MULTIDISCIPLINARY DAMAGE ANALYSIS OF TEXTILE REINFORCED COMPOSITES FOR IMPACT AND CRASH APPLICATIONS

W. Hufenbach[1], N. Petrinic[2], R. Böhm[1], J. Wiegand[2],
A. Langkamp[1], F. Marques Ibraim[1], B.C.F. Elliot[2]

[1] Institute of Lightweight Structures and Polymer Technology (ILK), TU Dresden, 01062 Dresden, Germany
[2] Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK

ABSTRACT

Several studies have shown the numerous advantages of using composite materials for impact loaded structures in aircraft and aerospace engineering. With adapted tailored reinforcement, the composite structures provide a much better response to impact loads than metal components and bring additional advances concerning weight savings and structural stiffness. Unfortunately, the still limited capability of simulating composite material response to impact loading prevents the optimised usage of these promising materials. This deficiencies result in insufficient structural and material optimisation via numerical modelling because of missing fundamental knowledge of the damage phenomenology of this novel group of textile composites or via expensive and difficult experimental tests. To overcome those difficulties, multidisciplinary damage approaches that involve theoretical damage modelling as well as numerical strategies and experimental work are essential. The present work will discuss this multidisciplinary damage analysis approach, which consists of phenomenological damage mechanics based models for textile reinforced composites, the implementation into proprietary software developments and the verification by suitable experiments as well as by inverse modelling.

Within the investigation, basic failure and damage models will be presented and verified. Essential mechanical questions will be clarified regarding the definition and the size of representative volume elements. A phenomenological model in the framework of continuum damage mechanics will be introduced, where damage is defined as the change of the tensor of elasticity. Damage variables are introduced to describe the evolution of the damage state and as a subsequence the degradation of the material stiffness. New failure criteria like fracture mode concepts (FMC) consider different composite failure modes as well as further fracture types influenced by the textile reinforcement. The failure criteria are obtained by equations for the failure surfaces in stress space. They interact with damage thresholds for the determination of the stiffness degradation of the composite. These damage models have been implemented into a FE environment. Additional research has been performed to include strain rate dependencies and to reduce mesh sensitivity. For efficient parameter identification, interdisciplinary experimental verification strategies are inevitable. Thus, combined approaches including ultrasonic wave speed measurements, acoustic emission analysis and classical impact and crash tests have been used. To consider the anisotropic nature of damage under various loading conditions, the damage models generally require a number of parameters that are very extensive to be determined by experiments. Newly numerical techniques such as inverse modelling will allow for a virtual parameter optimisation to be applied to model parameter identification procedure. Additional to the expected cost savings for material characterisation, the understanding of the performed experiments and the interpretation of experimental data will be improved substantially.

KEYWORDS: textile composites, damage, impact loading, CDM,
experimental verification, inverse modelling

INTRODUCTION

Novel textile reinforced composites provide a high lightweight potential as well as an excellent capability of absorbing energy during crash and impact loading. For this reason, they are best suited for high performance structures in diverse fields of application. Due to the broad variety of available reinforcing fibres - like carbon, aramid or glass – and textile preforms in combination with matrix systems with optimised properties like polymers, ceramics or light metals, this young material class distinguish oneself by a wide freedom of design [1].

To take advantage of the material specific potential of textile reinforced composites, the development of adapted simulation models is required. These models enable an efficient virtual material development by means of the prediction of the anisotropic material behaviour and form the foundation for a load adapted design of dynamically loaded textile reinforced composite structures. Such simulation concepts need to consider the extremely complex interactions between the microscale, the mesoscale and the macroscale. At the same time, they must satisfy the requirements of a practical structural design [2].

In particular for textile composites, a damage analysis under highly dynamic loading conditions causes considerable difficulties because the failure phenomena on the microscale must be taken into consideration within multi-scale damage models. Such deficits lead to structures that are conspicuously overdesigned and therefore not cost-effective [3]. This low efficiency gets in the way of the virtual breakthrough of this young material class. Therefore, novel multidisciplinary approaches and according overall simulation methods need to be developed [1-3].

