CHINESE PUZZLES OF TEXTILE COMPOSITES PROPERTIES

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Abstract

The paper overviews several examples of integrated research of textile composites behaviour, when the properties of the same material are studied through all the stages of its production and performance. The chain or rather "Chinese puzzle" includes: (1) internal structure of the reinforcement, measured via micrography or microCT, including variability of the internal structure; (2) deformability of the reinforcement: its resistance and change of the internal structure in shear, biaxial tension, compression and bending; (3) drapability and behaviour in forming; (4) permeability, including permeability in deformed state; (5) impregnation of a composite part; (6) defects in the consolidated composite; (7) stiffness of the composite; (8) damage behaviour and strength under quasi-static loading;(9) fatigue behaviour.

This type of research creates insight in the material's behaviour throughout its production and performance. If the material is chosen cleverly, then the understanding can be applied to a whole family of materials. It also provides full benchmarking data for any simulation, with all the input available, thoroughly studied and documented.

The paper summarises such a "Chinese puzzle" studies for non-crimp fabric and 3D woven glass and carbon composites, which were conducted throughout several years in KU Leuven, with clustering the work, keeping the puzzle in the "inner eye" focus in different projects with different funding sources.

Keywords: textile composites, internal structure, deformability, permeability, mechanical properties

1. Introduction

Textile composites can be characterised as fibrous structured materials. Therefore the mechanical behaviour of a textile composite is defined by mechanical properties of the fibres and matrix, transformed into mechanical behaviour of the composite by the reinforcement structure. Hence the structural dependency of the textile composite mechanical properties is of the paramount importance for its performance. It its turn, the structure of textile reinforcement is not something that can be defined with all certainty just based on the textile specification (e.g. "carbon fibre 5H satin fabric of 300 g/m^2"). The most important parameter for the composite, fibre volume fraction, is defined by the reinforcement compaction during production. Moreover, the textile reinforcement deforms during the composite production, with the geometry of the fibres changing. The situation is complicated by the presence of defects induced during the production, like fibre misalignment, deviation of the fibres from their “ideal” positions, prescribed by the textile geometry and possible presence of (micro) voids. Figure 1 illustrates these interactions.

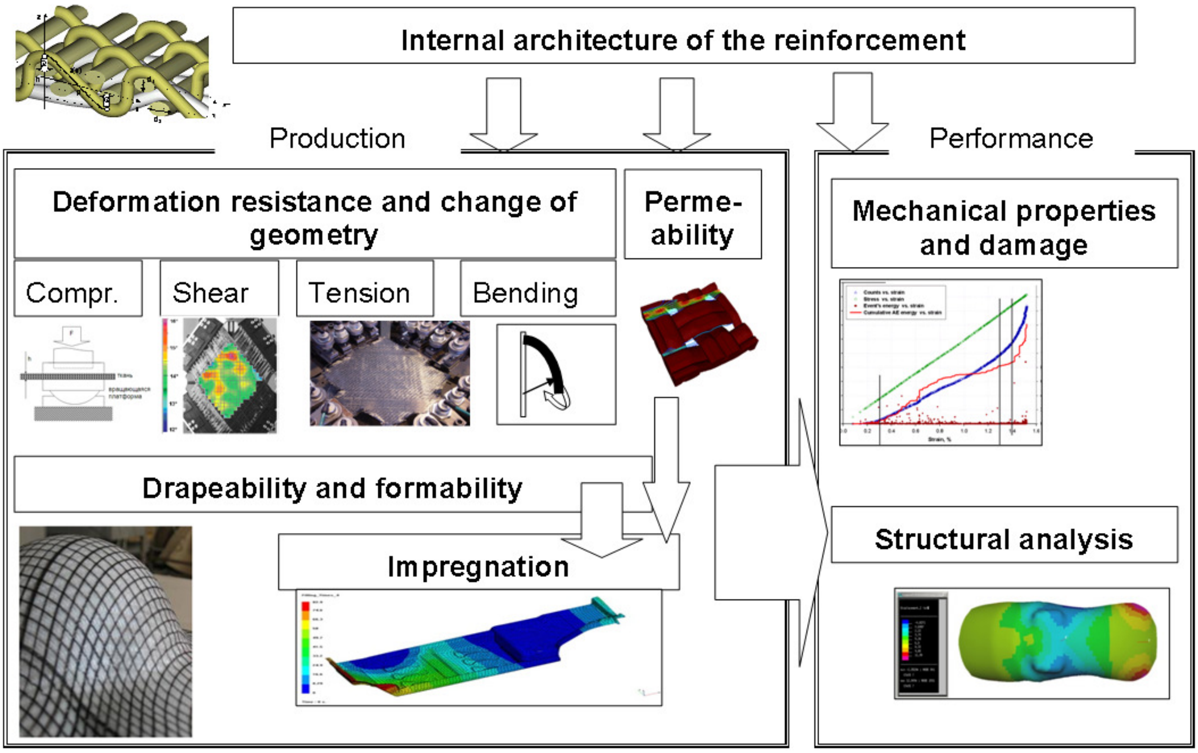


Figure 1 Interrelation of internal geometry, deformation, impregnation and performance of a textile composite

