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Probabilistic failure simulation of glass fibre reinforced weft-knitted thermoplastics

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ABSTRACT

If textile-reinforced composites should be put into practice, the proof of load-bearing capacity has to be provided. For this purpose, deterministic overall safety proofs without material adapted partial safety factors are used which do not meet the textile-specific scatter characteristics and therefore neglect many advantages of those composites. Based on deterministic stress-based failure criteria and given loading conditions, a probabilistic methodology to predict the joint failure probability is proposed. The methodology is verified experimentally for hybrid yarn based textile thermoplastics. A statistical material characterisation using flat specimens, multi-axial tests with tube specimens and a Monte-Carlo simulation are used for that purpose. As a significant outcome of the study, the reliability of the failure prediction is significantly improved especially for multi-axial stress states with failure mode interaction. Based on the improved knowledge about the anisotropic material uncertainties, a more significant partial safety factor can be determined.

1. Introduction

While fibre reinforced composites (FRC) with thermoset matrices have prevailed in aerospace applications, particularly composites with thermoplastic matrix systems show optimal conditions for a mass production-capable use in automotive engineering [1,2]. Hybrid yarn based textile thermoplastic composites were especially investigated in recent years [3–5] because of the possibility to achieve very short cycle times during manufacturing.

In the framework of a safe structural design of such composites, both the non-linear material behaviour and the scattering of the material properties have to be considered. A description of the non-linear material behaviour is possible nowadays because a large number of phenomenological material models have been developed both for UD plies and for textile composites, see e.g. [6–10]. Most of these models rely on physically-based fracture criteria like [11,12,14]. Due to continuous developments, such stress-based criteria can meanwhile be used for thermomechanic, cyclic and dynamic loading conditions [15–18].

In [19] it was shown that the damage initiation in composites mainly results from probabilistically characterised local effects. Thus, a consideration of stochastical influences during material modelling seems meaningful. However, the scattering of different material properties of composites is normally unknown or has to be measured within a large experimental test programme. The missing information about the property scatter can be a major drawback when novel composite types should be used for structural components. In this case, statistically validated properties have to be used which is largely regulated by corresponding standards and guidelines. Significant progress is therefore needed on two fields: developing probabilistic material models which are able to determine failure probabilities under multi-axial stress states and providing statistical meaningful material data for different composite types. Especially in civil engineering publications it was shown that the distribution function of the failure probability is determined by the phenomenology of failure [20]. As a consequence, semi-probabilistic safety concepts with independent partial safety factors for load and strength were introduced. Such safety concepts are also used for the design of composite components especially for safety-relevant structures [21,22]. Thereby, the separately developed design verification procedure for unidirectional composite, which consists of a deterministic (failure mode related) stress criterion and a downstream stochastical evaluation of the stress state, is also used for complex multi-layered composites.

First approaches for a probabilistic-based design of UD composites have been recently published. They are either based on micromechanical approaches which analyse geometrical uncertainties like fibre undulations, voids or matrix pockets [23–26] or on mesomechanical approaches analysing the scatter of characteristical UD properties like stiffnesses and strengths [27]. Self-contained probabilistic approaches for proving the strengths do not exist for textile composites. This paper provides a numerical

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probabilistic approach based on the Monte-Carlo method and an extensive experimental statistical material characterisation to overcome the drawbacks mentioned above. So called biaxially reinforced weft knitted composites made from hybrid yarns (glass/polypropylene) are used as a characteristical example for that study. The proposed model is based on previous works [28,29] and uses experimentally determined stiffness and strength data to evaluate the probability of failure under uniaxial and multi-axial stress states.

2. Experimental

2.1. Material

The textile preforms for this study are made of online commingled glass fibre polypropylene (GF/PP) hybrid yarns. Multi-layered flat bed weft-knitted fabrics (MKF) are manufactured from the hybrid yarns [3]. The biaxial fibre reinforcement in warp and weft direction (Twintex RPP 82, 1398 tex, 62% glass fibre content) is fixed with an additional knit thread system (ITM HY, 138.5 tex, 27.6% glass fibre content) in a textile manufacturing process, see Fig. 1. Thus, MKF reinforced composites belong to the group of 3D-reinforced composites since the GF knit thread realises a reinforcement in *z*-direction and reduces the risk of delamination [15]. The warp-weft ratio is 1:1. An areal density of 944.3 g/m^2 (standard deviation: 12.6 g/m^2) was measured.

