen that C_f decreases as the flatness of the fibre cross section increases. Moreover the values of C_f are less than unity for all values of K. Consequently it appears that the critical fibre length for flat cross section fibres is always smaller than that of a circular cross section fibre of equal area, strength and interfacial strength.

Although the current analysis has focussed on the non-circular cross-section of flat glass fibres it should be noted that many other reinforcement fibre have non-circular cross-sections. In particular natural fibres rarely have either a circular or a uniform cross section, the cross section shape varies hugely from fibre to fibre and also significantly along the length of individual fibres [9–17]. The literature on carbon fibres also reveals a wide range of fibre cross section shapes [3–7]. It seems reasonable to assume that the increased perimeter of the fibre cross-sections in all these cases will lead to the need to modify the critical fibre length equation and values in order to accurately characterise the properties of the fibre–matrix interface in these systems. This

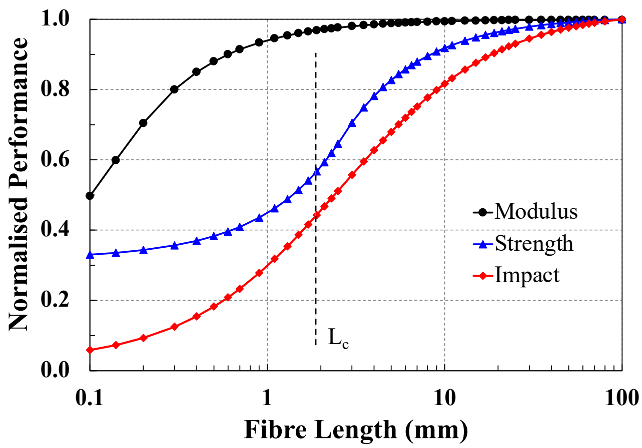

Fig. 5. Prediction of normalised performance of GF-PP composite versus fibre length [4]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

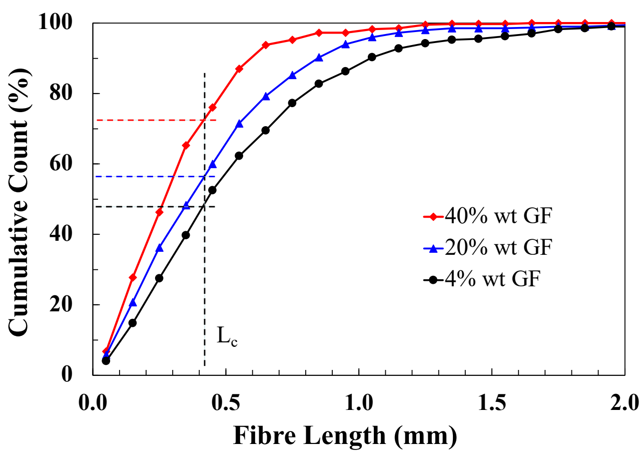

Fig. 6. Some fibre length distributions in injection moulded GF-PA composites [22]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

idea will be further explored in another paper on the subject [41]. It is also worth pointing out that this analysis implies that accurate characterisation of fibre perimeter is critical in the application of single fibre techniques such as the fragmentation test and the fibre pull-out and microbond test to obtain values of the interfacial stress transfer capability or IFSS. Both these techniques require accurate determination of the fibre perimeter in order to obtain accurate estimates of the IFSS of the fibre–matrix system. Approximating the perimeter of a non-circular fibre to that of a circular fibre will lead to an overestimation of IFSS in all cases. In particular, the commonly used simple analysis of fragmentation test results [21–23] depends directly on evaluating the critical fibre length. It is clear from the preceding modelling and analysis that ignoring non-circular fibre cross section or significant levels of surface roughness in the calculations may well lead to significantly erroneous results.

