# 1
# Composite forming mechanisms and materials characterisation

A C LONG and M J CLIFFORD, University of Nottingham, UK

## 1.1 Introduction

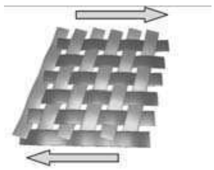
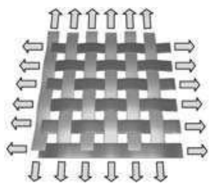
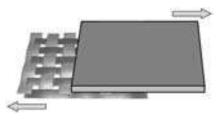
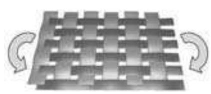
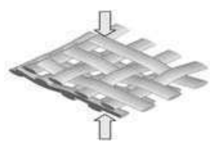
This chapter describes the primary deformation mechanisms that occur during composites forming. Experimental procedures to measure material behaviour are described, and typical material behaviour is discussed. The scope of this description is reasonably broad, and is relevant to a variety of manufacturing processes. While other materials will be mentioned, the focus here is on forming materials based on continuous, aligned reinforcing fibres. Specifically, materials of interest here include:

- Dry fabrics, formed to produce preforms for liquid composite moulding.
- Prepregs, comprising aligned fibres (unidirectional or interlaced as a textile) within a polymeric (thermoset or thermoplastic) matrix.

While other materials are also formed during composites processing, the above have received by far the most attention amongst the research community. The techniques described here can also be applied to polymer/polymer composites, although these materials present a number of challenges (see Chapter 9). Moulding compounds such as glass-mat thermoplastics (GMTs) and thermoset sheet moulding compounds (SMCs) are formed by a compression (flow) moulding process; here formability is usually characterised by rheometry (see Chapter 6).

Focusing on continuous, aligned fibre materials, a number of deformation mechanisms during forming can be identified (Table 1.1). The remainder of this chapter will focus on methods for characterising materials behaviour. Materials testing typically has a number of objectives. Often the primary motivation is simply to understand materials behaviour during forming, and in particular to rank materials in terms of formability. If this can be related to the material structure, then this understanding may facilitate design of new materials or optimisation of manufacturing process conditions. Another aim may be to obtain materials data for forming simulation. For the most advanced codes, this may

*Table 1.1* Deformation mechanisms for continuous, aligned fibre based materials during forming

| Mechanism | Schematic | Characteristics |
|---|---|---|
| Intra-ply shear |  | • Rotation of between parallel tows and at tow crossovers, followed by inter-tow compaction<br>• Rate and temperature dependent for prepreg<br>• Key deformation mode (along with bending) for biaxial reinforcements to form 3D shapes |
| Intra-ply tensile loading |  | • Extension parallel to tow direction(s)<br>• For woven materials initial stiffness low until tows straighten; biaxial response governed by level of crimp and tow compressibility<br>• Accounts for relatively small strains but represents primary source for energy dissipation during forming |
| Ply/tool or ply/ply shear |  | • Relative movement between individual layers and tools<br>• Not generally possible to define single friction coefficient; behaviour is pressure and (for prepreg) rate and temperature dependent |
| Ply bending |  | • Bending of individual layers<br>• Stiffness significantly lower than in-plane stiffness as fibres within tows can slide relative to each other; rate and temperature dependent for prepreg<br>• Only mode required for forming of single curvature and critical requirement for double curvature |
| Compaction/ consolidation |  | • Thickness reduction resulting in increase in fibre volume fraction and (for prepreg) void reduction<br>• For prepreg behaviour is rate and temperature dependent. |

require a full mechanical characterisation of the material under axial, shear and bending loads. The use of such data is described in detail in Chapter 3.

In almost all cases, test methods are non-standardised and have been developed by designers or researchers with a particular material and process in mind. This means that test methods, specimen dimensions, data treatment and presentation differ between practitioners. Here we will give a description of what we believe to be 'best practice', although this is clearly a subjective assessment. Benchmarking and comparison of results between laboratories is being addressed within an international exercise; this is discussed in detail in Chapter 13.

## 1.2 Intra-ply shear

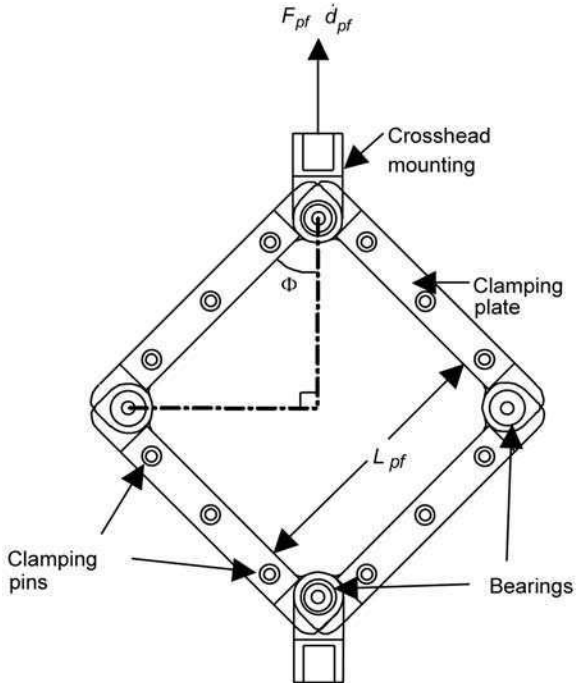
This mechanism occurs when the material is subjected to in-plane shear. This essentially corresponds to relative sliding of parallel tows within a fabric layer or composite ply, and (for textile-based materials) rotation of tows at their crossovers. Intra-ply shear is usually considered to be the primary deformation mechanism for aligned fibre-based materials. Coupled with low bending resistance, the ability of materials to shear in this way allows them to be formed to three dimensional shapes without forming folds or wrinkles. A good analogy here is to compare a woven fabric to a sheet of paper. Both may have a similar bending stiffness, but unlike paper the ability of the fabric to shear allows it to be formed over shapes with double curvature.

