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Control and design of volumetric composition in pultruded hybrid fibre composites

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Abstract. Hybrid composites consist of two of more fibre phases in a common matrix phase. This is a challenge for the control and design of the volumetric composition and microstructural uniformity of such composites. In the present study, a model is presented for the prediction of the complete volumetric composition (i.e. volume fractions of fibres, matrix and porosity) in hybrid fibre composites. The model is based on a constant local fibre volume fraction criterion. Good agreement is found between model predictions and experimental data of pultruded hybrid kenaf/glass fibre composites with variable hybrid fibre weight mixing ratios. To demonstrate the suitability of the model, simulations are performed for four different cases of volumetric composition in hybrid kenaf/glass composites.

1. Introduction

The use of more than one type of reinforcement fibres in a common matrix is denoted as hybrid fibre composites [1]. Such composites have attracted the interest of researchers and industry due to the potential synergistic effect of having two (or more) types of fibres with different properties [2]. Furthermore, it makes it possible to allow for more optimal design of the properties of composites to meet the required specifications.

The properties of composites depends on a number of materials parameters, such as the fibre and matrix properties, the fibre orientation, the fibre/matrix interface properties, and the volumetric composition (volume fractions of fibres, matrix and porosity). The latter parameter is vital for reliable predictions of mechanical, physical, and thermal properties of composites [3]. In many cases, the volumetric composition of composites can be accurately controlled during manufacturing of composites, and as such, it can be used as a direct controllable parameter for the performance of composites.

Composites are heterogeneous materials consisting of a fibre phase and a matrix phase. In hybrid composites, the degree of heterogeneity is further increased by the addition of an extra fibre phase. Therefore, control and design of the volumetric composition in hybrid composite is one the main challenges in the manufacturing of such composites. Similarly, the higher degree of heterogeneity of hybrid composites is challenging with respect to controlling the microstructural uniformity. To the best of the author's knowledge there is just one previous study [2] on the analysis of the volumetric composition and microstructural uniformity of hybrid composites. In that study, hybrid glass/carbon

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fibre composites were manufactured by a vacuum infusion technique. The concept of so-called local fibre volume fractions was proposed, which is based on the volumes of the local non-hybrid composite regions in the hybrid composites. It was found that the local fibre volume fractions in the hybrid glass/carbon composites with different hybrid fibre mixing ratios were constant, and equal to the fibre volume fractions in the related non-hybrid composites. A model for the prediction of the fibre and matrix volume fractions in the composites was developed [2]. The model, however, was limited in assuming zero porosity in the composites.

In the present study, firstly, a generic model for the complete volumetric composition in hybrid fibre composites is developed. Secondly, the constant local fibre volume fraction criterion is used for controlling the volumetric composition and microstructural uniformity of pultruded hybrid kenaf/glass fibre composites. The experimental volumetric composition in the pultruded hybrid composites is analysed by the developed model. Finally, model simulations are made to demonstrate the suitability of the model for designing the volumetric composition in hybrid composites.

2. Theory

2.1. Development of model for volumetric composition in hybrid composites

In conventional non-hybrid composites, one type of fibres is embedded in a matrix. This is illustrated in Figure 1a showing an example of a unidirectional fibre composite where the single fibres are uniformly dispersed in the matrix. In hybrid composites, in principle, several different types of fibres can be combined, however, in practice, the combination of two fibres is the most common [4]. Since the two types of fibres are mixed and embedded in a common matrix, different fibre intermixing configurations exist. Figure 1b shows three different fibre intermixing configurations in hybrid composites: layer/layer mixing, bundle/bundle mixing, and fibre/fibre mixing. This exemplifies the range of possible dispersions from a non-uniform dispersion (layer/layer) to a uniform dispersion (fibre/fibre). The actual fibre intermixing configuration in hybrid composites depends on the configuration of the fibre performs, together with the applied composite manufacturing technique.

In both non-hybrid and hybrid composites, regardless of the fibre intermixing configurations, the volumetric composition is conventionally given by the volume fractions of fibres, matrix and porosity which are related to the total volume of the composite. This so-called *global volumetric composition* is illustrated in Figure 1c. However, as indicated in Figure 1b, and exemplified in details in Figure 2, the two fibre types in hybrid composites can be thought to form local and discrete non-hybrid composite regions consisting of only one fibre type. This leads to the concept of *local volumetric composition*, where the volume fractions of fibres, matrix and porosity are related to the volume of the local non-hybrid composite region. This is readily acceptable for the cases of layer/layer and bundle/bundle mixing configurations, where the distinction between the non-hybrid composite regions is clear; it has however a more conceptual meaning for the case of fibre/fibre mixing configuration. Altogether, as illustrated in Figures 1c and 1d, the global volumetric composition in hybrid fibre composites can be separated into two local volumetric compositions.

