DATA BANK FOR VALIDATION OF FINITE ELEMENT ANALYSIS OF TEXTILES AND TEXTILE COMPOSITES: A PROPOSAL

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ABSTRACT

Meso-scale (unit cell of textile) finite element (FE) modelling of dry textile reinforcements and textile composites is a powerful tool for studying the manufacturing (formability and permeability) and performance (mechanical properties, damage initiation and development, strength) of textile composites. FE tools allow very detailed modelling, producing enormous amount of data including stress-strain fields, damage propagation, details of flow etc. The hierarchical, multi-scale structure of textile reinforcements and composites causes significant complexity in the phenomena observed during mechanical loading of the materials. This level of detail and quantity of experimental data cannot be included in the framework of a scientific publication. We propose to go beyond the limits of a journal paper, and create a data bank of experimental studies, which will be recognised by the scientific community as reliable and suitable for validation of meso-level FE models, promoting quantitative comparison of predictions from various analysis strategies and geometric idealisations. The data bank will also contain results of FE modelling, to permit comparison between different modelling approaches. The paper presents the initial proposal for the structure of the data bank and of the organisation of the data collection and sharing; it is intended to be a seed for this new benchmarking activity.

1 INTRODUCTION

Meso-scale (unit cell of textile) finite element (FE) modelling of dry textile reinforcements and textile composites is a powerful tool for studying the manufacturing (formability and permeability) and performance (mechanical properties, damage initiation and development, strength) properties of textile composites [1]. The recent developments of meso-FE modelling tools, based on both commercial and in-house FE packages, make it clear that integrated modelling systems are the order of the day, and that such systems are emerging and will reach maturity in the coming years. Such systems will be suitable not only for academic research and illustration of principles, but also for analysis of practically important textile composites with complex architecture. They will allow rapid variation of the reinforcement structural parameters and mechanical properties of the constituents via user friendly interfaces and will provide results with sufficient accuracy for linear and non-linear mechanical behaviour, damage and permeability. Development of such predictive FE tools necessitates validation of the modelling against reliable and detailed experimental data.

The hierarchical, multi-scale structure of textile reinforcements and composites causes significant complexity in the phenomena observed during mechanical loading of the materials. Conversely, FE tools allow very detailed modelling, producing enormous amount of data including stress-strain fields, damage propagation, details of flow etc. However, without validation by comparison with experimental data with the same level of detail, there is a danger that the results of the FE analysis are simply ‘pretty pictures’, without separation of physically significant features of the calculated fields from numerical artefacts.

The discussion of these issues during the symposium “Meso-FE modelling of textiles and textile composites” (St.-Petersburg, 2007) has created an understanding that this level of detail and quantity of experimental data cannot be included in the framework of a scientific publication. We propose to go **beyond the limits of a journal paper**, and create a data bank, or archive of experimental and numerical studies, which will be recognised by the scientific community as reliable and suitable for validation of meso-level FE models, promoting **quantitative** comparison of predictions from various analysis strategies and geometric idealisations.

The conventional journal format is incompatible with the complexity of data being generated by three-dimensional analyses of textile composites. At best a journal paper describes a few insights distilled from extensive numerical simulations. Often there is insufficient information to replicate the models even if one did have the time and tools necessary. The proposed archive is not intended to replace journal papers, but to provide enhanced access to simulation data. An archive that provides detailed information about models and the results of simulations can be used for multiple purposes, such as

- Evaluation of existing or new techniques for analysis of textile composites
- Performance of parametric studies that go beyond the tools available to and time constraints of a single organization
- Examination of the raw data with new perspectives/ideas not anticipated when the simulations were conducted.

The archive extends the "lifetime" of the raw data and makes it available to a broad "virtual" research group.

An important component of the data bank will be the provision of a complete set of input data for each of the studied textiles and composites. An entry in the data bank, freely formatted by a research group owning the data, should enable other users of the bank to perform FE modelling of the test stored in the bank.

