"BAM" – A Collaborative R&D Project for the Development of a Simulation Based Solution for the Design and Manufacture of 3D Woven Composites

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Abstract

Breakthrough Aerospace Materials (BAM) is a collaborative R&D project based in the UK [1]; led by industry and co-funded by the British Government via the Innovate-UK under its Aerospace Technology Institute (ATI) R&T Programme. The overall objective of BAM is to develop a complete process that will enable aerospace industry (and others) to design and manufacture complex shaped components using 3D woven composites. This material offers great advantages particularly for producing lightweight structures with high resistance to impact loading and damage - yet, there is still no evidence of it been widely adopted by industry!

It is agreed that one of the major reasons behind slow adoption of the 3D woven composites by industry is the lack of industrial simulation tools that can be used effectively by design and analysis engineers. A consortium consisting of 12 partners, involving 9 from industry and 3 from academia, was set up to work towards this goal over a period of three years. As it is less than a year since the kick-off of the project, this paper will mainly introduce the general approach for now - leaving the full demonstration of applying the developed technologies on industrial cases for follow up publications. However, a few independent illustration examples are still presented - while elaborating on the current status of development at various steps in the process and its associated challenges. The paper also aims to highlight the interdependence between industrial and academic partners for their success in pushing the required technology up the TRL (Technology Readiness Level) scale.

Two leading CAE software developers (ESI Group and MSC Software) are involved in BAM, and both are working on developing their own strategy to tackle the problem. The paper will elaborate on the approach adopted by ESI in particular, which is aligned with its global strategy for providing virtual end-to-end solution for composites product development.

1. 3D Woven Composites: advantages & challenges.

3D woven fabrics are typically comprised of multiple layers of warp and weft yarns which are bound together through the interweaving of binder yarns. The presence of the binder yarn enhances the through thickness performance of 3D woven composites, as it allows for through thickness stresses to be resisted by fibres [2, 3]. 3D woven fabrics offer a great solution for the two major drawbacks of composites structures in general (i.e. low through-thickness strength and high cost of production). It offers the ability to produce near net shaped preforms directly from the loom - significantly reducing part count and layup time (Figure 1)

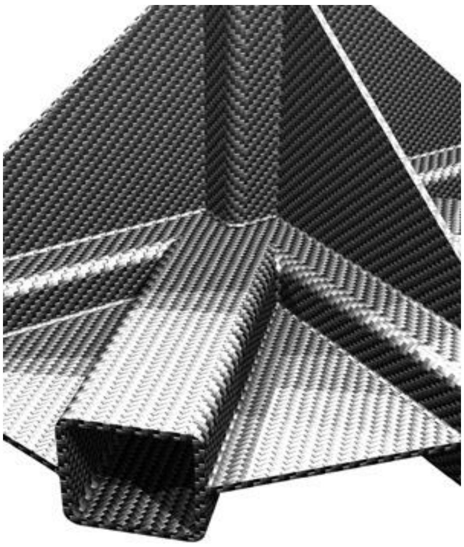


Figure 1: An example of a near net-shape structure made from 3D woven fabrics (provided by Sigmatex, based on their work in a previous project)

With the recent developments in complex 3D preforms, which have the geometry integrated directly into the textile architecture, 3D woven composites have the potential to become an optimal solution for complex structural joints.

However, the enhanced through thickness properties come at the cost of lower in-plane mechanical properties [4, 5]. A trade-off between in-plane and out-of-plane properties must be made - making the need for simulation tools to support design and development even more critical.

The simulation tools available commercially for composite simulation so far are mainly dedicated to laminated composites and not for 3D reinforced composites. In addition to the lack of such tools, there is also a lack of mathematical models that can address the behaviour of 3D composites. The practical way to simulate these materials is through the use of generic 3D anisotropic material models in association with extensive physical testing and measurements. Such an approach does not address the fundamental characteristic of the 3D composites. For example, starting from a single weaving pattern, one may have a very large number of effectively different patterns in the final manufactured part - due to the forming operations and related textile architectures deformations. For each pattern, there has to be an associated dataset for: permeability data, elastic data, failure data and for progressive damage evolution data. Hence the multi-scale approach, introduced in Section 3 below, was adopted in BAM as the computational-based approach to address the design and development of 3D-woven composite parts.

