STRENGTH, CRACK INITIATION AND CRACK PROPAGATION IN FABRIC BASED FLEXIBLE AND SEMIFLEXIBLE COMPOSITES

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SUMMARY : Flexible composite materials is a class of engineering materials based on load bearing fibres tensile strength and stiffness in matrix materials with capability of large strain deformation and low bending stiffness. Coated fabrics, tyres and hoses are examples of typical products. The possible extreme fracture toughness is due to meso-structures distributing the concentrated loading over some volume of material and thus creating complex energy absorbing deformation and fracture mechanisms. Limited infiltration into twisted or blown yarns gives a core of free fibres, distributing concentrated loads over some additional volume of material. Properties obtained from fabrics of woven and knitted types are compared. Semiflexible composite materials are based on these meso-structures and conventional matrix material. Initiation and propagation of fracture is studied. The tensile properties of semiflexible composites with controlled limited infiltration from fast processing of thermoplastic split-film co-knitted preforms.

KEYWORDS : Flexible composites, semiflexible composites, woven fabrics, knitted fabrics, fracture, damage resistance, initiation of damage, crack propagation

1. INTRODUCTION

Compared with their constituents, conventional hard fibre composite materials usually possess high stiffness, strength and improved but still not very good damage tolerance. Flexible composite materials is a class of engineering materials based on load bearing fibres, with possibilities to build in extreme fracture toughness using complex deformation and fracture mechanisms limiting the stress concentrations. Coated fabrics, tyres and hoses are typical flexible composite products with continuous reinforcement. Typical for these materials is ductile behaviour with distinct plastic zone formation before crack propagation [1-3]. Transitions from ductile to brittle fracture behaviour at low temperature and/or high deformation rates however also belong to the technical realities and the scope of this work. The disappearing plastic zone is typical for the brittle fracture. A new class of materials in-between hard and flexible composites, semiflexible composites with high damage tolerance is discussed and compared with the traditional hard and flexible types of fibre composites.

The reinforcement of flexible composites, i.e. coated fabrics, tubes and tyres were originally designed to take advantage of existing textile structures for specific purposes as tensile reinforcement of natural resins like rubbers and waxes with very low tensile modulus, but capability of taking large strain deformations [4,5]. The traditional modelling of flexible composites with continuous reinforcement is based on the textile pattern unit cell approach [4, 9-11].

The flexibility is usually obtained by having the fibre reinforcement in the neutral layer or as a backing. When using yarns with twisted or intermingled fibres and crimped fabrics, some localised fibre buckling of radius much bigger than the fibre radius is introduced by the textile structure. Compressional stress build-up due to small radius buckling or kinking in the fibre reinforcement due to the bending is thus avoided.

2. RULE OF MIXTURE - TENSILE BEHAVIOUR.

The present approach is in the first stage based on the rule of mixtures, ROM, and then micro-mechanical modelling of fracture processes as the basis for further predictions [1,3,5]. ROM-modelling of the tensile strength and elastic modulus is based on the assumption of uniform strain over the loaded area. These holds for flexible composites based on DOS-structures and very low twist yarns when uniformly loaded and gives a first approximation according to [1], there it is illustrated a scheme for the use of the rule of mixture, ROM, for predictions of tensile modulus and strength of flexible composites.

The losses in tensile modulus related to the fibres in an ideal twisted yarn due to the non-axis loading are geometrically given [5-7].

$$E_y = \frac{E_f}{1 + 4\pi^2 R^2 \mathrm{T}^2}$$

T, twist of the yarn, [r/m] and R, radius of the yarn, [m]

For heavy coated fabric use, according to this model a typical yarn of radius in the range 10^{-4}m to 10^{-3}m and twist in the range $10 m^{-1}$ to $100 m^{-1}$ thus gives losses in elastic modulus below 30%, with the technically typical figures below 1% and thus almost negligible.

In a real yarn however with deviations from the ideal helix path of the fibres, the fibre migration gives redistribution of the fibres into stable structures with efficient load sharing after some pre-loading. The mechanical properties are thus expected to be depending of the thermo-mechanical history of the material, with the model figures giving the fully ordered upper limit.

3. DAMAGE TOLERANCE

For flexible composites in structural end uses the fracture toughness and damage tolerance are the most important end user properties beside the tensile stiffness and the flexibility. Semiflexible composites are composites employing the same mechanisms for damage tolerance and fracture toughness as the flexible composites.