The depicted interrelations make it highly desirable to organise a material research in such a manner that all the dependencies are clearly visible and, most important, traceable throughout the different chains appearing in Figure 1: structure – manufacturing – performance, micro – meso – macro scale, ideal geometry – stochastic variations – defects etc. The most straightforward way of such an organisation is to trace the behaviour of one material, preferably one batch of a given material through these chains. Because of complex interrelations the linear chains become a puzzle of connections.

2. Chinese puzzle of textile composites

The aim of a thorough study of a textile composite is creation of insight in the material’s behaviour throughout its production and performance. If the material is chosen cleverly, then the understanding can be applied to a whole family of materials. The study also provides full benchmarking data for any simulation, with all the input available, thoroughly studied and documented. Such a study can include experimental characterisation of:

- internal structure of the reinforcement, measured via micrography or microCT, including variability of the internal structure;
- deformability of the reinforcement: its resistance and change of the internal structure in shear, biaxial tension, compression and bending;
- drapability and behaviour in forming;
- permeability, including permeability in deformed state;
- impregnation of a composite part;
- defects in the consolidated composite;
- stiffness of the composite;
- damage behaviour and strength under quasi-static loading;
- fatigue behaviour

Schematically this set of experimental (and possibly modelling) measurements is shown in Figure 2. In the following sections this approach is illustrated on examples of NCFs and 3D woven orthogonal non-crimp composites.

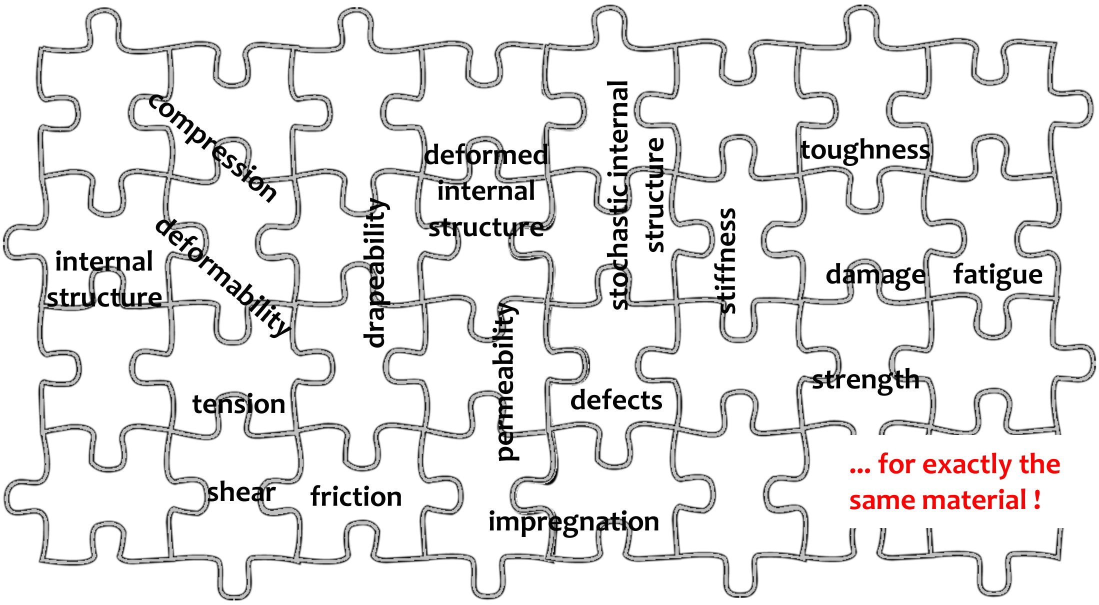


Figure 2 Chinese puzzle of textile composites

3. NCF

“Non-crimp fabrics” (NCF), is a textile engineers’ answer to a long-standing challenge faced by designers of composite parts: to combine a perfect placement of the reinforcing fibres with easy, inexpensive, automated manufacturing of the part. A part made using unidirectional tapes, placed by hand or by robot and consolidated in an autoclave, has ideal fibre placement and the best local mechanical properties due to the unidirectional (UD) microstructure of the reinforcement. However, the manufacture of such parts is cumbersome and costly. On the other hand, an out-of-autoclave manufacturing process, for example vacuum assisted RTM, which uses woven laminates, is relatively cheap and takes advantage of easy handling of large sheets of the fabric. In this case, however, the local mechanical properties are affected, because the fibres deviate from their ideal directions due to the crimp (inherent to the woven fabric) and because of the necessary presence of the second fibre system, lying transverse to the direction of the design loads. Hence the challenge to create a reinforcement which would combine unidirectional fibres with integrity, ease of handling and drape of textile fabrics.