2. The Consortium and the Project in a nutshell

The consortium consists of 12 partners in total; Sigmatex is the coordinator and the two major end users are BAeSystems and Rolls Royce. In addition to Sigmatex, there are another two weavers (M. Wright & Sons, and Antich & Sons) who represent typical SME companies in the supply chain for aerospace (and other sectors) in the UK. Parts manufacturing will be carried out by Meggitt (who has joined the consortium recently as replacement of a previous partner), and QinetiQ is providing additional testing and expertise in composites and NDT.

Three world leading academic groups in their own fields, based at the Universities of: Bristol, Manchester and Nottingham are supporting the development and validation of both simulation and manufacturing challenges addressed throughout the project. The individual contribution of each academic team will become clearer while elaborating on the adopted approach in Section 3, and testing and validation in Section 4.

Both of the CAE software developers (MSC Software and ESI Group) are, more or less, following the same philosophy by adopting the multi-scale approach. MSC is building their solution based on Digimat Software [6], whilst the major new developments carried out by ESI are based on their Virtual Performance Solution (VPS) software package [7]. ESI will also be utilising some of the off-the-shelf existing capabilities under its PAM-COMPOSITES package to address aspects related to forming, permeability and resin infusion processes in collaboration with some of the academic partners.

Simulation of the weaving process itself is out of scope in BAM, and the developed tools will accept any fabrics architecture as designed by external software, such as TexGen, or directly from 3D images tomography. The project however will focus on two main styles of weaving, i.e. layer to layer and angle interlock.

3. Computational-based approach as adopted in BAM

The challenge associated with simulation and modelling of 3D reinforced composites is to be able to capture the great wealth of details found in the 3D textile architecture during and following the various manufacturing operations and then to use such complex information in standard homogenised FEA models. A multi-scale approach is therefore necessary. The natural vehicle for such an approach is the virtual characterisation of the material for the impregnation process and for the mechanical behaviour based on a description of the local reinforcement architectures resulting from the initial weaving and from the deformation preforming process.

Such a virtual characterization of the mechanical properties of 3D textiles is crucial for the effective performance analysis at the early design stage. It allows for significant reduction in costs by saving lots of experimental testing.

The sub-sections below describe this approach in action throughout the manufacturing steps until the simulation of the mechanical performance of the final product.

3.1 Geometrical modelling of the weave patterns

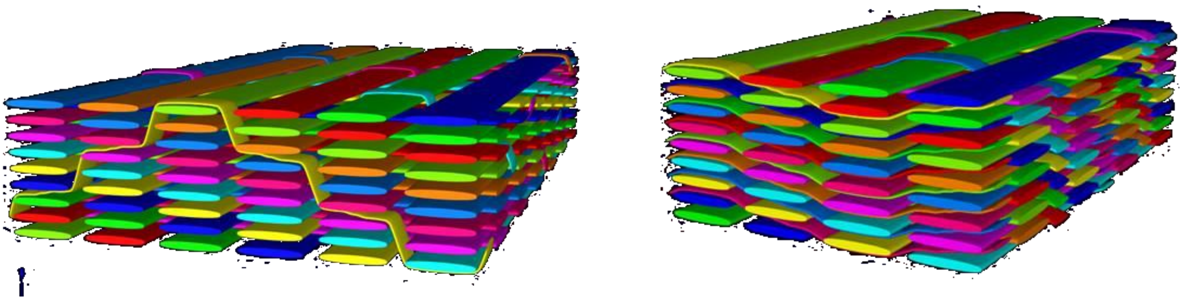
Modelling the geometry of the weave pattern (referred to as the 3D fabrics, or the textiles, in this paper and wider literature) is an essential step of the “pre-processing stage”. An idealised 3D geometrical representation of the textile is created to form the computational model of a representative “unit cell” (RVE, Representative Volume Element) that can be used eventually for:

- Modelling the mechanical properties of fabrics for determining forming behaviour
- Predicting the permeability of fabrics for processing of composites.
- Modelling the mechanical properties of composite parts and their damage behaviour for use in engineering applications

The open-source software TexGen [8], developed at the University of Nottingham, has been adopted here. Textiles are modelled within TexGen by specifying: (A) yarn centrelines and (B) cross-sections along the length of those yarns. From these the yarn surfaces are generated, building up the 3D model of the textile. In order to create realistic models cross-sections can be varied along the length of the yarn and can be either predefined shapes such as ellipse, power ellipse or lenticular, or can be a polygon defined by a set of points. The geometrical modelling theory is described in more detail by Long and Brown [9].