Because the macromechanical material characterisation forms the origin of structural simulations, the formulation of textile-adapted material laws and failure criteria are of major importance. In particular for textile composites, the occurring failure mechanisms depend on a variety of parameters (textile geometry, manufacturing parameters and loading conditions). So-called modified physically based failure criteria are auspicious approaches to consider these influences, and furthermore form the starting point for the development of suitable degradation and damage models [4-7]. This paper gives a general overview about the mechanical framework of damage analysis for textile-reinforced composites and shows how existing models for laminates need to be adapted in order to characterise the different damage behaviour of textile composites. The experimental determination of the associated material parameters is of principal importance for the development of such textile-adapted material models. This issue will be discussed briefly here and more detailed in [8-10]. The degradation models generally require a number of parameters that are very extensive to be determined by experiments. Thus, model parameters may be determined alternatively by inverse identification. The proposed model will be exemplarily used to characterize the damage behaviour of dynamically loaded fanblades in multi-material-design.

PHENOMENOLOGICAL DAMAGE MODELS FOR TEXTILE COMPOSITES

The structural behaviour of textile reinforced composites is very complex [6, 7, 11]. The spatially curved fibre alignment complicates the description and modelling of representative volume elements (RVE) in the design process, as they can be found in the design of metal composites (unit cell) or fibre-reinforced composites (UD unit cell). Presently, drastic and trivialising simplifications are taken up for the definition of textile unit cells that frequently foil a possible adaptation of the yarn architecture according to the acting loads under consideration of restrictions of the manufacturing process. Furthermore, the mechanical engineer usually adopts a more macroscopic point of view. The difference comes from the fact that the engineer is interested in designing structures and, therefore, needs to develop design tools that can be integrated into structural calculation procedures (e.g. finite element simulations). The models are meant to be simple and robust, and the material parameters should be easy to adjust. Thus, it seems to be very beneficial to describe the relative characteristics of the composite material properties by means of a more general approach: by means of suitable *equivalent single layers* [6].

Due to the complex yarn intersections and yarn enlacements, normally a non-linear stress-strain behaviour occurs on the structural level (macroscale) [6]. Simultaneously, different microscopic failure modes interact, which causes unusual linking effects on the macroscale. This structural complexity results in a complex damage behaviour and subsequently in complex constitutive equations under static loads as well as under dynamic loads. Hence, in the following we will embark on a strategy that describes the non-linear behaviour of the novel textile composites in a practically efficient way on the level of the equivalent single layer (Fig. 1).

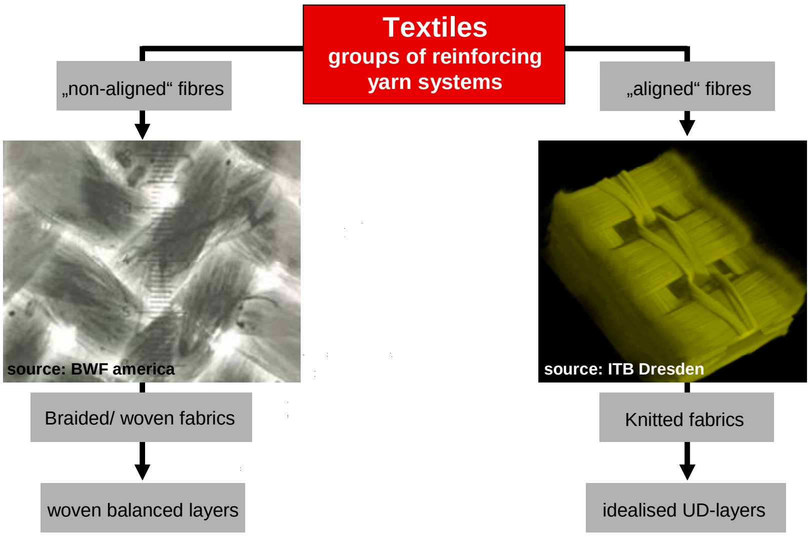

Fig. 1 Characteristics of textile composites and resulting equivalent layer [11]

