VIRTUAL DESIGN OF TEXTILE COMPOSITES STARTS ON A FILAMENT LEVEL

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Abstract

As a result of lightweight motivated engineering, continuous textile reinforced composites came into the focus of research. When using continuous textiles for reinforcement, such as woven fabrics made of technical high performance fibres (carbon, glass or aramid), the composite mechanics can be regarded as a function of the textile's mechanical behaviour. A reliable development chain of textile reinforced composite materials has to be flexible, fast and cost-effective [1]. For this reason, a virtual development chain for structural parts made of composite material is aspired. On the basis of the geometrical structure of a woven textile, a numerical model based on finite elements was developed, which accounts for the correct mechanical behaviour of the textile structure regarding the anisotropy and the non-linearity [2]. The textile micro-scale model was used directly for composite calculations by coupling its structure into the isotropic matrix model [3]. The mechanical behaviour of the introduced composite model was found to match the analytical composite theory very well. This effort enables purposeful composite developments and reduces trial-and-error experiments which can be identified as the most time and cost consuming part of the composite development chain.

1. Introduction

The use of textile reinforced composites made of continuous technical textiles and thermoplastic or thermoset matrix material is very advantageous in many applications. The mechanical properties of the composite material result mainly from the properties of the reinforcement fraction, especially its geometry and the mechanical behaviour of the textile fibres themselves. Since composite materials are used in high performance applications, numerical models for simulating the complex and anisotropic behaviour are developed. The developed models become more and more detailed which is mainly owned by the increasing computational possibilities and the decreasing calculation costs.

Models for textile reinforced composite materials can be realized at different levels of objectivity, just like numerical models of the textile material itself. Macroscopic models are very well known and they are used for mechanical simulations of composite materials and their failure behaviour [4]. They are used with shell [5] or solid elements [6] and are able to predict the mechanical behaviour under different load cases. Macro-scale models are advantageous due to their calculation efficiency. However, all mechanical parameters have to be measured in actual mechanical tests, which is time and cost consuming. Models with a higher resolution of the fibrous structure were developed on the meso- [7] or micro-scale [3]. Their difference lies in the way how the multifilament yarns are represented. These models are able to represent the actual geometry, the volume fraction and the mechanics of the reinforcement fibres. Therefore, they are suitable for parameter studies concerning the reinforcement textile. Different weave patterns [8], effects of compaction [9] or process caused deflections of the fibres[10] can be analysed. Actual mechanical tests can be reduced to the general identification of the mechanical behaviour of the reinforcement fibre and the matrix material. However, the textile

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construction significantly influences the resulting mechanical behaviour. Therefore, the correct modelling of the textile geometry, which is mainly represented by the trace of the fibres and the correct reproduction of the textile structure, is the challenging task when using meso- or micro-scale composite models. Examples of the different levels of objectivity for textiles and textile reinforced composite materials are given in Figure 1.