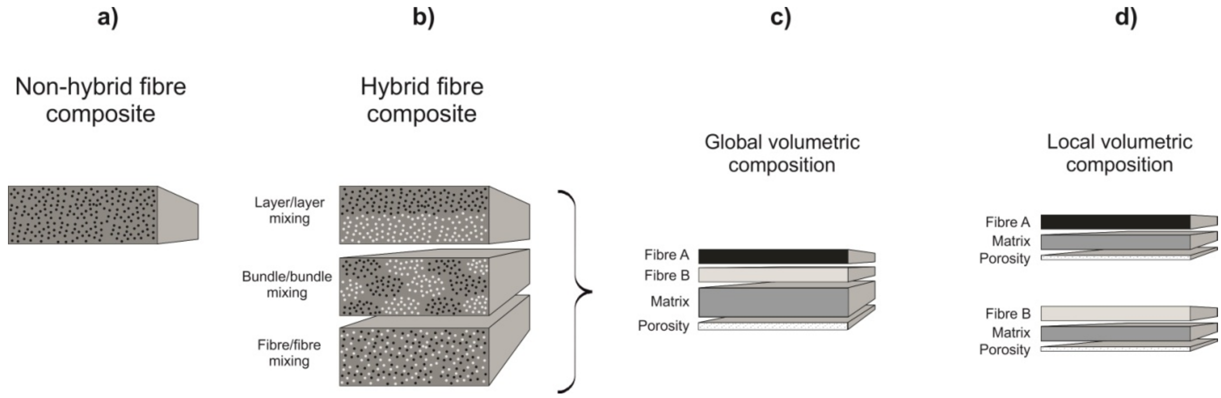

Figure 1. Schematised drawing of the typical fibre configurations in unidirectional (a) non-hybrid and (b) hybrid fibre composites. The concept of (c) global volumetric composition, and (d) local volumetric composition in hybrid fibre composites is illustrated by slab models.

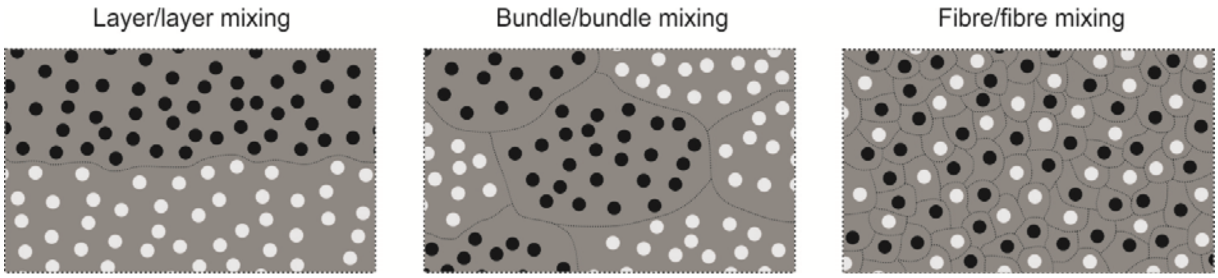

Figure 2. Schematised drawing of the two non-hybrid composite regions (belonging to the black and light gray fibres, respectively) in hybrid fibre composites with different fibre intermixing configurations.

Here follows a presentation of the developed model of the volumetric composition in hybrid composites. The volumetric composition is calculated as a function of the so-called *hybrid fibre mixing ratio*, and the *local fibre volume fractions are used as input parameters*.

The hybrid fibre mixing ratio is the ratio between the two fibre types in the hybrid composite, and it can be quantified by weight (β) or by volume (γ) of the fibres.

$$\beta = \frac{m_{fB}}{m_{fB}+m_{fA}} \quad (1)$$

$$\gamma = \frac{v_{fB}}{v_{fB}+v_{fA}} \quad (2)$$

where m_f is the fibre mass, v_f is the fibre volume, and the subscripts A and B denote the two fibre types. For β and γ equal to 0, the composite consists only of type A fibres, and for β and γ equal to 1, the composite consists only of type B fibres. Thus, β and γ equal to 0 or 1 define the situation of the two non-hybrid composites. Values of β and γ between 0 and 1 define the situation of hybrid composites with different fibre mixing ratios.

An equation for the relation between β and γ can be formed as following [2]:

$$\gamma = \frac{v_{fB}}{v_{fB}+v_{fA}} = \frac{\frac{m_{fB}}{\rho_{fB}}}{\frac{m_{fB}}{\rho_{fB}}+\frac{m_{fA}}{\rho_{fA}}} = \frac{\rho_{fA}\, m_{fB}}{\rho_{fA}\, m_{fB}+\rho_{fB}\, m_{fA}} \quad \rightarrow \quad \gamma = \frac{\rho_{fA}\,\beta}{\rho_{fA}\,\beta+\rho_{fB}\,(1-\beta)} \tag{3}$$

where ρ_f is the fibre density.

Before derivation of the model equations, some helpful support equations can be established as follows:

$$\gamma = \frac{v_{fB}}{v_{fB}+v_{fA}} = \frac{1}{1+\frac{v_{fA}}{v_{fB}}} \quad \rightarrow \quad \frac{v_{fA}}{v_{fB}} = \frac{1-\gamma}{\gamma} \tag{4}$$

$$\gamma = \frac{v_{fB}}{v_{fB}+v_{fA}} = \frac{V_{fB(\mathrm{II})}v_{c(\mathrm{II})}}{V_{fB(II)}v_{c(II)}+V_{fA(\mathrm{I})}v_{c(\mathrm{I})}} \quad \rightarrow \quad \frac{1}{\gamma} = \frac{V_{fA(\mathrm{I})}v_{c(\mathrm{I})}}{V_{fB(\mathrm{II})}v_{c(\mathrm{II})}}+1 \quad \rightarrow \quad \frac{v_{c(\mathrm{II})}}{v_{c(\mathrm{I})}} = \frac{V_{fA(\mathrm{I})}\gamma}{V_{fB(\mathrm{II})}(1-\gamma)} \tag{5}$$

where v is the absolute volume, V is the volume fraction, the subscript c is the composite, and the subscripts I and II designate the two non-hybrid composite regions for type A fibres and type B fibres, respectively.

