Mechanics of Flexible Textile Composites

H Arshad, R Ramgulam, P Potluri
The University of Manchester, Textile Composites Group
PO BOX 88, Sackville Street, Manchester M60 1QD
H.Arshad@postgrad.manchester.ac.uk

SUMMARY

This paper concerns the mechanical behaviour of woven fabric structures in flexible composites. Mechanics of such structures can be acknowledged by understanding the behaviour of constituent yarns upon tensile loading, and the influence of polymer matrix on it. The yarns are treated as elastica in the model.

Keywords: flexible composite, woven fabric, tensile loading, load-deflection, elastica

TEXILE COMPOSITES

Textile composites are effectively engineering materials comprising of two or more phases acting in conjunction to yield desired composite properties while retaining their individual characteristics. These two phases refer to a reinforcing textile substrate and a matrix component. Various combinations and quantities of fibre types, reinforcing structures and matrix materials may be used to customise properties for a giving application [1].

The most commonly discussed reinforcing materials include glass, carbon and aramid woven fabrics along with polymer matrices such as epoxy and polyester. Due to their high stiffness and strength-to-weight ratio, composites made using these materials greatly serve automotive, aerospace, and marine industries. Resin curing processes such as hand lay-up, Resin Transfer Moulding and injection moulding are commonly used for making such composites and are utilised for shaping by taking advantage of the hardening nature of the matrix component. In such 'common' cases, the cured matrix primarily serves, along with other requirements, to restrict fibre mobility and maintain dimensional stability and composite shape [1, 2].

Flexible Composites

Flexible textile composites comprise of rubbery elastomeric or viscoelastic matrix materials which greatly limit bending stiffness and allow the composite to become ductile; the textile reinforcement maintains dimensional stability and tensile stiffness. Similar to conventional composite materials, tensile strength of these composites relies purely on matrix and reinforcement material properties. However, flexible composites are capable of withstanding relatively much larger deformations while offering good toughness, damage resistance, and high load tolerance altogether [3, 4].

High-performance/industrial/technical coated and laminated fabrics qualify as flexible textile reinforced composite materials. Such materials cover a broad range of applications as they involve coating or treating various textile substrates with different polymers types. Continuous coating and laminating processes generally involve controlled polymer deposition on the textile substrate and are capable of producing flexible composites on a large production scale. More specifically, coating refers to direct spreading of dense liquid or paste on the fabric substrate using knife or rolling coating, or impregnation techniques, whereas lamination involves combining of fabric substrate with polymer film with the help of adhesive bonding. Lamination methods may include flame/hot-melt lamination, infra-red heating and powder scattering [5, 6].

MATERIALS AND CONSTRUCTIONS FOR FLEXIBLE COMPOSITES

Flexible composites demand careful selection of base fabric materials and constructions, and coating/laminate materials. All fabric types, including warp/weft knitted, nonwovens, stitch-bonded, and woven fabrics, have been used for making industrial coated fabrics. Warp knitted and woven fabrics, especially plain, basket, and twill weave structures generally offer good dimensional stability and low stretchiness in all directions thus making them popular reinforcements for high performance flexible composites. This research concerns plain woven fabric reinforcements (Figure1).

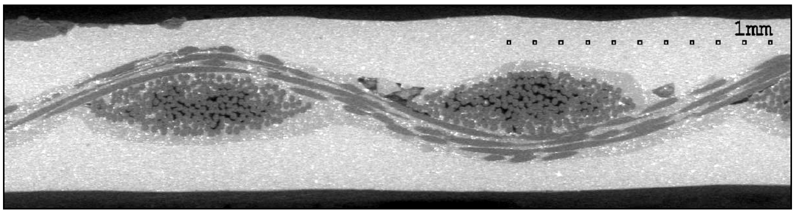

Figure1 – Cross-section of PVC coated polyester fabric.

Some degree of fabric openness assists penetration of the coating material; however coating may fail to seal completely if the structure is very open. Films used for laminating are generally impermeable. Following fabrication of the base fabric it is essential to perform scouring to rid the substrate off any contaminants that may affect bonding or cause delamination. Heat-setting is required to overcome shrinkage during coating or laminating processes which involve high curing temperatures [6].