To some extent, the damage tolerance depends on the type of fibres:

1. Tough fibres, i.e. textile fibres and steel wire exhibiting complex behaviour with plasticity followed by deformation hardening. Some deformation with very little stress build up is thus possible. The fracture process is due to large strain to fracture deformation much energy consuming and ends with an increasing load taking capability before the fracture process.

2. Fibres with intermediate behaviour have some fracture toughness due to plasticity in transverse properties and compression, i.e. aramides.
3. Brittle fibres, i.e. glass, carbon and ceramic fibres have high elastic moduli and strength and their dimensional stability due to the absence of the plastic deformation mechanisms of textile fibres, mild steel wire or aramides.

3.1 Influence of the textile structure

Two types of textile structure, with crimp and without crimp in the load bearing yarn system are discussed.

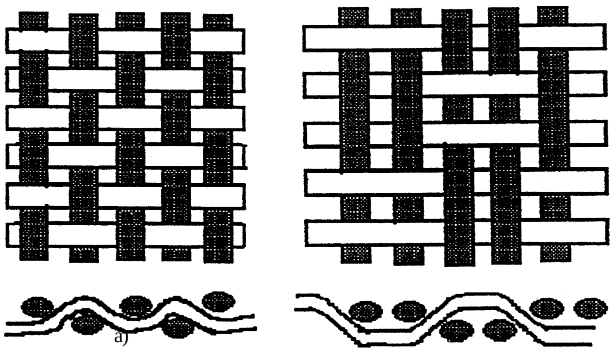


Fig.1 illustrates woven structures, a) plain weave and b) panama weave. The crimp pattern is illustrated at the bottom.

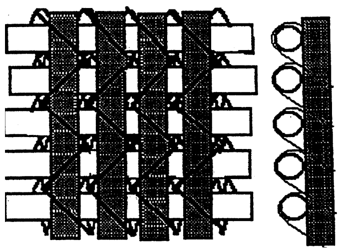


Fig.2 illustrates a DOS warp-weft inserted warp knitted structure without crimp in the insert system and the crimp taken by the knitted loops, as illustrated in the side view.

Woven and braided structures on one side and DOS, weft-warp insert warp knitted structures on the other give principally different tear crack propagation due to different arrangements of the crimp [1,3]. Both kinds of structure can however provide plastic zone behaviour around the crack fronts at ductile fracture.

3.2 Free length of fibres:

Multifilaments and staple fibres are twisted or intermingled by for example air blowing or false twisting into yarns, and with limited penetration of matrix into discrete fibre bundles, the applied load is distributed over a volume of material determined by the twist or periodicity of the yarn and the volume fraction of the yarn being penetrated [2].

The free fibre length, the length of the fibres in the non infiltrated part of a twisted yarn, is given from the standard model for the twist of a yarn as a helix, with the fibres coming to the surface twice pro turn. The periodicity for a thin yarn is thus 1/2T [m], where T is the twist of the yarn, [r/m].

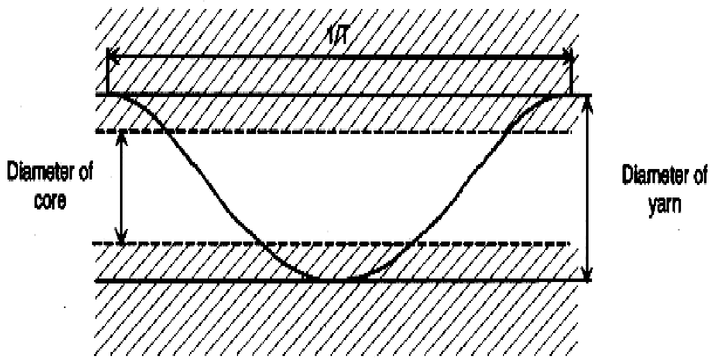


Fig.3 illustrates the free length of a filament in a partially infiltrated twisted yarn [2].

The free length of non coated fibres, l_{core}, in the core of the yarn is given by:

$$l_{core} = \frac{(1-V_m)}{2T} \quad (1)$$

V_m Volume fraction of the coating in the yarn. This gives the length of coated fibres, l_{skin}, in the skin of the yarn:

$$l_{skin} = \frac{V_m}{2T} \quad (2)$$

Making the assumption of perfect bonding and thus no fibre pull out an underestimate of the specific work of deformation over the cross section of the yarn, W_{yarn}, [J/m^2] is given by:

$$W_{yarn} = W_{af} + \frac{(1-V_c)}{2T}\int_0^{\varepsilon_{fb}} \sigma(\varepsilon_{core})d\varepsilon \quad (3)$$

W_{yarn} is the specific work of fracture of the yarn when it is bonded to the matrix:
- tensile work of fracture W_{core} depending on the free fibre length, i.e. the twist and volume fraction of the matrix.
- absorbed work W_{af} in the composite skin not depending on the free fibre length.