Hereafter follows derivation of the model equations. The equations for the global volume fractions of the two types of fibres (V_{fA} and V_{fB}) are derived as follows:

$$V_{fA} = \frac{v_{fA}}{v_c} = \frac{v_{fA(\mathrm{I})}}{v_{c(\mathrm{I})}+v_{c(\mathrm{II})}} = \frac{v_{fA(\mathrm{I})}}{\frac{v_{fA(\mathrm{I})}}{V_{fA(\mathrm{I})}}+\frac{v_{fB(\mathrm{II})}}{V_{fB(\mathrm{II})}}} = \frac{1}{\frac{1}{V_{fA(\mathrm{I})}}+\frac{\frac{\gamma}{1-\gamma}}{V_{fB(\mathrm{II})}}} = \frac{V_{fA(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} \tag{6}$$

$$V_{fB} = \frac{v_{fB}}{v_c} = \frac{v_{fB(\mathrm{II})}}{v_{c(\mathrm{I})}+v_{c(\mathrm{II})}} = \frac{v_{fB(\mathrm{II})}}{\frac{v_{fA(\mathrm{I})}}{V_{fA(\mathrm{I})}}+\frac{v_{fB(\mathrm{II})}}{V_{fB(\mathrm{II})}}} = \frac{1}{\frac{\frac{1-\gamma}{\gamma}}{V_{fA(\mathrm{I})}}+\frac{1}{V_{fB(\mathrm{II})}}} = \frac{V_{fA(\mathrm{I})}V_{fB(\mathrm{II})}\gamma}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} \tag{7}$$

The equations for the global volume fractions of matrix and porosity (V_m and V_p) are derived as follows:

$$V_m = \frac{v_m}{v_c} = \frac{v_{m(\mathrm{I})}+v_{m(\mathrm{II})}}{v_{c(\mathrm{I})}+v_{c(\mathrm{II})}} = \frac{v_{m(\mathrm{I})}+v_{m(\mathrm{II})}}{\frac{v_{m(\mathrm{I})}}{V_{m(\mathrm{I})}}+\frac{v_{m(\mathrm{II})}}{V_{m(\mathrm{II})}}} = \frac{1+\frac{V_{m(\mathrm{II})}v_{c(\mathrm{II})}}{V_{m(\mathrm{I})}v_{c(\mathrm{I})}}}{\frac{1}{V_{m(\mathrm{I})}}+\frac{\frac{V_{m(\mathrm{II})}v_{c(\mathrm{II})}}{V_{m(\mathrm{I})}v_{c(\mathrm{I})}}}{V_{m(\mathrm{II})}}} = \frac{1+\frac{V_{m(\mathrm{II})}V_{fA(\mathrm{I})}\gamma}{V_{m(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}}{\frac{1}{V_{m(\mathrm{I})}}+\frac{\frac{V_{m(\mathrm{II})}V_{fA(\mathrm{I})}\gamma}{V_{m(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}}{V_{m(\mathrm{II})}}} = \frac{V_{m(\mathrm{II})}V_{fA(\mathrm{I})}\gamma+V_{m(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} \tag{8}$$

$$V_p = \frac{v_p}{v_c} = \frac{v_{p(\mathrm{I})}+v_{p(\mathrm{II})}}{v_{c(\mathrm{I})}+v_{c(\mathrm{II})}} = \frac{v_{p(\mathrm{I})}+v_{p(\mathrm{II})}}{\frac{v_{p(\mathrm{I})}}{V_{p(\mathrm{I})}}+\frac{v_{p(\mathrm{II})}}{V_{p(\mathrm{II})}}} = \frac{1+\frac{v_{p(\mathrm{II})}}{v_{p(\mathrm{I})}}}{\frac{1}{V_{p(\mathrm{I})}}+\frac{\frac{v_{p(\mathrm{II})}}{v_{p(\mathrm{I})}}}{V_{p(\mathrm{II})}}} = \frac{1+\frac{V_{p(\mathrm{II})}v_{c(\mathrm{II})}}{V_{p(\mathrm{I})}v_{c(\mathrm{I})}}}{\frac{1}{V_{p(\mathrm{I})}}+\frac{\frac{V_{p(\mathrm{II})}v_{c(\mathrm{II})}}{V_{p(\mathrm{I})}v_{c(\mathrm{I})}}}{V_{p(\mathrm{II})}}} = \frac{1+\frac{V_{p(\mathrm{II})}V_{fA(\mathrm{I})}\gamma}{V_{p(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}}{\frac{1}{V_{p(\mathrm{I})}}+\frac{\frac{V_{p(\mathrm{II})}V_{fA(\mathrm{I})}\gamma}{V_{p(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}}{V_{p(\mathrm{II})}}} = \frac{V_{p(\mathrm{II})}V_{fA(\mathrm{I})}\gamma+V_{p(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} \tag{9}$$

In the equations above, γ is applied as the independent variable. In some cases, however, it might be more suitable to use β as the independent variable, since the two types of fibres usually are mixed and controlled by their weights in the hybrid composites. The relation between γ and β is given by Equation (3).

Having derived equations for the four global volume fractions, it can be verified that their summation is equal to one, as required:

$$V_{fA} + V_{fB} + V_m + V_p = 1 \rightarrow$$

$$\frac{V_{fA(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)+V_{fA(\mathrm{I})}V_{fB(\mathrm{II})}\gamma+V_{m(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)+V_{m(\mathrm{II})}V_{fA(\mathrm{I})}\gamma+V_{p(\mathrm{I})}V_{fB(\mathrm{II})}(1-\gamma)+V_{p(\mathrm{II})}V_{fA(\mathrm{I})}\gamma}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)}$$

$$= \frac{V_{fA(\mathrm{I})}\gamma\left(V_{fB(\mathrm{II})}+V_{m(\mathrm{II})}+V_{p(\mathrm{II})}\right)+V_{fB(\mathrm{II})}(1-\gamma)\left(V_{fA(\mathrm{I})}+V_{m(\mathrm{I})}+V_{p(\mathrm{I})}\right)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} = \frac{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} = 1 \qquad (10)$$