The paper presents the initial proposal for the structure of the data bank and of the organisation of the data collection and sharing; it is intended to be a seed for this new benchmarking activity.

2 SCOPE OF THE DATA BANK

2.1 Meso-scale

Textile composites are structured, hierarchical materials, having three structural levels:

1. The macro(M)-level defines the 3D geometry of the composite part and the distribution of local reinforcement properties. The latter is connected to the former, as local parameters of the reinforcement (such as fibre volume fraction, reinforcement thickness and shear angle, hence local composite stiffness) are defined by the draping process during forming of the part. “Local” on the M-level means averaging (homogenisation) of the properties on the scale of one or several adjacent unit cells of the material, and corresponds to “global” on the meso-level. “Global” on the M-level means overall loading conditions of the part.

2. The meso(m)-level defines the internal structure of the reinforcement and variations of the fibre direction and the fibre volume fraction inside the yarns and the fibrous plies. The internal structure is defined by the reinforcement textile architecture and deformations applied to the reinforcement during the part forming. “Local” on m-level means averaging (homogenisation) on the scale of several fibres (representative volume element (RVE) for fibre packing inside the yarn) of properties such as fibre direction, fibre volume fraction and stiffness of the impregnated yarn. “Global” on the m-level means “local” on the M-level.

3. The micro(μ)-level defines the arrangement of the fibres in the RVE of the impregnated yarn or fibrous ply. “Local” data on μ-level are properties of fibres, matrix and their interface. Homogenised, “global” parameters are used as “local” data on the m-level.

At this stage the proposed data bank is focused on the second, **meso-level**. This means that the reinforcement architecture should be defined, and the resolution for the registered (measured and/or predicted) mechanical variables should be enough to recognise the features of the field at the scale of the individual yarns of the reinforcement.

2.2 Mechanical phenomena

The proposed content of the data bank includes experimental and meso-FE results for:

- Deformability of dry textile reinforcements (biaxial tension, shear, compression)
- Flow through textile reinforcements, also through deformed reinforcement [2]
- Mechanical behaviour of textile composites in quasi-static loading (elastic response and damage, fatigue)

3 CONTENTS OF THE DATA BANK

The initial version of this archive will focus on three categories of data:

1. Experimental results for validation of meso-FE simulations
2. Basic input data for finite element analysis of textile composites and documented results from finite element simulations
3. Numerical test cases

The first category describes **experimental data**, both for the material characterisation and the results of mechanical testing. Figure 1 illustrates the relationship between the details of experimental data and the complexity of the results of FE modelling of textile composites for the case of studies of elastic behaviour and damage initiation and development. The equivalent schemes for textile deformability and permeability are simpler, as these studies do not include damage (or other μ-scale) characterisation. For the former (deformability) the experimental data, apart from the characterisation of the textile, would include load/deformation diagrams from tensile (uni- or biaxial), picture frame, bias extension or compaction tests and the full-field measurement of meso-scale distribution of strains [3]. For the latter (permeability) the experimental data will be limited to values of the homogenised permeability.

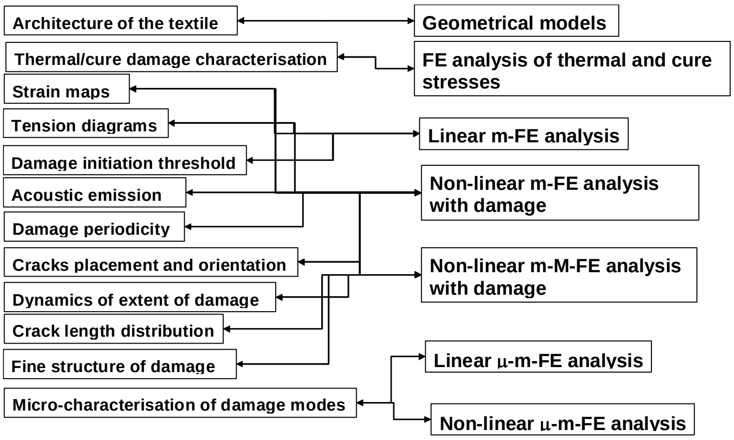

Figure 1 ***Experimental data for validation of meso-FE analysis of mechanical behaviour of textile composites*** **[4, 5]**