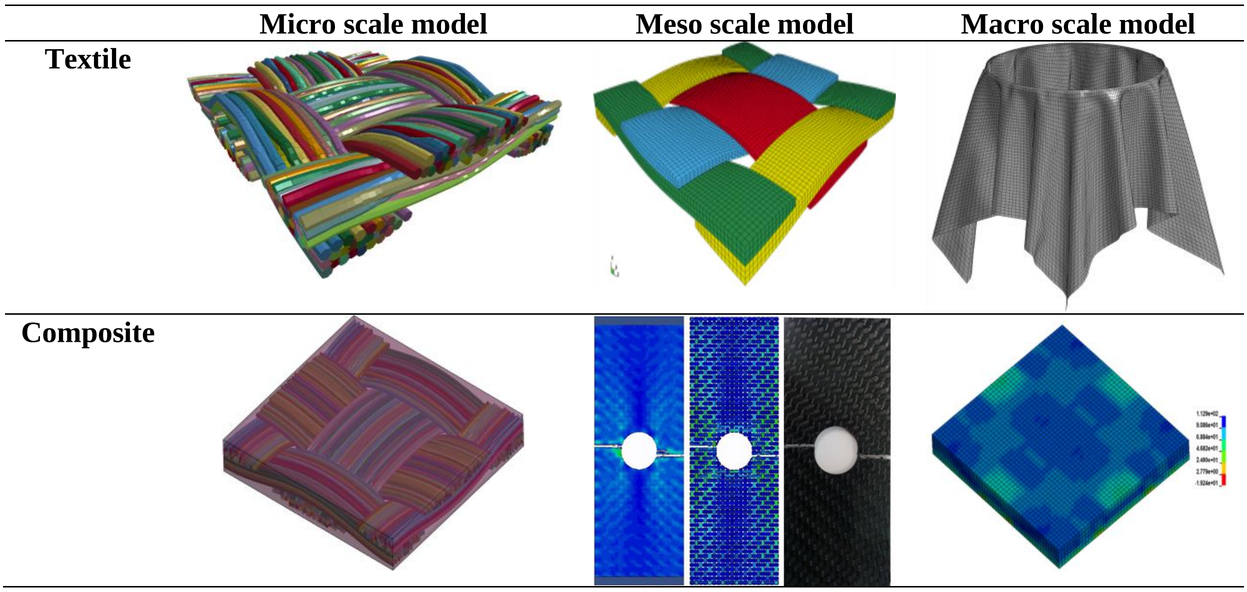
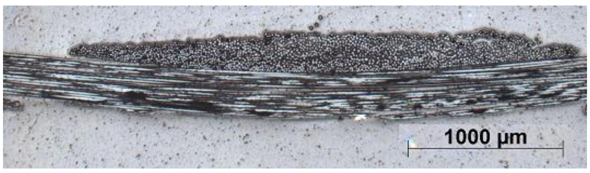


Figure 1. Levels of objectivity in textile and composite modelling

2. Material

The results presented in this paper are obtained by analysing a plain woven fabric made of 900 tex glass multifilament yarns (900 tex EC-GF) as described in Section 3. Geometrical data were obtained by optical analyses of scanner and micrograph images. The results of the optical analysis of the examined fabric and the used yarn material are presented in Table 1. The geometrical parameters are used as input values for the construction of a representative volume element (RVE).

Table 1. Glass yarn characteristics and examined plain woven fabric

	Material properties		Microscope and scanning images
Yarn Material: 900tex EC-GF	Yarn height weft	0.268 mm	
	Yarn width weft	3.172 mm	
	Yarn height warp	0.302 mm	
	Yarn width warp	2.826 mm	
	Cross-section weft	2.665 mm²	
	Cross-section warp	2.678 mm²	
Fabric material: Plain woven fabric	Fabric thickness	0.552 mm	
	Crimp weft yarns	0.345 %	
	Crimp warp yarns	0.173 %	
	Weft distance	~3.33 mm	
	Warp distance	~3.63 mm	

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3. Micro-scale modelling

3.1. Textiles

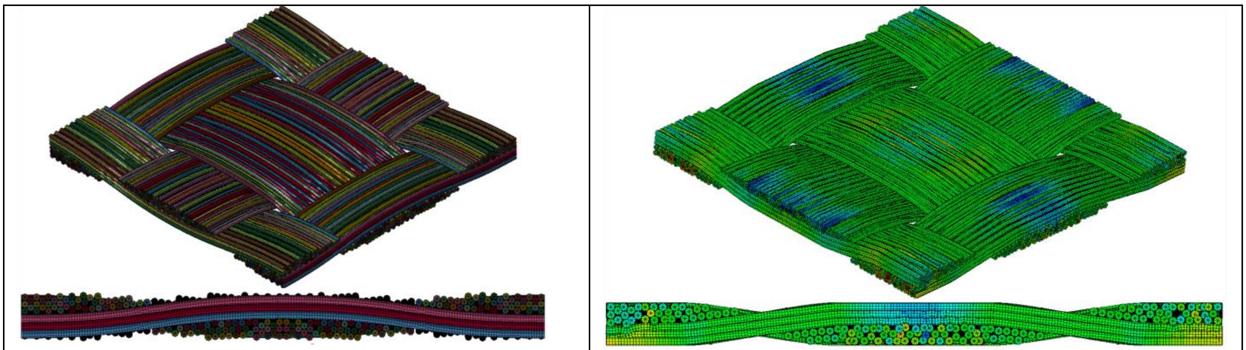
Modelling textiles on the micro-scale rather than the macro-scale, requires knowledge of the textile construction itself, the yarn geometry, and the yarn mechanical behaviour. Textiles manufacturing parameters can be taken into account [2] to generate a virtual model, which behaves like the aspired textile material. This method was used for the modelling of the textile material introduced in Section 2. To account for the characteristic textile behaviour, the digital element approach [11] was used which neglects the bending stiffness of every single fibre in the model. Due to the very small bending stiffness found in textile materials, this can be regarded as consequential simplification. A discretization of 70 fibres per multifilament yarn was chosen. This amount was found to be efficient and very good results were achieved with this level of detail [12]. The different steps of the generation process of the plain woven fabric are shown in Figure 2.