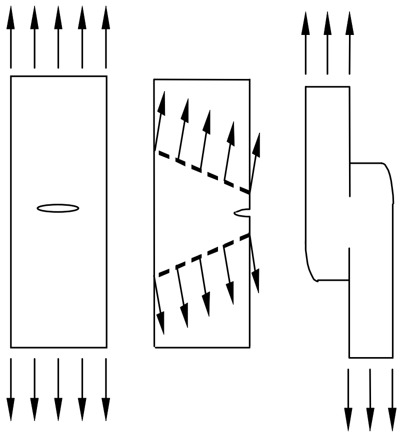
If the bonding is not perfect and the yarn debonds, this process will absorb energy and an increase in the plastic zone formed. The free fibre length absorbing work will thus increase. At the same time the strain velocity decreases and the toughness of the matrix will increase. The total toughness will thus to some extent increase.

The internal friction in the twisted and intermingled yarns is a mechanism absorbing energy, if the fibres can slide and rearrange, i.e. when the frictional forces are below a critical limit, determined by the twist or intermingling and the fibre surface properties. The friction can be modelled as an additional matrix [1]. Transitions from ductile to brittle behaviour due to excessive frictional stress build up in yarns are also well known from practical experience.

3.3 Tear crack propagation

The fracture toughness of flexible composites is usually tested by some tear method giving some mixed mode measure of the fritter toughness, Figs. 4-5.

The crack propagation of woven and braided structures on one side goes on with slowly decreasing tear force due to damage accumulation. The crack propagation of a plain weave is illustrated in Fig.6, below. A panama weave usually has higher toughness then a plain weave due to the distribution of the applied force on neighbouring yarns.



a b c

Fig.4 illustrates the geometry of three tear testing methods, a) pre-cracked, and b) trapezoid and c) tongue [1].

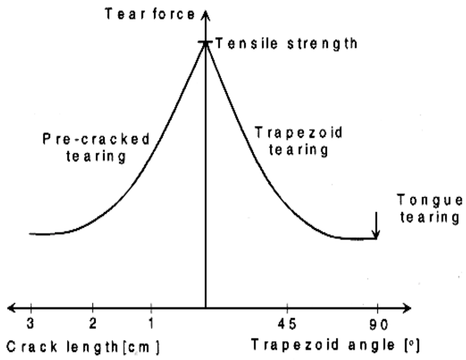


Fig.5 illustrates schematically the relations between the tensile strength and tear strength [1].

The plastic zone formation due to the limited infiltration discussed above is also limited by the friction between the crossing yarns in the del of a woven fabric.

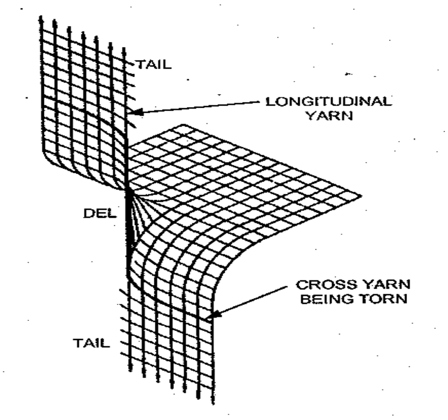


Fig.6. illustrates the mechanism of tongue tear crack propagation in a plain weave [9].

This mechanism of crack propagation in a woven structure will proceed at constant slightly decreasing force. The extension of the plastic zone is primarily limited by the penetration of matrix into the yarns, the internal friction, the plasticity of the matrix and the friction between the yarns. For twisted yarns however, the torque and misalignment of the fibres due to the twist are also of importance for the formation of the plastic zone.

In the optimal case, the tongue tear crack propagation of insert warp knitted DOS-structures forms a delta giving an linear increase of the tear force due to the increasing length of the energy consuming plastic zone during the fracture process. The mechanisms are illustrated in Fig.7 below.