Fibre Types

Polyester and nylon fibres offer high strength at low costs; availably of their high tenacity/ low shrinkage variants makes them a popular choice for various high performance applications. Polyester offers better dimensional stability, shrink resistance and resistance to light/UV, whereas nylon is characterised with good elasticity and resilience, high abrasion resistance and thermal absorbancy. Aramids and used in cases requiring high strength to weight ratios and high temperature resistances, but they are unable to offer good light/UV resistance especially in outdoor applications, for which

Acrylics are a good choice. Glass fibres are used in high performance demanding materials, such as architectural ‘prestressed membrane’ structures [7], which require high strength along with low elongation and excellent flammability resistance; glass fibres however cannot be used where high bending is required. [6]

Coating/Laminating Materials

PVC (polyvinyl chloride) is a versatile low cost coating material and can be formulated to serve various industrial and architectural applications. It offers good weathering properties and flame resistance. PU (polyurethane) is available in many types of hard/soft compositions and is used in coating and laminating. High strength and toughness, and resistance to tearing and abrasion make PU suitable for protective applications; it is however a relatively expensive choice. Silicone rubber offers good resistance to chemicals, oxidation, ageing and micro-organisms, and can withstand temperatures ranging from -60^{O}c to 200^{o}C+; on basis of these properties and its mechanical characteristics silicone is greatly used applications demanding environmental and thermal durability. PTFE (polytetraflouroethylene), an expensive but important coating material, is particularly used for making architectures and conveyor/calender belts. It stands out for its non-stick properties and exceptional resistance to various environments and temperatures (-70^{o}C to 250^{o}C). [6, 8]

APPLICATIONS OF FLEXIBLE COMPOSITES

Flexible textile composites serve various applications that may be categorised as:

- <u>Protective</u>

  Spacesuits, fire-fighter suits, specialist military/protective clothing, coverings

- <u>Industrial</u>

  Tarpaulins, hydraulic hoses, conveyor belts, calender belts, geomembranes, sacks/container

- <u>Automotive</u>

  Airbags, tyres, seat coverings, headliners, convertibles’ rooftops

- <u>Aerospace</u>

  Hot-air balloons, airships, space landing airbag, parachutes

- <u>Marine</u>

  Inflatable boats, lifejackets, sails, hovercraft skirts

- <u>Building and Architecture</u>

  Permanent structures, tensgrity structure membranes, inflatable structures, tents, roofing materials, awnings

MECHANICAL BEHAVIOUR OF FLEXIBLE COMPOSITES

Woven fabric reinforcements comprise of warp and weft yarns which interlace so that they lie in the same plane but at right angles to each other. An unlimited number of weaves can be produced by modifying the order of interlacement of the constituent yarns. The most fundamental plain weave, which has a balanced 1/1 configuration is a popular choice as it is characterised by solidness and tightness as generally the warp and weft yarns per unit length are the same. Upon interlacing the yarns take up a wavy configuration referred to as crimp.

Tensile Deformation of Dry Textile Reinforcement

The warp (longitudinal) and weft (transversal) yarns are bent out of the central plane of the fabric due to interlacement and influence each other during load application. When force is applied, say in warp direction, tension builds up in the warp yarns causing them to have a compact round cross-section. Simultaneously, these yarns add on to the normal pressure experienced by the weft yarns at cross-over points, thus distorting them further and enhancing their flatness. Similar behaviour is observed, but in the opposite sets of yarns, when force is applied in weft direction. Figure 2 shows the interactional behaviour of these yarns when forces F acts on the fabric structure, resulting in yarn extension, compression and bending.

