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Micromechanical modelling for wood–fibre reinforced plastics in which the fibres are neither stiff nor rod-like

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ABSTRACT

Plant fibres distort to curved or kinked shapes during injection moulding, while glass fibres are relatively stiff and remain rod-like. The consequences of these differences were investigated for an example of wood fibre prepared by thermomechanical pulping to reinforce polypropylene in tensile test specimens. Krenchel's orientation factor increased with distance from the gate, reaching values similar to those published for glass-reinforced plastic. Halpin–Tsai and Mori–Tanaka micromechanical models predicted the tensile modulus within ±7% at low strain, despite implicit and incorrect assumptions of rod-like shape. Both models assumed elastic reinforcement with perfect fibre–matrix bonding, and therefore overestimated the tensile stress at higher strains.

1. Introduction

Injection-moulded short-fibre-reinforced plastics (SFRPs) are often used in manufacturing industries when the parent plastics show inadequate stiffness, strength or creep resistance [1]. The word 'short', in this context, refers to fibres that are shorter than a few millimetres in the moulded part [1]. Glass fibres are often used, but plant fibres are increasingly preferred in some applications such as light-weight components for automobiles [2]. Glass fibres retain their rod-like shape in moulded parts [3]. Plant fibres sometimes remain rod-like [4], but are less stiff than glass fibres and usually become distorted to curved or kinked shapes during moulding [5,6]. Deviations from rod-like shape can, in principle, have consequences for the mechanical properties of the SFRP. Three potential problems are considered in this paper:

(1) Curved fibres show a lower degree of flow alignment in moulding [7].
(2) Even if the fibres are well-aligned, fibre curvature can lead to a significant degradation of fibre properties [8].
(3) We hypothesise that the shear forces that cause curvature might also cause imperfections such as kinks, leading to deviations from elastic deformation.

Wood fibre was selected as an example of a reinforcement that shows deviations from rod-like shape when injection-moulded.

Krenchel's fibre orientation factor $\chi_x = \langle \cos^4\theta_x \rangle$ is sometimes used to characterise the degree of flow alignment [9]. Here X is the test axis, θ_x is the angle between the X axis and the longitudinal axis of a fibre, and the angular brackets indicate averaging over all fibres. A value of $\chi_x = 1$ corresponds to perfect alignment, and a value of $\chi_x = 3/8$ is expected for fibre orientations that are random in two dimensions [9], as might be achieved in moulding a thin sheet. If tensile test results are used to predict the mechanical performance of a commercial product, it is important to make allowance for the possibility that the value of χ_x in the product will be different from that in the test specimen.

A review of experimental values of χ_x for injection-moulded tensile test specimens (Table 1) indicates values in the range of 0.31–0.78 for SFRPs with plant fibre reinforcement [4–6], compared with values in the range 0.60–0.77 for SFRPs with glass fibre reinforcement [3,10–12]. While it might be premature to reach conclusions from such a small collection of published studies, it seems possible that some plant fibres do not become as well aligned as glass fibres.

In other published studies of SFRPs, the value of χ_x was regarded as an adjustable parameter. Those studies were excluded from Table 1, because they assumed the validity of micromechanical models and therefore cannot be used to test the validity of those models.

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Table 1
Orientation factors χ_x published for injection-moulded SFRPs in which the plastic was polypropylene and the mold shape was a dog bone or cylinder.

Fibre type	Fibre content (wt%)	Matrix[a]	χ_x	Reference
In "dog bones"[b]				
Glass	30	PA	0.44–0.58	[10]
Glass	30	PA	0.61	[11]
Glass	40	PA	0.60	[11]
Glass	30	PP	0.42–0.62	[12]
Abaca	40	PP	0.38	[4]
Deinked newspaper	40	PP	0.32	[6]
Mechanical pulp	40	PP	0.31	[6]
Jute	40	PP	0.31	[6]
In cylinders[c]				
Glass	20	PP	0.77	[3]
Bagasse	26	PP	0.78	[5]
Kenaf	24	PP	0.70	[5]

[a] PA = polyamide-6,6 and PP = polypropylene.
[b] "Dog bone" shapes made according to ASTM D638 or NFT 51-034.
[c] Cylinders of diameters 5–6 mm.

Even if the fibres are well-aligned, a second problem is potentially associated with deviations from rod-like shape. Several different micromechanical models have linked the mechanical properties of SRFP composites to the lengths of the reinforcing fibres, but the 20th Century models all used the same basic assumptions that the fibres were axi-symmetric and identical in shape and size [13]. When carbon nanotubes were developed as reinforcement for plastics, the mechanical performance of the products did not meet expectations. Electron microscopy showed that the nanotubes were curved or wavy [14], and the deviations from rod-like shape were considered as one of the factors affecting mechanical performance. Micromechanical modelling showed that fibre curvature can likewise affect the properties of SFRPs [8], but concluded that the curvature of a typical glass fibre was so small that any deviations from rod-like reinforcement could be ignored.

