



Controllable parameters as the essential components in the analysis, manufacturing and design of 3D woven composites

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ABSTRACT

The comprehensive design feasibility for woven composites has been established by identifying the missing component in the design tool for these materials, the so-called controllable parameters. These are the parameters that are involved, directly or indirectly, in manufacturing of woven preforms, and they include the tow densities, the number and the size of filaments in a tow and intra-tow fibre volume fractions. Controllable parameters have been related through a simple procedure to the conventional geometric parameters of woven composites, which eliminates the need for their costly, inefficient, and often unreliable measurements. The controllable parameters provide sufficient representation of woven geometry in terms of both modelling and manufacture, thus offering common terminology to the woven composite designers and manufacturers. This also allows to naturally involve the practical considerations and manufacturing restrictions in material design exercises. With controllable parameters being incorporated in woven composite design framework, a direct analogy can be drawn to classical lamination theory-based design for conventional laminates. The wide applicability of the design tool has been demonstrated via a series of systematic material characterisation exercises carried out with woven composites of sufficiently different internal architectures and constituents, which also showed good predictive capability of the models involved.

1. Introduction

The 3D woven composites are a type of advanced composites that have been actively explored over the last few decades. The state-of-the-art is that on the manufacturing side, modern weaving technology allows to produce woven preforms of very complex architectures [1], while from the research perspective, numerous models representing these materials have been developed and employed for prediction of their mechanical behaviour [2,3]. However, despite the significant advancements at both fronts, these two parts, the modelling and the manufacturing, still have not been consolidated into a single design methodology. In other words, design feasibility that allows for direct communication between the woven composite designers and the manufacturers has not been established, and design rules stating how to identify a reinforcement configuration best suited for given application have not been formulated.

The present paper aims to facilitate design feasibility of woven composites in applications where they are meant to sustain the lateral impact. Under such loading scenarios their main advantage, namely, the

integral construction in through the thickness direction, can be directly utilised. This offers effective means of suppressing the delamination, which is the inherent weakness of the laminates, and thus improves the impact performance [4,5].

It is worth noting that explorations into the 3D woven composites in general are largely biased towards the study of so-called orthogonal interlock [1,6,7] weaves that are often also referred to as a non-crimp weaves [8]. The weaves of this kind have the straight warp and the weft fibre tows arranged in the plane of the fabric while the third type of tows interlaces this structure ensuring the integrity of the construction. A schematic of such reinforcement is shown in Fig. 1(a). There is a reasonable volume of published research addressing the transverse impact resistance of these materials, e.g. Refs. [5,9,10].

However, non-crimp composites are just one type of the woven composites. Another general type are the angle interlock composites, such as layer-to-layer and the through the thickness angle interlock [2], illustrated in Fig. 1(b) and (c), respectively. The distinctive feature of angle interlock composites is that their warp tows undulate along their paths and are inclined to the transverse direction of the composites. It is

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usually argued that the crimp, or undulations of the tows, can significantly undermine the in-plane properties of the woven composites [11, 12]. While the crimp undoubtedly affects the mechanical performance, reduction of in-plane properties alone is certainly not a valid reason for assuming inferior performance under the lateral loading.

In fact, mechanically, non-crimp composites are by far not the best choice for sustaining the lateral impact. An elaborate explanation of appropriate mechanical considerations has been given in Ref. [13]. In short, aligning reinforcement with the transverse direction, e.g. by using stitches [14], z-pins [5] or orthogonal interlock weaves, reinforces the material against the deformation and failure resulting from direct stress in the transverse direction, e.g. against mode I delamination, yet does not necessarily deliver the desired resistance to shear. Yet at lateral impact, typical failure mechanisms are dominated by transverse shear stresses associated with mode II fracture, which is the main cause of delamination in conventional laminated composites. The most effective resistance to the transverse shear stresses will be delivered by reinforcements inclined relative to the transverse direction, preferably at $\pm 45^\circ$, as is schematically illustrated in Fig. 1(b). Note that in drawings of angle interlock composites only a single slice of the weave is shown that contains a single warp tow. The adjacent slice will be offset from the current one in the weft direction, and also shifted in the warp direction to ensure interlocking of the layers of weft tows. The through-the-thickness shear stress state would be sustained by the undulating warp tows in either tension or compression along fibres.

It is worth noting that there is some limited evidence suggesting better impact performance of non-crimp composites. Specifically, in Ref. [10], comparison of low velocity impact responses of non-crimp, angle and layer-to-layer angle interlock composites suggests that the former slightly outperforms the other two. However, the main issue with comparisons of this kind is that there is no ‘generic’ configuration for any type of woven composites that would be representative of all composites of this kind. Composites of the same type will vary greatly in terms of geometry, i.e. the dimensions of the tows, and topology, i.e. the relative arrangement of the tows within the weave. In fact, the main design challenge of woven composites is how to navigate a virtually infinite variety of woven reinforcements and choose the most appropriate one. In absence of systematic understanding of the mechanics of different types of composites, it is hardly possible to choose an appropriate composite meaningfully. Specifically, the layer-to-layer interlock composite in Ref. [10] was very similar, if not identical, to one of the composites tested under ballistic impact in Ref. [15], where it was found to deliver the worst ballistic impact performance. A more informative comparison therefore would have been between the best-performing composites from each group. However, in absence of robust design tools, there is nothing but intuition that can guide such choice.

With mechanical considerations in favour of using layer-to-layer angle interlock composites for resisting lateral impact given above, the focus of this paper will be on establishing the design feasibility for this type of composites. Recently, they have been fully parametrised and

unified in Ref. [16], and a highly automated material characterisation tool based on use of Python script has been produced. However, no consideration has been given on how this tool can be employed in woven composites design and manufacture. The answer will be given in this paper, where a set of co-called controllable parameters will be shown to be the essential design parameters. First, they are introduced as efficient means of determining the geometric parameters of woven composites. Once their sufficiency for representing the geometry of woven composites in modelling and manufacturing is established, the design feasibility relying on use of controllable parameters is formulated. Its practicality is demonstrated and its predictive capability is evaluated via a range of carefully devised characterisation exercises with necessary validations.

2. Analytical procedure for calculating geometric parameters of 3D weave

2.1. Parametrisation of the woven composites

The unification and parametrisation of layer-to-layer angle interlock composites reported in Ref. [16] showed that they can be parametrised by only five topological and seven geometric parameters. The former ones describe the path of the warp tow within the weave. They are assigned integer values as indicators of how the warp tows should undulate relative to the weft tows. By varying these parameters accordingly, a wide range of woven architectures can be reproduced, with few examples being shown in Fig. 2. As can be seen, in all cases the straight weft tows are arranged in the vertical columns, and the paths of the undulating warp tows corresponding to different sets of topological parameters vary significantly.

Essentially, topological parameters reflect the qualitative features of the weave. The quantitative definition of the weave is given by the geometric parameters. Seven geometric parameters introduced in Ref. [16] fully define the geometry of the tows and spacings between them. For the tow cross-section shape, defined in Ref. [16] as an assembly of a rectangle and two semi-ellipses, one at each end of the rectangle, the cross-sectional area is expressed as:

$$A = HW \left(\gamma \left(\frac{\pi}{4} - 1 \right) + 1 \right), \quad (1)$$

where A , H , W and γ are the cross-sectional area, height, width and the measure of roundness of tow cross-section, as introduced in Ref. [16]. For clarity, some of these parameters are also marked in Fig. 3(a) showing an idealised model of the weave. Usually, the weft and the warp tows have different shapes and dimensions, therefore subscripts ‘weft’ or ‘warp’ have been used to differentiate between them.

