# FRACTURE MODE DEPENDENT DAMAGE MODELLING OF 3D TEXTILE-REINFORCED COMPOSITES UNDER MULTIAXIAL FATIGUE LOADING

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## SUMMARY

For the simulation of the material degradation process of 3D textile-reinforced composites during multi-axial fatigue loading a new physically based damage model is developed based on the fracture mode concept (FMC) of CUNTZE and the continuum damage mechanics. The determination of the model parameters and the model verification is done in cyclic tests of glass/epoxy tube specimens, with multi-layered weft knitted fabric reinforcement, under superposed tension/compression-torsion loading.

Keywords: textile, composites, multi-axial fatigue loading

## INTRODUCTION

With multi-layered weft knitted fabrics a novel class of 3D textile-reinforcements has been introduced. 3D textile-reinforced polymers with multi-layered weft knit fabric reinforcement are characterised by a non-crimp arrangement of weft and warp fibres, which are fixed by a glass knit thread [1]. Due to their high specific strength and stiffness these textile composites are virtually predestined for applications in lightweight structures under cyclic loadings in automotive engineering as well as general machine building. For the development of structural concepts there is, however, a lack of well-founded knowledge of the fatigue degradation behaviour especially under superposed loading conditions.

In contrast to isotropic and macroscopic homogeneous engineering materials like metals, fibre-reinforced composites show a significant directional degradation of the stiffness and strength during cyclic loading. For the prediction of the material degradation many models have been developed in the past [2-4]. The existing fatigue damage theories for fibre- and textile-reinforced composites can be categorised into *general damage accumulation theories, stiffness and strength degradation theories* and *progressive damage models* with damage initiation and evolution.

*General damage accumulation theories* such as the Miner rule have been investigated extensively for the application in fibre-reinforced materials. But many investigators found the linear Miner rule insufficient for the description of the damage behaviour of fibre composites under cyclic loading.

To involve the characteristic stiffness and strength degradation into the modelling *stiffness and strength degradation theories* based on the phenomenological description of the macroscopic material degradation with the help of stiffness and strength degradation functions have been developed. As an example SHOKRIEH presented a damage model for multi-layered carbon fibre-reinforced epoxy based on the stiffness and strength degradation of the single layers. With the help of the modified failure criteria of HASHIN furthermore the lifetime of the composite has been calculated for various stress ratios and stacking sequences [3]. The model does however not take into account the difference in the damage behaviour of separately tested single layers and embedded layers in multi-layered or textile-reinforced composites.

A further improvement towards realistic degradation modelling has recently been achieved by stressing a new approach based upon multi-scale damage evolution modeling with the help of the continuum damage mechanics [2, 6]. The new group of *progressive damage models* aims for the realistic modelling of the macroscopic stiffness and strength degradation based upon the development and growth of damage on the meso- and microscale.

The experimental and theoretical investigations of this study aim at the development of a continuum damage mechanics model and focus on constant amplitude tests with pulsating load - selectively allocated to the respective type of fracture. The fatigue strength tests under uniaxial and defined superposed stress conditions are carried out on textile-reinforced tube specimens on a servo-hydraulic tension/compression-torsion (T/C-T) test machine. The determined fatigue strength, the dynamic stiffness values and the damage evolution and propagation are used to develop a fracture mode dependent damage model.

## THEORETICAL APPROACH

Reliable design tools for dynamically loaded composite structures require a realistic and physically based description of the damage evolution. Especially the mechanical representation of damage phenomena such as stiffness and strength degradation have to be modelled in detail. General life time calculation procedures which are currently used in Finite-Element-(FE-)software are not able to take into account material degradation and stress redistribution effects. In consequence to that, the life time prediction and optimisation of textile-reinforced composite materials is highly unreliable yet.

The material property degradation in the developed model is calculated stepwise (cycle by-cycle) according to Figure 1. Because of the cycle-by-cycle-calculation procedure and the continuum damage mechanics approach on the mesoscale, the model is capable of predicting the layerwise stiffness and strength degradation.