Various experimental methods exist to characterise the shear resistance of dry textiles and aligned or woven composite materials. Early developments here were for apparel fabrics; of particular relevance is the 'Kawabata Evaluation System for Fabrics (KES-F)', a series of test methods and associated testing equipment for textile mechanical behaviour including tensile, shear, bending, compression and friction.[1] However whilst this system has been used widely for clothing textiles, its application to reinforcement fabrics has been limited.[2] This is probably due to the fact that KES-F provides single point data at relatively low levels of deformation, coupled with the limited availability of the (expensive) testing equipment.

Amongst the composites forming community, two widely used test methods are the *picture frame test*[3–9] and the *bias extension test*.[8–12] In this section we present a guide to the use of these test methods and how to make good use of the output data.

### 1.2.1 Picture frame test

The picture frame (or rhombus) test can be used to measure the force generated by shearing technical textiles and textile composites, including thermoplastic and thermoset based materials. Cross-shaped test samples can be cut or stamped




*1.1* Schematic of picture frame shear rig. $L_{pf}$ is the side length measured between the centres of the bearings, $F_{pf}$ is the axial force measured by the load cell, $\dot{d}_{pf}$ is the rate of crosshead displacement and $\Phi$ is the frame angle.

from rolls or sheets of material using a template. Great care should be taken to ensure that the fibres are perfectly aligned with the edges of the template. Test samples are held in a purpose-built square frame, hinged at each corner (see Fig. 1.1). The frame is loaded into a tensile test machine, and two diagonally opposite corners are extended, imparting pure and uniform shear in the test specimen on a macroscopic scale. There is no uniformly applied standard test procedure. Depending on the material to be tested, various methods can be used to restrain test specimens. For dry fabric, impaling samples on a number of pins may improve repeatability. This approach avoids imparting tensile strain in the fibres and reduces bending of tows.[9] Other materials, such as thermoplastic composites, may need to be tightly clamped to prevent fibres from slipping.[7]

During the test, the axial force required to deform the sample is recorded. Since many impregnated composite materials are based on polymers with viscosities that depend on shear rate, it may be useful to perform tests at different cross-head displacement rates. It is important to observe the surface of the test samples during the test, as misaligned or poorly clamped samples can wrinkle almost from the start. These results should be discarded. It is usual for samples to wrinkle towards the end of the test (between 50º and 70º of shear deformation) and by careful observation the test can be used to estimate the 'locking angle' of a material. For successful tests, shear force can be calculated from the cross-head force using:

$$F_s = \frac{F_{pf}}{2\cos\Phi} \qquad 1.1$$

where $\Phi$ is the frame angle and $F_{pf}$ is the measured axial picture frame force. Test data can be normalised by dividing the shear force by the length of the picture frame, $L_{pf}$. Graphs of shear force against shear angle can be produced, where the shear angle is defined as:

$$\theta = \pi/2 - 2\Phi \qquad 1.2$$

The shear angle can be calculated from the cross-head displacement, $d_{pf}$, by

$$\theta = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} + \frac{d_{pf}}{2L_{pf}}\right] \qquad 1.3$$

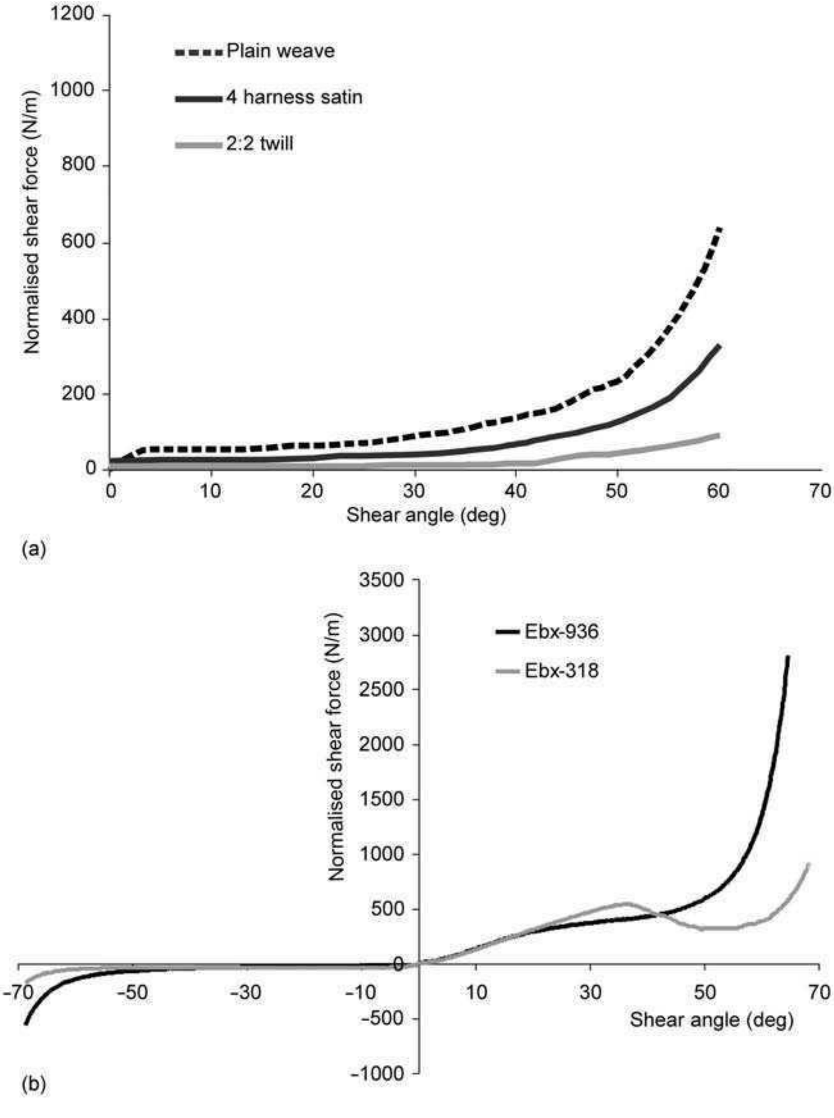
The picture frame test procedure is relatively simple to perform and results should be reasonably repeatable if sufficient care is taken in cutting test samples and the correct clamping technique is used. The major benefit of the test is that shear angle and angular shear rate can be easily calculated from the cross-head displacement and displacement rate.