An important feature of geometric parameters in Eq. (1) is that they are generic for woven composites. When generating a finite element model of a woven composite, different combinations of cross-sectional area, width and height parameters and some measure of the roundness

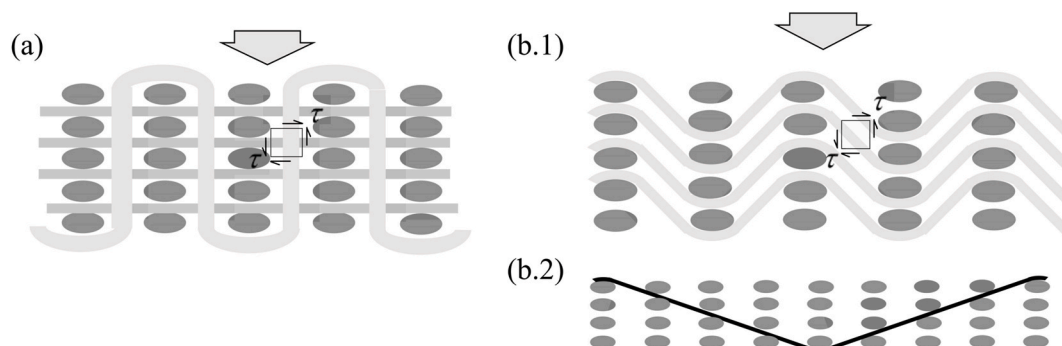


Fig. 1. Two major generic types of 3D woven composites, (a) orthogonal and (b) angle interlock: (b.1) layer-to-layer and (b.2) through the thickness, as special cases.

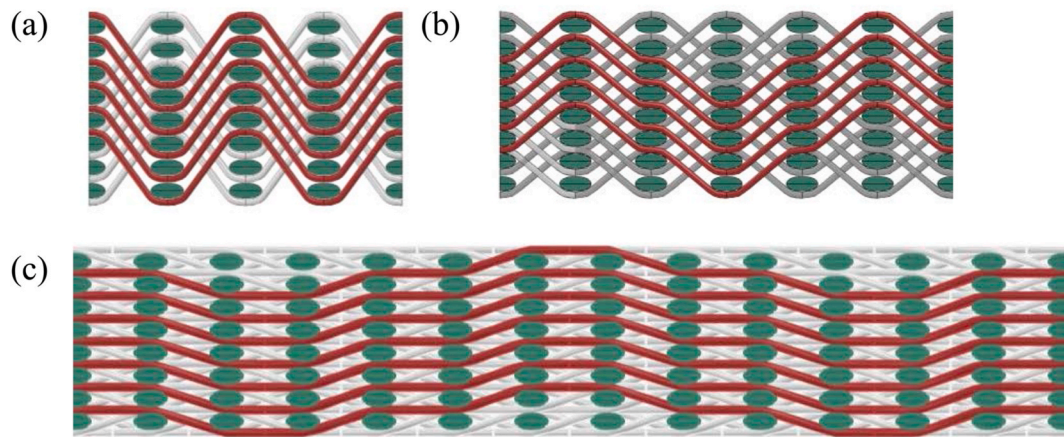


Fig. 2. Examples of weaves topologies that can be generated employing parametrisation, referring to topological parameters introduced in Ref. [16]: (a) $n_{skip} = 1$, $n_{deep} = n_{steep} = 3$; (b) $n_{skip} = 1$, $n_{steep} = 2$, $n_{deep} = 4$; (c) $n_{skip} = 2$, $n_{steep} = 1$, $n_{deep} = 2$.

of its profile form an essential geometric parameter input. Typically, these parameters are determined via a direct measurement, which is very time-consuming and costly. Usually, it requires micro-CT imaging of the samples, following which multiple measurements of the parameters have to be taken and then processed to produce an average of some kind [17]. Even then, the values determined may not be the most representative ones. Given considerable geometric variability in cross-sectional views of six woven composites in Fig. 4, the mere definition of what can be considered the tow cross-section height and width can be very subjective.

Another challenge associated with the geometric parameters is that it is unclear how they would change if the architecture of the weave was altered, i.e. tow size is increased or reduced. One certainly cannot rely on their physical measurement every time when the architecture is modified. Without capability to define such changes in geometry any serious design exercise cannot be accomplished.

In this work, the procedure for determining the geometric properties has been established that naturally incorporates such predictive capability. It can also be applied in a straightforward manner to determine geometric properties for the weave. The detailed description of the procedure is given in the subsections below.

2.2. Controllable parameters

To produce a woven preform, the weaver should define designated weaving parameters. Some of them are explicitly specified in the preform datasheet, namely:

- i) Number of filaments in the warp and the weft tows, F_{warp} and F_{weft} .
- ii) Number of the warp and weft tows per unit length, n_{warp} and n_{weft} . In this paper, they are referred to as the tow densities and are defined as the number of the tows per 10 mm of length along the warp or the weft direction, respectively.
- iii) Thickness of the composite panel, T .
- iv) The number of the warp and the weft tows through the thickness, K_{warp} and K_{weft} . illustrated in Fig. 3(a). Note that these parameters are usually not quoted by the manufacturer explicitly, but their values should always be defined by the manufacturer to proceed with the weaving. They can easily be counted from the cross-section of the woven composite once it is produced.

This list should also be supplemented with another set of parameters that can be used for estimating the total fibre volume fraction of the preform. It is evaluated prior to producing the preform and its value is also usually specified in the preform datasheets. This is an essential step

in preform manufacture because practical fibre volume fraction is imperative for satisfactory mechanical performance of composites made based on such preforms. Weavers have their own standard methods and parameters for evaluating the total fibre volume fraction, but the procedure developed in the present paper utilises properties that are primarily used in numerical modelling of the woven composites, namely:

- i) Filament diameter, d_f . Note that the same tow material and hence the fibre diameter is assumed for the warp and the weft tows, as is the case in most modern practical weaves. Different diameters can be easily accommodated in the formulation, if necessary.
- ii) Fibre volume fractions in the warp and for the weft tows, $V_{f,warp}$ and $V_{f,weft}$. These parameters are measurable, and it will be shown that they can in fact be considered constant for a wide range of composites.

These are the parameters that are involved in manufacture of woven reinforcements irrespective of their specific architectures. In terms of manufacture of woven composites, they uniquely define the composite configuration. By varying, or controlling, these parameters, the weave architecture can be modified. Because of this, they will be referred to as the ‘controllable parameters of the weave’. Note that the topology of the weave is equally important in defining the composite configuration. However, as was explained earlier, the topological parameters define only the qualitative features of the weave and have no relevance to the geometry of the tows. Because of that, the topological parameters are considered separately from the controllable parameters.

2.3. Relationship between the geometric and the controllable parameters

For layer-to-layer angle interlock composites, the unified formulation and parameterisation of which have been established in Ref. [16], the controllable parameters are related to the geometric ones in a straightforward manner. Firstly, the tow cross-sectional area, previously expressed by Eq. (1), can alternatively be calculated as

$$A = \frac{A_{fibre}}{V_f}, \quad (2)$$

where

$$A_{fibre} = \pi \frac{d_f^2}{4} F \quad (3)$$

is the portion of cross-sectional area formed exclusively by the cross-sections of the fibres. The the intra-tow fibre volume fraction, V_f , and fibre count, F , have already been introduced in the previous subsection,