a) Initial configuration	b) Prescribed configuration	c) Static equilibrium (final model)

Figure 2. Micro scale unit cell of the plain woven fabric

3.2. Composites

The created micro-scale model is used for composite calculation, development and optimisation. For building micro-scale models of textile reinforced composite materials, the introduced micro-scale model for textile materials cannot be used directly due to geometry changes during composite manufacturing [13]. The infiltration process and especially the consolidation process are characterized by large out-of-plane displacements of the initial textile construction. Therefore, the compaction of the textile has to be considered. This step is necessary to account for the correct composite mechanics, which are mainly influenced by the geometry of the reinforcement textile. But it also enables a study of the process parameter influence, since consolidation processes are performed under different atmospheric and tool induced pressures. An example of a textile compression simulation is given in Figure 3 for the introduced plain woven fabric loaded by the pressure of one atmosphere.



Initial plain woven unit cell	Compaction of unit cell by 1 atmosphere

Figure 3. Simulation of textile compaction

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After creating a model of a compressed micro-scale textile, the obtained micro model of a compacted textile is implemented into a solid element model that represents the isotropic matrix material. A binary micro model of a textile reinforced composite results from the kinematically coupling as shown in Figure 4. An example of such a model is displayed in Figure 5. Here, the model itself with matrix fraction and the containing reinforcement fibres, the stress occurring in the composite under in-plane tension and the forces in the reinforcement fibres are shown.