Non-linear damage model

MATZENMILLER et al. [12] proposed a model, based on CDM, for the non-linear analysis of composite materials. It could be shown that this model could be used for textile composites with idealised UD-layers (i-UD-layers), too [6, 7]. The lamina based model introduces three damage parameters; two associated with the in-plane principal lamina directions and one representing the effect of damage on shear. Then, the effective stiffness matrix of the orthotropic i-UD-layer results in

$$\tilde{\boldsymbol{C}}(\boldsymbol{D})=\begin{bmatrix}\tilde{C}_{11} & \tilde{C}_{12} & 0\\ \tilde{C}_{21} & \tilde{C}_{22} & 0\\ 0 & 0 & \tilde{C}_{66}\end{bmatrix}=\frac{1}{d}\begin{bmatrix}(1-D_{11})E_{\|} & (1-D_{11})(1-D_{22})\nu_{21}E_{\perp} & 0\\ (1-D_{11})(1-D_{22})\nu_{12}E_{\|} & (1-D_{22})E_{\perp} & 0\\ 0 & 0 & d(1-D_s)G\end{bmatrix}.$$

Textile composites with woven balanced (WB)-layers usually require a more formal description with more complex damage tensor representations. A suitable damage model for WB-layers without generalising assumptions about microcrack initiation and geometry was suggested by BASTE [13, 14]. The model is valid for the general case of anisotropic damage and, consequently, is also applicable if the principal material axes or even the symmetry class of the observed material changes during the damage process. The elastic constants of the equivalent single layer itself will be used for the description of the material damage. The origin of the model is the dispartment of the stiffness tensor in

$$\tilde{C}=C_0-C_d$$

with C_0 as initial stiffness and C_d as the stiffness loss due to damage. The change of the stiffness

$$\omega = C_d = C_0 - \tilde{C}$$

will be used as internal damage variable that characterises the particular damage state in the material. Traditionally, in continuum damage mechanics, the definition of damage variables takes place in such a way that these variables could only reach values between zero in the initial state and one in the completely damaged state. For the perpetuation of this definition and to assure that the stiffness tensor remains positive definite, the damage tensor components ω_{ij} must be normalised to their thermodynamically admissible values. The normalised components of the damage tensor finally result to

$$\omega_{ii} = 1 - \frac{\tilde{C}_{ii}}{C_{ii}^0} \qquad i = 1,2,...,6$$

$$\omega_{ij} = \frac{C_{ij}^0 - \tilde{C}_{ij}}{C_{ij}^0 + \operatorname{sign}\left(C_{ij}^0 - \tilde{C}_{ij}\right)\sqrt{C_{ii}^0\left(1-\omega_{ii}\right)C_{jj}^0\left(1-\omega_{jj}\right)}} \qquad i, j = 1,2,...,6;\, i \neq j\,.$$

Failure criteria

Only the development of a new type of so-called fracture mode criteria can enable a physically based description of the prevailing failure modes of textile reinforced composites using realistic fracture conditions. Subsequently, the invariant criterion of CUNTZE has been applied to the failure analysis of different textile reinforced composites [4] and correspondingly modified [2].

To improve the practical handling of physically based failure criteria, CUNTZE has developed a new approach which also aims at circumventing the problematical aspects of the HASHIN/PUCK criterion. On account of the practical factors involved, CUNTZE considers the establishment of a new approach for a realistic strength analysis which goes beyond the action plane approach of HASHIN/PUCK as an urgent necessity.. A composite failure does not always involve a fracture plane in the sense of the hypothesis proposed by MOHR, such as can be the case for cloth-reinforced fibre ceramics for example. Subsequently CUNTZE assumes that micromechanical and statistical interactions in particular in the case of multiaxial loading cannot be distinctly differentiated from each other. Taking these factors into account, CUNTZE worked out a failure mode related strength criterion that he formulated as invariant representation in order to enable a universal application and simple mathematical use [4].

Damage evolution laws

The damage growth laws used in the model are fairly general formulations that were originally used for unidirectional laminates [12]. The evolution laws are described via the coupling function

$$\dot{\boldsymbol{D}}_{\boldsymbol{i}} = \sum_{\boldsymbol{j}} \dot{\phi}_{\boldsymbol{j}} \boldsymbol{q}_{\boldsymbol{ij}}$$

where the scalar functions $\dot{\phi}_{\boldsymbol{j}}$ control the amount of damage and the coupling between the damage of the damage mode $\boldsymbol{j}$ and the damage variable $\boldsymbol{i}$ is described by a vector-valued function $\boldsymbol{q_{ij}}$. The effect of damage on the elastic properties in each mode is then provided by a damage rule of the form