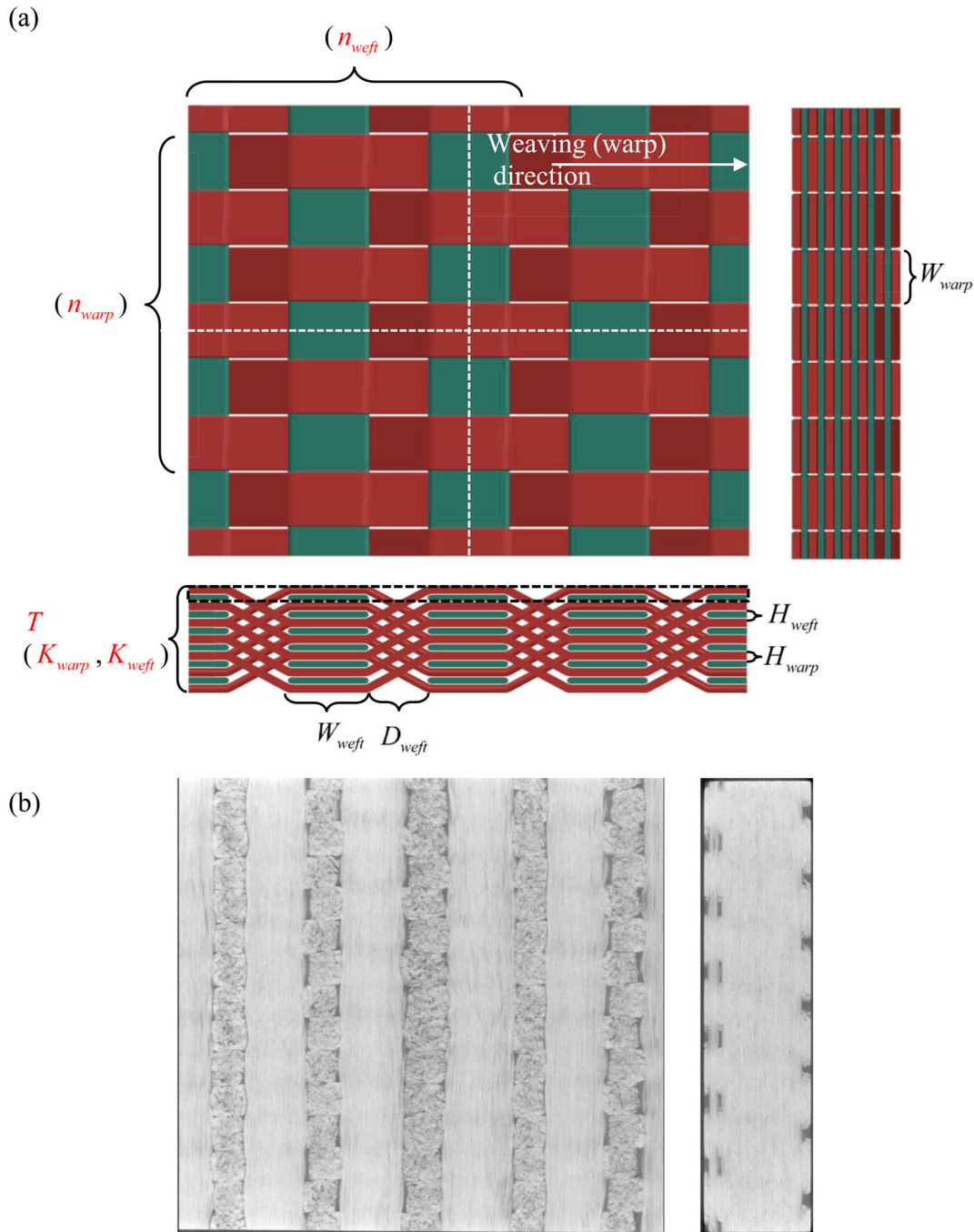


Fig. 3. Layer-to-layer angle interlock composite: (a) idealised model of the reinforcement; (b) micro-CT image of the weave.

where subscripts ‘warp’ and ‘weft’ were employed to differentiate between the parameters associated with the respective tows. Note that calculating the cross-sectional area of the tow using the intra-tow fibre volume fraction, as in Eqs. (2) and (3), may be considered rather unconventional. Typically, the measured cross-sectional area serves as means of determining the intra-tow fibre volume fraction [19]. Since the present work aims to replace the inefficient and unreliable direct measurements of geometric properties with simple numerical procedure, the tow cross-sectional area is treated here as a derived parameter.

Next, the thickness of the panel is comprised of the heights of the weft and the warp tows in a given weave, namely

$$T = K_{weft}H_{weft} + K_{warp}H_{warp}. \tag{4}$$

Finally, the weft and the warp tow densities, n_{weft} and n_{warp} , are

related to the width and the spacing between the tows as

$$n_{weft} = \frac{10}{W_{weft} + D_{weft}}, \tag{5}$$

where D_{weft} is the spacing between the weft tows, and

$$n_{warp} = \frac{10}{W_{warp}}. \tag{6}$$

2.4. Calculation of the geometric parameters

With relationships between the controllable and the geometric parameters being established, the latter are calculated following these steps:

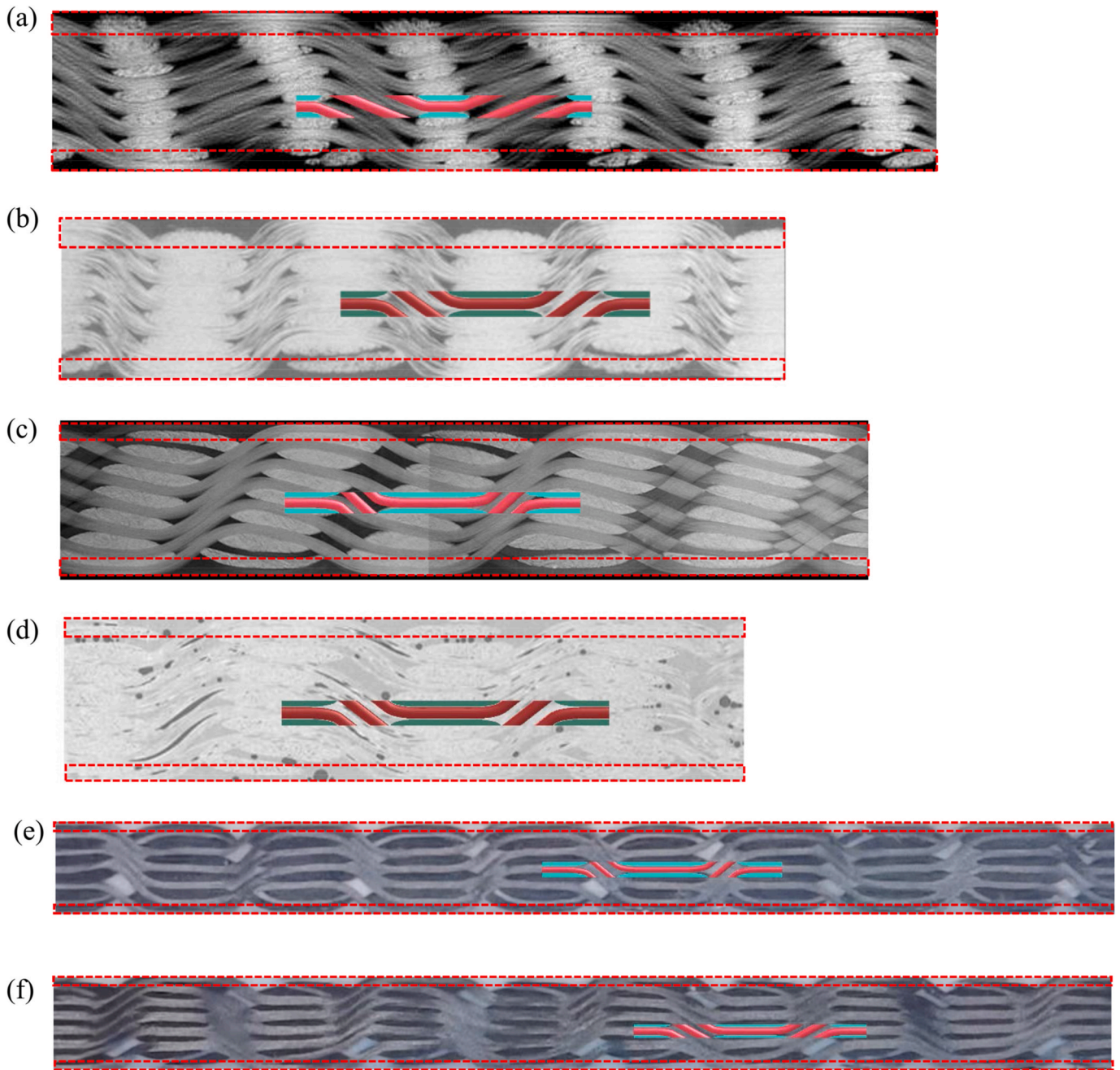


Fig. 4. Micro-CT images of cross-sectional views of composites from Ref. [18]: (a) GF-I; (b) GF-II; (c) T300 and (d) IM7; photographs of cross-sections of (e) TZ800-I and (f) TZ800-II. Composite notations are explained in Section 3.