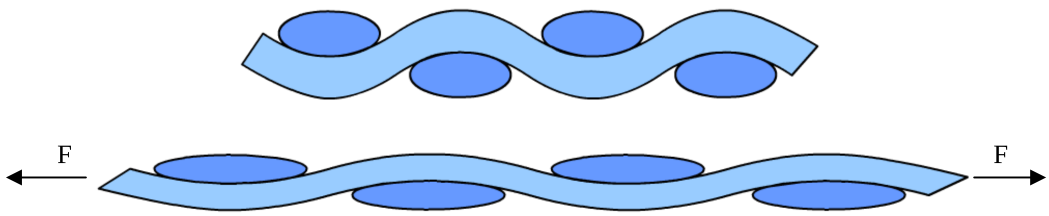

Figure 2 – Tensile deformation of plain woven fabric structure

During load application, frictional resistance to bending of the yarns is overcome initially which is then followed by de-crimping of the yarns lying parallel to the direction of force application; initial modulus is relatively low. Crimp-interchange causes the crimp in yarns lying perpendicular to this direction to increase until jamming point. The yarns experiencing applied load are restricted to move completely into the centre of the fabric plane when this limit is reached. Constituent filaments begin to extend beyond this limit yielding a relatively much higher modulus until complete tensile failure. This suggests that 'the load extension properties of the cloth are almost entirely governed by load-extension properties of yarns themselves' [9].

Tensile Deformation of Flexible Composite

Behaviour of interlacing yarns in fabric reinforcement, discussed above, is affected as a result of polymer deposition during coating/laminating process, especially during the decrimping phase of tensile load application. Generally the load-extension behaviour of coated/laminated fabrics depends upon fibre and coating/laminating material properties, and the degree of interaction between polymer and fabric reinforcement. Fabric structure and processing conditions do also greatly influence tensile properties. Fabric elongation can be greatly influenced during processing as fabrics generally experience high longitudinal (machine-direction) tension during continuous polymer application which can lower warp crimp and thus increase weft crimp. Heat, required for curing the deposited polymer may cause weft yarn shrinkage thus increase warp density as a result. These structural variations are bonded in place by the coating [8, 10].

Shear Deformation of Dry Textile Reinforcement

Extensions in any direction other than warp and weft are generally of higher amplitude, and relate to a different form of deformation such as shear deformation which is completely responsible for fabric modulus in the bias direction (45^o); it has no role to play in warp or weft directions [9]. Fabric shearing is an important behaviour as it allows the fabric structure to suit to any complex shape, which is important to flexible textile composites. Frictional forces exist between interlacing warp and weft yarns as they exert pressure upon each other at the cross-over points; these forces are responsible for generating initial loads. As shown in Figure 3, shear deformation leads to relative movement of the yarns, particularly rotation and slipping. Shear stiffness increases as the structure experiences increasing compaction upon increasing shear deformation. Structural jamming marks the limit to compaction and is followed by notable increase in stiffness. Fabric buckling or wrinkling is commonly observed as compressive stresses buildup [11, 12].

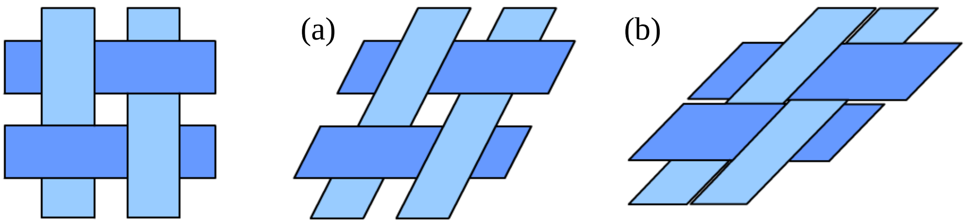

Figure 3 – Shear deformation of fabric; (a) rotation, followed by (b) structural jamming

Shear Deformation of Flexible Composite

Yarn rotation and slipping in fabric reinforcement is very likely to be damped in a flexible composite where the deposited polymer has a binding effect on the yarns as a result of polymer and fibre interaction. It is understood that at low shear angles the shear behaviour of coated fabrics is dominated by the coating material whereas the fabric component overtakes it at higher shear angles. This shift of shear from coating material to the fabric structure depends on the extent to which the coating material is capable of restricting the yarn mobility. Overall shear behaviour generally depends on various factors including fabric weave structure, yarn density, coating material properties and amount of coating material [13].