$$\phi_{\mathrm{i}} = 1 - \exp\left(\frac{1}{m}\left(1 - r_j^m\right)\right).$$

The exponential function is only driven by one independent parameter $\boldsymbol{m}$ for every individual failure mode $\boldsymbol{j}$. More accurate results could be achieved by choosing a damage growth law with two independent parameters, for instance

$$\phi_{\mathrm{i}} = 1 - \tanh\left(\alpha(1 - r)^m\right).$$

MULTIDISCIPLINARY VERIFICATION STRATEGY

Because no experimental technique is able to determine the complete damage behaviour of textile reinforced composites, a multidisciplinary verification strategy needs to be adopted. This strategy contains direct and indirect experimental techniques as well as numerical and micromechanical parameter studies.

Classical experimental tests with tube specimen form the basis for the experimental analysis of the fracture mode specific damage phenomena [15, 16]. Such specimens are loaded in so-called tension/compression-torsion-inner pressure-tests continuously as well as gradually. During the test, the deformation of the specimen in each direction is determined by means of adapted measuring systems. From the measured stress-strain-curves, the effective stiffnesses of the composite could be determined.

Besides the classical stress-strain-analysis, several adapted testing technologies like acoustic emission, ultrasonic measurements and video analysis are applied. These techniques enable an in-situ characterisation of the damage phenomena and therefore exhibit substantial advantages compared to gradually classical tests.

Within the acoustic emission analysis, two sensors have been used that enable the determination of the frequency spectrum, amplitude and energy of single and accumulated damage entities as well as a linear localisation. The results detected by acoustic emission could be compared with microscopic pictures of crack fields of damaged specimens. Therewith, a correlation between acoustic emission events and damage entity could be found [9].

In addition to the in-situ determination of damage phenomena by means of acoustic emission testing, an ultrasonic technique is used to determine the effective stiffness coefficients due to damage directly. This ultrasonic measuring approach is based on the determination of the velocities of longitudinal and transversal waves and uses the proportionality of wave velocity and stiffness [8, 17].

Finally to verify the numerical results from the impact simulation, several experimental plate bending impact tests have been carried out at several impact velocities [10]. The plate bending impact tests were performed with a modified Hopkinson device. The resulting experimentally obtained energy curves from the impacting tests were used to verify the validity of the phenomenological material model.

Only such multidisciplinary approaches for the verification of the extremely complex damage phenomena in textile reinforced composites ensure a secured evaluation of the prevailing failure and degradation mechanisms.

INVERSE MODELLING

Composite constitutive models are growing rapidly in complexity and the range of behaviour they are able to represent. The correct representation of failure initiation and the subsequent damage evolution requires many additional parameters. Some of these parameters can be obtained from experimental investigations of the material by idealised analytical considerations; but often the required tests are difficult or impossible to perform or measure (e.g. controlled multi axial loading) or the necessary analytical assumptions are violated (e.g. inhomogeneous geometry). This calls for an extension of the standard experimental material characterisation programs by hybrid experimental-numerical parameter determination procedures, such as identification by inverse methods [18].

The parameter identification inverse problem is the determination of the parameters of a constitutive model which can reproduce numerically the material behaviour observed with the greatest accuracy and confidence. Within an inverse identification scheme the results from preferably multiple experiments are compared with the numerical response of the models of such tests. Use of accurate numerical modelling techniques such as the finite element method means that calibration experiments with highly non-linear responses can be employed. An optimisation algorithm is used to minimise an objective function, which represents the error in the material response due to the constitutive parameters. The global minimum of the objective function represents the best possible choice of parameters for numerical representation of the observed behaviour (Fig. 2).

The obtainable results depend strongly on the capability of the model to represent the test and material correctly. A successful optimisation relies therefore on accurate experimental measurements, FE models built with great attention to detail and accurate material models.