The concept of non-hybrid composite regions in the hybrid fibre composites allows for a definition of the volumetric composition of the hybrid fibre composites with respect to the non-hybrid composite regions. Here follows derivation of the equations for the volume fractions in the two non-hybrid composites:

$$V_{c(\mathrm{I})} = \frac{v_{c(\mathrm{I})}}{v_c} = \frac{v_{c(\mathrm{I})}}{v_{c(\mathrm{I})}+v_{c(\mathrm{II})}} = \frac{1}{1+\frac{v_{c(\mathrm{II})}}{v_{c(\mathrm{I})}}} = \frac{1}{1+\frac{V_{fA(\mathrm{I})}\gamma}{V_{fB(\mathrm{II})}(1-\gamma)}} = \frac{V_{fB(\mathrm{II})}(1-\gamma)}{V_{fA(\mathrm{I})}\gamma+V_{fB(\mathrm{II})}(1-\gamma)} \qquad (11)$$

$$V_{c(\mathrm{II})} = 1 - V_{c(\mathrm{I})} \qquad (12)$$

In the developed model of the volumetric composition in hybrid composites, Equations (6) – (9), the global volume fractions (V_{fA}, V_{fB}, V_m and V_p) are calculated as a function of the hybrid fibre mixing ratio (γ or β). The input parameters in the model are the local fibre, matrix and porosity volume fractions ($V_{fA(\mathrm{I})}$, $V_{m(\mathrm{I})}$, $V_{p(\mathrm{I})}$ and $V_{fB(\mathrm{II})}$, $V_{m(\mathrm{II})}$, $V_{p(\mathrm{II})}$). For hybrid composites manufactured by certain manufacturing techniques, *the local fibre, matrix and porosity volume fractions are constant for all hybrid fibre mixing ratios, and they can thereby be set equal to the fibre, matrix and porosity volume fractions in the two non-hybrid composites*. This was demonstrated in study by Beauson et al. [2] to be the case for hybrid glass/carbon composites manufactured by vacuum infusion. In the present study, it will be demonstrated also to be the case for hybrid kenaf/glass composites manufactured by pultrusion.

3. Materials and methods

3.1. Materials

Glass fibre rovings with a linear density of 4800 tex (g/1000 m) were purchased from China National Building Materials (Group) Corporation. Kenaf fibre rovings (spun yarn) with a linear density of 1000 tex were provided by KEFI (Malaysia) Sdn.Bhd. Unsaturated polyester resin (Reversol P-9771) was obtained from Revertex (Malaysia) Sdn.Bhd. Calcium magnesium carbonate (Dolomite) was used as filler (7 wt%), and methyl ethyl ketone peroxide (Butanox M-50) was applied as catalyst (1 wt%). In the further analysis and modelling of the manufactured composites, the matrix phase of the composites is taken to be consisting of both the polyester and the filler.

3.2. Design and manufacturing of composites

Six pultruded composites were manufactured: two non-hybrid kenaf and glass composites, and four hybrid kenaf/glass composites. In the above presented model equations, the glass fibres correspond to the A fibre type, and the kenaf fibres correspond to the B fibre type.

The composites were manufactured in the form of cylindrical rods with a diameter of 10 mm by using an industrial pultrusion machine (Pultrex, PX-500-6 T) at Innovative Pultrusion Sdn.Bhd, Malaysia.

To determine the number of rovings to be applied for the manufacturing of the non-hybrid kenaf and glass composites, the wanted fibre volume fraction in the composites was set to be 0.40 and 0.60 respectively. The number of rovings was then calculated by using the following equation:

$$V_f = \frac{v_f}{v_c} = \frac{A_f}{A_c} = \frac{n_r\ T_r}{\rho_f\ \frac{\pi}{4} d^2} \quad \rightarrow \quad n_r = \frac{V_f\ \rho_f\ \frac{\pi}{4} d^2}{T_r} \tag{13}$$

where A_f is the absolute fibre area, n_r is the number of rovings, T_r is the roving linear density, ρ_f is the fibre density, and d is the die diameter.

In the selection of number of rovings to be applied for the manufacturing of the hybrid kenaf/glass composites, it was assured that *the local fibre volume fractions in the hybrid composites was kept identical to the fibre volume fractions in the non-hybrid composites.* The derivation of Equation (19) for the calculation of the required roving numbers in the hybrid composites is shown next.

First, equations for the local fibre volume fractions in the hybrid composites are established:

$$V_{fA(I)} = \frac{v_{fA}}{v_{c\,(I)}} = \frac{A_{fA}}{A_{c\,(I)}} = \frac{n_{rA}\ T_{rA}}{\rho_{fA}\ A_{c\,(I)}}; \quad V_{fB(II)} = \frac{v_{fB}}{v_{c\,(II)}} = \frac{A_{fB}}{A_{c\,(II)}} = \frac{n_{rB}\ T_{rB}}{\rho_{fB}\ A_{c\,(II)}} \tag{14}$$

Then, equations for the fibre volume fractions in the non-hybrid composites are established:

$$V_{fA} = \frac{v_{fA}}{v_c} = \frac{A_{fA}}{A_c} = \frac{n_{rA}^0\ T_{rA}}{\rho_{fA}\ A_c}; \quad V_{fB} = \frac{v_{fB}}{v_c} = \frac{A_{fB}}{A_c} = \frac{n_{rB}^0\ T_{rB}}{\rho_{fB}\ A_c} \tag{15}$$

where the superscript 0 is applied to define the situation for the non-hybrid composites.