Typical results from picture frame experiments conducted on a range of textile reinforcements and prepregs are shown in Figs 1.2 and 1.3. For clarity these graphs represent single experiments, although it should be noted that even well controlled experiments exhibit scatter of up to ±20% in shear force for a particular angle. Most materials exhibit some similarities in terms of their shear force curve. Initially the shear resistance is low – for dry fabrics this represents dry friction at tow crossovers, whilst for prepreg this corresponds to lubricated friction or viscous shear of polymer between fibres or yarns. Towards the end of the test the resistance increases significantly – this happens once adjacent yarns come into contact, representing yarn compaction (fabrics) or squeeze flow (prepreg). If the test were continued, the curve would tend towards an asymptote corresponding to maximum possible deformation. Non-crimp fabrics (Fig. 1.2b) exhibit more complex behaviour, as the shear resistance depends on the direction of shear. These materials consist of perpendicular layers of tows held together by a stitching thread. This thread restricts the movement of the tows, so that materials exhibit higher resistance to shear when they are sheared parallel to the stitch.

Based on the data given in Figs 1.2 and 1.3, at the simplest level the curve may be approximated using a bi-linear model:

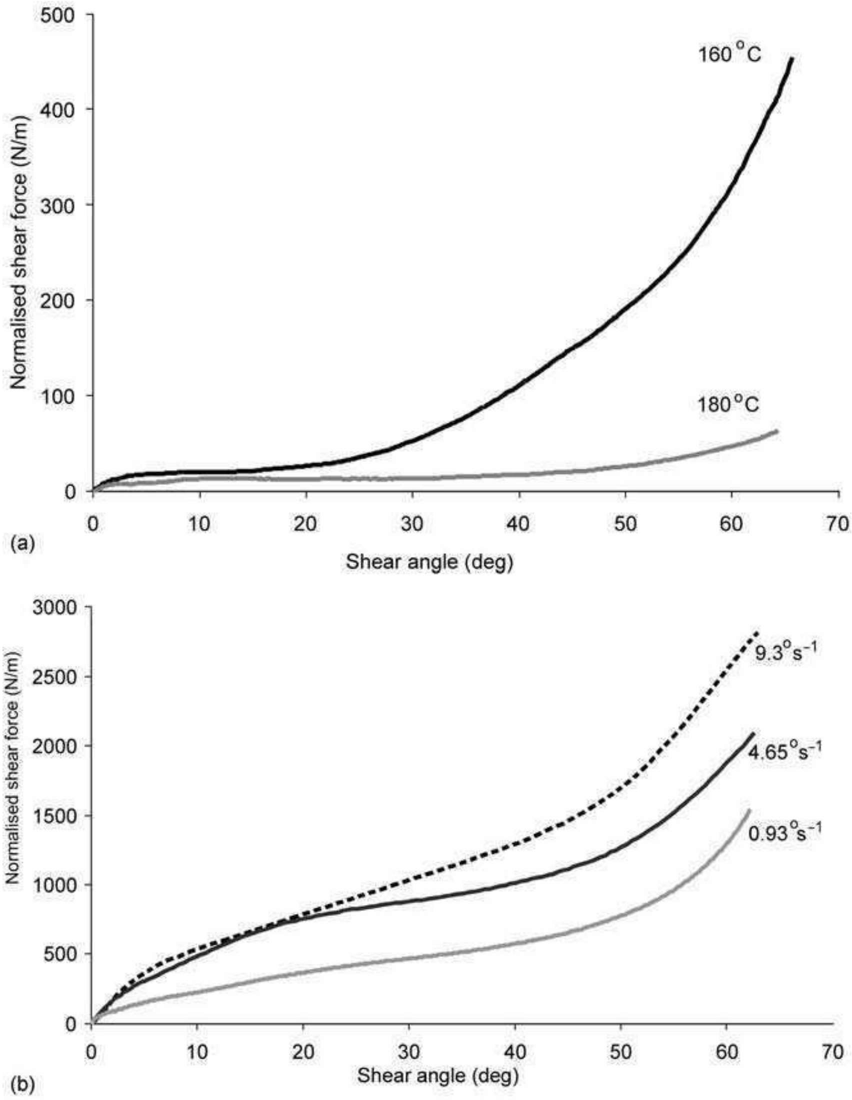
$$\begin{aligned} F_s/L_{pf} &= E_0 \tan\theta && (\theta < \theta_0) \\ F_s/L_{pf} &= E_0 \tan\theta_0 + E_\infty \tan(\theta - \theta_0) && (\theta \geq \theta_0) \end{aligned} \qquad 1.4$$

Clearly the material response (and hence the constants $\theta_0$, $E_0$ and $E_\infty$ in equation 1.4) depends on material type and (for prepreg) experimental conditions such as




*1.2* Picture frame shear data for dry glass fabric reinforcements. (a) Three woven fabrics with superficial density 800 g/m$^2$. (b) Non-crimp fabrics retained with tricot (Ebx-936) and chain (Ebx-318) stitch oriented at 45º to the tows in each case. Negative shear angle represents deformation perpendicular to the stitch.

rate and temperature. However, as a rough guide, $\theta_0$ is likely to be around 40º for dry fabrics and <30º for prepreg, and is indicative of the point at which the material starts to lock as adjacent tows come into contact. The ratio $E_0/E_\infty$ is of the order 3–4 for woven fabrics and closer to unity for prepreg. The most



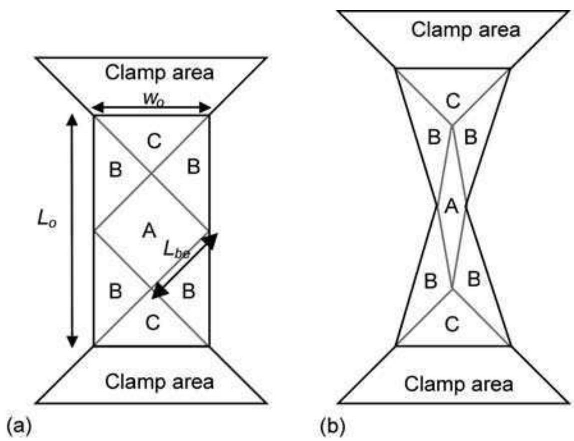

*1.3* Picture frame shear data for pre-impregnated composites. (a) 2:2 twill weave glass/polypropylene thermoplastic composite at two temperatures. (b) 5 harness satin weave carbon/epoxy prepreg at various angular shear rates (room temperature).

rigorous approach to intra-ply shear characterisation would require every material to be characterised under all possible forming conditions. As this is clearly not a practical proposition, researchers have attempted to develop models to predict materials formability from textile structure[13] and matrix rheology.[14] This approach is discussed further in Chapter 4.