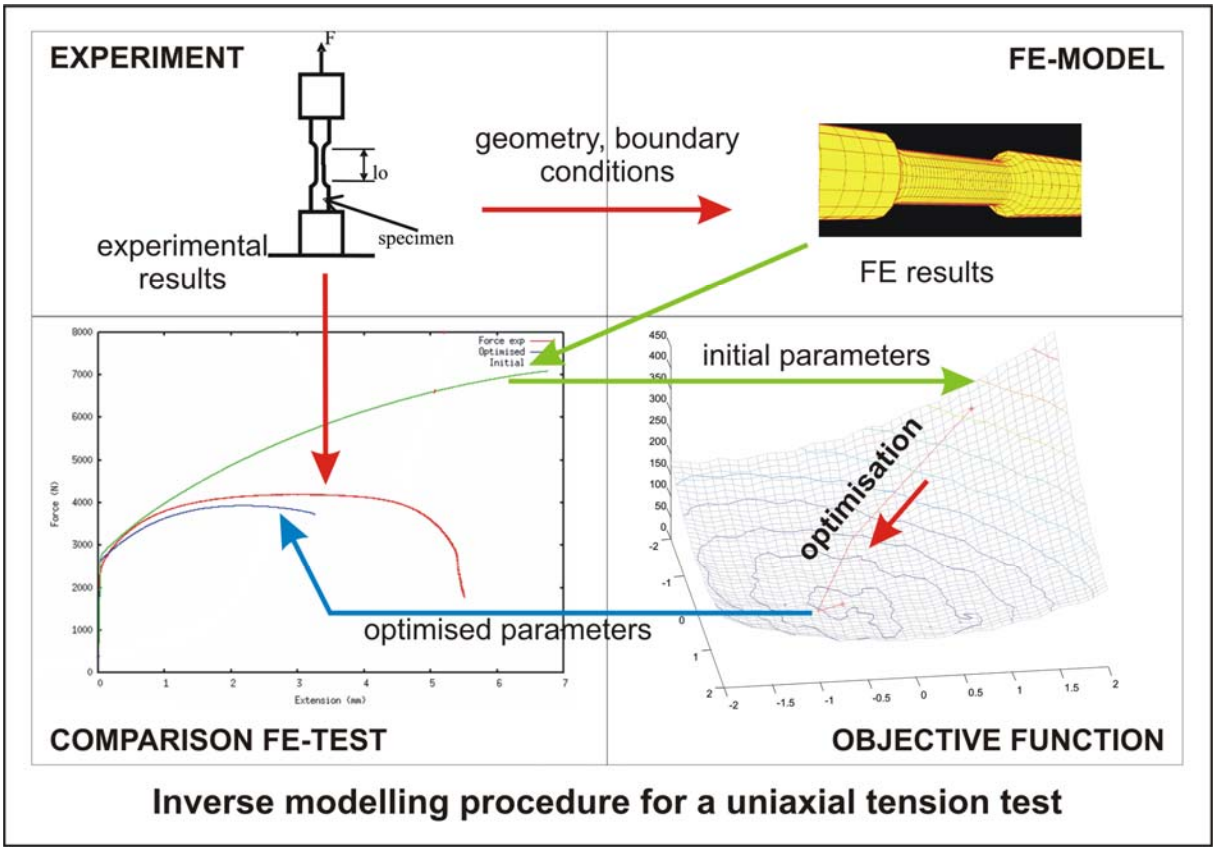

Fig.2 The inverse modelling procedure using a uniaxial tensile test

NUMERICAL MODELLING OF IMPACT AND CRASH PROBLEMS

Impact events are of highly dynamic nature. It is therefore necessary to take into account the effects arising from inertia and the propagation of stress waves in the material. Very often the material response is highly non-linear and large deformations occur. For these reasons explicit FE solvers like LS-DYNA or PAMCRASH are used to simulate impact problems.

Unlike the simulation of quasi static loading events, the numerical modelling of impact phenomena requires an extended knowledge of the material behaviour. Under these high-rate loading conditions many advanced materials like titanium or long fibre reinforced polymers show a rate dependent mechanical behaviour. Correctly predicting the materials performance during impact requires a detailed knowledge of the materials rate dependent properties. Complex testing facilities like gas guns or Split-Hopkinson-Bar loading devices are necessary to experimentally observe strain rate dependency. In order to understand how the materials stiffness and strength is affected at elevated strain rates, the materials are usually investigated at several different rates of strain.