Finally, the governing Equation (19) can be derived:

$$V_{fA(I)} = V_{fA} \ \rightarrow\ \frac{n_{rA}\ T_{rA}}{\rho_{fA}\ A_{c\,(I)}} = \frac{n_{rA}^0\ T_{rA}}{\rho_{fA}\ A_c} \ \rightarrow\ \frac{n_{rA}}{n_{rA}^0} = \frac{A_{c\,(I)}}{A_c} \tag{16}$$

$$V_{fB(II)} = V_{fB} \ \rightarrow\ \frac{n_{rB}\ T_{rB}}{\rho_{fB}\ A_{c\,(II)}} = \frac{n_{rB}^0\ T_{rB}}{\rho_{fB}\ A_c} \ \rightarrow\ \frac{n_{rB}}{n_{rB}^0} = \frac{A_{c\,(II)}}{A_c} \tag{17}$$

Since by definition

$$A_{c\,(I)} + A_{c\,(II)} = A_c \rightarrow \frac{A_{c\,(I)}}{A_c} + \frac{A_{c\,(II)}}{A_c} = 1 \tag{18}$$

it follows that

$$\frac{n_{rA}}{n_{rA}^0} + \frac{n_{rB}}{n_{rB}^0} = 1 \tag{19}$$

Hence, by selecting the number of rovings in the hybrid composites (n_{rA} and n_{rB}) to meet the condition of Equation (19), it is assured that the local fibre volume fractions in the hybrid composites, for all hybrid fibre mixing ratios, are kept indentical to the fibre volume fractions in the non-hybrid composites. This will allow to have composites with high degree of structural uniformity, where each type of fibre will have a constant effect on the mechanical properties of the composite. The hybrid effect can be more easily evaluated, which is useful for the design of properties of hybrid composites.

Two series of composites were produced (composites a1-f1, and a2-f2) with various process conditions. Table 1 shows the specifications of the manufactured pultruded hybrid kenaf/glass fibre composites.

Table 1. Specifications of the manufactured pultruded kenaf/glass composites: number of fibre rovings, hybrid fibre mixing ratio (β), die temperature and speed of machine.

Composite code	No of fibre rovings		Hybrid fibre weight mixing ratio, β	Die temperature (°C)		Speed of machine (m/min)
	Kenaf n_{rB}	Glass n_{rA}		1st section	2nd section	
a1 / a2	0	25	0.00	120 / 90	150 / 140	0.68 / 0.40
b1 / b2	10	20	0.09	120 / 90	150 / 140	0.68 / 0.40
c1 / c2	20	15	0.22	120 / 100	150 / 145	0.68 / 0.40
d1 / d2	30	10	0.38	120 / 90	150 / 150	0.68 / 0.40
e1 / e2	40	5	0.63	130 / 100	150 / 155	0.68 / 0.40
f1 / f2	50	0	1.00	140 / 140	150 / 150	0.40 / 0.40

3.3. Determination of volumetric composition in composites

The fibre weight fractions in the composites was calculated based on the applied number of fibre rovings and their linear densities, together with the measured linear density of the pultruded composite profile. The density of the fibres, the cured matrix, and the composites were measured experimentally. The gas pycnometry method was used for density measurement of the kenaf fibres. The buoyancy method was used for density measurement of the glass fibres, the cured matrix and the composites. Based on the found values for fibre weight fractions and materials densities, the global volumetric composition of the composites was determined by using standard composite equations. More details can be found in the study by Hashemi *et al.* [5].

4. Results and discussion

4.1. Experimental volumetric composition in pultruded hybrid kenaf/glass composites

The average density (± stdv.) of kenaf fibres, glass fibres and cured polyester matrix (with fillers) were measured to be 1.57 (± 0.01), 2.60 (± 0.03) and 1.30 (± 0.01) g/cm^3, respectively. Table 1 shows the determined fibre weight fractions, density and volumetric composition of the manufactured two series of pultruded hybrid kenaf/glass composites. It can be seen that the measured kenaf and glass fibre volume fractions on 0.43 and 0.59 in the non-hybrid composites (at β = 1 and β = 0, respectively) are almost identical to the predefined kenaf and glass fibre volume fractions on 0.40 and 0.60 (see Materials and methods section). This shows that the creation of porosity in the composites has no effect on the resulting fibre volume fractions, since these are directly controlled by the applied number of rovings in the pultrusion process. This is due to the constant composite volume (as controlled by the die dimensions) in the pultrusion process. Furthermore, in Table 1, it can be seen that the porosity volume fraction in the non-hybrid glass composite is zero, and the porosity is then increased when the kenaf fibre volume fraction is increased. It has previously been shown that there is a linear relationship (R^2=0.96) between the porosity volume fraction and the kenaf fibre volume fraction [5]. The slope of the regression line was found to be 0.66. This slope is equal to the so-called fibre porosity factor (α_{pf}), which is an important parameter for controlling the porosity volume in composites [3]. As was shown in the study by Hashemi et al. [5], the porosity volume fraction in composite type f1 on 0.18 is noticeably lower than the established linear relationship, and therefore, in the further modelling of the experimental results, the results for f1 are not used as model input.

Table 2. Fibre weight fractions, density and volumetric composition of pultruded hybrid kenaf/glass fibre composites.