Idealised textile models for the 3D weaves used in the BAM project, including layer-to-layer and angle-interlock weaves, can be generated quickly using the 3D wizard built into the software (Figure 2). Alternately a Python API both allows complex models to be created using Python scripts, and allows integration with external FEA packages.

During a previous project functionality was built into TexGen, based on observations from µCT images of textiles, to automatically refine idealised geometries of 3D orthogonal weaves, thus improving the accuracy of predictions generated using the models [10]. Observations from the 3D textiles fabricated during the BAM project will allow similar refinements to be implemented for these types of textiles.



(A) *(B)*

Figure 2: Idealised TexGen models: Angle Interlock (A), and layer-to-layer (B) textile

3.2 Forming and prediction of deformation

A major source of the in-plane property degradation in 3D woven fabrics is the crimp and waviness induced by the presence of the binder yarns, which is a result of the weaving, in forming and consolidation processes [11]. For traditional numerical modelling techniques this constitutes a significant challenge as the material can lose its periodicity and hence the material behaviour can no longer be assumed to be constant across the structure. For complex 3D preforms, this issue is magnified as non-periodicity is woven directly into the textile architecture. Consequently, new modelling approaches must be developed that are capable of predicting the mechanical performance of the 3D woven composites on the structural scale, while taking into account the internal deformations present at lower scales. The first step in achieving this is to develop tools that are able to predict the deformations to the 3D textiles induced during weaving of the textile and manufacture of the final composite structure.

Existing methods for modelling 3D composite structures focus on the unit cell scale, which include an idealised representation of the textile architecture, and are used to characterise the behaviour of the periodic composite structure. The behaviour can then be homogenised and exploited in higher scale structural simulations. A limitation of many of these unit cell methods is the analytical assumptions made for the yarn geometry, which is unable to accurately capture the yarn deformations during weaving and compaction. This results in inaccuracies developing at an early stage of the modelling process.

When the homogenised properties are then employed in the higher scale structural simulations, the assumption is made that the material behaviour is constant across the structure, and hence, does not consider any local deformations, or relative displacements of yarns, which may arise due to the forming of the textile into three dimensional structures. The extent of these deformations can result in significant changes to the internal architecture, causing a loss of periodicity and a degradation in properties at critical geometric features, making the assumption of constant material behaviour an oversimplification.

The Team at the University of Bristol has dedicated a substantial research effort to developing modelling tools to predict the as-woven and compacted 3D woven architectures at the unit cell scale [12, 13]. This kinematic modelling method approximates the weaving process of the textiles through yarn tension and, with the use of contact models, is able to simulate the complex interactions between fibres and yarns to make accurate predictions of the 3D textile geometry (Figure 3). This method has been used extensively as a pre-processor for the acquisition of the textile architecture for mechanical modelling of the composite unit cell [14, 15]

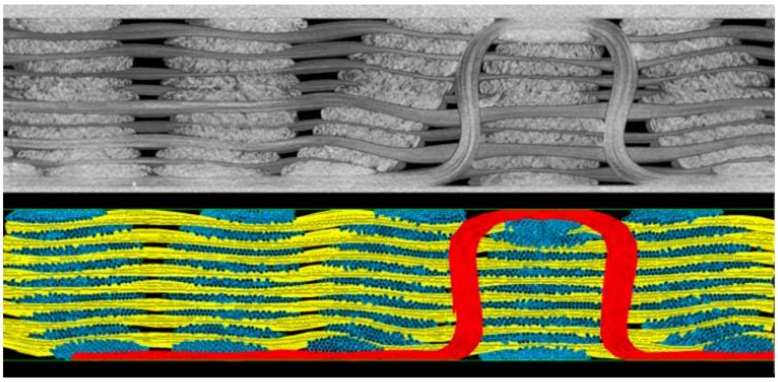


Figure 3: Compacted 3D orthogonal woven fabric, comparison between CT-Scans and predictions made by the kinematic modelling approach

By tessellating the unit cell geometry and meshing the yarns as single surfaced entities a method for simulating larger scale forming processes has also been developed [16]. This enables the interaction of the textile with complex tooling geometry to be simulated, allowing for predictions of the deformed textile structure to be made at the yarn scale (Figure 4). While these methods have shown to be very effective for simulating planar textiles, their development to simulate the forming and compaction processes of complex preform architectures has yet to be addressed.