1) From Eq. (6), the width of the warp tow becomes

$$W_{warp} = \frac{10}{n_{warp}}. \quad (7)$$

2) With of the width of the warp tow being known, its height is derived from Eqs. (1) and (2) as

$$H_{warp} = \frac{A_{warp}}{W_{warp}(\gamma_{warp}(\frac{\pi}{4} - 1) + 1)} = \frac{A_{fibre,warp}/V_{f,warp}}{W_{warp}(\gamma_{warp}(\frac{\pi}{4} - 1) + 1)}. \quad (8)$$

3) Having determined the height of the warp tow at the previous step, one can obtain the height of the weft tow from the re-arranged Eq. (4) as

$$H_{weft} = \frac{T - K_{warp}H_{warp}}{K_{weft}}. \quad (9)$$

4) Substituting the calculated height of the weft tow to the re-arranged Eq. (1) and making use of Eq. (2) gives the width of weft tow:

$$W_{weft} = \frac{A_{weft}}{H_{weft}(\gamma_{weft}(\frac{\pi}{4} - 1) + 1)} = \frac{A_{fibre,weft}/V_{f,weft}}{H_{weft}(\gamma_{weft}(\frac{\pi}{4} - 1) + 1)}. \quad (10)$$

5) Distance between the weft tows is expressed by re-arranging Eq. (5):

$$D_{weft} = \frac{1}{n_{weft}} - W_{weft}. \quad (11)$$

Table 1
Controllable parameters of woven composites.

		TZ800H-I	TZ800H-II	GF-I	GF-II	T300	IM7
Fibre count, $\times K$	F_{warp}	6	12	9	9	6	12
	F_{weft}	24	12	9	18	12	24
Tow density (1/cm)	n_{warp}	10	7	8	8	8	8
	n_{weft}	2.8	2.9	2.5	2.6	2.6	2.5
Number of tows in a column	K_{warp}	7	8	9	8	8	8
	K_{weft}	6	7	7	6	7	7
Thickness of the panel, mm		2.8	2.8	4.1	4.2	3.8	4.2

As can be seen, one parameter is determined at each step, and the steps should be taken consecutively, since the parameter calculated at the previous step is involved in the definition of the parameter at the current step.

It should be noted that an attempt to directly involve the manufacturing parameters in woven composite modelling has also been reported in Ref. [20]. It flags up the question of proper definition of the design parameters, and many of the parameters employed there are equivalent to controllable parameters introduced in subsection 2.2. However, main focus of [20] was on the development material characterisation model for the orthogonal interlock composite, that was the type of woven composites considered there. Also, the procedure employed for determining the geometric properties has not been truly streamlined and its systematic verification has not been attempted.

3. Sufficiency of controllable parameters

With clear link between the controllable and geometric parameters being established in the previous section, the sufficiency of these parameters for uniquely representing the woven composite in numerical modelling will be demonstrated in this section based on practical examples. The procedure will be applied to determine the geometric properties of six woven composites whose through-the-thickness cross-sections are shown in Fig. 4. All six composites had identical topologies, in terms of the relative arrangements of the tows in the weave. Referring to Ref. [16], the topological parameters corresponding to such arrangement were $n_{skip} = 1$, $n_{steep} = n_{deep} = 2$. Condition $n_{skip} = 1$ signifies that along its path the warp tow skips one weft tow before turning; $n_{deep} = 2$ indicates that in through the thickness direction it moves past two rows of the weft tows before making a turn, and $n_{steep} = 2$ means that it moves past two rows of weft tows before crossing a column of the weft tows. At the same time, the reinforcement geometry and/or the constituent materials were substantially different in all cases. For ease of referencing, the woven composites will be referred to by the material of the reinforcement, where GF denotes the E-glass fibre reinforcement, and T300, IM7 and TZ800H refer to the respective carbon fibres. The GF and TZ800H composites came in two different configurations, that are denoted by Roman numerals 'I' and 'II'.

All six woven reinforcements (prepregs) were manufactured by Sinoma International Engineering, China [21]. The E-glass fibre and T300 carbon fibre tows were provided by the preform manufacturer, and IM7 carbon fibre tows came from Hexcel [22]. These composites were manufactured applying a vacuum-assisted resin transfer moulding (VARTM) process using the facility available at the University of Nottingham [17]. For them, Gurit PRIME™ 20LV epoxy infusion resin with a slow hardener was used. The TZ800H carbon fibre tows were supplied by Weihai Guangwei Group, China. In terms of properties, they are meant to be equivalent to conventional T800H tows. The TZ800H composites were manufactured using the RTM process by AVIC Composite Corporation, China, and for them ACTECH 1304 epoxy resin system [23] was used.

3.1. Definition of the controllable associated with weaving

For the six woven composites described above, the preform parameters that represent some of the controllable parameters are summarised in Table 1. All of them were taken directly from the manufacturer datasheet, except for numbers of tows in the column that were counted from images in Fig. 4.

Using these parameter values directly for calculating the geometric properties is not advisable if the number of tows through the thickness is relatively small. The procedure described in subsection 2.4 essentially produces average dimensions of the tow cross-sections. For them to be of an acceptable accuracy, the tow cross-sections in the weave should be reasonably similar for a given type of tows, because otherwise, the average value may not be the most representative one. In real weaves, however, there will always be surface layers, marked by dashed rectangles in Fig. 4, where the tows tend to be more compacted compared to those inside the weave. If the number of the tows through the thickness is large, the error resulting from the mismatch in dimensions of the tows at the surface and inside the weave will be 'distributed' between the numerous tows; otherwise, the calculated tow dimensions will be too different from the actual ones.

The error caused by distorted surface layers can be eliminated simply by discounting their contribution when calculating the geometric parameters. Essentially, the surface layers are comprised of the tows, or their parts, where their cross-section shape become significantly different from those of the rest of the tows. Referring to the idealised model in Fig. 3 and cross-sectional views of six composites in Fig. 4, each surface layer, marked by the dashed rectangle, comprises the outmost layer of the weft tows and the parts of the warp tows adjacent to the surface of the composite panel.

For the six composites in this study, the calibrated thickness and the number of tows in a column are specified in Table 2 along with the measured surface layers thicknesses. The latter corresponded to the heights of the dashed rectangles.

3.2. Definition of the intra-tow controllable parameters

The most challenging controllable parameters to be defined are the intra-tow fibre volume fractions of the warp and the weft tows, because they are not readily available and can only be obtained experimentally.

Here, the intra-tow fibre volume fractions have been measured from the microscopy images of three woven composites, GF-II, T300 and IM7. Small cuboidal samples were cut out of the composite panels. The cutting planes, marked by dashed white lines in Fig. 3(a), were chosen to pass through the centre of the weft or the warp tows to expose their most compacted cross-sections. The samples were mounted in the epoxy resin disk as shown in Fig. 5(a). Prior to imaging, the samples were polished to ensure the sufficient smoothness of the surface. For each composite, two samples were prepared, one exposing the cross-sections of the weft and another of the warp tows.

Typical micrograph of a specimen taken using optical microscope is shown in Fig. 5(b). From each such image, the number of the whole fibre cross-sections was counted as well as the parts of cross-sections along the

Table 2
Controllable parameters corresponding to weave with the discounted surface layers.