Composite code	Fibre weight fractions		Density (g/cm^3)	Fibre volume fractions		Matrix volume fraction	Porosity volume fraction
	Kenaf	Glass		Kenaf V_{fB}	Glass V_{fA}	V_m	V_p
a1	0.00	0.74	2.05	0.00	0.59	0.41	0.00
a2	0.00	0.74	2.05	0.00	0.58	0.41	0.00
b1	0.07	0.65	1.86	0.08	0.47	0.40	0.05
b2	0.07	0.65	1.85	0.08	0.47	0.40	0.06
c1	0.15	0.56	1.62	0.16	0.35	0.36	0.13
c2	0.16	0.56	1.65	0.16	0.36	0.36	0.12
d1	0.27	0.43	1.43	0.24	0.24	0.33	0.19
d2	0.25	0.40	1.52	0.24	0.24	0.41	0.12
e1	0.41	0.25	1.24	0.33	0.12	0.32	0.23
e2	0.42	0.25	1.26	0.34	0.12	0.32	0.22
f1	0.57	0.00	1.18	0.42	0.00	0.40	0.18
f2	0.62	0.00	1.08	0.43	0.00	0.32	0.25

4.2. Modelling of volumetric composition in pultruded hybrid kenaf/glass composites

Figure 3 displays the experimental volumetric composition as a function of the hybrid fibre weight mixing ratio (β) for the two series of composites. The model lines in Figure 3 are calculated by the presented volumetric composition model, Equations (6) – (9). The used input parameters are shown in Table 3.

Table 3. Input parameters for the modelling of experimental and simulated cases of volumetric composition in hybrid kenaf/glass fibre composites.

Case	Local volume fractions in glass composite region			Local volume fractions in kenaf composite region		
	Glass $V_{fA(I)}$	Matrix $V_{m(I)}$	Porosity $V_{p(I)}$	Kenaf $V_{fB(II)}$	Matrix $V_{m(II)}$	Porosity $V_{p(II)}$
Experimental case	0.59	0.41	0.00	0.43	0.32	0.25
Simulated case A	0.60	0.40	0.00	0.40	0.60	0.00
Simulated case B	0.60	0.40	0.00	0.50	0.50	0.00
Simulated case C	0.60	0.40	0.00	0.50	0.40	0.10
Simulated case D	0.60	0.35	0.05	0.50	0.40	0.10

As can be seen in Figure 3, there is an excellent agreement between the experimental data points for the kenaf and glass fibre volume fractions, and the model lines. This is due to the good control of fibre volume fractions in the pultrusion process, as also mentioned above. The fibre volume fractions in the hybrid composites are accurately given by the number of fibre rovings calculated by Equation (19). The experimental data points for the matrix and porosity volume fractions, however, deviate slightly from the model lines. The reason for these deviations can be explained by the typical scatter of porosity in composites. The model assumes that the local porosity volume fraction in the non-hybrid kenaf composite region is constant at 0.25 for all hybrid fibre mixing ratios (i.e. equal to the porosity volume fraction in composite f2, at β = 1). However, due to the stochastic element in the creation of porosity in composites, and the influence of many factors, porosity in composites cannot be accurately foreseen. Thus, the likely scatter of the local porosity volume fraction in the hybrid composites explains the slight deviations of the experimental matrix and porosity volume fractions from the model lines in Figure 3. The matrix and porosity volume fractions in the pultruded hybrid composites are directly correlated with each other; if one of them is increased (e.g. the porosity), the other one is decreased (e.g. the matrix).

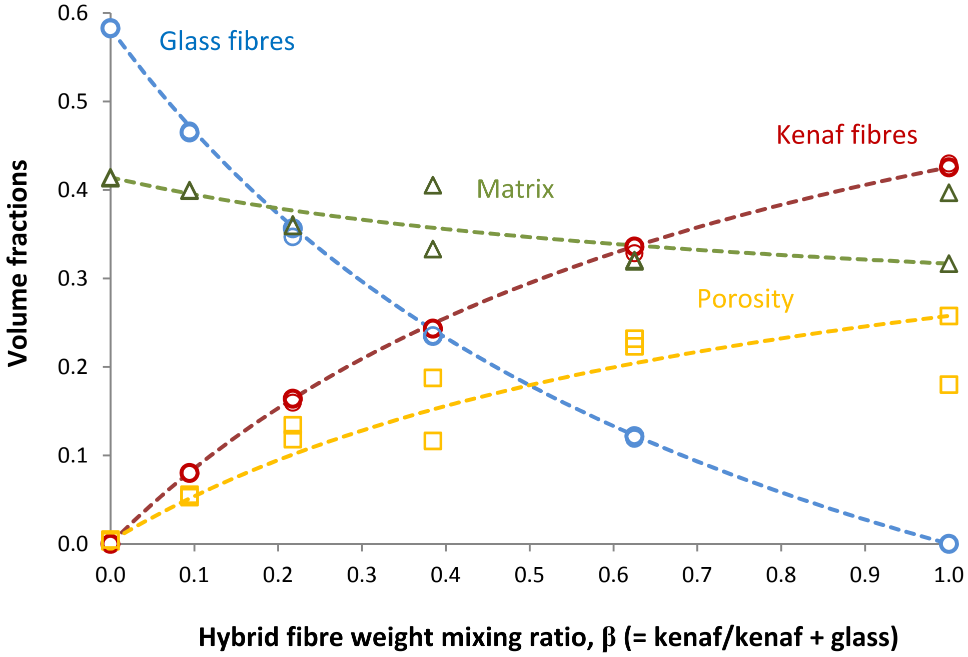

Figure 3. Volumetric composition in pultruded hybrid kenaf/glass composites as a function of the hybrid fibre weight mixing ratio. Shown are experimental data points and model lines.

4.3. Model simulations for different cases of volumetric composition in hybrid kenaf/glass composites
In this section, simulation of the volumetric compositions in hybrid kenaf/glass composites will be performed for four different cases: A, B, C and D. Table 3 shows the model input parameters for these cases. The plots with the model lines are shown in Figures 4-7.