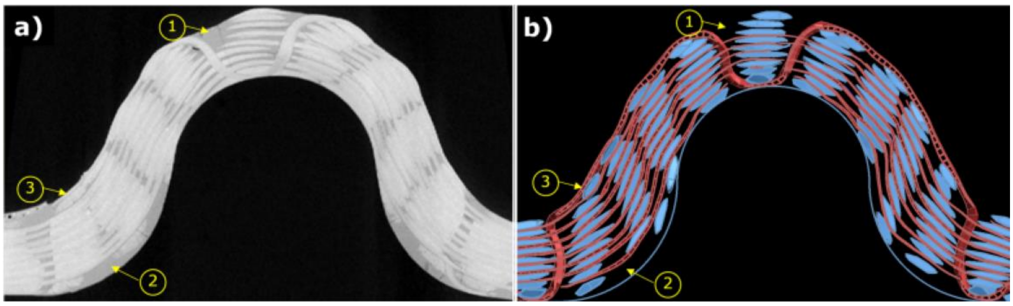


Figure 4: Forming and compaction of 3D orthogonal weave over humpback tool, comparison between CT-Scans and structural scale forming simulation.

This is a significant challenge as the current methods rely on the periodicity of the weaving process as input to generate the initial as-woven geometry. As complex 3D preforms have non-periodicity woven directly into their architecture, the ability of these existing methods to simulate the processing of complex 3D preforms is limited. As part of the BAM project, the University of Bristol will therefore be developing capabilities to simulate these non-periodic preform architectures and the subsequent deformations that may occur during processing. These methods will not only form a foundation for the development of high fidelity mechanical models of the composite structure but will also be able to aid in the design and development of new complex preform architectures.

3.3 Permeability and impregnation

In the manufacture of (thick) composite components with 3D woven reinforcement, Liquid Composite Moulding (LCM) processes are typically employed to impregnate the dry reinforcement with a liquid thermoset resin system. Once the reinforcement is impregnated, the resin matrix is cured to solidify, and the component can be finished. The relation between the applied flow-driving pressure gradient and the resin flow velocity during the impregnation stage, i.e. the ease of reinforcement impregnation, is described by the reinforcement permeability. The permeability determines resin flow patterns, which need to be optimised (e.g. through appropriate placement of resin injection gates and vents in the tooling) to achieve complete impregnation of the reinforcement, and the process cycle time. Hence, it is a parameter with high practical relevance for application of LCM-technology in industrial production.

Characterising the reinforcement permeability is a pre-requisite for running numerical simulations using software packages such as PAM-RTM, part of the PAM-COMPOSITES suite from ESI [17], to predict the outcome of impregnation processes at the component-scale (Figure 5). For this project, the in-plane permeability of 3D woven fabrics is determined in unsaturated radial flow experiments at constant injection pressure, based on measurement of the flow front position as a function of time along three co-planar axes. The through-thickness permeability is measured in saturated unidirectional flow experiments at constant flow rate. Previous experimental results showed that impregnating resin flow is more complex for 3D woven fabrics than for thin fibrous structures because of the presence of additional through-thickness yarns.