The extreme loading conditions require extended constitutive models which consider the rate dependent material behaviour and at the same time cope with large deformations and non-linear material response. The nature of impact phenomena usually does not permit the reduction of the problem to plane stress or strain conditions. A suitable constitutive model should therefore be fully 3 dimensional. Material failure is a common phenomenon during impact. The chosen constitutive model needs to be able to realistically predict the initiation of failure and the subsequent propagation of damage. Sophisticated phenomenological composite damage models are thereby indispensable tools. Currently, damage is mainly represented by means of continuum damage mechanics. Therefore the initiation and propagation of damage is modelled smeared over a certain volume depending on the chosen modelling scale (representative volume element). This approach often results in severe mesh dependent damage propagation. A regularised damage evolution can reduce this mesh dependency [19]. A more appropriate way of modelling failure due to impact is a discontinuous representation of damage. The propagation of cracks is modelled by element splitting [20]. Unfortunately, the limited computational power still prevents a broad application of such tools.

EXAMPLES

One of the most attractive application fields for impact simulation of composites is the one of turbine engine components, where very light and resistant structures must be designed to sustain extraordinary loads well above their normal loading condition. The case of a fan blade root overload due to bird strike represents very well one of the aforementioned design cases (Fig. 3). An experimentally based approach to design the root against this extraordinary load would be very expensive and would provide limited insight on the key design variables responsible for the structural resistance. A sufficiently accurate numerical tool for the design of such structures makes the design iteration process much faster and efficient by means of reducing the experimental tests to the required minimum.

Fig. 3 depicts exemplarily a numerical simulation performed in DYNA3D with the drafted orthotropic damage based material model. The failure modes and the crack propagation can be simulated fairly well with this approach. The correct prediction of the damage phenomena shows the accuracy of the failure criteria and the damage evolution laws used in the modelling approach. The use of damage to represent micro-cracking induced stiffness reduction as well as element erosion to minimise crack growth and its effects on the local load redistribution matches pretty well the experimentally obtained results (Fig. 4).