Attention should be drawn to the detailed description of the reinforcement structure and mechanical properties of the fibres. Characterisation of the reinforcement as “standard 5H carbon fibre”, which is common in some publications, cannot be used to create a FE model.

The testing methods for textile deformability and permeability are not standardised, hence the detailed description of the test method in these cases is of extreme importance. The same applies to the conditions of gripping of the composite sample on a testing machine and the extensometry technique employed, which is important for the assessment of the boundary conditions for the FE simulation.

Table 1 Preform characterisation: Minimum set of parameters

Woven or braided fabric	**Non-crimp fabric**
Areal density	Areal density
Weave / braiding pattern	Stitching pattern
Spacing of the yarns (ends/picks count)	Stitching periods
Linear density of the yarns	Material and linear density of the stitching yarns
Dimensions (width, thickness) of the yarns	

The second category refers to **input data for a finite element code and results of the simulation**. That is, complete numerical descriptions of the geometry (i.e. mesh), boundary conditions, etc. are provided. A potential user might have to write a translator to obtain the format needed, but no special tools are needed. The documentation would also include sample results obtained with the input data. The section on FE simulations would not necessarily provide complete detailed numerical input data for easy replication of the simulations, but it would include complete specification of the configuration. The type of results would depend on how the model is documented. For example, if a mesh is not provided, then nodal displacements are almost worthless, but a collection of deformed mesh plots and stress contours could be useful. If detailed input data is provided (such as the mesh), then useful information would include nodal displacements, stresses, strains, and integration weights and volumes at quadrature points. Data of this form could be postprocessed in various ways by persons who do not have the tools to actually perform the stress analysis. If smoothing techniques have been developed to postprocess the stresses and strains, then also including the smoothed data along with a description of the technique would be very useful.

The third category includes **numerical test cases**, designed to check the specific features of the FE models. Examples of such tests are:

- Problem of a degraded (damaged) “spot” in a UD reinforced material, used for testing damage propagation models [6]
- One-element test cases with one fibre direction used for testing the objectivity (or material indifference) of the approach at finite strains [7]
- One or few elements test cases used for testing the specific feature of textile simple shear (e.g. picture frame test) with two fibre directions [8]

4 ORGANISATION OF THE DATA BANK

The data bank “The Textile Composite Archives” will be hosted on a server at Texas A&M University. The bank will be a collection of data sets in a format defined by the research author(s) of the data. The entries will be organised by the nature of the textile reinforcement (2D and 3D woven, 2D and 3D braided, non-crimp, structurally stitched), with a special section for general numeric test cases. The organisation of entries within the sections will be “linear” directories structure with a cumulative table of annotations for the entries.

Before publishing, the data will be reviewed by a Steering Committee of the archive, to avoid publication of data not coherent with the aims of the archive, or unreliable data. The contents of the archive will be regularly reviewed by the members of the Steering Committee in scientific journals; comparative studies based on the archive materials will be encouraged. A discussion forum will be opened on the site.

5 EXAMPLES OF THE (FUTURE) DATA ENTRIES

5.1 Different types of woven structures (Texas A&M University)

Models of various weaves will be provided, such as those in Figure 2. This will allow others to explore possible similarities and differences in response (and metrics for describing response) due to the fibre architecture, and differences between these idealizations and other models that might be developed. For some of the weaves, the meshes will range from very coarse to quite refined, giving systematic convergence behaviour. Results will include displacements and quadrature point stresses and a few stress contour plots.