Tear Deformation of Dry Textile Reinforcement

Tear behaviour of woven fabrics can be explained with regard to the trouser-type tear test which involves load application to two fabric ‘legs’ lying in the same plane in opposite directions (Figure 4) . The initial load falls on the longitudinal yarns, which are parallel to the direction of load application, thus causing decrimping; transverse yarns ‘align themselves with the applied load to bridge the gap’ between the legs. As load increases the longitudinal yarns maintain their parallel alignment whereas the transverse yarns drift towards the ‘del’ region where tearing occurs. Angular pulling-in of transverse yarns and pulling-in of longitudinal yarns takes place at this region; tension develops as the yarns experience frictional interaction and bending as crowding occurs. Tearing is discontinuous, however it remains a steady process once commenced as the number of del yarns at any given time remain unchanged. Structural jamming occurs ahead of del region i.e. the un-torn area. Tearing involves sudden shifts from one del region to another [8, 14].

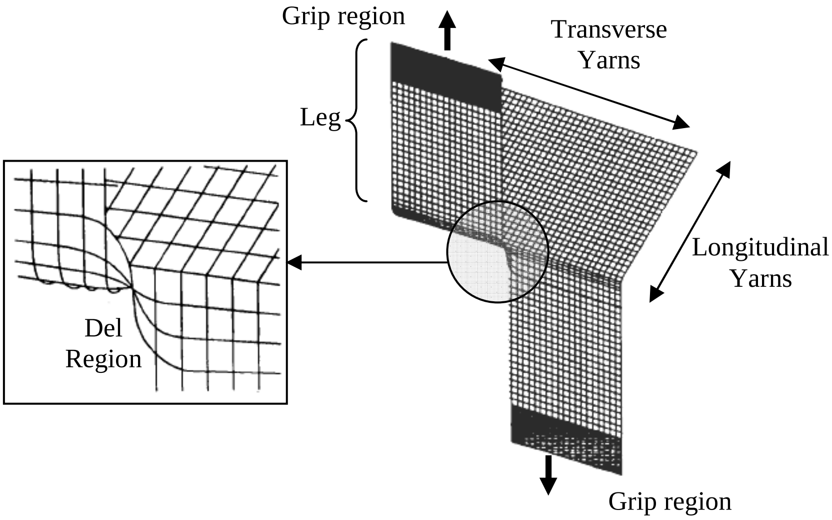

Figure 4 – Fabric tear involving yarn crowding at the del region during fabric tear [14]

Tear Deformation of Flexible Composite

Tear strength of flexible composites is an important property and relies primarily, other than yarn strength, on yarn mobility in fabric structure. Mobile yarns are capable of bundling together and hence yield high tear strength. Coating or laminating generally limits yarn movement and thus lowers tear strength [8, 10].

MODELLING PREFORM TENSILE BEHAVIOUR

The model is based on load-deflection of planar inextensible and extensible elasticas considered to be representative of yarns in woven fabric structures. It involves solving a system of first order linear differential equations using Runge-Kutta method which relate variables such as bending and tensile moduli, moment, curvature, and applied loads and dimensions. To accomplish the model’s adaptability to woven fabrics, factors relating to non-linearity in both, elastic behaviour and bending rigidity of yarns have been acknowledged.

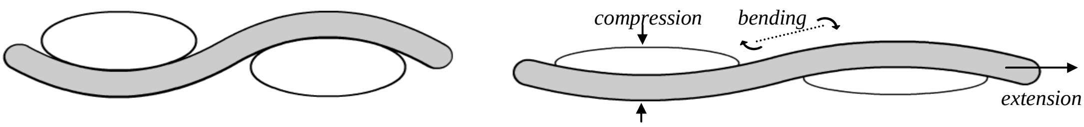

Figure 5 – Plain weave structure (a) prior to, and (b) after tensile loading

Numerical methods such as Newton-Raphson are used to evaluate unknown variables based on certain known initial and boundary values. Since the application, with regard to flexible composites is plain woven fabric reinforcement, unknown variables are evaluated by assuming yarns to behave like interlacing elasticas. Measured yarn properties and dimensions, and fabric geometry are thus used as inputs. Behaviour of interlacing warp and weft yarns during tensile loading, leading to yarn extension, bending, and transverse compression (Figure 5) are analysed accordingly.