		TZ800H-I	TZ800H-II	GF-I	GF-II	T300	IM7
Thickness of a surface layer, mm	top	0.40	0.26	0.63	0.76	0.44	0.47
	bottom	0.40	0.26	0.50	0.54	0.41	0.40
Panel thickness without the surface layers, mm		2.00	2.28	2.98	2.90	2.95	3.33
Number of tows in a column	K_{warp}	5	6	5	5	6	6
	K_{weft}	4	5	5	4	5	5

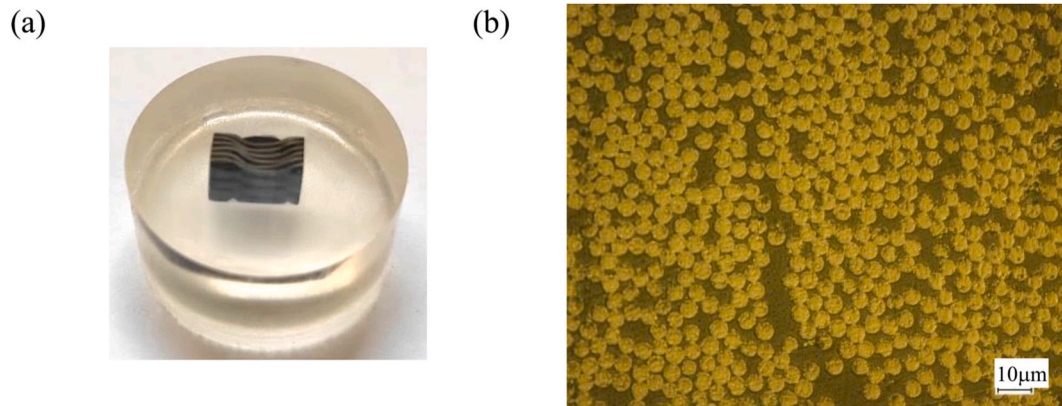


Fig. 5. (a) Typical composite sample prepared for microscopy and (b) a micrograph of the fibre tow cross-section of IM7 composite.

Table 3
Intra-tow controllable parameters.

		Average filament diameter, μm	Intra-tow fibre volume fraction			
			warp	SD	weft	SD
T300	7 [24]		0.659	0.044	0.674	0.009
IM7	5.2 [22]		0.702	0.014	0.677	0.002
GF-II	6		0.739	0.037	0.707	0.036

edges of the image whose area was larger than the half of the whole cross-section. The fibre volume fraction, V_f , was then estimated as

$$V_f = \frac{A_{fibre}}{A_{image}}, \quad (12)$$

where A_{image} is the total area of the image and A_{fibre} is the total cross-sectional area of all fibres. The latter is calculated according to Eq. (3) where the fibre count, F , is replaced by the number of whole and half cross-sections counted from the given image.

For each specimen, four micrographs were obtained and processed. The calculated intra-tow fibre volume fractions are listed in Table 3 along with their standard deviations. As can be seen, the measured values tend to be $\sim 70\%$. This is within the range of volume fraction measurements reported in [7,19], where similar measurement approaches were used. The results in Table 3 suggest that the weft tow fibre volume fraction tends to be a few percent smaller than the warp one. Referring to the warp and the weft tow cross-section images in Figs. 3(b) and Figure 4, respectively, it is easy to see that the warp tow is constrained from four sides, which results in its rectangular profile, while the weft tows have more freedom to spread sideways. It is therefore natural to expect that the fibres will be more compacted within the warp tow, resulting in fibre volume fraction being larger. Note that the intra-tow fibre volume fractions for T300 composite show an opposite trend, however, the standard deviation for warp tow fibre volume fraction measurements is five times larger than that for the weft tow, which indicates that the measured value may not be the most representative compared to those of other composites.

The diameters of the fibres, which are the final controllable

parameters to be specified, have also been included in Table 3. For T300 and IM7 carbon fibres, they were taken from the supplier datasheets. It could not be recovered for E-glass fibres, therefore it was estimated from the microscopy images. Note that for GF-II, unlike for the other two composites, the E-glass fibre sizes varied significantly, therefore the value specified in Table 3, and consequently the measurements of the fibre volume fractions, are likely to be less accurate than those for the other two composites.

3.3. Calculation of the geometric parameters of the weave

Based on parametrisation [16], to completely define of geometry of the woven composite, seven parameters are required. However, in subsection 2.4, only five of them are defined explicitly in terms of controllable parameters. Two geometric parameters, γ_{weft} and γ_{warp} , have been left loose. Parameter γ was introduced in Ref. [16] as the measure of roundness of the cross-section that can vary in the range of (0,1], where zero corresponds to a rectangular cross-section and unity to an elliptical one.

Considering cross-sectional images of the woven composites in Fig. 4, it is easy to see that practical definition of this parameter is even more subjective than that of any other, because the cross-sections of individual tows and rather irregular and their idealisation in a model is to a large extent a matter of personal preference. The considerations behind the choice of γ_{weft} and γ_{warp} in the present work are as follows. Provided that the warp tows are tightly packed in the transverse direction, as is often the case in practical layer-to-layer angle interlock composites, their cross-section is nearly rectangular, which fully justifies $\gamma_{warp} = 0.05$. The shape of the weft cross-sections, on the other hand, is closer to an elliptical one. However, it was noticed that at aspect ratios γ_{weft} close to unity, the meshing problems are likely to occur. On balance of these two considerations, it was assigned value of $\gamma_{weft} = 0.5$. It is true that value of γ_{weft} can be chosen from a wider range than that of γ_{warp} . Given the sequential geometric parameter calculation procedure in subsection 2.4, the choice of γ_{weft} will affect only the calculations of the width of the weft tows and the spacing between them. It is anticipated that such variation should not have a significant effect on the mechanical performance, while such sensitivity study is beyond the scope of the

Table 4
Calculated geometric parameters of six woven composites.

	Warp tow		Weft tow D_{weft}		
	H_{warp} , mm	W_{warp} , mm	H_{weft} , mm	W_{weft} , mm	D_{weft} , mm
GF-I	0.294	1.25	0.301	1.393	2.607
GF-II	0.294	1.25	0.358	2.345	1.501
T300	0.267	1.25	0.269	2.829	1.017
IM7	0.294	1.25	0.313	2.288	1.713
TZ800H-I	0.170	1.00	0.287	2.702	0.870
TZ800H-II	0.238	1.43	0.170	2.281	1.291

present paper.

If one is prepared to accept an assumption on the choice of parameters γ_{weft} and γ_{warp} , the geometric parameters implied by parametrisation [16] can be calculated following the procedure established in subsection 2.4. The controllable parameters specified in subsection 2.2 will be fully sufficient for this purpose. As an illustration, the geometric parameters for six woven composites under consideration have been calculated based on values of controllable parameters determined in the previous subsections. They are listed in Table 4.

4. Role of the controllable parameters in design of the woven composites

The main objective in the conventional laminate design is to determine the lay-up that would deliver the required performance in given application. The main design tool for laminates is the classical lamination theory (CLT) [25]. Its inputs are the material properties of constituents and the parameters associated with the lay-up configuration, namely, the orientations and the thicknesses of the unidirectional plies comprising the laminate. The former have a limited scope for variation, therefore it is primarily the lay-up parameters that are varied in the design exercises. These design parameters are well-defined, and the laminate designer can translate the design requirements directly to the manufacturer simply by specifying these parameters. A complete design cycle has been summarised in a flowchart in Fig. 6(a).

For woven composites, there are no established design tools available; furthermore, their design principles have not been clearly formulated yet. Unit cell modelling methodology is the most robust method for textile composite characterisation available nowadays. If the unit cell is treated as a design tool for the woven composites, the analogy with the CLT analysis for laminates is apparent, as illustrated by a flowchart in Fig. 6(b). Indeed, the unit cell modelling delivers the same kind of the outputs as the CLT, namely, the effective elastic properties and the

stress/strain distributions. It requires input parameters from the same two categories, i.e. the material properties and the parameters associated with the architecture of reinforcement. Same as for laminates, the desired performance is to be obtained via the variation of the architecture.