The "puzzle" for NCFs (Table 2) was created investigating fabrics depicted in Figure 3 (properties shown in Table 1).

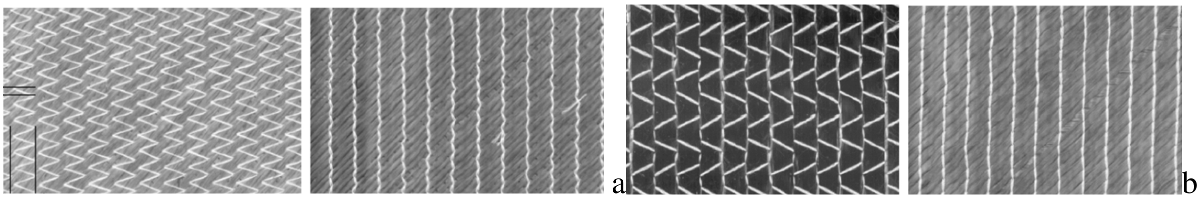


Figure 3 Biaxial (a) and quadriaxial (b) NCFs

Description	*Ply angles*	*Mass, g/m²*	*Stitching pattern*	*Gauge*
Bidiagonal carbon fabric	+45;-45	322	Tricot	5
Quadriaxal carbon fabric	0;-45;90;+45	629	Tricot-Warp	

Table 1 Properties of NCFs

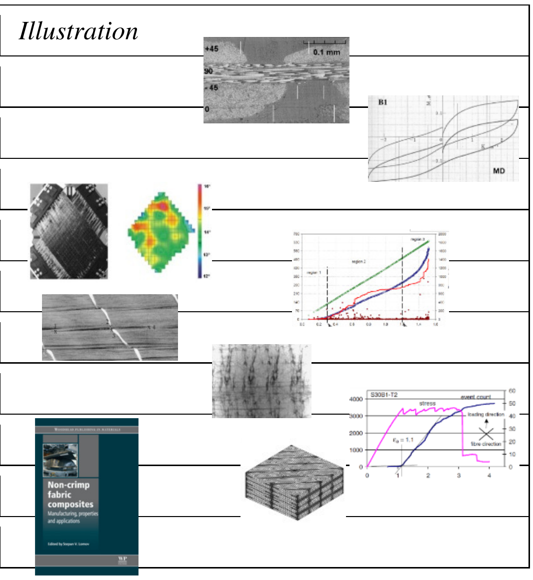
Year	*Property*	*Reference*	*Illustration*
2002	Internal geometry	[1]	
2003	Deformability (KES-F)	[2]	
2003	Permeability	[3]	
2005	Deformability (large deformation)	[4]	
2005	Stiffness and strength, damage	[5]	
2006	Deformed geometry	[6]	
2007	Fatigue	[7]	
2008	Damage sheared, FEM	[8]	
2008	Damage, FEM	[9]	
2011	Book: NCF fabric composites	[10]	

Table 2 NCFs and NCF composites studies

4. Glass 3D non-crimp orthogonally woven composites

Composites fabricated by VARTM technology with the use of single-ply non-crimp 3D orthogonal woven preforms 3WEAVE® find fast growing research interest and industrial applications. It is now well understood and appreciated that this type of advanced composites provides efficient delamination suppression, enhanced damage tolerance, and superior impact, ballistic and blast performance characteristics over 2D fabric laminates. At the same time, this type of composites, having practically straight in-plane fibers, show significantly better in-plane stiffness and strength properties than respective properties of a "conventional" type 3D interlock weave composites.

The "puzzle" for glass 3D non-crimp orthogonally woven composites (Table 4) was created investigating fabrics depicted in Figure 4 (properties shown in Table 3).

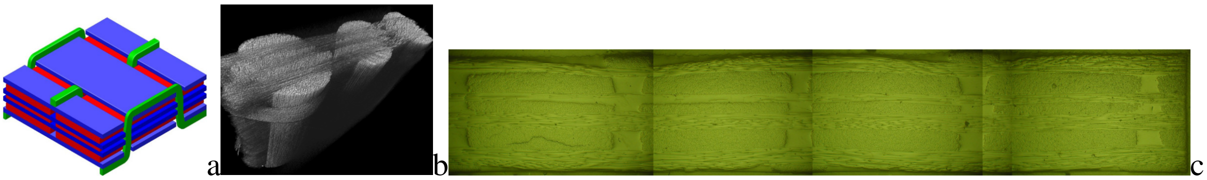


Figure 4 Glass 3D non-crimp orthogonally woven composite: (a) unit cell; (b) micro-CT image; (c) cross section along warp yarns