4. Composite strength effects

It is interesting to consider what the consequences of such a difference in critical fibre length might mean for composite performance. The composite application where the concept of critical fibre length is most commonly applied is that of discontinuous fibre reinforced composites and most often those short fibre thermoplastics (SFT) and long fibre thermoplastics (LFT) processed by injection moulding. Thomason has discussed in detail the role of L_c on the performance of these composites and Fig. 5 shows a summary of how the performance characteristics of composite modulus, strength, and notched impact relate to the fibre length of a unidirectional discontinuous glass fibre reinforced polypropylene [18–20,37]. It is important to note that, for this definition of critical fibre length, the fibre contribution to the composite strength has only reached 50% of the maximum fibre contribution at L_c. To attain greater than 90% of the maximum attainable strength would require using fibres with length greater than 5 L_c. In a similar vein, to attain 90% of the maximum notched impact in this system would require a fibre length greater than 10 L_c. The results shown in Fig. 5 have been obtained for single values of fibre length, however in real injection moulded SFT and LFT there is usually a very broad range of fibre lengths present. Fig. 6 shows some fibre length distributions obtained from injection moulded short glass fibre reinforced polyamide composites with different fibre contents. It can be seen that a significant proportion of the fibres in such composites are shorter than L_c.

The effects of these differences in L_c on composite strength can be modelled using micromechanical methods such as the Kelly-Tyson equation for the prediction of the strength (σ_{uc}) of a composite reinforced with discrete aligned fibres [21,37–39]. This model is well known and can be expressed as $\sigma_{uc} = \eta_o(X + Y) + Z$, where Z is the matrix contribution, X is the sub-critical fibre contribution, and Y is the super critical contribution, in reference to the critical fibre length defined by equation (2). Although the model was originally developed for aligned discontinuous fibre composites ($\eta_o = 1$) it is often presented with an additional average fibre orientation factor (η_o) when used for the performance of injection moulded composites. The orientation factor accounts for the reduced contribution to the composite stress level of fibres which are not oriented parallel with the applied load. When expressed in terms of the critical fibre length the full Kelly-Tyson equation can be written as

$$\sigma_c = \eta_o \sigma_f \left(\sum_i \left[\frac{L_i V_i}{2L_c} \right] + \sum_j \left[V_j \left(1 - \frac{L_c}{2L_j} \right) \right] \right) + \sigma_m V_m \tag{13}$$

By considering the previous discussion on the effect of fibre cross section shape on the critical fibre length it is relatively simple to show that equation (13) should be modified to account for the flat fibre cross section shape factor (C_f) to give

$$\sigma_c = \eta_o \sigma_f \left(\sum_i \left[\frac{L_i V_i}{2C_f L_c} \right] + \sum_j \left[V_j \left(1 - \frac{C_f L_c}{2L_j} \right) \right] \right) + \sigma_m V_m \tag{14}$$

Where the sub-critical and super-critical fibre lengths are now defined with respect to the modified values of L_c (equation (12). It can easily be seen that if C_f is always less than unity for flat cross section fibres then equation (14) will always give a higher predicted value of stress than equation 18 (when all other input parameters in the two equations are kept equal).

It should be remarked at this point that, due to the focus of this work being to identify the possible ramifications of the effect of fibre cross section shape on the interfacial stress transfer profile in these composites, and also due to the current lack of any published experimental data on the required input parameters in equations (13) and (14) for flat fibre composites, it has been necessary to use input parameter values available for circular cross section fibres in both equations (13) and (14) and assume that these are unchanged for flat fibres. It is reasonable to assume fibre cross sectional areas and composite fibre contents can be kept constant in the fibre production and composite production processes. Similarly, it can be assumed that the same E-glass formulation would be used for both fibre types and that the same sizing would be used for compatibility with the polymer matrix. Hence, at the macroscopic fibre production level one could expect similar levels of IFSS from both fibre types. It is possible that there may be differences in how the sizing