Though laminate architecture is very different from that of a 3D woven composite, a direct analogy between their architectural parameters can be established. The lay-up sequence in laminates is equivalent to the topological parameters in woven composites, because both define the reinforcements paths within the composites, namely, the fibres in laminates and the tows in the woven composites. The important difference is that the ply orientation concept is understood and used by both the designers and the manufacturers, while for woven composites, there no common notations for describing their topology. The current approach of transferring the desired topology requirements from the designer to manufacturer is to generate an explicit model of the weave, such as one shown in Fig. 3(a) and supplement it with some verbal description. The model of the weave can be generated in specialised software such as TexGen [26]. For efficient communication between the designers and the manufacturers, it would be certainly advantageous to develop a common systems of notations, and the weave topology parameterisation proposed in Ref. [16] can be a potential solution.

Addressing geometry input in woven textiles composites is even more complicated. Introducing controllable parameters that are easily understood by the weavers is key to fulfilling the complete design cycle for the woven composites. Indeed, involving geometric parameters directly in design exercises in a similar way as the ply thickness is involved in CLT would be a wrong design strategy for two main reasons. Firstly, the geometric parameters, such as the height and the width of the tows, cannot be directly interpreted by the manufacturers, who would still need to convert them to weaving parameters first. This complicates the communication between the designers and the manufacturers.

One may argue that relationship between the geometric and the controllable parameters established in subsection 2.3 would greatly facilitate this communication. However, the design produced this way may still not be viable from the manufacturing perspective. Specifically, an important practical restriction on the woven composite design is that the variations of the controllable parameters are supposed to be discrete. Two obvious examples are.

- 1) Fixed sizes of fibre tows, e.g. 6K and 12K. While the tows can be split or combined to form different sizes of the tows, in practice, there is only a finite number of such combinations.
- 2) Manufacturing restrictions on the tow density. Specifically, when ordering the preforms for the composites used in this study, the

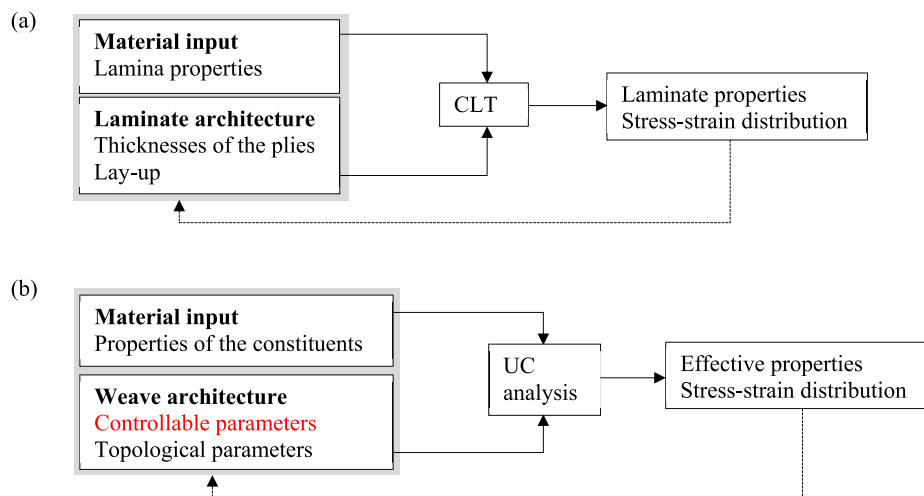


Fig. 6. Design cycle for (a) conventional laminates; (b) 3D woven textile composites.

authors have been informed by the manufacturer that the warp tow density should be either an integer <10 , or multiple of 10. Different weavers may have slightly different restrictions, but they will always be present.

Obviously, the geometric parameters cannot reflect this discreteness in a straightforward manner, which is the second reason why they should not be used directly in material design. On the other hand, in the design based on the controllable parameters, any restriction on values of the controllable parameters can readily be accounted for by selecting their values from the permitted ranges, and, once the design is finalised, the manufacturing requirements will be clear to the weaver, because they will be formulated using the same terminology.

In this sense, the procedure relating the geometric parameters to the controllable parameters is of higher relevance to the composites designer, who will be its primary user. The benefit for the weaver is that the design based on controllable parameters would naturally involve the check of the feasibility of manufacture of given configuration. In other words, the weaver would always find that the requested architecture of the preform is realistic from the manufacturing perspective, because this practical consideration would already be incorporated in the design.

5. Practicality of controllable parameters in modelling

Given the significance of controllable parameters in material design, it will be informative to understand how well they perform in the numerical analysis of woven composites. To demonstrate their practicality, elastic material characterisation was carried out for woven six composites employing geometric parameters determined earlier. Through this, practical implementation of the design cycle in Fig. 6(b) is demonstrated and an assessment of the predictive capability of the numerical model involved is conducted.

5.1. Unit cell model

The formulation of the unit cell modelling methodology employed in the present work has been established by the last author of this paper. The most complete account on its formulation is given in Ref. [13], while its application to unit cells of various shapes have been reported in numerous publications over the years, e.g. Refs. [27,28]. The mechanical consistency of formulation is ensured by deriving the boundary conditions from the basic principles of deformation kinematics and through proper use of the translational symmetries. The characterisation procedures, from model generation to calculation of the effective elastic properties, have been fully automated for a range of typical composites via the use of Python scripts, which were consolidated in a UnitCells© material characterisation tool [29].

The formulation of the unit cell for the parameterised layer-to-layer angle interlock composite and its implementation as a Python script has

already been reported in full in Ref. [16]. With this functionality, the only effort required from the user is to specify the input parameters from the two groups indicated in Fig. 6(b). The material properties input will be elaborated in the subsection below. Parameters associated with the weave architecture include controllable parameters, that will be automatically converted to the conventional geometric parameters, and topological parameters previously introduced in Ref. [16].

Unit cells for six composites under consideration were generated in Abaqus/Standard solver based on geometric parameters from Table 4, with typical unit cell model being shown in Fig. 7. It was meshed with C3D4 tetrahedral elements of 0.06 global element size. To produce a preliminary qualitative comparison, the geometric models of the unit cells have been superimposed on the cross-sectional images of their respective composites in Fig. 4. As can be seen, the qualitative features of the weave, such as the relative dimensions of the tow sizes and the distances between the weft tows are reproduced well in the unit cell models.

5.2. Material property input

The necessary material property input in elastic characterisation of woven composites are the elastic properties of the constituents, namely, the matrix and the fibre tows. The epoxy resins are isotropic materials, therefore only two material properties, the Young's modulus and the Poisson ratio, should be defined for the matrix. The former can be found in material datasheets, while the latter can be determined from the standard tests. In this work, the Poisson ratios for resins were assigned typical values provided in Ref. [30].

The properties of the tows were obtained via the numerical characterisation using the UnitCells© tool [29] by considering them as unidirectional (UD) composites at a micro-scale. The required input were the properties of the constituents, namely, the fibres and the matrix, and the intra-tow fibre volume fractions.

Again, the material datasheets for the tows only provide only one elastic property, the longitudinal stiffness of the fibres. Glass fibres can generally be considered isotropic and hence require definition of just one more parameter, the Poisson ratio, to fully describe their elastic behaviour. In the present work, its benchmark value provided in Ref. [30] was used.

The carbon fibres have a marked transverse isotropy. In absence of experimental means to determine the remaining elastic properties, the practical way to define them is via a 'reversed' characterisation. Specifically, having the complete set of measured elastic properties for a UD composite, the fibre properties are determined via the parametric studies, by varying them in characterisation cases until the calculated effective properties come in close agreement with the experimental ones. This method was adopted to obtain the properties of IM7 UD composite, for which the complete set of elastic properties was taken from Ref. [31]. Note that when carrying out the reversed



Fig. 7. Typical FE model of a unit cell: (a) tows; (b) matrix constituent.

Table 5
Properties of the constituent materials.