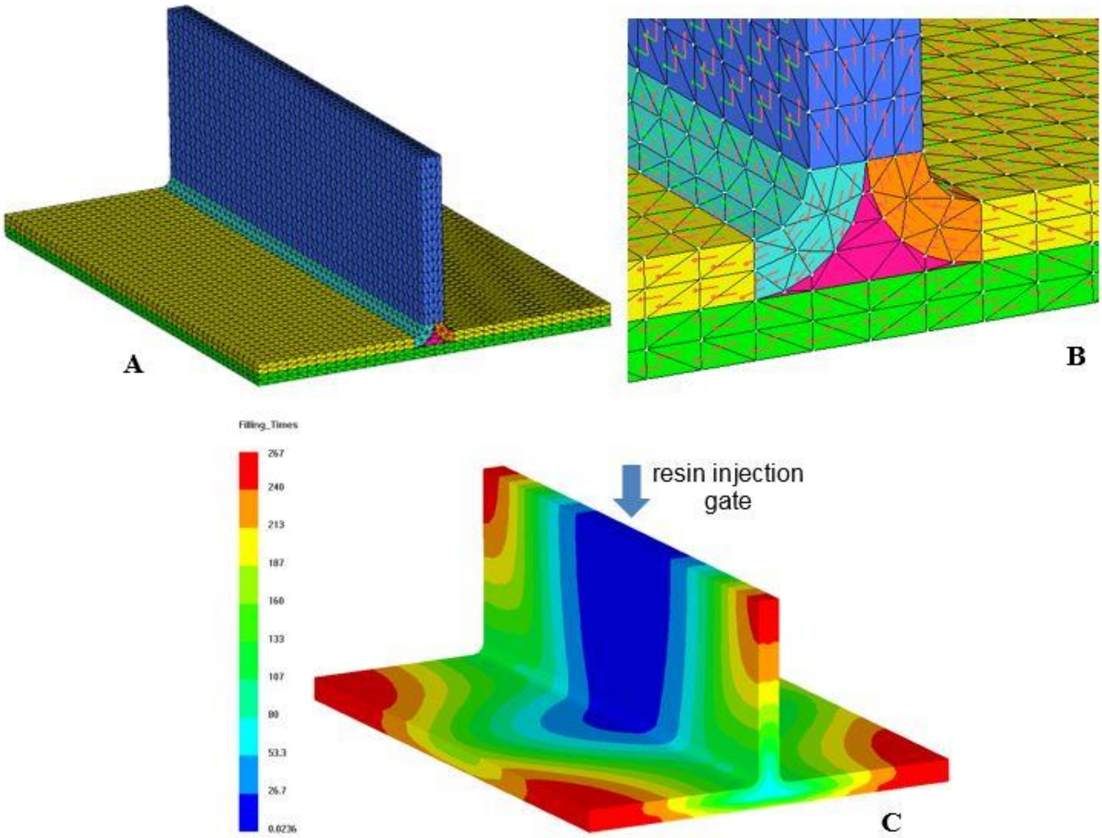


Figure 5: An illustration of the simulation of infusing one of the sub-components in BAM (T-joint) using PAM-RTM – based on permeability values determined experimentally; (A)3D mesh of the T-joint geometry; (B) geometrical detail with material orientations; (C) resin flow fronts at different injection times.

Alternatively, representative geometrical parameters for 3D woven fabrics are quantified experimentally, and unit cell models are generated at a high level of geometrical detail, including systematic local variations in yarn paths and yarn cross-sections. These unit cell models are used for Computational Fluid Dynamics (CFD) simulation of resin flow through the pore network formed between fibres in the fabrics, which enables numerical prediction of the reinforcement permeability without the need to conduct flow experiments (Figure 6). This method was found to give results with good accuracy [18], to be used then for simulating the impregnating processes of complex shaped parts. It can also be used to develop a better understanding of how the microstructure in the reinforcement and its variability affects the permeability. This would allow analytical permeability models to be derived and would help to inform weavers on fabric design.

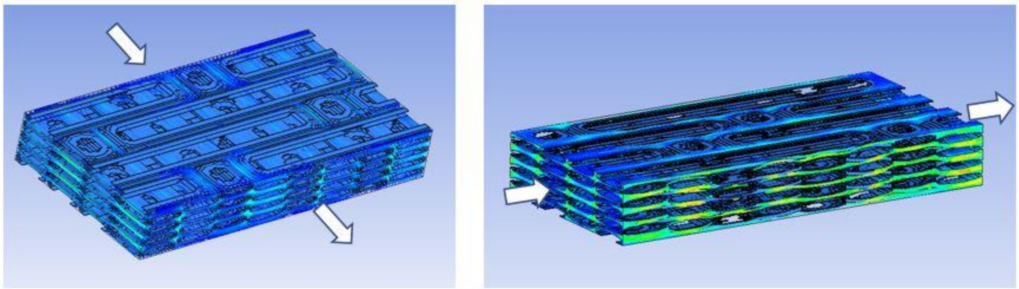


Figure 6: Illustration of a typical CFD results (flow velocity of the resin in-plane) based the unit cell of the Layer-to-Layer weaving design proposed by Sigmatex.