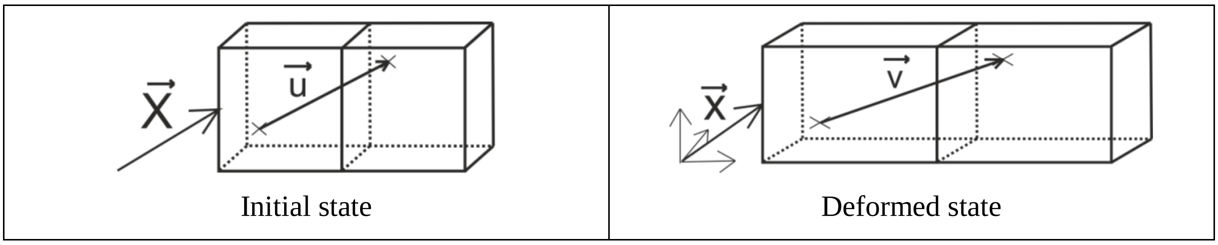

Figure 4. Scheme of kinematically coupling beam elements in solid elements

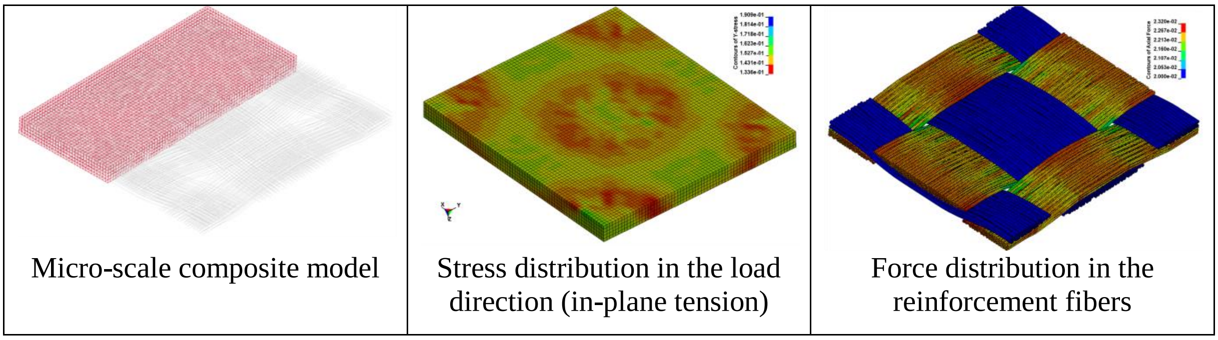

Figure 5. Results of micro-scale composite modelling

4. The virtual development chain of textile reinforced composite materials

Micro-scale models for textile structures enable several possibilities in virtual analysis. Since a high detailed model of the textile structure is available, properties such as yarn deformation, fabric porosity, forming induced deformation and failure analyses are possible. Despite the numerical effort, micro-scale models of textile structures are useful in the composite development chain since textiles process parameter studies are enabled and the influence of changing manufacturing parameters on the mechanical behaviour can be examined on a virtual level. In Figure 6, the mechanical in-plane tensile properties of the introduced plain woven fabric are shown, manufactured according to the parameters shown in Table 1 (grey plot) and with modified manufacturing parameters (increased warp yarn tension, blue plot).

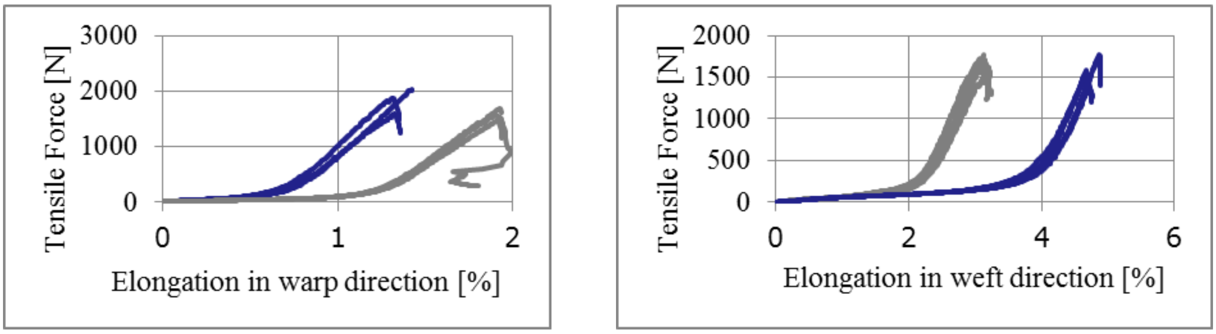

Figure 6. Example of process parameter influence on textiles mechanical properties

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It is obvious that the manufacturing parameters have a great influence on the resulting mechanical properties of the reinforcement textile as well as on the composite material. These effects cannot be examined visually, but must be investigated by extensive mechanical tests. Micro-scale models created with process parameter related methods are able to account for such effects and are able to benefit from this information at virtual composite investigations.

Virtual development chains enable a flexible and efficient way of material examination. Validated models can be used for structural calculations and gathered information can directly be attributed to the manufacturing process. A scheme for an iterative composite development chain, supported by numerical tools which enable a virtual development chain is shown in Figure 7.