### 1.2.2 Bias extension test

The bias extension test involves clamping a rectangular piece of bidirectional material such that the tows are orientated initially at ±45° to the direction of the applied tensile force. The material sample can be characterised by the aspect ratio, $\lambda = L_o/w_o$, where the sample width $w_0$ is usually greater than 100mm. Figure 1.4 shows an idealised bias extension test sample with $\lambda = 2$. The sample is divided into a number of regions which deform at different rates as the test proceeds. Generally it can be shown that the shear angle in region *A* is always twice that in regions denoted *B*, while region *C* remains un-deformed. The deformation in region *A* is the same as the deformation produced by the picture frame test, as long as intra-ply shear is the only mechanism; in practice the angle will be somewhat lower than in an equivalent picture frame sample as intra-ply slip will occur (i.e. tow spacing will increase) particularly as the material approaches locking. The sample aspect ratio must be at least two for the three different deformation regions to exist. Increasing the length/width ratio, $\lambda$, to higher values serves to increase the area of region *A*.

Bias extension tests are simple to perform and can provide reasonably repeatable results. Axial force and cross-head displacement are recorded during a test. The test provides a useful method to estimate the locking angle of a material; once the material in region *A* reaches the locking angle, it usually ceases to shear. As with the picture frame test, different clamping conditions have been suggested by various researchers, but the boundary conditions tend to affect the data much less than for picture frame tests. The method may be preferred for gaining shear data at elevated temperatures for thermoplastic composites, since the influence of relatively cool material adjacent to the metal clamps during high temperature testing is of less importance than in picture frame tests.




*1.4* Idealised bias extension test sample with $\lambda = L_0/w_0 = 2$, where $L_0$ and $w_0$ are respectively the initial length and width of the specimen.

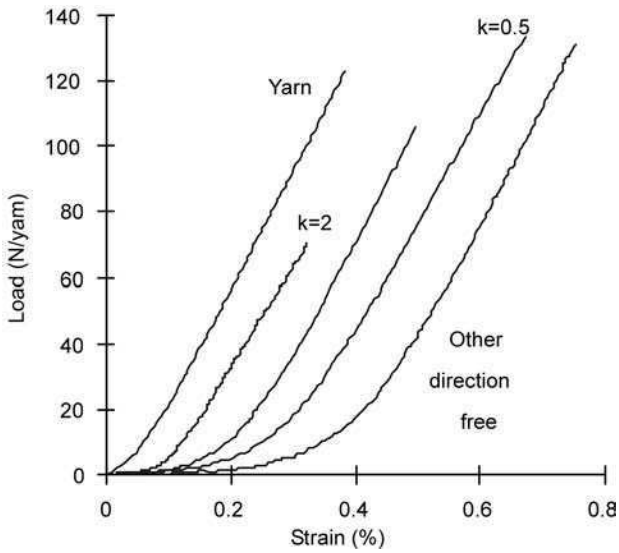
Producing graphs of shear force against shear angle can be achieved by following the same data analysis procedure as for picture frame test data, considering region *A* to be equivalent to a picture frame specimen with side length $L_{be}$ (see Fig. 1.4). However, for increased accuracy, it may be necessary to measure the shear deformation rather than rely on the material following idealised deformation kinematics. This can be achieved by visual analysis, which can prove time consuming without an automated image acquisition and analysis approach.

Forces from bias extension tests can be normalised by dividing by a characteristic dimension, such as sample width. However, this does not allow data from samples with different aspect ratios to be compared directly. Recent work by Harrison[9] considered the energy dissipated within regions *A*, *B* and *C* to develop a more sophisticated normalisation technique for bias extension test data. In addition to allowing results from different aspect ratio samples to be compared, this also allows picture frame and bias extension test data to be correlated directly. Whilst this might allow mechanical data to be extracted in terms of shear force versus shear strain in a form suitable for simulation software, the data analysis procedure is extremely complex and hence at present the picture frame test is preferred for this purpose.

## 1.3 Axial loading

Loading of aligned fibre based materials along the fibre axis or axes typically results in very large forces and very low maximum strains in comparison to intra-ply shear. This might suggest that deformation under axial loading is of secondary importance, and indeed this is reflected in the relatively limited attention received by this topic. Boisse[15] has long argued that this behaviour cannot be neglected, since the high magnitude of the axial stiffness indicates that tensile loading of the fibres accounts for the majority of energy dissipated during forming.

Axial loading of textiles and composites can be conducted using standard tensile testing equipment, although as for the bias extension test (Section 1.2.2) wide samples are usually used. Unidirectional fibre materials will typically exhibit a linear force-displacement response when loaded parallel to the fibre axis. This is not the case for textile based materials, which exhibit an initial, non-linear stiffening due to crimp in the tows. As the fibres become aligned with the direction of loading, the response becomes linear and is determined by the fibre modulus and volume fraction. The importance of this 'de-crimping' depends on the properties of the transverse tows, and in particular their resistance to bending and compaction. If the transverse tows are also loaded, then the de-crimping zone will decrease in magnitude. Boisse[16] has analysed a wide range of fabrics using a specially designed biaxial loading frame. Some typical results are given in Fig. 1.5 for a plain weave fabric. When loaded




*1.5* Results of biaxial tensile tests for a balanced glass plain weave fabric.[17] The load is measured along one tow direction, with the constant *k* determining the ratio between strains in the loading and transverse directions.

uniaxially (denoted 'other direction free'), the non-linear force region extends to a strain of approximately 0.5%, but the force to completely straighten the tows is low. As the ratio between strains in the tested (warp) and transverse (weft) directions increases, the force curve tends towards the behaviour of an individual tow (yarn). The testing procedure and relevance of this behaviour to composite forming simulation are described in detail in Chapter 3.