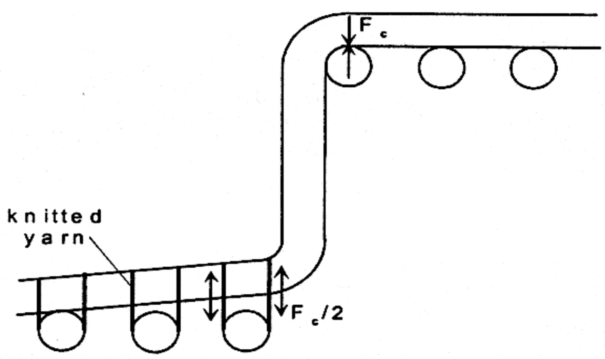


Fig.7. illustrates the mechanisms with tensile fracture of the knitted loops and friction between the inserted yarns during tongue tear crack propagation in a DOS-based flexible composite [2,3].

- Sliding friction of insert yarns and knitted loops.
- Yield flow of matrix between insert yarns.
- Tensile deformation and fracture of knitted loops and insert yarns.

WEAVING VS. WARP KNITTING

Technical characteristics of Loomstate Substrates

			DOS	Plain weave
Diolen PET yarn	type		190 ST	190ST
Linear density	dtex		1100	1100
Sett	thr/cm	Warp/weft	7.9/8.0	7.7/8.0
Thixckness	mm		0.47	0.31
Square weight	g/m^2		206	178
Elongation at break	%	warp/weft	22.8/22.0	21.6/21.5
Tensile strength	daN/5cm	warp/weft	331/301	281/290
Yarn tensile strength	daN/thr	warp/weft	8.37/7.70	7.31/7.24

WEAVING VS. WARP KNITTING

Technical characteristics of Coated Substrates

			DOS	Plain weave
Sett	thr/cm	warp/weft	8.0/8.0	8.1/8.0
Thickness	mm		0.62	0.62
Square weight	g/m^2		717	713
Elongation at break	%	warp/weft	18.4/20.3	17.3/23.1
Tensile strength	daN/5cm	warp/weft	317/298	288/271
Yarn tensile strength	daN/thr	warp/weft	7.92/7.44	7.19/6.78

WEAVING VS. WARP KNITTING

Coated Substrates - Tear Test Results

			DOS	Plain Weave
Trapezoidal	daN	warp/weft	34.2/31.4	28.6/2.7
Spike tear	mm	warp/weft	50.9/7.1	80.3/44.7
Falling cone tear	J/m	top/reverse	129/124	107/104
Initiation	daN	warp/weft	280/230	210/200

The properties of the matrix and interface are of viscoelastic or rubber-elastic nature and thus strain rate and temperature depending, with ductile to brittle traditions when increasing strain rate and/or decreasing temperature [5]. This kind of transition is reviewed in the classical textbooks on mechanical properties of materials and can be expected for any kind of structure.

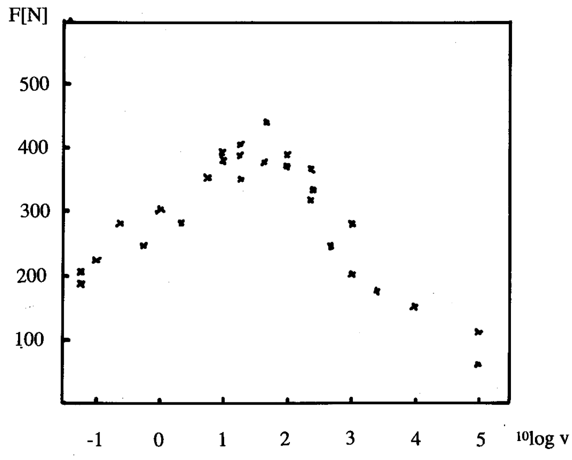


Fig. 8 illustrates the velocity dependence of the tongue tear force of the PVC-coated plain weave.

The velocity-dependence of the tongue tear force of the PVC-coated PET-multifilament weave is illustrated in Fig.8 above [3]. At low velocity, stress relaxation limits the loading. At high velocity, the strain to failure and thus the energy take up decreases, the plastic zone disappears and the mode of fracture mode turns brittle.

A new method to simulate the high local strain-rates initiating damage in many applications is based on the use of triangular 45^o-45^o-90^o clamps with rounded edges and tips, r=0,5mm, giving a central initial gauge length L_0 (0) =1mm. The gauge length L_0 increases with the distance from the centre x, $L_0 = 1 + 2x$. The width of the basis of the triangle was 100mm in order to avoid edge effects. The interaction between the surrounding yarns in the structure however is expected to limit the local stress build up in the tip and form some plastic zone close to the tip.