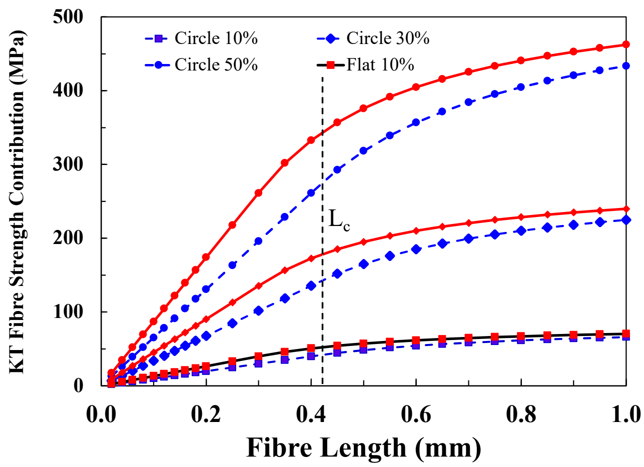

Fig. 7. Kelly-Tyson equation prediction of flat and circular fibre strength contribution in unidirectional discontinuous GF-PA composites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

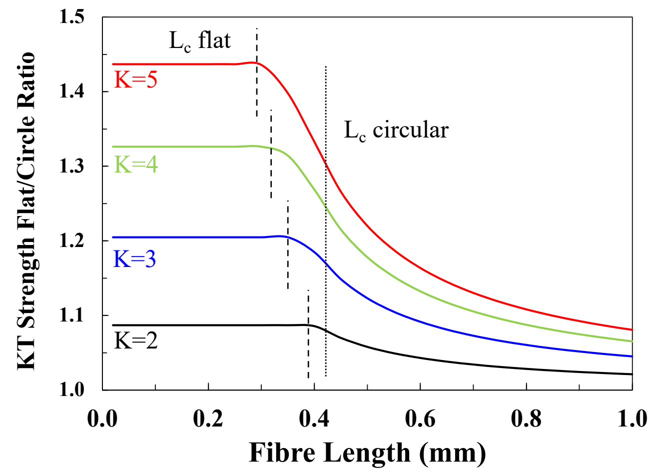

Fig. 8. Kelly-Tyson equation prediction of flat/circular strength contribution ratio in unidirectional discontinuous GF-PA composites for fibre with different flatness ratios (K). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distributes itself on the fibres after application, during drying and where it ends up in the composite. However, there is currently no good understanding or data available of how this might happen with the reference circular cross section fibres so we are limited in suggesting how this may impact the values of IFSS to be used in equations (13) and (14).

Since fibre cross sectional area is kept constant then the pristine fibre strength for both fibre types can be assumed to be equal. Of course the actual value for fibre strength used in either equation 13 or 14 is something which cannot be predicted analytically. The strength of any individual glass fibre in a composite is not a unique material value – but a combination of the base material constitution, the processing and damage accumulation history of that fibre, and the manner and conditions under which the strength is measured. So this includes the fibre forming conditions (bushing size, cooling rate, type of size applied and its distribution and redistribution through the collected fibre bundle, fibre–fibre contacts and fibre-equipment contacts during pulling and drying, and most importantly for the chopped fibres under consideration here – the level of fibre damage experienced during the chopping process). There is potential for further fibre damage occurring during transportation and processing into the extrusion process. Extrusion and injection moulding are simply a very large fibre grinding and breaking operation which simultaneously involves further flaw-inducing damage to the fibre and at the same time the elimination of most, if not all, of the flaws on the fibre – as this is where the fibre is most likely to break during these two melt processing steps. Consequently, it is all but impossible to predict what the strength of a fibre in a test composite bar will be and so most researchers are reduced to using experimentally determined values for this type of modelling. Such values for flat glass fibres are currently not available in the literature and so we have had no alternative but to use the same values as those that are available for circular cross section fibres.

It is certainly possible to hypothesise that at least one approachable difference in fibre strength distribution might be caused by the increased surface area of flat fibres – since Weibull theory assumes that the probability of failure at any stress level is proportional to the probability of a critical flaw (for that stress) is found within the test volume (which is assumed to be directly related to the surface area of that volume for surface crack initiation) [42]. Assuming that the flaw distribution of the two fibre types is the same, it is possible to estimate the effect of the increased surface area of flat fibres on strength using the Log strength vs Log length relationship commonly used to extrapolate single fibre tensile strength approach at L_c. A K = 4 flat fibre has approximately 25% more surface (for an equal cross sectional area). Using published Weibull parameters from a fibre strength vs gauge length for E-Glass study [43] indicates that that will make a difference of just 3.2% in fibre strength between flat and circular cross section fibres at any gauge length. This is well within the confidence limits for the experimental measurement of this property, if such a direct measurement were actually possible at sub-millimetre gauge lengths. Consequently, many of the input parameters for equations (13) and (14) have been set equal in the production of the following results.