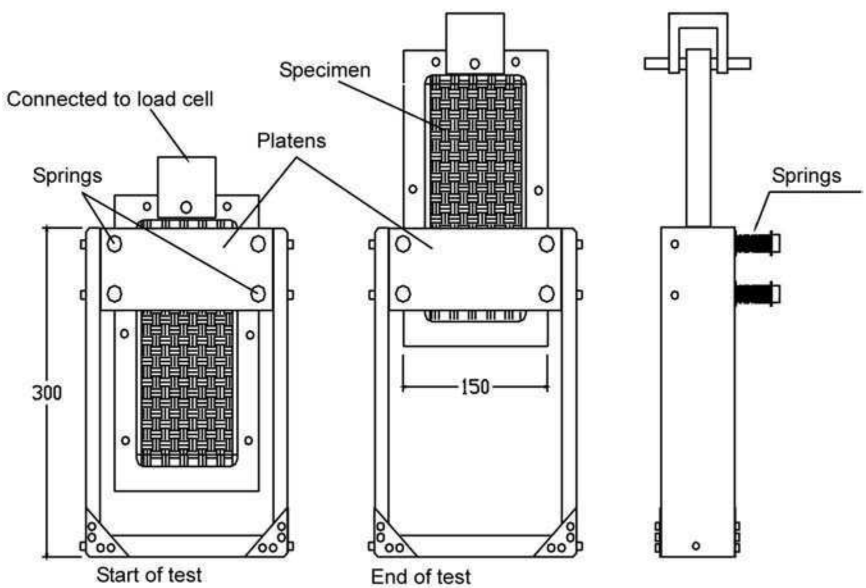
## 1.4 Ply/tool and ply/ply friction

During an automated forming operation, friction between the material and forming tools governs the transfer of loads to the material. In multi-layer forming processes, friction between individual layers of material is also of importance. For example, when forming layers of prepreg at different orientations to each other, compressive forces generated by intra-ply shear in one layer may be transferred into adjacent layers, causing compression along the fibre direction and hence wrinkling of the form. Hence to model forming processes accurately, measurement of friction at ply/tool and ply/ply interfaces is important.

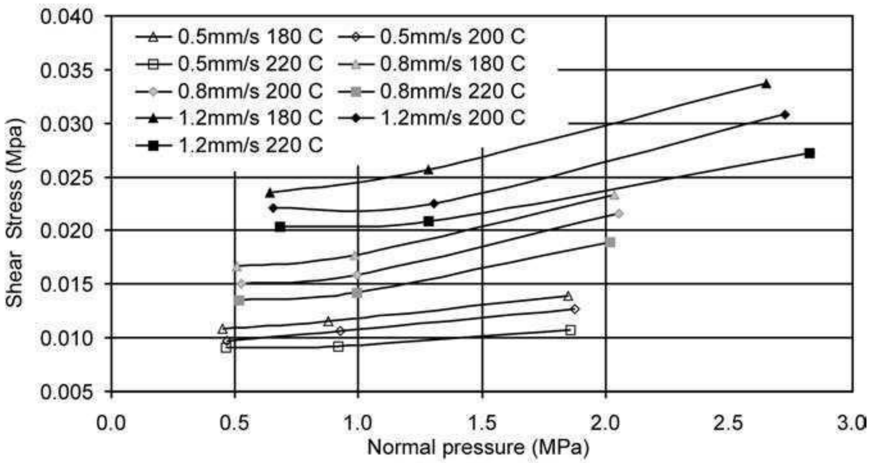
A number of test methods are possible for measurement of friction. The simplest approach is the so-called 'inclined plane method'. Here a block of tooling material is placed on a piece of fabric/prepreg mounted on a rigid plate. The plate is then inclined until the block starts to move, with the tangent of the angle of inclination defining the friction coefficient. More sophisticated variations on this approach exist, for example pulling the block along the surface of fabric/prepreg and measuring the force required to maintain a constant velocity. However, these techniques are best suited to materials that exhibit a constant coefficient of friction. Unfortunately this does not tend to be the case for fabrics or prepregs.

Several alternatives to the above have been developed to allow variables such as normal pressure, testing rate and temperature to be varied. Ply pull out tests have been used to measure ply/ply friction.[18] Data from such tests are discussed in Chapter 10. Murtagh[19] developed a device whereby a layer of thermoplastic prepreg or tooling material was sandwiched between two prepreg layers, held together with a controlled normal pressure. The whole apparatus was heated to evaluate the effect of temperature on behaviour, and the tooling material was withdrawn at various rates with the required force measured using a load cell. Wilks[20] designed apparatus based on a similar principle to Murtagh, although here a layer of fabric/prepreg was sandwiched between two layers of tooling material (Fig. 1.6). For friction between dry fabric and tooling materials, some dependence on normal pressure is observed, with friction reducing marginally with increasing pressure as the fabric surface was flattened against the tool. Friction coefficients of between 0.2 and 0.4 have been measured between glass fabrics and tooling materials.

Typical results are shown in Fig. 1.7 for friction between a glass/polypropylene thermoplastic composite and a steel tool. Shear stress increases




*1.6* Schematic of ply/tool friction measurement apparatus.




*1.7* Shear stress at the interface between steel tools and glass/polypropylene under applied normal pressure.[20] Results are for velocities of 0.5, 0.8 and 1.2 mm/s at 180°C, 200°C and 220°C.

with normal pressure, although the relationship is not linear. At a given normal pressure, the shear stress increases with increasing rate and with decreasing temperature.