In the simulated case A, the local kenaf and glass fibre volume fractions are set equal to the predefined values of 0.40 and 0.60, respectively, which are almost identical to the experimental values, and then, the local porosity in the kenaf composite is set equal to zero. Thus, case A reflects the situation where the process conditions have been optimised towards avoiding porosity in the kenaf composite region. The model lines are shown in Figure 4. In comparison to the experimental case (Figure 3), the matrix volume fraction in case A is not decreased as a function of β, but instead the matrix volume fraction is increased as a function of β .

In the simulated case B, the fibre volume fraction in the kenaf composite is set equal to 0.50. Thus, case B reflects the situation where the process conditions have been further optimised towards being able to increase the fibre volume fraction in the kenaf composites. The model lines are shown in Figure 5. The maximum obtainable fibre volume fraction in natural fibre composites is typical below the one for glass fibre composites due to the lower packing ability of natural fibres [3].

In the simulated case C, the porosity volume fraction in the kenaf composite is set equal to 0.10 to reflect the realistic situation of not being able to fully avoid porosity in these composites. One type of porosity in natural fibre composites is the one located inside the fibres, in the lumen [3]. The model lines for case C are shown in Figure 6. It can be observed that for these settings, the matrix volume fraction in the hybrid composites is constant at 0.40.

In the simulated case D, the porosity volume fraction in the glass composite is set equal to 0.05 to reflect the likely situation where some porosity is also present in the glass fibre composite. The model lines are shown in Figure 7. The model line for porosity does not start at zero at $\beta = 0$, but it starts at 0.05, and it is increased to 0.10 at $\beta = 1$. Thus, case D reflects the situation of two composites with different (non-zero) porosity contents.

Altogether, the four cases of model simulations, together with the good agreement with the experimental data, demonstrate that the model is suitable for controlling and designing the volumetric composition in pultruded hybrid composites. In further work, the model should be used together with micromechanical models for composites (e.g. see [6]), in order to calculate mechanical properties of hybrid composites as a function of the hybrid fibre weight mixing ratio. In this way, hybrid composites can be accurately designed to meet the mechanical specifications of given applications.

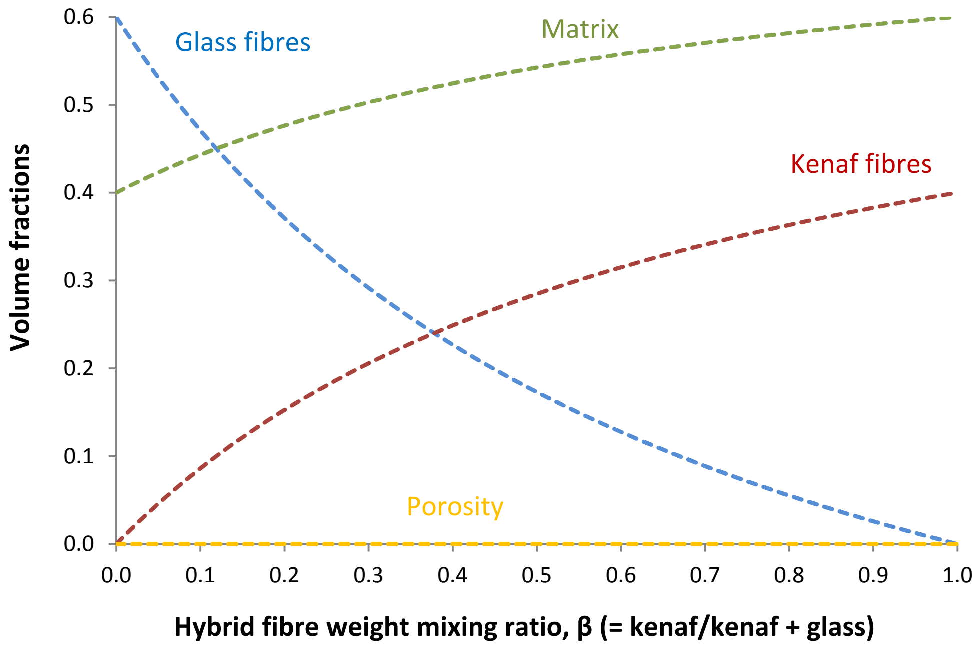

Figure 4. Simulated case A for volumetric composition in hybrid kenaf/glass composites.

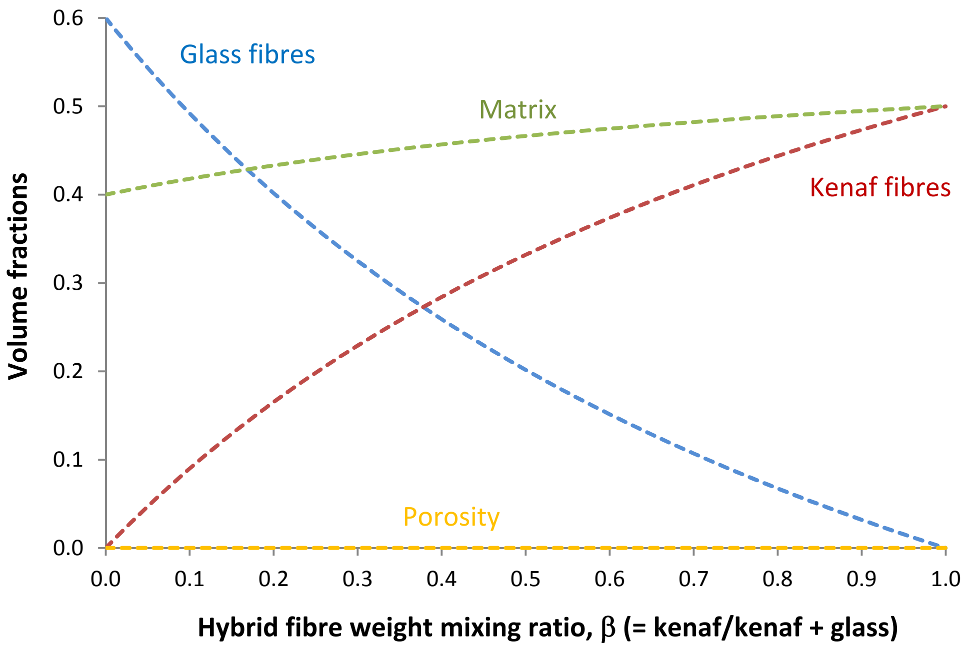

Figure 5. Simulated case B for volumetric composition in hybrid kenaf/glass composites.