EXPERIMENTAL RESULTS

Tensile Testing of Flexible Composites

Tensile tests are performed on two flexible composite types, specified in Table 1, both of which concern very different applications; both materials comprise of a plain weave fabric as reinforcement. The main motive of these tests is to understand the influence of polymer matrix on the behaviour of constituent yarns upon tensile loading. Type A is PVC coated plain woven high tenacity polyester fabric used in architectural structures. Type B is a silicone coated plain woven nylon66 fabric commonly used in automotive airbags. The main purpose of the coating in this application is to provide controlled permeability and pressure retention whereas the fabric reinforcement is solely responsible for mechanical strength.

Table 1 – Specifications of flexible composites A and B.

Property	Flexible Composite A	Flexible Composite B
Fabric reinforcement	Plain woven polyester HT multifilament yarn fabric	Plain woven nylon66 multifilament yarn fabric
Fabric weight (gsm)	137	216
Coating	PVC – both sides	Silicone – one side
Coating weight (gsm)	723.11	73
Yarn linear density (dtex)	1100	470
Warp/weft; yarns/cm	5.8/6.3	22/19
Warp/weft; Crimp%	1.46/4.13	10.9/4.3

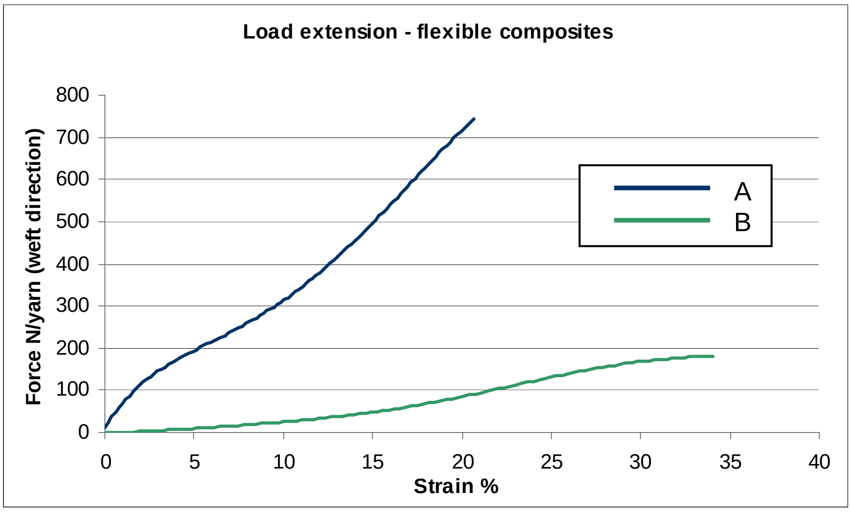

Figure 6 – Tensile behaviour of flexible composites A and B

Figure 6 shows tensile load extension curves for flexible composites A and B, normalised to force per unit (weft) yarn in fabric. The curves show the effect of coating material on the reinforcement fabric tensile behaviour. Curve relating to material B (silicone coated airbag fabric) is a close representation of a tensile behaviour of dry fabric reinforcement in which a relatively low modulus is observed initially, which suggests yarn decrimping. The modulus increases as the yarns experience load after decrimping; the silicone coating does not influence fabric behaviour significantly. This is clearly not the case in material A which yields an unusual high modulus towards the beginning, suggesting a locking effect of the PVC coating applied to either side of the fabric reinforcement. Decrimping of yarns experiencing applied tensile load is limited significantly due to high stiffness of the PVC matrix.

Validation of Model Used For Analysing Tensile Behaviour of Textile Reinforcement

In order to simulate load extension for a given fabric, specific details of the constituent yarns are used as inputs. These include yarn min/max diameters, number of filaments, filament diameters, yarn load extension data, yarn bending modulus, and compression factor. Relevant tensile and bending tests and cross-sectional imagining using Scanning Electron Microscope (SEM), as shown in Figure 7 are performed to establish this data. Uncoated plain woven nylon66 (airbag) fabric is used for this analysis.