Along with other published studies, the results in Fig. 1.7 suggest that for prepreg, the friction coefficient (ply/tool and ply/ply) should be defined as a function of rate, temperature and pressure. Wilks[20] suggested a phenomenological model for shear stress at the interface of the form:

$$\tau = \eta\dot{\gamma} + \mu P \qquad 1.5$$

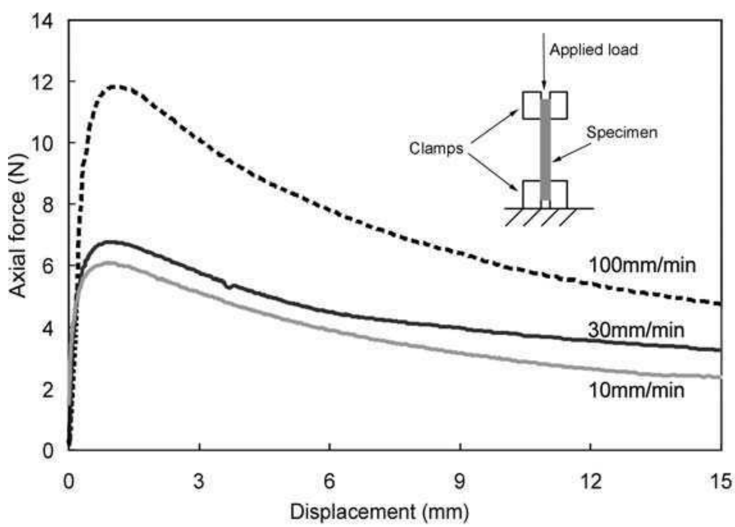
where the first term represents shearing of a polymer film at the prepreg surface (with viscosity $\eta$ and shear strain rate $\dot{\gamma}$) and the second term representing Coulomb friction caused by fibre reinforcement penetrating the polymer film (with friction coefficient $\mu$ and normal pressure $P$). In practice the values of $\mu$ and the polymer film thickness used to define $\dot{\gamma}$ must be determined empirically.

## 1.5 Ply bending

The ability of fabric or prepreg to bend out of plane is of course critical for forming of curved components. It is perhaps surprising then that this topic has received relatively little attention, at least for fabric reinforcements and composites. One reason may be that the bending resistance is usually orders of magnitude lower than intra-ply shear resistance, which in turn is significantly lower than tensile stiffness in the fibre direction(s). However, in terms of modelling, this in fact presents a problem as traditional shell element formulations will have a bending stiffness related to the in-plane stiffness of the material. Hence it is necessary to understand the relative magnitude of bending stiffness so that the forces associated with out of plane bending can be scaled appropriately.

Bending stiffness has long been measured for apparel fabrics.[1,21] A standardised test can be performed for bending resistance of fabric under its own weight.[22] This involves sliding a strip of fabric off the edge of a platform until the self-weight causes it to bend to a specified angle (41.5º is specified in the standard). The length of strip necessary to reach this threshold value is recorded, from which the bending rigidity is approximated. Results for woven apparel fabrics indicate that the bending rigidity in the fibre directions is significantly higher than in the bias (±45º) direction. Young *et al.*[23] have applied this technique to calibrate a finite element model for composite bending. The procedure involved simulating the experiment and adjusting a bending scale factor so that the predicted bending behaviour matched experimental observations.

More informative techniques measure the mechanical resistance to bending using, for example, cantilever, three-point bending or axial buckling experiments, and such tests have been applied recently to prepreg. For example Martin *et al.*[24] measured the three-point bending behaviour of unidirectional glass/polypropylene composites using a V-shaped punch. At elevated temperature this resulted in an increase in bending force with increasing displacement rate. All tests exhibited an initial increase up to a peak value, after which the force plateaued or reduced gradually. One issue with this approach is that the material has to be supported during bending to stop it from deforming under its own weight. To avoid this problem a simple buckling test can be used.[25] Wang *et*




*1.8* Bending/buckling behaviour of unidirectional carbon/epoxy thermoset prepreg under axial compressive loading at different rates.

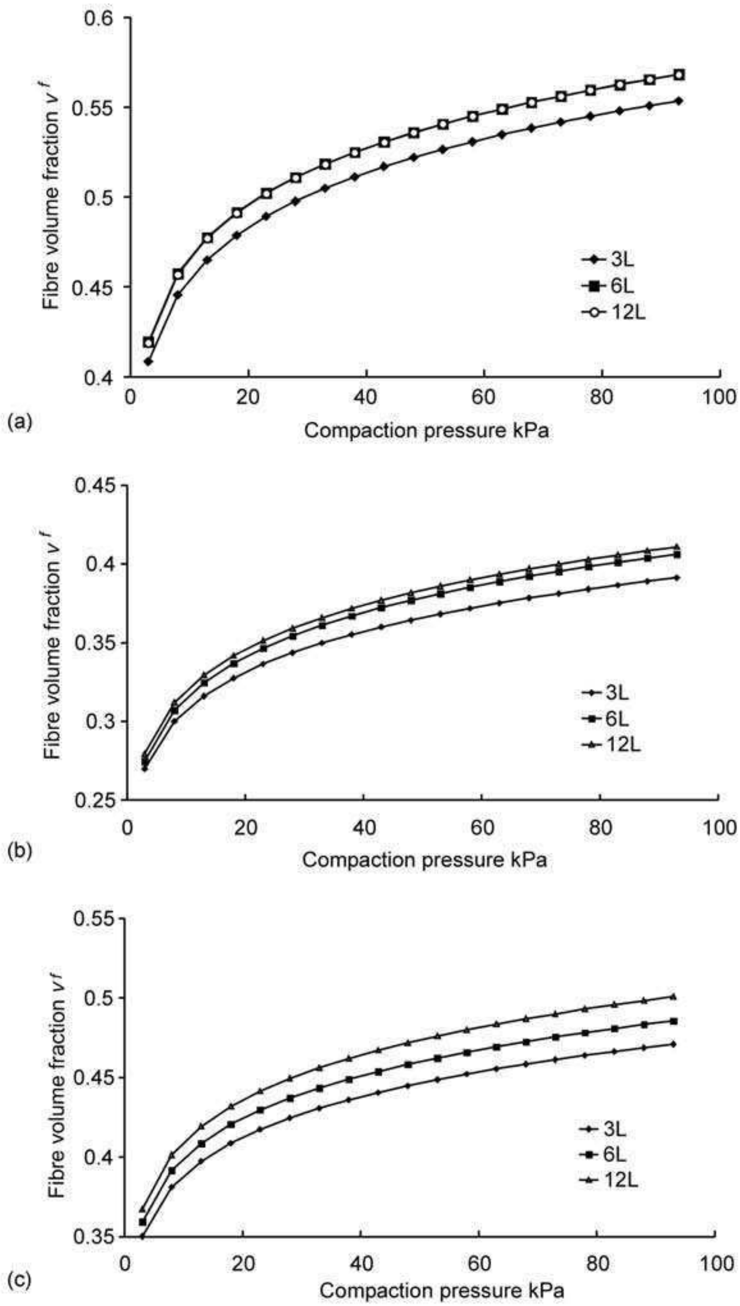
*al.*[26] have applied this technique to thermoset prepreg, including unidirectional and woven carbon/epoxy composites. Typical data are included in Fig. 1.8 for unidirectional prepreg, illustrating the effect of rate on bending/buckling behaviour. The force response increases linearly with increasing rate, suggesting that the phenomenon is dominated by flow of the polymer between fibre layers. The curve shape illustrates a peak load corresponding to buckling, followed by a reduction in force as displacement is increased. Similar tests for woven fabrics show an initial peak followed by a small reduction and then a plateau in the force, illustrating that the fibre architecture has a clear effect on the bending behaviour. Both material response curves fall within the range observed for dry textiles,[25] although for such materials no clear rate effect is observed.