Fig. 7 compares the prediction of the Kelly-Tyson equation (equation (13) and modified Kelly-Tyson equation (equation (14) for the fibre contribution to the strength of a short glass unidirectional reinforced polyamide as a function of the fibre length for different fibre weight fractions. The input parameters used were flatness $K = 4$, $\tau = 30$ MPa, $\sigma_f = 1.8$ GPa, and circular fibre diameter $D = 14$ μm [39]. It can be seen that the flat fibre composites have a consistently higher fibre contribution to their strength over the entire fibre length range. The higher strength contribution for flat fibres is also greater as the fibre content increases. The ratio of flat fibre strength contribution to circular fibre strength contribution is equal at all fibre contents and the ratio of the two is shown in Fig. 8 as a function of fibre length for different values of flatness (K) as a function of fibre length. The flat fibre advantage is a constant maximum for fibre lengths shorter than the flat fibre critical fibre length (equation (12). Note that the flat fibre critical fibre length decreases as K increases. The flat fibre strength advantage also increases in proportion to the value of K. For the typical $K = 4$ value of commercially available flat glass fibres this means an apparent 33% greater contribution to composite strength for all fibres shorter that flat fibre critical fibre length. For fibre lengths greater than the flat fibre L_{cf} the strength advantage decreases from the maximum value and tends to a value of one as the fibres become much longer. This is a logical effect as the fibre strength contribution will tend towards that of endless fibres which is assumed to be equal for all values of K in this analysis.

Greenveld and Wagner used a somewhat similar approach when calculating the effect of the more complex shapes of nanotube reinforcements on their critical fibre length [40]. They employed similar considerations of the effect of reinforcement fibre perimeter and area on its critical fibre length. They then modelled the effect of different nanoreinforcement shapes on the strength of composites using the X,Y, and Z components of the Kelly-Tyson equation considering the two cases of the fibre length being either above or below L_c. Similar to the results in Fig. 8 they found that, for fibre lengths shorter than L_c, a thin wall ribbon shape filler (e.g. graphene) improved the reinforcement contribution to composite strength by a factor of two over that of a thin walled

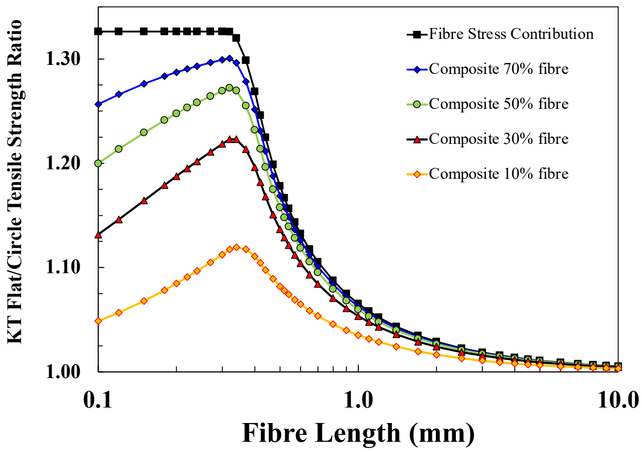

Fig. 9. Kelly-Tyson equation prediction of flat/circle strength ratio for unidirectional reinforced GF-PA including matrix contribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