The usual descriptions of the geometry, material properties, etc. that one might find in a journal paper will be given. In addition, complete input files and documentation of the input and output will be provided, including the multipoint constraint information that allows one to exploit symmetries in the configurations. There are many details that can affect the results produced by a finite element model, especially for less refined meshes. Some are a bit subtle, such as the order of integration or the way in which stresses are smoothed when drawing contour plots. The goal will be to provide a complete description.

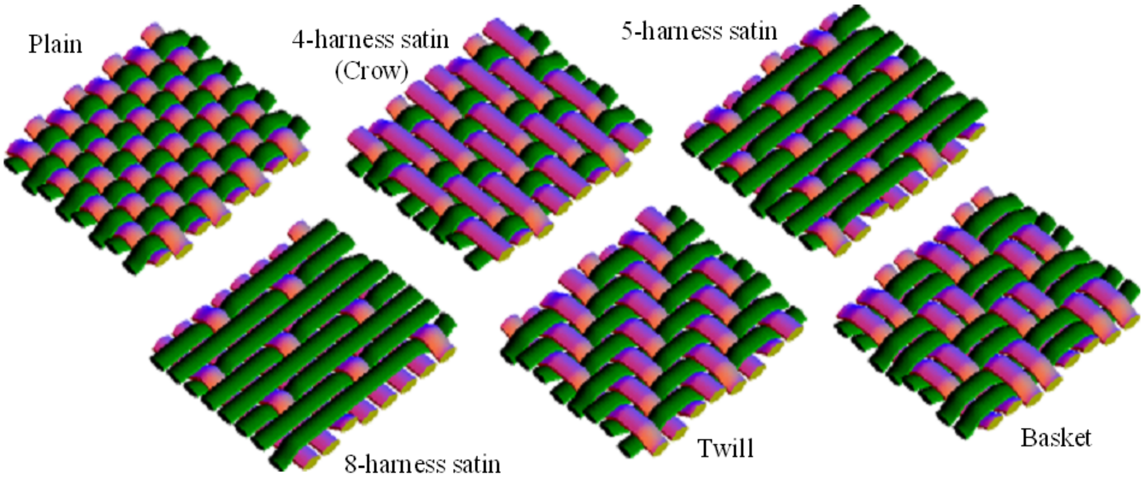

Figure 2 FE models of different weaves

5.2 Plain woven glass/polyester composite (University of Nottingham Polymer Composites Research Group)

As an initial submission to the databank, the University of Nottingham Polymer Composites Research Group intends to publish data relating to composites manufactured from a Vetrotex plain-woven glass reinforcement, RT600, by resin transfer moulding (RTM) using Reichhold Norpol 420-100 unsaturated polyester resin.

The reinforcement material is a balanced E-glass plain weave, having a weight of 600 gm^{-2}. Nominal dimensions of the weave are given in Table 2. Laminates of approximately 3.8 mm thickness were manufactured by RTM using seven layers of reinforcement, giving a nominal fibre volume fraction (V_f) of 0.42.

Table 2 Approximate measured geometric parameters of textile reinforcement.

Tow linear density, ρ_t (tex)	1200	Tow height, h_t (mm)	0.25
Tow width, w_t (mm)	3.0	Tow spacing (pitch), s_t (mm)	4.0

Data to be published will include geometric characterisation based on optical microscopy. Yarn outline shapes were recorded and averaged using an image analysis technique described by Ruijter in [9]; the processed images are shown in Figure 3a. Data from these measurements, which will be included in the databank, were used to define a suitable initial cross section for yarns in a TexGen [10] model of the fabric. This TexGen model, shown in Figure 3b, will also be made available.