## 1.6 Compaction/consolidation

At the end of forming, the material must be compacted or consolidated to increase the fibre volume fraction and (for prepreg) eliminate voids. An understanding of compressibility, typically in terms of compaction pressure versus thickness or fibre volume fraction, allows the required pressure to be determined for the target fibre content. For multi-layer, multi-material reinforcement preforms, the compressibility of each material type is likely to be different, so that each layer attains a different fibre volume fraction under the imposed compaction pressure (or at the desired laminate thickness). Compaction has received a great deal of attention, particularly for dry fibre mats and fabrics. Robitaille[27] has published an extensive review of both experimental methods and modelling approaches for reinforcement compaction, whilst Garcia[28] has reviewed similar techniques for thermoplastic and thermoset prepreg. Testing procedures appear relatively simple, with material compacted between two parallel platens within a universal testing machine. The platens are moved together usually at constant rate to either a pre-determined load or thickness. At this point either the thickness or force can be held constant to measure relaxation or compaction creep. Care must be taken to ensure that the platens are as flat and as parallel as possible, and their relative displacement must be measured carefully – best practice here is to attach an LVDT (linear variable displacement transducer) between the platens.

### 1.6.1 Compaction behaviour of reinforcements

A great deal of experimental data exists for fabric reinforcements, and it is beyond the scope of this chapter to provide a comprehensive review. Large data sets have published by Robitaille[27] and Correia,[29] and these form the basis for the present discussion. Typical data are included in Fig. 1.9. The graph shows the evolution of average fibre volume fraction ($V_f$) as a function of compaction pressure ($P$) for multiple layer stacks of a range of materials. All results show




*1.9* Typical dry glass fabric compaction behaviour at low pressures (up to 1 bar) for 3, 6 and 12 material layers: (a) triaxial non-crimp, (b) unidirectional non-crimp, (c) plain weave.

that fibre volume fraction initially builds up rapidly with pressure, tending towards a plateau defining the maximum practical fibre content. Each graph shows that for low pressure compaction (as illustrated here), increasing the number of layers within the stack can ease compaction (i.e. lower pressure to attain the required fibre volume fraction). This applies particularly to woven fabrics (e.g. Fig. 1.9c) and may be explained by nesting between the layers.

Other effects observed experimentally include:

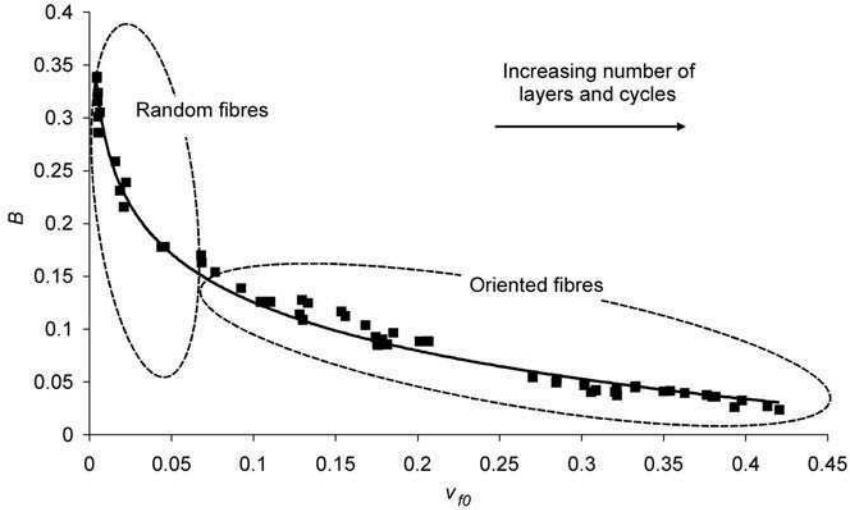
- Number of compaction cycles – if the platens are moved apart, the unloading curve does not superimpose on the loading curve and the unloaded material will generally have a higher fibre volume fraction than before compaction due to unrecovered compaction within the tows. Subsequent loading cycles will each attain a higher fibre volume fraction for the same applied pressure, converging on a maximum value after a number of cycles. This is relevant for example in liquid composite moulding, where two compaction cycles may be applied – firstly during preform manufacture and again on mould tool closure.
- Saturation – at low rates (where fluid flow effects are negligible), the compaction curve is usually shifted to the right if the material is lubricated, i.e. the material is more compressible, so that lower pressures are required to achieve a given fibre volume fraction. This is relevant in vacuum infusion (a.k.a. VARTM), where the material is compacted under atmospheric pressure as the resin front advances, with the reinforcement behind the flow front lubricated.

Several authors have presented models for compaction behaviour of fabric reinforcements. These fall into two groups: phenomenological models based on solid mechanics principles, and empirical models to provide a simple representation of the data. Phenomenological models are based typically on representation of reinforcement fibres as a series of beams contacting at a finite number of points along their length. The number of contacts typically increases during compaction, so that the bridging fibre sections gradually stiffen. For example, Cai and Gutowski[30] have proposed a series of models, providing valuable insight into compaction behaviour. However, the models are not strictly predictive, as whilst they consist of physically meaningful parameters, the values of these must be adjusted to fit to experimental data.