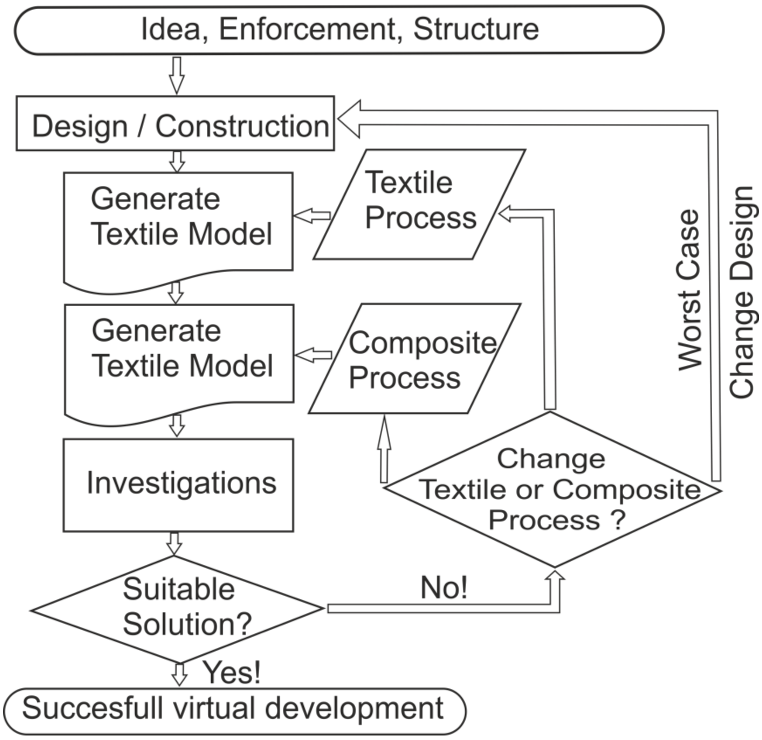

Figure 7. Virtual development chain for composite materials

According to this development chain, the influence of different parameters included in the development chain have been analysed to investigate the effect on the composites in-plane tensile modulus. The material introduced in Section 2 was modelled for the use in numerical finite element simulations. On a pure virtual level, process parameters of the textile manufacturing process have been changed. Higher warp yarn tension was applied and, thus, mechanical in-plane behaviour according to the blue plot in Figure 6 was achieved. It is obvious that the difference in the mechanical behaviour cannot be examined visually. As a factor that represents the influence of the composite manufacturing process, the textile compaction, as shown in Figure 3, was changed from 0 bar to 1 bar compaction pressure which represents the use of the vacuum assisted resin infusion (VARI) process (1 bar) or a simple hand layup procedure (0 bar). The results for the in-plane Young's moduli in function of the manufacturing parameters are shown in Table 2. For the composite reinforced by the source textile (Table 1) and manufactured by the VARI method, actual measured composite properties are added for model validation purposes.

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Table 2. In-plane composite properties (Source textile according Table 1)

	Source textile		Modified textile	
Hand layup	$E_{0,sim}$ = 13.2 GPa	$E_{90,sim}$ = 14.5 GPa	$E_{0,sim}$= 14.6 GPa	$E_{90,sim}$= 13.8 GPa
	Fibre volume content = 0.51 $\%_{Vol}$ Composite thickness = 0.6273		Fibre volume content = 0.51 $\%_{Vol}$ Composite thickness = 0.6315	
VARI consolidation	$E_{0,sim}$ = 16.5 GPa	$E_{90,sim}$ = 17.7 GPa	$E_{0,sim}$= 18.4 GPa	$E_{90,sim}$= 16.8 GPa
	$E_{0,exp}$ = 15.3 GPa	$E_{90,exp}$ = 18.3 GPa		
	Fibre volume content = 64.53 $\%_{Vol}$ Composite thickness = 0.50 mm		Fibre volume content = 63.99 $\%_{Vol}$ Composite thickness = 0.51 mm	

5. Conclusions

Textile reinforced composites are complex materials whose mechanical properties can be influenced by several parameters. Both, the textile reinforcement structure and the consolidation process are influencing the resulting material and its mechanical properties. Mechanical test are time and material extensive, which can be directly linked to development costs. Especially in the field of development and research investigations are common, where many parameters have to be changed and their influence on the product have to be studied. Virtual development chains enable cost and time efficient investigations along the complete manufacturing chain of textile reinforced composite materials. Micro-scale models are of high interest as they are a very good simplification of the actual material with a high level of detail. They are able to account for all the process parameters which are influencing the textile manufacturing process as well as the composite consolidation process. Therewith, investigations on the parameters influence can be studied along the whole manufacturing chain on a micro level.

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