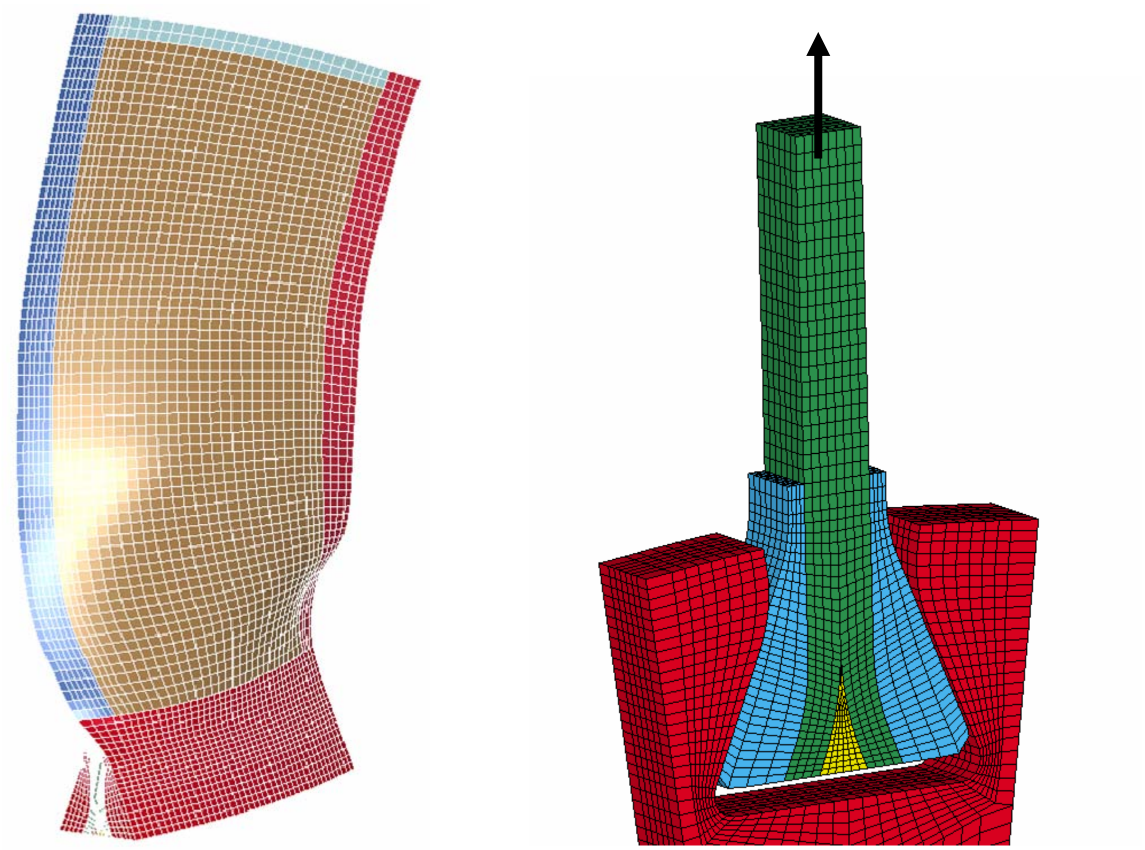

Fig. 3 Fanblade and root component in multi-material design (FE-mesh)

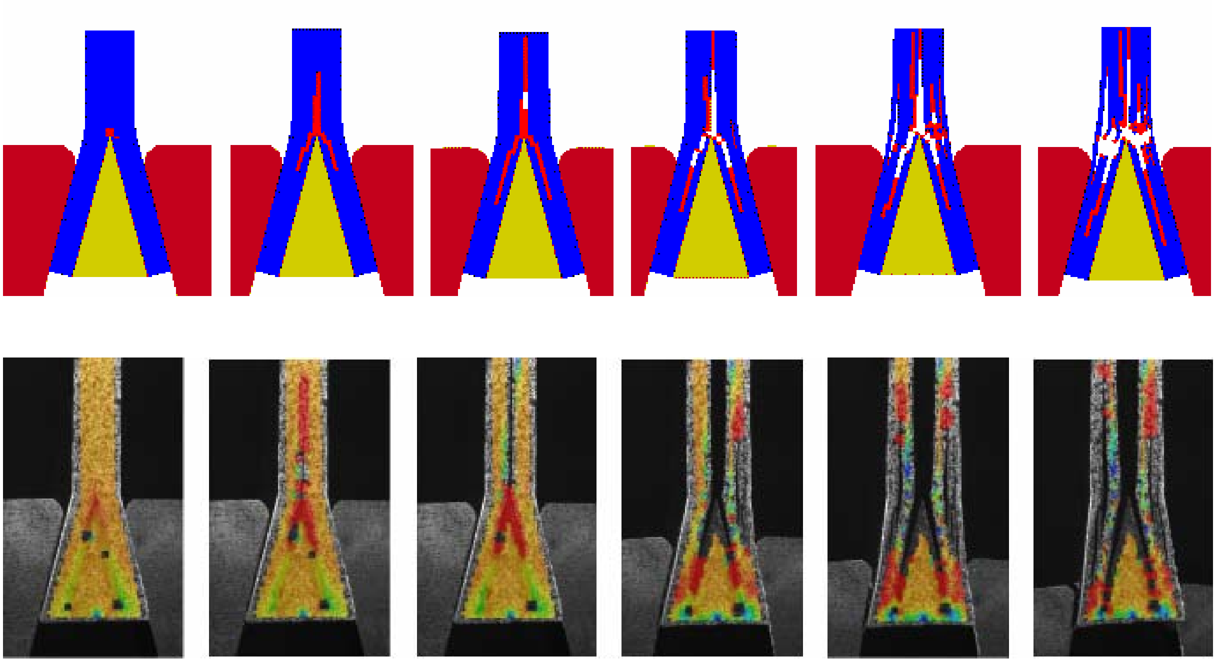

Fig. 4 Simulation of crack growth and delamination progress in a root component (top); Strain field (ε_x) of a root component in a tensile test (bottom)

CONCLUSIONS

This investigation considers the development of material adapted simulation methods for textile reinforced composites that enable an efficient virtual material development by means of predicting their anisotropic damage behaviour. These models form the basis for the structural design of dynamically loaded composite structures. As especially topical examples, fanblades in multi-material-design for airplane engines are chosen to demonstrate the features of the developed method. The novel simulation tools allow the virtual construction of customised textile reinforced composites for extreme lightweight applications. Therewith, the material specific potential of textile composites can be fully used and so far unavoidable overdimensioned structures can be eliminated in the future. It could be concluded that such multidisciplinary damage analysis concepts will have a markedly leverage effect for several product ranges in many industrial sectors.

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