Transversely isotropic materials				Isotropic materials			
Property	TZ800H	T300 [24,30]	IM7	Property	E-glass fibre [30]	Gurit Prime™ 20LV	ACTECH 1304
E_1 , GPa	294 [33]	230	276 [22]	E , GPa	74	3.5 [34]	3.53 [23]
$E_2 = E_3$, GPa	15	15	25	ν	0.2	0.35	0.35
$\nu_{12} = \nu_{13}$	0.28	0.2	0.3				
ν_{23}	0.35	0.5	0.35				
$G_{12} = G_{13}$, GPa	15	15	20				

characterisation, the longitudinal Young's modulus of the fibres, E_1 , was kept fixed at the value provided by the manufacturer. The remaining fibre properties were varied until the error between the laminate properties from Ref. [31] and their calculated effective counterparts reduced to 3% or lower. Same procedure was followed for TZ800H UD composite; unfortunately, the only set of its elastic properties that could be found in the literature [32] was incomplete, which may have affected the accuracy of the fibre property estimate. Finally, elastic properties of T300 fibres were taken directly from Ref. [30]. The properties of all the constituent materials have been summarised in Table 5.

Note that the accuracy of fibre properties obtained via the reversed characterisation is directly affected by the accuracy of the UD composite properties. Ideally, the latter are to be determined experimentally, but even nowadays, there is a severe shortage of comprehensive data sets for UD composites in the literature in general. While a complete set of data for IM7 UD laminate have been provided in Ref. [31], it is not clear how exactly such properties were obtained. Likewise, the T300 fibre properties in Ref. [30] are meant to represent some typical values. Because of that, some error is likely to be present in definition of the constitutive properties of carbon fibres specified in Table 5.

The remaining components required for tow characterisation are their fibre volume fractions. Based on their experimental definition in subsection 3.2, $V_{f,warp} = 0.70$ for the warp and $V_{f,weft} = 0.68$ for the weft tows have been used as sufficiently representative intra-tow fibre volume fractions for all composites. However, in the finite element models of unit cells it was necessary to introduce small gaps between the adjacent tows to ensure that they do not come into contact. Otherwise, there would be sharp corners in the geometric model of the matrix constituent in the vicinity of such contact zones, which would cause errors during meshing

To avoid this, the width of the warp tow was reduced a factor of $r_W = 0.96$ as

$$W_{warp}^r = r_W W_{warp}, \quad (13)$$

and the heights of the warp and the weft tow were reduced by a factor of $r_H = 0.95$ as

$$H_{warp}^r = r_H H_{warp}, \quad (14)$$

$$H_{weft}^r = r_H H_{weft}, \quad (15)$$

where henceforth superscript 'r' refers to the reduced geometric

parameters of the tows.

Because of these artificial reductions, the tow cross-sectional areas and dimensions in the FE model are smaller than their input (calculated) values, as is schematically shown in Fig. 8. Consequently, the tow volume fraction and hence the total fibre volume fraction will be under-represented in the FE model.

Misrepresentation of the fibre content is likely to result in reduced accuracy in predictions. Therefore, it was recovered by calibrating the values for intra-tow volume fractions. For the weft tow, only the height of the cross-section was reduced, therefore, the reduced cross-sectional area is related to the original one as:

$$A_{weft}^r = H_{weft}^r W_{weft} \left(\gamma_{weft} \left(\frac{\pi}{4} - 1 \right) + 1 \right) = r_H H_{weft} W_{weft} \left(\gamma_{weft} \left(\frac{\pi}{4} - 1 \right) + 1 \right) = r_H A_{weft}. \quad (16)$$

Substituting Eq. (2) into Eq. (16) yields

$$A_{weft}^r = \frac{r_H A_{fibre,weft}}{V_{f,weft}}, \quad (17)$$

which indicates that to retain the same fibre content in the weft tows of reduced cross-section dimensions, the actual value of the fibre volume fraction in the weft tows should be calibrated as

$$v_{f,weft} = \frac{V_{f,weft}}{r_H}, \quad (18)$$

where $v_{f,weft}$ is the calibrated value of the fibre volume fraction in the weft tow.

For the warp tows, both the width and the height were reduced according to Eqs. (13) and (15), respectively. Therefore, the expression for the reduced cross-sectional area becomes

$$A_{warp}^r = H_{warp}^r W_{warp}^r \left(\gamma_{warp} \left(\frac{\pi}{4} - 1 \right) + 1 \right) = r_H H_{warp} r_W W_{warp} \left(\gamma_{warp} \left(\frac{\pi}{4} - 1 \right) + 1 \right) = r_H r_W A_{warp}. \quad (19)$$

Given Eq. (2), it can be re-written as

$$A_{warp}^r = \frac{r_H r_W A_{fibre,warp}}{V_{f,warp}}, \quad (20)$$

which yields the calibrated intra-tow fibre volume fraction, $v_{f,warp}$, in the warp tows as

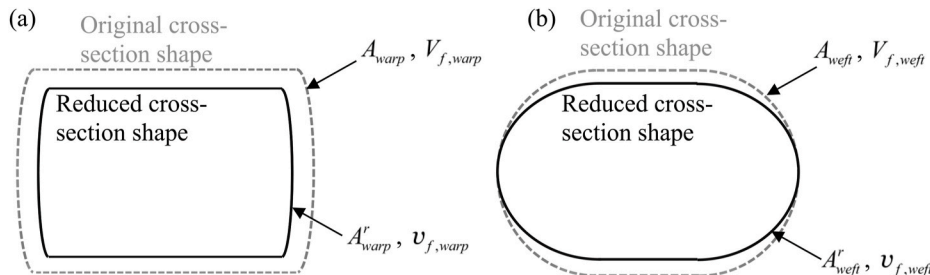


Fig. 8. Schematic of the tow cross-section reduction: (a) warp; (b) weft.

Table 6
Effective properties of the tows.

	GF-I, GF-II		T300		IM7		TZ800H-I, TZ800H-II	
	weft	warp	weft	warp	weft	warp	weft	warp
E_1 , GPa	53.934	57.595	165.549	177.250	198.364	212.52	211.25	226.33
$E_2 = E_3$, GPa	17.590	21.334	9.391	10.162	12.201	13.686	9.481	10.025
$\nu_{12} = \nu_{13}$	0.2354	0.2281	0.2372	0.230	0.312	0.310	0.298	0.294
ν_{23}	0.3532	0.3307	0.4910	0.491	0.410	0.399	0.414	0.403
$G_{12} = G_{13}$, GPa	6.407	7.801	5.283	6.165	5.774	6.863	5.313	6.197
G_{23} , GPa	6.500	8.016	3.149	3.408	4.328	4.892	3.353	3.651

Table 7
Geometric properties of woven composites.

		GF-I	GF-II	T300	IM7	TZ800H-I	TZ800H-II
Tow volume ratio, %	$V_{T,warp}$	47.1	44.7	49.1	47.8	35.8	55.4
	$V_{T,weft}$	15.0	28.4	31.3	29.3	40.3	22.6
Interlocking angle, °		22	36	42	38	39	29
Fibre volume fraction, $V_{f,total}$		0.468	0.547	0.601	0.577	0.566	0.587

$$v_{f,warp} = \frac{V_{f,warp}}{r_H r_W} \quad (21)$$

The values of the calibrated volume fractions calculated based on Eqs. (18) and (21) become $v_{f,weft} = 0.716$ and $v_{f,warp} = 0.768$ for the weft and the warp tows, respectively. They have been used for the micro-scale characterisation of the fibre tows, along with the properties of the constituents specified in Table 5. The calculated effective properties of the tows that were obtained from such analyses are listed in Table 6.

5.3. Comparison with the experiments

With the model input being fully defined, the unit cell analysis was carried out for all six woven composites. As an initial verification, the geometric properties of the composites were assessed. They comprised the volume ratios of the weft and the warp tows, $V_{T,weft}$ and $V_{T,warp}$, the interlocking angle and the total fibre volume fraction. The tow volume fractions are readily available as an additional output from the automated analysis of unit cells. The interlocking angle is the angle defining the slope of the inclined part of the warp tow, and it is calculated explicitly as part of the formulation of the parameterised model [16].