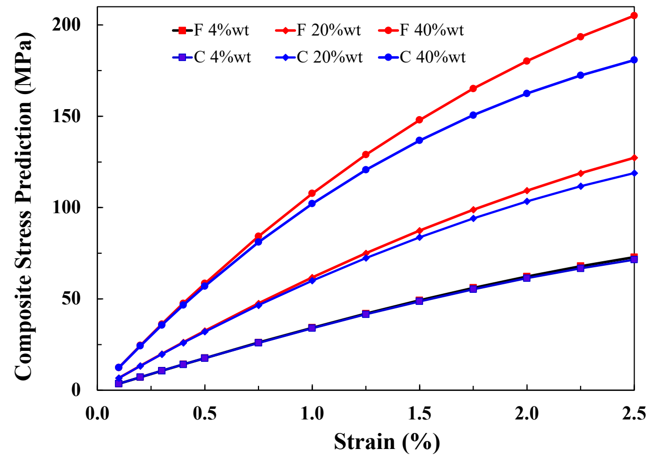

Fig. 11. Kelly-Tyson equation prediction of stress–strain of injection moulded GF-PA with flat (K = 4) and circular cross-section fibres. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

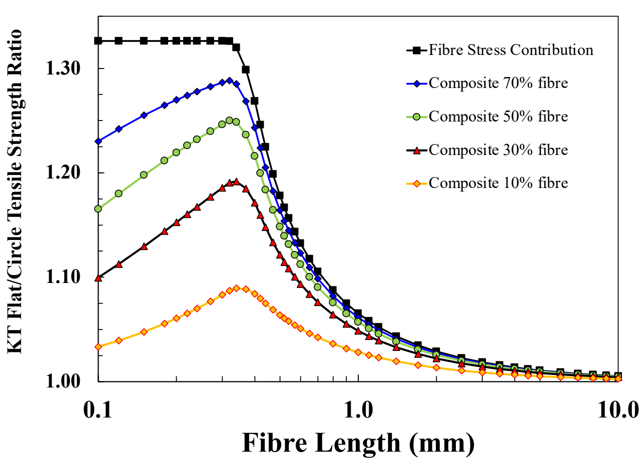

Fig. 10. Kelly-Tyson equation prediction of flat/circle strength ratio for GF-PA including matrix contribution and average fibre orientation for injection moulded samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

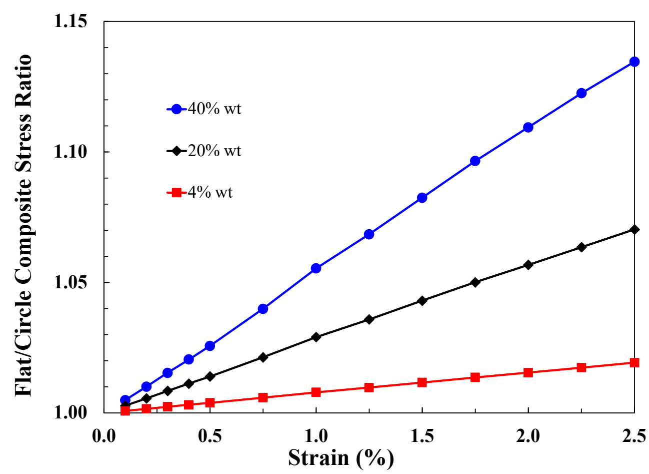

Fig. 12. Flat/circle ratio of stress in GF-PA composites for K = 4 flat fibres. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hollow filler (of arbitrary shape). They noted that this was due to the doubling of the interfacial area. For filler lengths greater than L_c they also noted that the maximum strength contribution, in both cases, tended towards the simple rule of mixtures for continuous reinforcement and hence the difference in the strength contributions of different shape fillers disappear (assuming they have the same ultimate strength) as also shown in Fig. 8.

However, for a prediction of the flat fibre effect in real composites equations (13) and (14) indicate that the matrix contribution, the average fibre orientation parameter, and the fibre length distribution, must also be taken into account. Fig. 9 shows the flat fibre strength advantage predictions for unidirectional glass reinforced polyamide composites as a function of fibre length. The data in this Figure now include the effect of the matrix contribution to the composite strength. It can be seen that the flat fibre advantage is now dependent on the fibre content and decreases with decreasing fibre content. This is due to the fact that the matrix contribution to both flat and circular fibre reinforced composites is equal and proportionally greater as the fibre content of the composites is decreased. Most interestingly the data in Fig. 9 now predicts that, for any fibre content, the flat fibre advantage is a maximum at the value of flat fibre critical fibre length L_{cf}. This should not be misinterpreted as meaning that flat fibres have their best performance at L_{cf} as Fig. 7 clearly shows that overall composite performance still increases as fibre length increases. It does however mean that the flat fibre advantage over circular fibres will be most obvious in composites which contain a significant fraction of their fibres with lengths at or below L_{cf}.