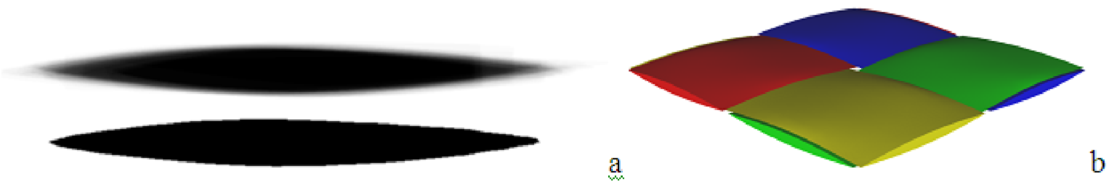

Figure 3 (a) Sum of 80 outlined yarn cross sections from a plaque made 2 layers of RT600 reinforcement, shown in greyscale (above) and, after thresholding, in binary [9]; (b) TexGen model of Vetrotex RT600 plain woven E-glass reinforcement [11]

Tensile test specimens were cut in the bias direction and tested to failure. Longitudinal strain was measured using a clip-on extensometer while transverse strain was obtained from a strain gauge. Stress-strain data will be published in the databank.

To illustrate the effects of draping, data from laminates manufactured using reinforcement subjected to in-plane shear deformation will also be published, showing the changes in mechanical behaviour resulting from the evolution of the meso-structure.

In the near future it is anticipated that results from finite element (FE) analysis of the repeating unit cell will be prepared for publication in a suitable form in order to present thorough validation with experimental data. In the longer term, data on mechanics of dry fabrics and on reinforcement permeability will also be published, as will data relating to other fabric architectures, including 3D weaves.

5.3 3-axial braided composite (K.U. Leuven)

3-axial braided carbon/epoxy composites were experimentally studied in tension tests with acoustic emission (AE) monitoring of damage and full-field registration of strain fields on the surface of the sample using the ARAMIS system. [4, 12]. The parameters of the composite are given in Table 3 and Figure 4.

Table 3 Parameters of carbon/epoxy 3-axial braided composite

Fibres	**carbon T700**	**Matrix**	**epoxy**
Diameter, µm	6.9	Young modulus, GPa	2.7
Young modulus, GPa	230	Poisson coefficient	0.4
Transversal Young modulus, GPa	14	Strength, MPa	70
Poisson coefficient	0.3	**Composite tensile specimens**	
Yarns	**24 K**	Number of layers	4
Linear density, tex	1600	Thickness, mm	3.09 ± 0.06
Thickness, mm, braiding/inlays	variable	Width x Length, mm	40 x 250
Width, mm, braiding/inlays	4.21 ± 0.21 / 3.75 ± 0.16	Fibre volume fraction, %	44 ± 1
Fabric	**Figure 3**		
Spacing between yarn centre lines, mm, braiding/inlays	5.03 ± 0.24; 9.25 ± 0.03 / 20		
Areal density, g/m^2	600		

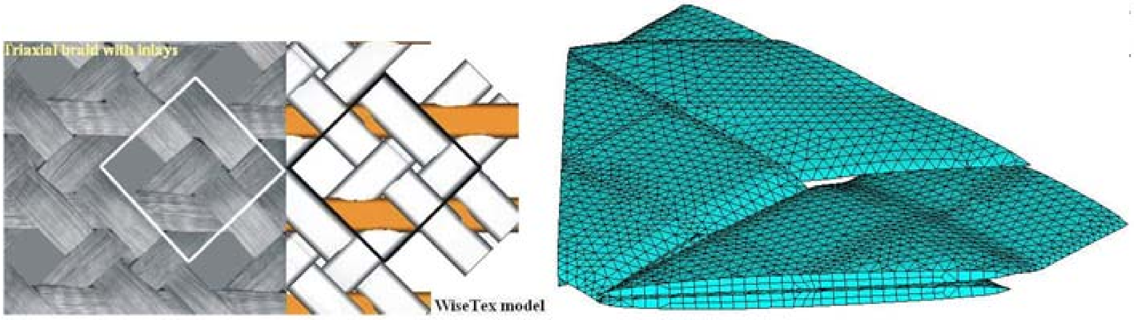

Figure 4 3-axial carbon/epoxy braided composite: photo, WiseTex model and FE mesh of the reinforcement

The measured and calculated data, which will be stored in the archive, include:

- Geometrical characterisation, based on microscopic measurements, and implemented in WiseTex model [13]
- Results of tensile tests, including surface strain fields and damage characterisation
- FE mesh (based on the geometrical model, corrected to exclude interpenetration of the yarn volumes), full FE problem, including periodic boundary conditions for ¼ of the unit cell

– Results of the FE analysis, including damage modelling.