2. Materials and methods

2.1. Composite preparation

Thermomechanical pulp was produced at Scion, New Zealand, from *Pinus radiata* wood chips. The pulped fibre (95% w/w) was combined with binding agents (5%) and formed into pellets using a method described in a patent application [15]. The pellets (20% w/w), polypropylene (Seetec M1600, 77% w/w), and maleic anhydride-grafted polypropylene compatibiliser (Eastman G3015, 3% w/w) were oven-dried and combined by extrusion compounding using a co-rotating twin screw LABtech™ vented extruder (LTE 26-40). The temperature of the melt was kept below 200 °C. The weight fraction of fibre was converted to a volume fraction of 0.138 using a composite density of 980 kg/m^3, a matrix density of 910 kg/m^3, and assuming negligible void volume.

The extrusion-compounded pellets were injection moulded using a BOY 35 M moulding machine and a mold in the shape of an ISO 527-2 type 1A tensile specimen [16], 3.9 mm thick, 20.0 mm wide and 170 mm long, with a gate at one end (Fig. 1).

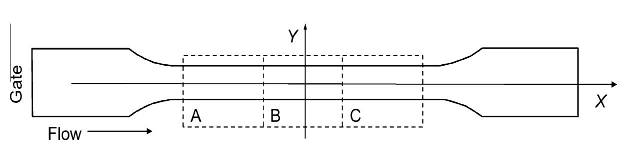

Fig. 1. Definition of coordinates for a tensile test specimen. Boxes indicate the three test positions. The *Z* axis is oriented out of the paper.

Specimens of unreinforced polypropylene were likewise moulded for comparison.

Extrusion blending and injection moulding breaks fibres [17], so the mean fibre length was measured for fibres removed from the polymer matrix by Soxhlet extraction for 4 h using xylene as the solvent. Lengths were measured using a Andritz-Sprout-Bauer Fiberscan, i.e., a capillary flow device with resolution of 28 μm. The number-weighted mean length was 0.44 mm, with a standard deviation of 0.32 mm. The length-weighted mean length was 0.67 mm. For comparison, the length-weighted mean length of fibres in a similar thermomechanical pulp, measured before extrusion blending, was 2.5 mm. The length-weighted mean was considered more appropriate than the number-weighted mean, since weighting reflects the relatively large volume occupied by relatively long fibres, and therefore their relatively large contribution to reinforcement of the composite.

2.2. Mechanical testing

Tensile properties were measured using an Instron 5566 machine according to ISO 527-2 [16], except that the gauge length was decreased to 25 mm so that it was possible to measure the elastic modulus at three positions along the narrow portion of the specimen (Fig. 1). An extensometer (Instron 2630-100) was used to measure strain across the gauge length. The test speed was 1 mm/min, 10 specimens were tested for each position, and the elastic modulus was determined as the slope of the stress–strain curve between strains of 0.0005 and 0.0025.

2.3. Microscopy

Surfaces were prepared by grinding using a Presi Mecapol P320 grinding unit and abrasive papers ranging from 320 grit for initial grinding, to 4000 grit for polishing. The final polishing was performed using a fabric pad. The polishing was performed dry, without any lubricant and was intermittent to avoid heat generation. The exposed surface was stained with 0.5% aqueous methylene blue for 45 min, rinsed in water and allowed to air dry. Surfaces were polished again, using the fabric pad, to remove irregularities on the surface attributed to fibre swelling. Three separate specimens were used in imaging, i.e., one specimen was cut in the *XY* plane, one in the *XZ* plane and one in the *YZ* plane, using *X*, *Y* and *Z* axes defined in Fig. 1. The *XY* surface was displaced 0.3 mm above the origin, the *XZ* section was displaced 2.0 mm from the origin, and the *YZ* section passed through the origin. No sections were duplicated, so it was not possible to calculate the mean values and standard deviations of orientation factors.

An overlapping grid of images was acquired using a Leica MZ12 stereomicroscope fitted with a Leica EC3 digital camera. The field of view was approximately 3 × 4 mm. A typical image is shown in Fig. 2a. The illumination background was subtracted, and the individual images were stitched using a pairwise technique [18], to produce an 8-bit greyscale image at 8 μm/pixel. Local contrast was enhanced using the CLAHE plugin (ImageJ) [19], with a block size of 25 pixels, 127 bins and a slope of 2, and the images were binarised using a default threshold. The area *A*, Feret's length *f* and Feret's angle ϕ were calculated from the binarised images, using ImageJ V1.47c [20]. Feret's length is defined as the distance between two parallel lines that restrict a two-dimensional shape, and Feret's angle as the angle between a specified axis and a line perpendicular to the parallel lines. In the present context, the value of ϕ was chosen to maximise the value of *f*. Fig. 2b illustrates measurement of *f* and ϕ for a typical fibre section in a binarised image.

Some of the shapes in Fig. 2b were too small to be attributed to intact wood fibres, and were attributed instead to fragments of cell walls. Thermomechanical pulp fibres obtained from pine wood