3.4 Effective mechanical properties

This section, describes the method used for Material Virtual Mechanical Characterisation within the global multi-scale approach. Based on models of the local material structure, as described in the previous sections, and on the mechanical properties of the individual constituents, the method can predict effective properties through simulation.

The prediction of effective mechanical properties for the local heterogeneous material structure requires the definition of an averaging assumption. For the derivation of effective elastic properties this can be accomplished using Hill-Mandel condition [19, 20]. It is an energy equivalence theorem, which relates local effective virtual work on the macroscale (M) to the volume average of the variation of work on the sub-scale (m)

$$\boldsymbol{\sigma}^{\mathrm{M}}:\boldsymbol{\delta\varepsilon}^{\mathrm{M}} = \frac{\mathbf{1}}{\boldsymbol{V}^{\mathrm{RVE}}}\int_{\boldsymbol{\Omega}^{\mathbf{RVE}}}\boldsymbol{\sigma}^{\mathrm{m}}:\boldsymbol{\delta\varepsilon}^{\mathrm{m}}\boldsymbol{dV}.$$

It can be shown that for certain boundary conditions, namely constant traction, linear displacement or periodic displacement, the macroscopic virtual work can be calculated from the product

$$\sigma^{\mathbf{M}}:\boldsymbol{\delta}\varepsilon^{\mathbf{M}} = \langle\sigma^{\mathbf{m}}\rangle:\langle\boldsymbol{\delta}\varepsilon^{\mathbf{m}}\rangle$$

of the averaged stress- and strain-field on the subscale

$$\langle \sigma^{\mathrm{m}} \rangle = \frac{1}{V^{\mathrm{RVE}}} \int_{\Omega^{\mathrm{RVE}}} \sigma^{\mathrm{m}} d\boldsymbol{V}, \qquad \langle \boldsymbol{\delta} \varepsilon^{\mathrm{m}} \rangle = \frac{1}{V^{\mathrm{RVE}}} \int_{\Omega^{\mathrm{RVE}}} \boldsymbol{\delta} \varepsilon^{\mathrm{m}} d\boldsymbol{V}.$$

Motivated by the periodicity of the reinforcement structure of the considered 3D textiles, periodic displacement and antiperiodic traction boundary conditions are used for the determination of the effective elastic properties.

This approach has already been implemented in the finite element package ESI Virtual Performance Solution (VPS). The subsequent determination of elastic properties is obtained through analysing the RVE response for a set of six deformation modes (Figure 7). The quality of the prediction has been analysed in the 1st level of the Micromechanics Challenge organized by the *Composite Design & Manufacturing Hub* (cdmHUB) [21]. It has been recorded that the VPS' prediction of effective elastic properties shows good results for a variety of different composite structures [22].

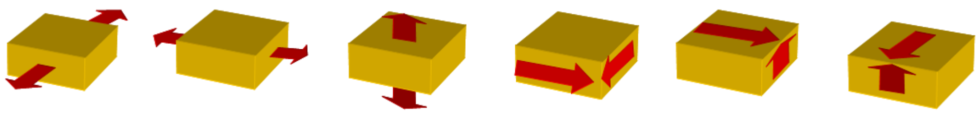


Figure 7: Six deformation modes used to predict the effective elastic stiffness.

3.5 Failure analysis

Besides the prediction of stiffness properties, the multiscale framework can be used to analyse effective failure and damage properties. To this end, characteristic failure phenomena need to be taken into account. On the meso-scale these are fibre breakage, fibre-matrix debonding and matrix cracking. Using existing FEA packages this can be done in a routine way for unidirectional, NCF and woven fabrics composites [7]. ESI's further work during the next two years in the BAM project will focus more on the development and validation of a new failure criterion for 3D woven composites.

4. Testing and validation

Whilst there is an extensive list of publications available on testing 2D laminate, the amount of work reported to date for 3D woven composites is very limited [23 - 25]. There are a number of challenges associated with testing 3D woven composites in general - particularly when it comes to measuring out of plane properties. Addressing all these challenges and carrying out a comprehensive set of tests, considering various weaving architectures and impregnating processed, could easily qualify for another R&D project beside BAM!