The total fibre volume fraction, $V_{f,total}$ can easily be recovered of as

$$V_{f,total} = V_{T,weft} v_{f,weft} + V_{T,warp} v_{f,warp} \quad (22)$$

These geometric properties are specified in Table 7. They show that the total fibre volume fractions of all composites are within the practical range of 50–60% except for the GF-I composite, in which it was just under 50%. The interlocking angles and the tow ratios vary from composite to composite over wide ranges, which signifies that their internal structures are sufficiently different. This is highly advantageous as far as validation of the predictive capability of the unit cell model is concerned. Specifically, if the effective properties will be consistently predicted with reasonably good accuracy in each case irrespective of the specific geometry and/or type of the composite, this would serve as an effective validation of the design process proposed.

The predicted effective Young's and in-plane shear moduli of six composites are summarised in Table 8, along with the respective experimental data. The tensile and the in-plane shear tests were conducted following ASTM D3039 [35] and ASTM D7078 [36] standards. Detailed description of the experiments conducted with GF-I, GF-II, T300 and IM7 composites is provided in Ref. [18], and the TZ800H

Table 8
Measured and effective elastic stiffnesses.

Composite	Property, GPa	Experiment	SD	Effective (calculated)	Error, %
GF-I/Gurit Prime™20LV ^a	E_x	15.92	0.55	18.37	15.4
	E_y	24.77	3.12	23.68	4.4
	G_{xy}	4.03	0.14	4.13	2.5
GF-II/Gurit Prime™20LV ^a	E_x	25.67	1.45	24.98	2.7
	E_y	21.83	0.76	20.74	5.0
	G_{xy}	4.06	0.5	4.54	11.8
T300/Gurit Prime™20LV ^a	E_x	55.16	N/A ^b	57.77	4.7
	E_y	48.68	N/A ^b	38.65	20.6
	G_{xy}	3.41	N/A ^b	4.16	23.1
IM7/Gurit Prime™20LV ^a	E_x	62.71	0.43	65.80	4.9
	E_y	35.79	3.43	44.33	23.9
	G_{xy}	3.85	0.42	4.37	13.46
TZ800H-I/ACTECH 1304	E_x	81.80	5.75	90.10	10.2
	E_y	34.06	3.38	40.55	19.1
	G_{xy}	3.61	0.38	3.98	10.2
TZ800H-II/ACTECH 1304	E_x	50.71	5.87	54.38	7.2
	E_y	51.83	2.33	61.12	18.0
	G_{xy}	4.69	0.24	4.26	9.1

^a Experimental data are taken from [18].

^b Due to shortage of material, only one or two tests were carried out at each loading mode.

composites coupon tests are elaborated in Ref. [15].

In general, stiffness predictions for glass fibre composites were found to be more accurate than those for carbon fibre composites, with errors for most properties being below 5%. For carbon fibre composites, the highest accuracy was obtained for the weft Young's moduli, for which errors were generally within 10%. The results for the shear modulus were less accurate, and the largest errors of around 20% were observed for the warp Young's moduli. The only exception was the T300 composite, for which the shear stiffness was predicted with the smaller accuracy than the warp Young's modulus. Another anomaly associated with this composite is that its warp Young's modulus was under-predicted by 20%, as opposed to other carbon fibre composites, for which it was overpredicted. It is worth noting, however, that the experimental results for T300 are likely to be the least representative, because they reflect only one or two measurements. Furthermore, as can be seen in Fig. 4, T300 composite had a pronounced offset in the weave in a sense that columns of the weft tows were not vertical. It is possible that lack of representation of this offset in the unit cell model is also partially responsible for reduced accuracy of predictions.

Lower general accuracy of carbon fibre composite property predictions and large overprediction for weft Young's moduli for carbon fibre composites were two systematic trends. Given that the weave geometry in all cases was defined from the controllable parameters following the same procedure, any deficiencies of the procedure would have affected the results for glass and carbon fibre composites in a similar way, which was not the case. A much more likely potential source of inaccuracy are errors in definition of constituent properties of carbon fibres that have been detailed in the previous subsection. Specifically, there is less room for error in definition of two material properties of isotropic glass fibres, while for transversely isotropic carbon fibres only one independent parameter out of five, the longitudinal Young's modulus, can be considered truly reliable. The remaining four independent parameters are likely to involve some error, which will become absorbed in the values effective properties of the fibre tows as specified in Table 6, and consequently in predictions of the effective properties of woven composites.

In view of the above, the effective longitudinal Young's modulus of the tows should be predicted to the highest accuracy, since it is closely related to the longitudinal modulus of the fibres. When the weft tows are sufficiently thick, as was the case for all but GF-I composite, woven composite would resist loading in the weft direction primarily through the longitudinal tension of straight weft tows. The weft Young's modulus of woven composite would then be strongly influenced by longitudinal modulus of the tows. Given that the latter is supposed to be reasonably accurate, one may expect close agreement in measured and effective weft modulus.

The mechanics of woven composites under other types of loading is much more complex, and one cannot easily associate the remaining effective properties with material properties of constituents. However, it is clear that the material properties other than the longitudinal modulus would have strong effect on the mechanical performance under such loading cases, and any errors in their definition would add to errors in predictions of the respective effective properties.

One may argue that error around 20% in some validation exercises could be considered large, especially when analysing linear elastic behaviour of the material, as is the case in the present paper. The issue with woven composites analysis is that their models involve large number of parameters, both material and geometric, and definition of these parameters is often uncertain, as has been argued throughout the present paper. Because of that, one can easily gain close agreement between the experiments and simulations simply by tweaking some of the parameters to achieve the goal. Such method certainly would not deliver a model of good predictive capability that could be reliably applied to composites of different architectures and constituents. In the present paper, the input for all composites involved have been unified in a sense that the parameters were determined following the same

routines, and no additional assumptions for individual cases have been introduced. Given the unified input definition and the fact that the composites analysed were substantially different in terms of their internal architectures and constituents, the predictive capability of the model was assessed objectively, checking the consistency of predictions and revealing trends in errors. In absence of other systematic validation exercises of this kind, the maximum error around 20% can be viewed as the state-of-the-art in woven composite modelling and can serve as a benchmark if any modifications aiming to improve the accuracy are introduced.

6. Conclusions

The controllable parameters have been introduced as efficient means of determining the geometry of the woven reinforcements in 3D woven composites of layer-to-layer angle interlock architecture. They have been related through simple expressions to the geometric parameters of the weave. This procedure offers an efficient alternative to direct measurement of the latter. Even greater significance of these parameters is that they are conventionally used hence can be easily understood by the weavers, which allows for efficient communication between them and the woven composite designers.

A systematic material characterisation exercise has been devised to demonstrate the practicality of controllable parameters in numerical modelling, and at the same time to assess the predictive capability of such modelling. In all characterisation cases, every aspect of the model input has been critically assessed and every effort has been made to eliminate the assumptions and potential errors in both the geometric parameters and the constituent material properties. For six woven composites considered, the errors between the effective and measured elastic properties were generally within 20%. Given the careful definition of the input parameters for all composites, and lack of systematic comparisons of this kind in the literature, such accuracy represents the state of the art in the subject. Validation employing composites of different architectures and constituents, rather than that based on test data for just one composite, has been shown to be a more informative and reliable method, because it allows to conduct systematic assessment of the errors and identify their potential causes.

It has been demonstrated that the controllable parameters are the final essential component missing from the woven composites design tool. Having established controllable parameters as effective and reliable means of defining the geometry of the weave, design methodology for woven composites can be formulated by replacing the geometric parameter input, as is the dominant approach nowadays, with controllable parameter input. The main contribution of the controllable parameters is that they provide common interface between the woven composites designers and the manufacturers, thus truly streamlining the design process. Having established the design feasibility for the woven composites in the present paper, the authors aim to formulate the design principles for these materials in publications to follow.

CRedit authorship contribution statement

Elena Sitnikova: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Mingming Xu:** Software, Investigation. **Weiyei Kong:** Investigation, Funding acquisition. **Shuguang Li:** Methodology, Supervision, Writing – review & editing, Project administration, Funding acquisition.

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

Data will be made available on request.

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