Fig. 10 shows the effect of adding an average orientation parameter of $\eta_o = 0.65$ (typical for injection moulded short fibre composite ASTM type tensile test bars [39]) to the K-T model predictions. The main effect is for a further reduction in the flat fibre composite strength advantage. Hence from an experimental viewpoint this means that the advantage of flat fibre over circular cross section fibre will be easier to resolve the closer the average fibre orientation is to unidirectional and conversely less easy to resolve as the average fibre orientation becomes more randomised.

Up to this point we have only considered the predictions of the Equations (13) and (14) for any individual fibre length. However, as mentioned above injection moulded composites contain a wide distribution of fibre lengths and so this too must be added to the modelling. Thomason has reported the fibre length distribution in real injection moulded short glass fibre reinforced polyamide for a range of fibre weight fractions [39]. These distribution have been used in Equations (13) and (14) to calculate composite tensile stress–strain curves for both

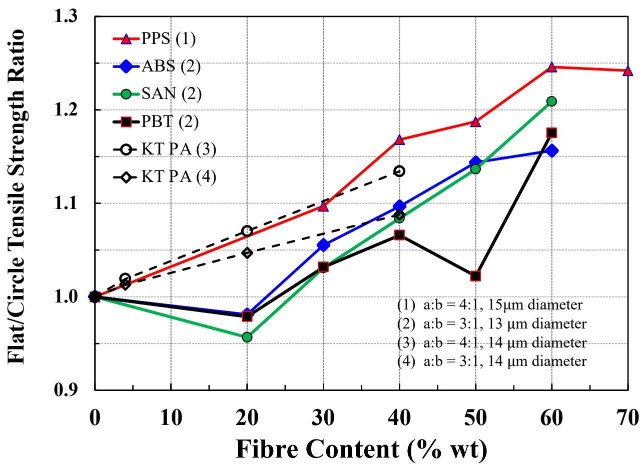

Fig. 13. Literature data on tensile strength ratio of injection moulded glass reinforced thermoplastics with flat and circular cross- section fibres with equal area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

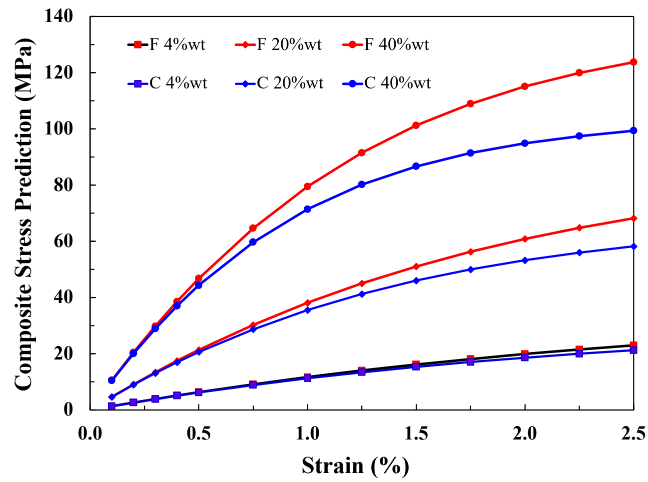

Fig. 14. Kelly-Tyson equation prediction of stress–strain GF-PA with flat (K = 4) and circular cross-section fibres after 24 h water boil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