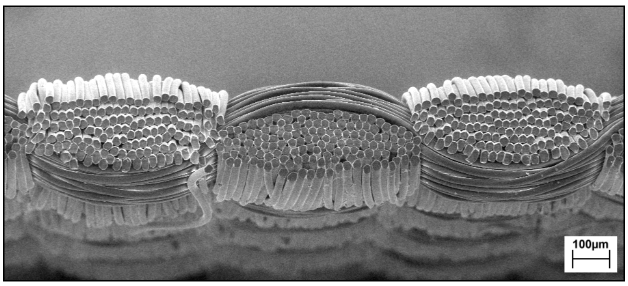

Figure 7 – SEM cross-sectional imaging to evaluate yarn and filament dimensions

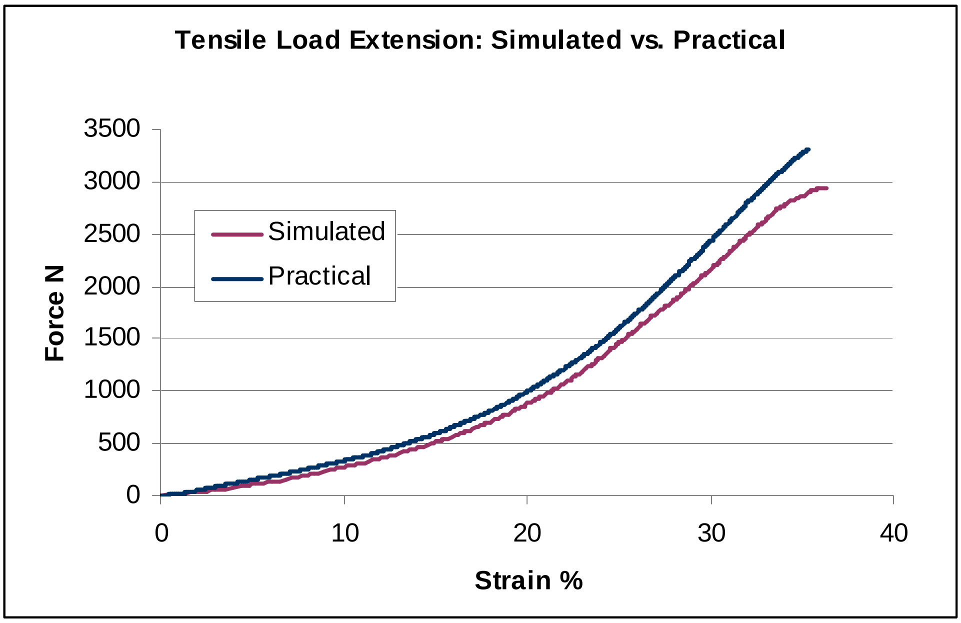

Figure 8 – Simulated and experimental load-extension curves

Figure 8 shows that the simulated load-extension curve matches very well with its experimental counterpart throughout all phases suggesting that the model is capable of simulating the interaction of interlacing yarns experiencing tensile loading.

CONCLUSION

Flexible composites tend to serve a broad range of high performance applications and woven coated/laminated fabrics are a popular choice with regard to their stability and performance. Various fabric reinforcements and coating/laminating materials can be used in different combinations to serve different applications. The effect of different coating materials on fabrics has been shown, and this highlights the importance of understanding mechanical behaviour of flexible composites with regard to the mechanical influence of individual components and their level of interaction. The tensile model set forth helps analyse mechanical behaviour of the fabric reinforcement based purely on fabric/yarn/filament parameters. Further research is being carried out to understand the influence of coating/laminating material on yarn bending, compression and extension which take place during tensile deformation. It is vital to acknowledge physical properties of these materials and quantify the level of fibre/polymer bonding for this purpose. Shear and tear deformation analysis and modelling methods further need to be established.

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