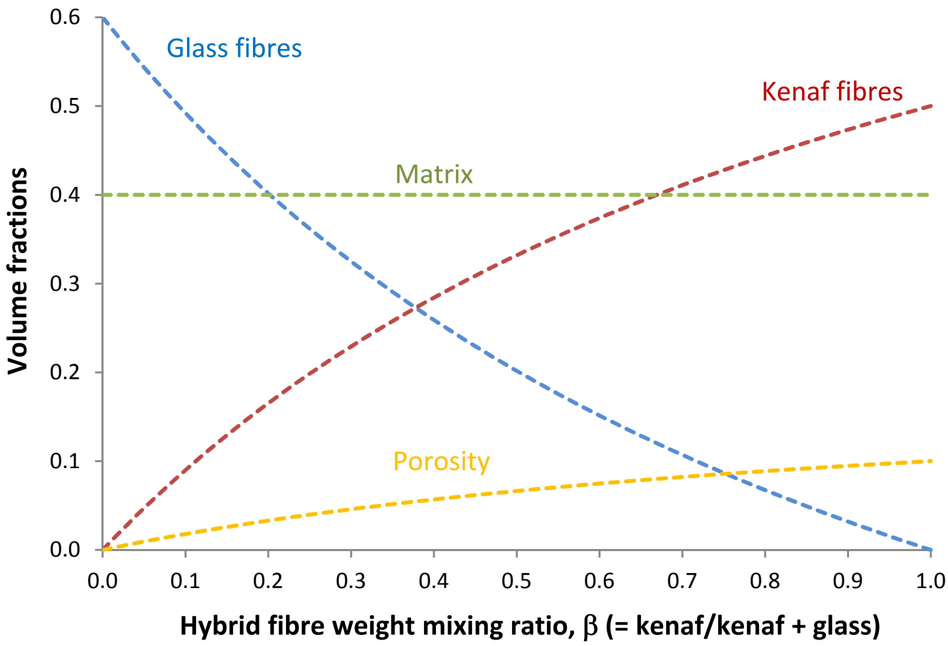

Figure 6. Simulated case C for volumetric composition in hybrid kenaf/glass composites.

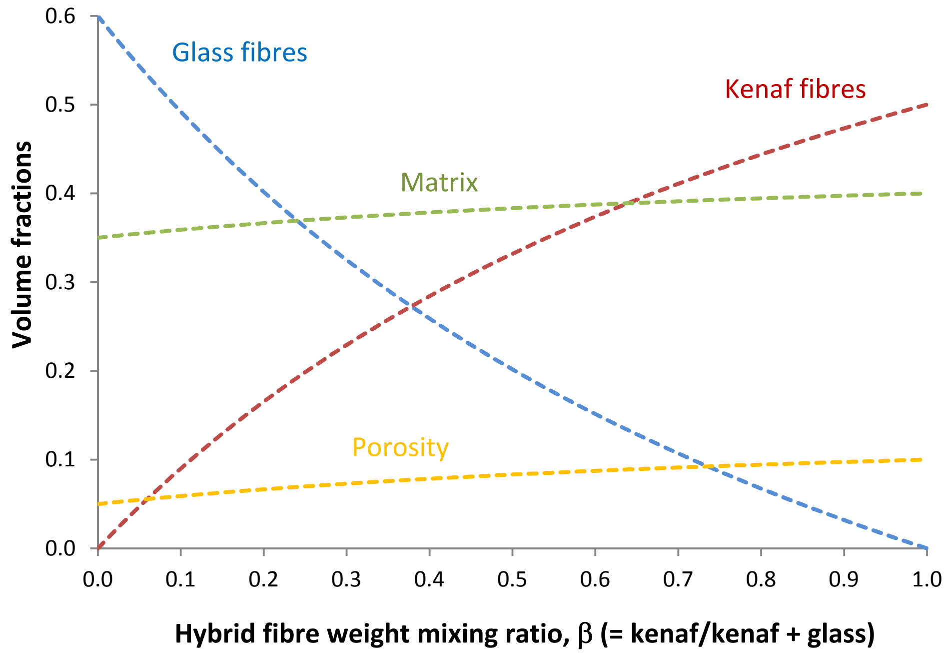

Figure 7. Simulated case D for volumetric composition in hybrid kenaf/glass composites.

5. Conclusions

In the present study, the constant local fibre volume fraction criterion is used for controlling the volumetric composition in pultruded hybrid kenaf/glass composites with five different hybrid fibre weight mixing ratios. Gravimetrical methods are used for the determination of the volumetric composition (i.e. volume fraction of fibres, matrix and porosity) in the composites. A generic model is presented for the prediction of the volumetric composition in hybrid composites, and good agreement with the experimental data is found. It is demonstrated that the model is a suitable tool for control and design of the volumetric composition in pultruded hybrid composites.

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