flat and circular fibre composites at three different fibre contents. It should be noted that it is assumed that both flat and circular fibre composites have the same fibre length distribution at any individual fibre content. The resulting predicted stress–strain relationships are shown in Fig. 11 for three fibre weight fractions. It should be noted that the assumption here is that both flat and circular fibres have the same fibre length distribution. Typical non-linear stress–strain curves are predicted for all composites. Nevertheless, it can be seen that the flat fibre composites are always at higher stress levels for any fixed strain value and that this difference increases with increasing strain and increasing fibre content. These differences are further emphasised in Fig. 12 which shows the relative ratio of composite stress (flat/circular) at different strain levels and for each of the three fibre contents used for Fig. 11. This plot was obtained by simply dividing individual values for flat fibre composite stress in Fig. 11 by the corresponding value obtained for circular fibre composite stress. The final flat fibre strength advantage over circular fibres will lie somewhere on the lines shown in Fig. 12. The actual value will depend on what the strain to failure is for these composites. The analytical prediction of the failure strain of injection moulded thermoplastic composites remains a challenge. There is no one simple event, such as fibre failure or interface failure, on which to model such a predicted value [44]. The failure initiation and propagation is acknowledged as being highly complex, dependent on both material microstructural parameters and sample configuration and testing parameters. Consequently we must revert to experimentally obtained strain to failure values for injection moulded circular fibre reinforced polyamide. For circular fibres Thomason reported values in the range 2.5–3.0 % [39] which would result in a predicted strength advantage for injected moulded short flat glass fibre reinforced polyamide of approximately 10–15% for a typical moulding compound fibre contents in the 30–40% by weight range. Clearly it is worth recapping at this point that this analysis assumes that the flat glass fibre composites have the same fibre strength distribution, fibre orientation distribution, fibre length distribution, and strain to failure, as the circular glass fibres.

As mentioned above, there is very little experimental data available in the literature comparing the effects of flat fibre versus circular fibre on the tensile strength of injection moulded short fibre thermoplastics at different fibre contents. This paucity of useful experimental data may be due to the only relatively recent availability of flat glass fibre samples for study possibly combined with a general lack of interest in the academic community due to the funding for such unsexy materials as injection moulded glass fibre thermoplastics being scarce. Fig. 13 summaries the available data from the scientific and patent literature. The flat to circular fibre reinforced composite tensile strength ratio is shown as a function of fibre content for four glass reinforced thermoplastic systems. Fig. 13 includes data for the K = 4 glass reinforced PPS system published by Heo et al [32] and the data for three K = 3 systems (in ABS, SAN and PBT) published in a patent from Koike et al [45]. Although the data is for four different thermoplastic matrix systems it does appears that the flat: circular tensile strength ratio does increase systematically with increasing glass fibre content. Moreover, the higher *K* value also appears to give a higher level of composite property advantage at all fibre contents. The dashed lines in this Figure show the theoretical values taken from Fig. 12 (at 2.5% strain to failure) for $K = 4$ and further values calculated for the GF-PA system for $K = 3$. Despite the difference in polymer matrices for all of these systems it does appear that the theoretical values calculated in this work agree well with the limited experimental data available.

Fibre reinforced polyamides are excellent composite materials in terms of their high levels of mechanical performance and temperature resistance. However, the mechanical properties of polyamide based composites decrease markedly upon absorption of water and other polar fluids. In service, fibre reinforced polymers are exposed to environments in which the temperature and moisture contents vary in a prescribed manner. This combined change of temperature and moisture, known as the hygrothermal effect, is damaging to the composite mechanical performance. Short fibre reinforced thermoplastics have been used in the automotive industry for many years and there has been a strong growth in their use in under-the-hood applications [46]. There are many automotive applications for polyamide-based composites in contact with fuel and coolant liquids which place stringent requirements on the materials in terms of dimensional stability and mechanical, temperature, and chemical resistance. Typical testing for these applications involves measurement of mechanical properties before and after conditioning of the composites in model fluids for a fixed time, up to 1000 h, at temperatures in the 100 –150 °C range. One relatively quick measure of the hydrolysis resistance of a polyamide composite is to quantify the reduction in tensile strength after a 24 h immersion in boiling water.