The team from University of Manchester has direct access to the National Composites Certification and Evaluation Facility (NCCEF), which is an independent ISO 17025 accredited test laboratory and has been accredited by the United Kingdom Accreditation Service (UKAS) as well. There is a wide range of facilities and expertise available at the NCCEF for mechanical and impact testing, ballistic impact, non-destructive testing, and material characterisation. This team, in collaboration with the project partners, has compiled an extensive list of tests – making sure that all essential data needed to validate the developed simulation tools, as well as to demonstrate that the designed/ manufactured materials will meet the requirements of the End Users, are available.

All necessary properties for the constituent materials (fibres and matrix) are to be made available directly by the material supplier. The 'test-matrix' itself in BAM aims to do the tests at several levels starting from the coupon level and then moving up to features, sub-elements and, potentially, full demonstrators. Feature profiles to be considered in BAM include I, T, Pi, L, and Trapezoid. Coupon tests include: in plane tension and compression for both solid specimen and with open hole, through-thickness tensile strength & modulus, in plane shear, double notch shear, apparent strain energy release (mode I, II and mixed), single and double shear bolt bearing.

Most of the coupon specimen have already been manufactured by now, and a few in plane compression and tensile tests are just being finalised at the time of writing this paper. Figures 8 and 9 below show early results from the coupons tested for in plane compression and in plane tension. These samples were fabricated using a layer-to-layer weaving architecture with 6 warp and 7 weft layers based on Hexcel IM7 tows and impregnated with Hexcel RTM6 resin.

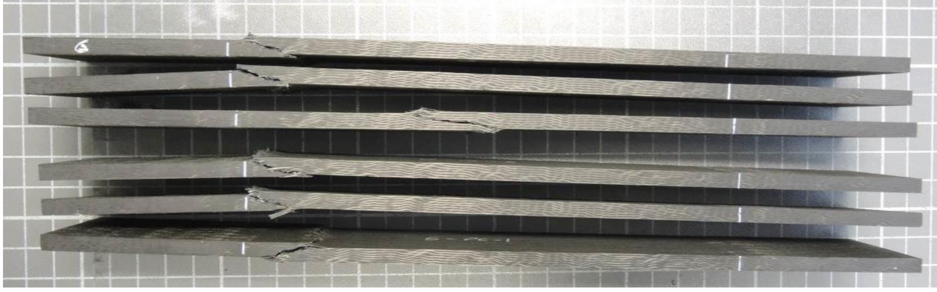


Figure 8: An example of the coupon tests (in plane compression).

Figure 9: An example of the coupon tests (in plane tensile).

In a first analysis trial case, an idealized model of the Layer-to-layer material structure has been generated using TexGen (Figure 10).

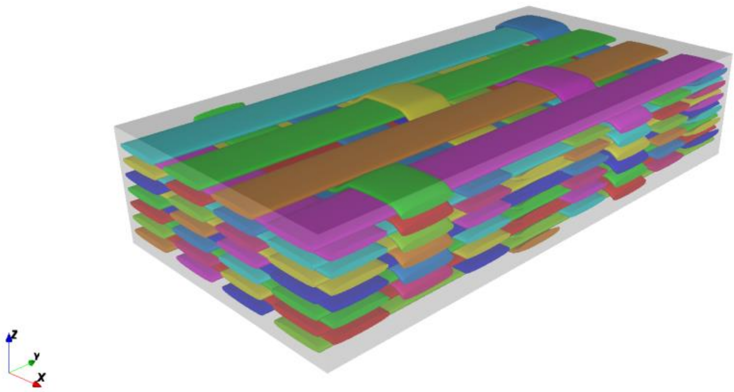


Figure 10: Illustration of the Layer-to-layer unit cell (designed by Sigmatex using TexGen)

The geometrical model has been further processed using ESI VPS to perform a FE based homogenization according to the approach given in section 3.4. The resulting local deformation of the RVE undergoing the six deformation modes can be seen in Figure 11. These results are here for illustration purposes more than thorough comparison and validation, which is to follow up in future publications.