5.4 In plane shear deformation of a glass plain weave (LaMCoS, Lyon)

The in plane shear strain is of main importance in preforming because it is the deformation mode that permits one to obtain double curved shapes. The mesoscopic simulation permits computation of an accurate permeability tensor [2]. The deformed shape could also be used for damage initiation within the composite with the deformed reinforcement. The specific mechanical behaviour due to the fibrous nature of the yarn is modelled using a hypoelastic law with an objective derivative based on the rotation of the fibre [7, 14]. The results of the computation are validated using experiments by the comparison of the computed and experimental torque obtained from the load on the texting machine in a picture frame test [14]. A more detail experimentation is obtained by the comparison of the local deformed geometry (Figure 5 and Table 4) with full field optical measurements [3, 15].

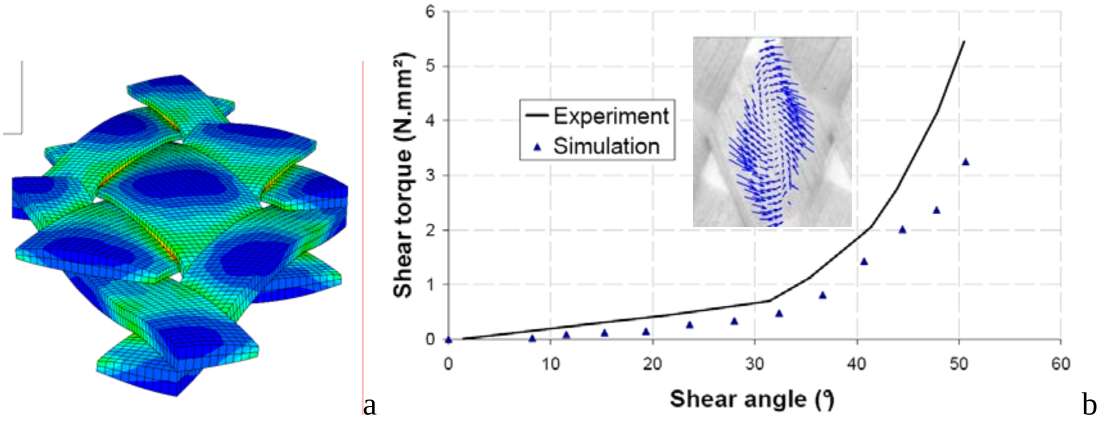

Figure 5 Shear of woven fabric: (a) Deformed unit cell. Plots of local compaction; (b) Experimental and numerical shear curve. Full field analysis of the mesoscopic deformation

Table 4 Balanced glass plain weave. Dimensions and material properties

Weave	Plain weave		Longitudinal Young modulus E_1 = 35400 MPa Transverse Young modulus E_2 or E_3 $2.5E-5.\varepsilon_{22}^2.\lvert\varepsilon_{11}\rvert+4.0$ MPa with i=2,3 Poisson ratios = 0; Shear modulus = 10 MPa
Yarn width, warp/weft, mm	3.2 / 3.1		
Ends/picks count, yarn/mm	0.251 / 0.248		
Crimp, warp/weft, %	0.5 / 0.54		
Areal density, g/m²	600		

6 CONCLUSIONS

The proposed data bank is expected to be operational by the end of 2008. We anticipate that the databank will function as a place to make results openly accessible to scrutiny and to enable the sharing of data to facilitate complementary research.

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