4. SEMIFLEXIBLE COMPOSITES

Crimp-free E-glass/PP composites of two types, flat laminates and deep drawn half spheres with limited infiltration of matrix into discrete yarns were produced from split-film co-knitted DOS-fabrics by low pressure pressing starting with the fabrics clamped in the cold tool. The preform fabrics are reviewed for example in [6]. Consolidation was done by a fast electromagnetic heating route generating the heat in situ in the interface tool-composite at 15^o/s followed by keeping the tool at 210^oC for approximately 1 min and rapid cooling [12]. The volume fraction of fibres was 38% and the degree of infiltration obtained was approximately 70%.

The material was characterised by tensile testing in the velocity range from 5 mm/min to 500 mm/min. Some typical features of the tensile behaviour illustrated in Fig. 9 indicate damage tolerance and non-catastrophic fracture behaviour.

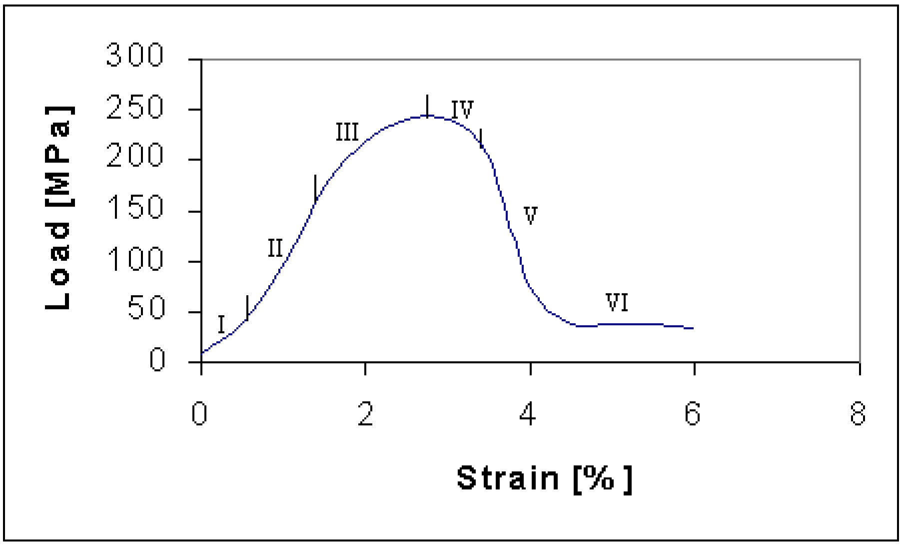


Fig.9 illustrates the typical features of the fracture behaviour of the semiflexible E-glass/PP composites.

I. Initial fibre migration and increased orientation, strain hardening
II. Linear elastic region, typically from 10 to 210 MPa.
III. σ_y, yield point, initial damage, debonding, migration and fracture of fibres, typically from 210MPa to 250MPa.
IV. σ_{max}, maximum load, instability region
V. σ_f, rapid fibre fracture distributed over the length of the specimen
VI. $\sigma_{friction}$,, residual strength with still intact fibres and fibre fragments taking load by sliding friction

4. CONCLUSIONS

ROM-modelling gives first estimates of tensile strength and elastic modulus of coated fabrics. The damage resistance depends on the plastic zone behaviour and exhibits very strong velocity dependence. The force for propagation usually exhibits stress relaxation at near static conditions, a pronounced maximum at moderate velocity and then transition into brittle behaviour. The presented results and the discussion indicate that the free fibre length, the viscous deformation and large strain behaviour of the matrix, the textile structure and the adhesion and internal friction are of vital importance. The viscoelasticity, the internal friction and the adhesion properties are however all strain-rate and temperature depending. The results indicate that the velocity dependence of the behaviour of the semiflexible E-glass/PP composites was not as strong as the velocity dependence of the tear crack propagation of the organic fibre based flexible composites.

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The basis of this work is found in the extensive experience and the experimental results collected and discussed in the group for Industrial Textiles at TEFO. This program was initiated and run for 20 years by Dr. G. Nordhammar. These results were released and used by P.Gredinger in his M.Sci. thesis, with use of methods and models for composite materials and modelling the influence of friction and non-balanced twist on the work of fracture of flexible composites. The discussions with Mr. G. Lönngårdh, Mr. E. Wallin and Prof. P. Schwartz were of great value for this work.

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