Thomason has shown hydrolysis of injection moulded glass fibre reinforced polyamide significantly reduces the apparent IFSS (τ) for the system and also leads to significant plasticisation of the polyamide matrix. These changes affect the values for τ and σ_m which should be used in equations (13) and (14). The modelling analysis comparing flat and circular fibre reinforced composite performance was repeated using $\tau = 18$ MPa [47] and values for the polyamide matrix contribution [48] to composite stress–strain curves appropriate for polyamide after a 24 h

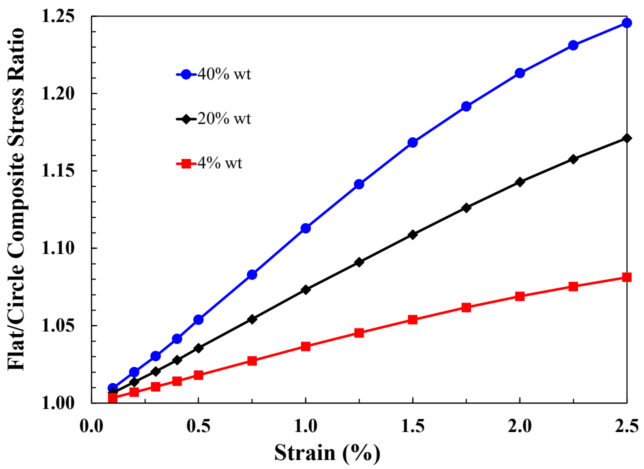

Fig. 15. Flat/circle ratio of stress in GF-PA composites after 24 h boil for K = 4 flat fibres. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

boil. The results are summarised in Fig. 14 which can be directly compared to Fig. 11 for the "dry as moulded" results previously discussed. In comparison to dry polyamide composite results (Fig. 11) it can be seen that the 24 h boiling water treatment severely reduces the polyamide composite ability to carry applied stress at any particular strain level. Nevertheless the strength advantage of flat glass fibre over circular glass fibre is still apparent in all cases and increases with increasing strain and higher fibre content. Interestingly the results in Fig. 15 show that the flat fibre advantage is predicted to be significantly greater after hydrolysis, almost double in comparison to the results for dry samples in Fig. 12. Consequently it appears that this analysis predicts that the advantage of flat fibre over circular fibre in the tensile strength of injection moulded glass fibre reinforced polyamide will be more clearly evidenced after hydrolysis treatment. We are unaware of any available published data which might be used to verify this prediction at this time.

5. Conclusions

The perimeter of non-circular cross section fibres is always greater than that of a circular fibre with equal cross sectional area. Analytical modelling of this phenomenon showed that consequentially the critical fibre length (L_c) in composites with non-circular flat glass fibres is always less when compared to circular glass fibres with an equal cross sectional area. Examples based on the shape of commercially available flat glass fibres revealed that L_c depends on the flatness parameter of the fibres and can result in reductions of up to 30%. This has important implications for characterising values of the interfacial stress transfer capability or IFSS of non-circular cross section fibres using single fibre techniques such as the fragmentation test and the fibre pull-out and microbond test. In particular values for IFSS obtained for non-circular cross section glass fibres using the fragmentation test, which depend on estimating L_c, will need to be modified to account for the larger fibre perimeter. By analogy this conclusion will also apply to any reinforcement fibres, such as some carbon fibres and most natural fibres, with a non-circular cross-section.

Further modelling of the strength of discontinuous fibre reinforced composites using the Kelly-Tyson theory predicted that flat glass fibres provide a consistently higher fibre contribution to composite strength than circular fibres over the entire fibre length range. This effect is at a maximum for short fibres with lengths below the flat fibre critical fibre length. Further modelling, which accounted for the matrix contribution and fibre orientation and length distribution effects typical in injection moulded composites, predicted a flat fibre advantage in composite tensile strength which increased with fibre flatness and composite fibre content. This was shown to result in a predicted strength advantage for injected moulded short flat glass fibre reinforced polyamide of approximately 10–15% for typical moulding compound fibre contents in the 30–40% by weight range. It was also predicted that the advantage of flat fibre over circular fibre in the tensile strength of injection moulded glass fibre reinforced polyamide will be more clearly evidenced after hydrolysis treatment. Comparison of these predictions with the very little experimental data available in the literature appeared to show good agreement.

CRediT authorship contribution statement

James L. Thomason: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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