For convenience simple empirical models may be preferred. Power law relationships have been proposed by several authors, for example:

$$V_f = V_{f0} \cdot P^B \qquad 1.6$$

Here $B$ is an empirical factor often referred to as the stiffening index, and $V_{f0}$ is equivalent to the fibre volume fraction at a compaction pressure of 1 Pa (although $V_{f0}$ is also usually determined empirically). This type of equation has been found to fit well to experimental data for a wide range of materials.[27,29]




*1.10* Compaction master curve, showing the relationship between stiffening index (*B*) and initial fibre volume fraction ($V_{f0}$) from equation (1.6) for a range of dry reinforcements.

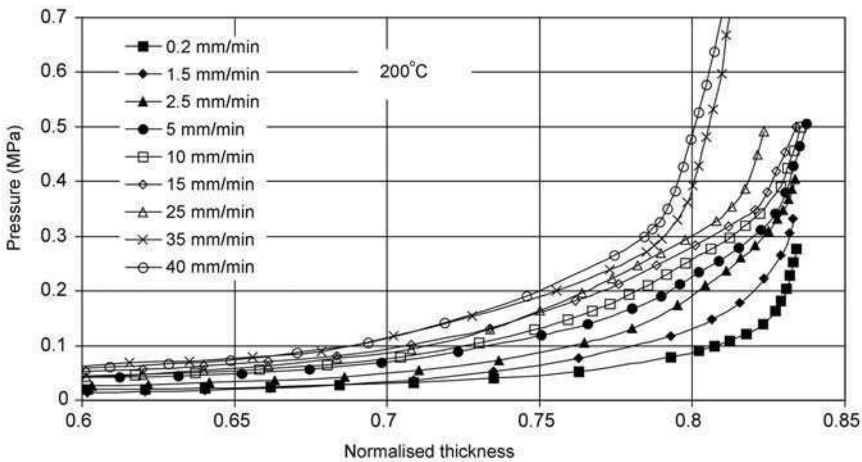
Correia[29] recently showed that the two parameters in equation (1.6) appear to be related, as indicated in Fig. 1.10. This also provides a good way of characterising material behaviour, with highly compressible materials (such as random mats) towards the left of the curve and less compressible materials (based on highly aligned fibres, e.g. non-crimp fabrics) towards the right.

## 1.6.2 Consolidation behaviour of prepreg

The majority of thermoset and thermoplastic prepreg materials undergo limited reductions in thickness during consolidation (typically <20%). This is because materials in semi-finished (i.e. as supplied) form are usually relatively well consolidated, and all that is required is the reduction of void content to an acceptable level (typically <1% for aerospace applications). Unfortunately as the materials have no clear paths for entrapped voids to escape, very high pressures may be required to achieve the desired degree of consolidation. Hence reasonably powerful hydraulic presses or high-pressure autoclaves are usually employed to consolidate these materials. A number of authors have conducted consolidation experiments for both thermoset and thermoplastic materials,[31–33] using a similar approach as described above for dry fabric. As would be expected behaviour is highly dependent on temperature and rate, with increasing time at pressure resulting in a reduction in void content to a limiting value.

In an attempt to reduce the pressure levels required for consolidation, various partially impregnated or 'semi-preg' materials have been developed in recent years. The general idea is to minimise the required polymer flow distances and provide continuous channels for air removal within the mould. For example, materials can be assembled as layers of resin film and dry fibre, with the resulting process often referred to as resin film infusion. One popular family of thermoplastic materials is based on co-mingled yarns, where reinforcement fibres are intimately mixed with polymeric fibres. Such materials can be processed by heating, pressure application and cooling. Pressure application can be undertaken within a hydraulic press at modest pressures or using a vacuum bag.

A number of studies have been published on consolidation behaviour of co-mingled fabrics, following initial work by Van West.[32] Wilks[20] analysed consolidation behaviour of co-mingled glass/polypropylene between parallel platens at various rates and temperatures. Typical results are included in Fig. 1.11. Consolidation pressure increases with reducing thickness (increasing normalised thickness) and this increase becomes steeper as the material approaches full consolidation. The pressure to achieve a given thickness increases approximately linearly with compaction rate. In the tests shown here, voids could not be eliminated completely as the compaction pressure was limited to 0.7 MPa. Garcia Gil[28] performed a similar analysis for vacuum consolidation, demonstrating that void contents of <2% could be achieved under atmospheric compaction pressure within 300 seconds at 180ºC. Here the vacuum-based process is advantageous as it removes most of the air from the material prior to significant polymer flow. A matched mould process in contrast may allow voids to become entrapped within the material before the target thickness is reached.




*1.11* Typical consolidation behaviour for a commingled glass/polypropylene material, showing required pressure as a function of normalised thickness (or degree of consolidation) at 200ºC for various consolidation rates. Normalised thickness is the fully consolidated thickness (zero voidage) divided by the current thickness.

Various models have been proposed for prepreg consolidation, based typically on a combination of fabric compaction and fluid flow.[28,31–33] Where voids are entrapped within the material prior to consolidation (e.g. for traditional prepregs or co-mingled fabrics consolidated without a vacuum) it is important to consider the pressure generated within entrapped voids, which can be done conveniently using the ideal gas law.

## 1.7 Discussion

This chapter has described the deformation behaviour of reinforcements and composites, focusing on the key deformation mechanisms. Clearly the majority of attention amongst the research community has been on intra-ply shear and compaction behaviour, and here a wealth of data are available in the literature. Less attention has been applied to tensile and bending loads for materials used within composites, although much may be learned here from the large body of work on conventional textiles. The majority of the tests used are non-standard, and as materials data are required increasingly for manufacturing process simulations, this issue must be addressed as a matter of urgency. Some initial efforts here are discussed in Chapter 13.

Almost all of the effort in the field of materials characterisation for composites forming has involved analysis of a single deformation mechanism in isolation. In practice of course several modes will occur simultaneously, for example intra-ply shear and in-plane tension. Coupling between these mechanisms is not clear at present, and may provide insights allowing increased accuracy from forming simulations. Given the wide variety of materials available, predictive modelling to determine material behaviour from constituent properties becomes highly desirable. Such 'virtual testing' tools would allow a wide range of materials to be analysed prior to component manufacture, facilitating selection and design of new materials with formability in mind. This is the subject of Chapter 4.

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