Symmetric and balanced layer compositions were built up of the MKF preforms with four bidirectional layers ($[90/0//0/90]_s$) stacked and manufactured to a composite. The final consolidation takes place using an autoclave manufacturing process (197 °C, 6 bar and 45 min dwell time). There, the textile layers were placed at the plate shape tool in a vacuum bag and were exposed to a defined pressure and temperature autoclave regime [15]. The cooling down process to room temperature takes place in the forming tool. It can be shown that no significant residual stresses arise after consolidation. A balanced bidirectional MKF–GF/PP composite with a glass fibre volume fraction of 54.7% (standard deviation: 0.7%) results after consolidation. Because this scatter is very low, an influence on the scatter of the mechanical properties can be neglected. Finally, flat specimens were cut out with different material orientations (warp direction, weft direction, 45°) by water jet from the consolidated plates which had a thickness of approximately 2.1 mm.

Additionally, tube specimens have been manufactured to selectively induce superimposed stress states (tension/compression–torsion tests (T/C–T tests)). In contrast to flat specimens, tube specimens have no free edges so that failure-critical boundary effects can be avoided. Standardised tubular test specimens according to [13] are manufactured in a manufacturing process that was especially modified. The modification became necessary in order to guarantee a similar symmetric stacking sequence compared to the flat specimens and to secure the position of the textile preform in the tool. A two-step manufacturing process was developed which contains of a pre-consolidation of the textile preform as a plate and a subsequent winding into the tool. The manufacturing parameters (195 °C, 7 bar, 150 kN clamp force and 10 min closing duration) are derived from the autoclave process to secure a comparability.

The tube specimen geometry was statistically analysed. An outer diameter of 44.253 mm (standard deviation: 0.086 mm) and a wall thickness of 2.206 mm (standard deviation: 0.266 mm) was evaluated. All geometrical values are normally distributed. The specimen geometry has been selectively chosen to reduce stress concentrations during loading. The warp fibres are oriented in the longitudinal direction of the test specimens.

2.2. Statistical material characterisation and failure analysis

The probabilistic failure simulation requires a statistically safe experimental concept to identify the uncertain model parameters and to verify the failure analysis concept. Uniaxial fracture tests with flat specimens are performed to characterise the scattering of the properties (engineering constants and strengths) in warp and weft direction as well as for shear. Multi-axial tests with tube specimens are used to verify the probabilistic failure analysis concept. Within the probabilistic approach, epistemic uncertainties during experimental testing have to be eliminated by a significantly increased scope of testing on the one hand and an adapted test procedure on the other hand.

2.2.1. Uniaxial fracture tests

A Zwick universal testing machine Z250 was used for statistical material characterisation (max. load 250 kN). The machine contains a temperature chamber to secure the necessary strict requirements with respect to fluctuation of test temperature. Preliminary tests have shown that tests without a strict temperature regulation lead to a larger scatter because the glass transition zone of the GF/PP matrix system is identified from −10 °C to +20 °C [15]. 250×20 mm^2 flat specimens have been used. The force measurement is carried out with standard load cells. The strain detection was performed using the optical 3D measuring system ATOS.

In order to eliminate influences from measurement uncertainties, it has to be proved that those uncertainties are sufficiently small compared to the natural fluctuations due to aleatory uncertainties. Based on [31,32], the size of the measurement uncertainties has been determined for every test parameter (here: strengths, engineering constants). These uncertainties result from portions from force and strain measurement and cross section determination. The determined measurement uncertainties (±0.5 up to 0.8%) are significantly lower than the experimentally determined scatter of the material properties (±2.0 up to 2.5% with a confidence level of 95%) and are therefore insignificant for probabilistic modelling. and are therefore neglected during modelling. The required number of tests results from the requirements for the

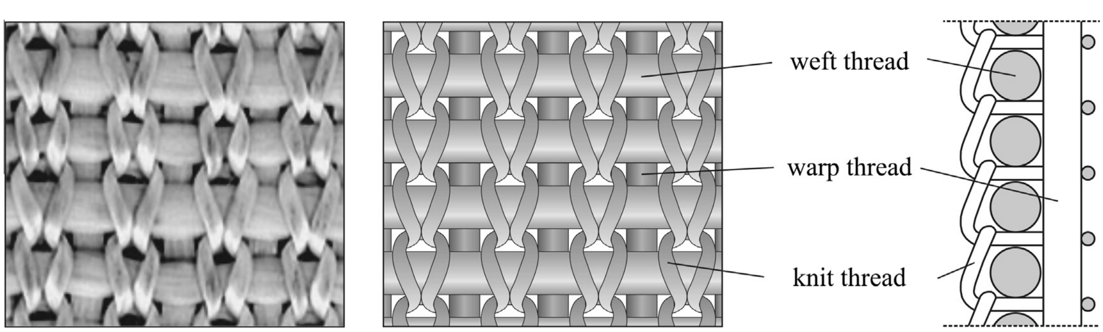

Fig. 1. Picture and scheme of the biaxial weft-knitted fabric.