Areal weight [g/m^2]	3255
number of warp layers end count [ends/layer/cm] warp size [g/km]	3 2.76 layers 1&3: 2275 layer 2: 1100
number of weft layers pick count [picks/layer/cm] weft size [g/km]	4 5.28 735
z yarn size [g/km] Ends/layer per z yarn Pick/layer per z yarn	276 1 2

Table 3 Parameters of glass (Hybon 2022 yarn) 3D non-crimp orthogonally woven fabric

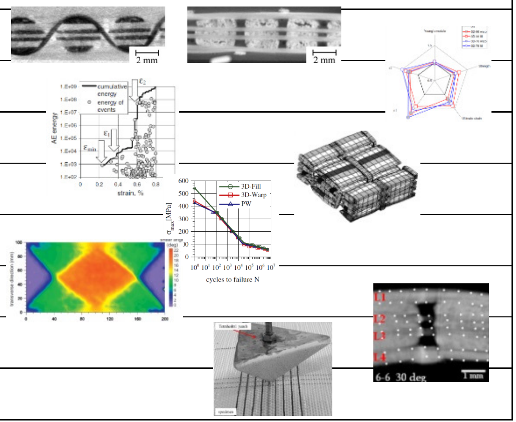
Year	*Property*	*Reference*	*Illustration*
2005	Internal geometry	[11]	
2009	Stiffness, strength	[12]	
2009	Damage	[13]	
2009	Damage: FEM	[14]	
2010	Fatigue	[15]	
2012	Deformability	[16]	
2012	Deformed geometry	[17]	
2013	Drapability	[18]	

Table 4 Studies of glass 3D non-crimp orthogonally woven composite

5. Carbon 3D non-crimp orthogonally woven composites

The principal current trend in the aerospace industry, regarding advanced composite materials, is to develop "Out-of-Autoclave" manufacturing technologies that would enable the same level of composites' properties as conventional pre-impregnated tape laminates, but at significantly reduced manufacturing cost and time. Among recent textile preform manufacturing technologies, the 3D non-crimp orthogonal weaving approach originated at North Carolina State University has gained fast growing interest from the industry in the last decade. It enables industrial-scale production of unitized (i.e., single-ply, seamless) thick preforms on the specialty, fully automated 3D weaving machines.

The "puzzle" for carbon 3D non-crimp orthogonally woven composites (Table 4) was created investigating fabrics depicted in Figure 4 (properties shown in Table 3).

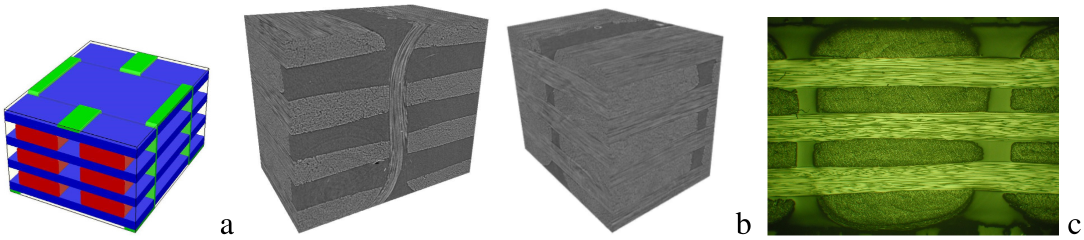


Figure 5 Carbon 3D non-crimp orthogonally woven composite: (a) unit cell; (b) micro-CT image; (c) cross section along warp yarns

Weave	see Figure 5	Areal density, g/m^2	2499
Warp yarns	Toho Tenax 12K, 800* tex	Ends count, warp per inch in layer	12*
Fill yarns	Toho Tenax 2x6K, 800* tex	Pick count, pick per inch in layer	10*
Z yarns	Toho Tenax 1K, 66* tex	Fiber diameter, μm	7*
Thickness	2.76 mm	Fiber volume fraction in the composite	51.1%

Table 5 Parameters of carbon 3D non-crimp orthogonally woven composite

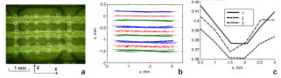
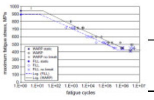
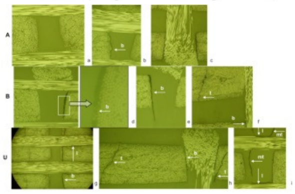
Year	*Property*	*Reference*	*Illustration*
2010	Internal geometry	[19]	
2011	Fatigue	[20]	
2013	Mechanical properties and damage	[21]	
2014	Acoustic emission	[22]	

Table 6 Studies of carbon 3D non-crimp orthogonally woven composite

6. Conclusion

The presented "Chinese puzzle" is a preferred approach for composites materials research

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