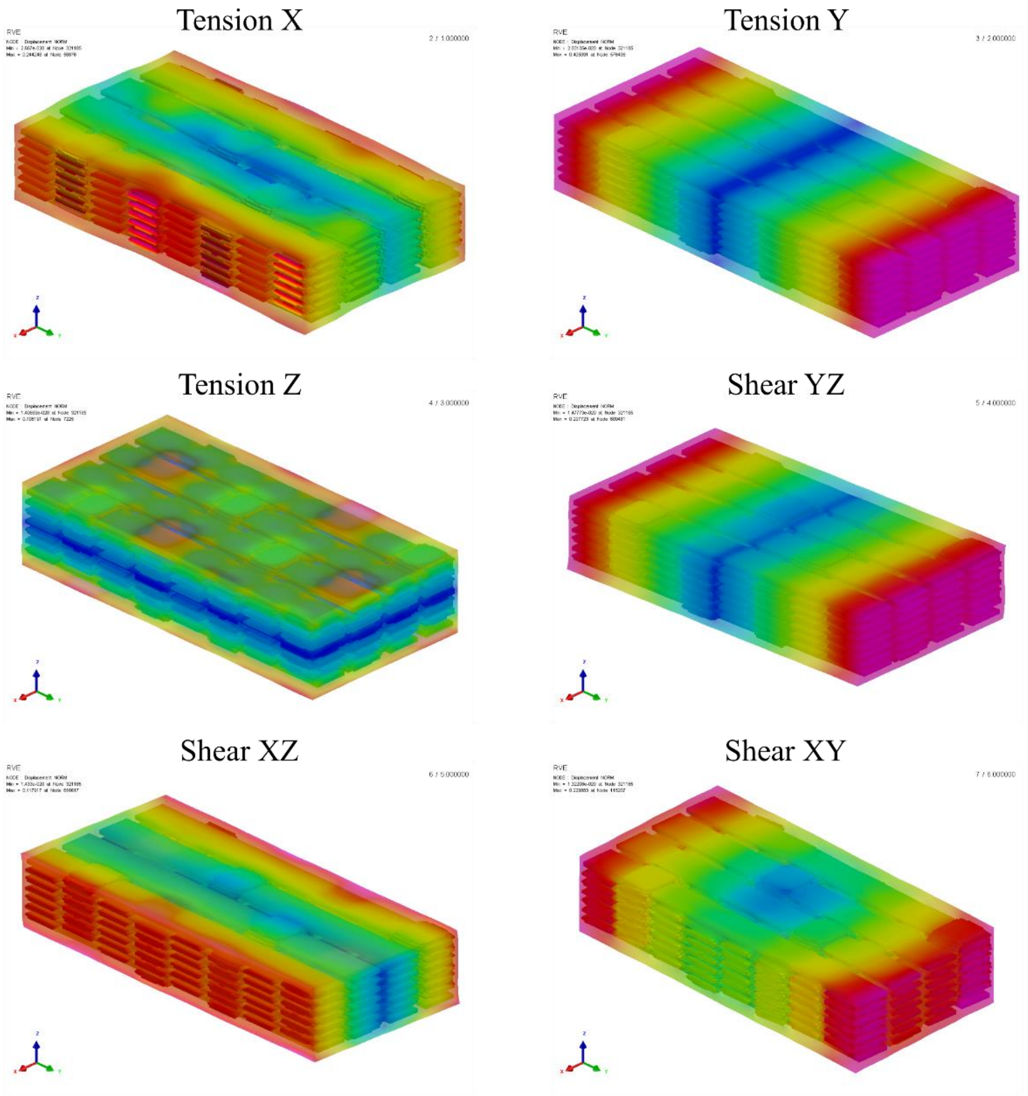


Figure 11: Deformation of the Layer-to-layer unit cell during FE based homogenization in ESI VPS.

5. Conclusions

Motivations behind building the BAM consortium, and the demands that industry has for developing dedicated simulation tools to be used in the design and manufacture of 3D reinforced composites, were discussed. The balanced structure of the consortium was highlighted – showing the effective outcome from combining forces between academia and industry.

An overview of the general approach adopted to address the challenge was presented at a high level – considering that the project is still in its first year. A few illustration examples were shown while elaborating on the individual steps involve in the multi-scale solution for material virtual characterisation. Early results from the simulation carried out by ESI on an RVE associated with a case of layer-to-layer weave were presented. Initial comparison against coupon tests for in plane compression/ tension behaviour looks very encouraging, and the authors look forward to presenting more details at the conference in June and future publications.

Acknowledgments

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