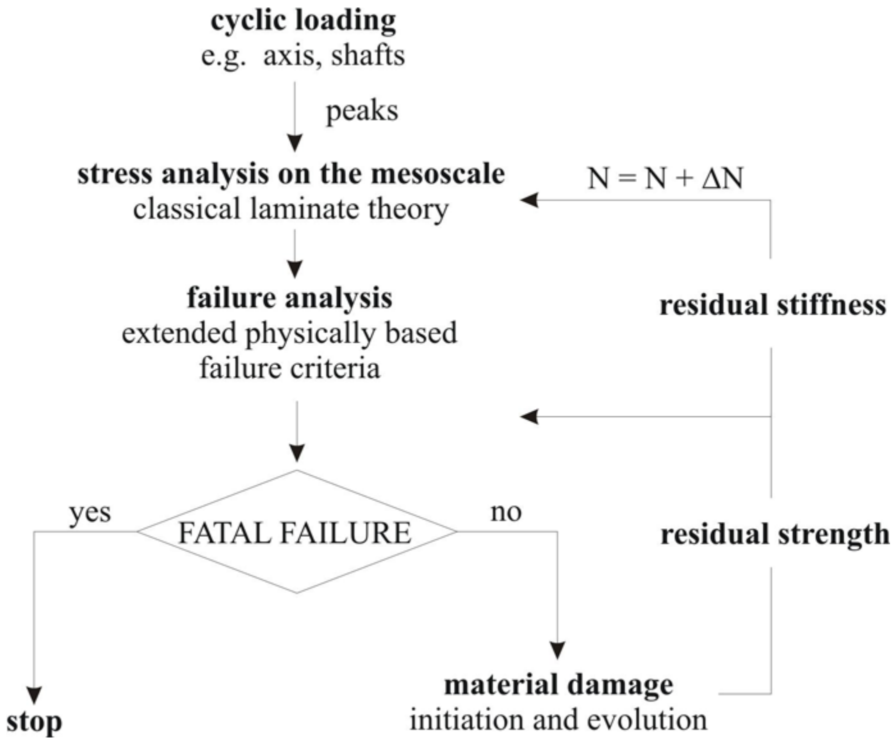


Figure 1: Cycle-by-cycle calculation procedure for the damage propagation in textile-reinforced composites under cyclic loading

In the first step of the calculation procedure the peaks of the cyclic loading are translated to the multi-axial stress representation in the layered material by structural models based on the classical laminate theory (CLT). Composites reinforced by crimped fabrics, such as woven or braided fabrics, can be virtually broken down in a mechanical sense to bidirectional layers [5]. In the case of fabrics with straight fibre orientation and less fibre ondulation such as the focused multi-layered weft knit fabrics the mechanical response of the structure can be modelled based on idealised unidirectional (i-UD) layers [6]. By introducing the effective stress $\tilde{\sigma}$ in the damaged material with

$$\tilde{\sigma} = D_{ij}\sigma_j \tag{1}$$

where $D_{ij}$ denote the damage parameters, the constitutive law for the damaged i-UD-layer can be given by

$$\varepsilon_i = S_{ij}^o \tilde{\sigma}_j = S_{ij}^o D_{ik}\sigma_k = \tilde{S}_{ij}\sigma_j \tag{2}$$

with the compliances $S_{ij}^o$ and $\tilde{S}_{ij}$ of the undamaged material and the damaged material respectively. Due to crack closure effects a separated formulation of the compliance matrix $\tilde{S}_{ij}$ for tension and compression states of stresses have to be introduced.

Assuming

$$\tilde{\upsilon}_{12}^{t} = (1 - D_1)\upsilon_{12}\,,\; \tilde{\upsilon}_{12}^{c} = (1 - h_1 D_1)\upsilon_{12}$$
$$\tilde{\upsilon}_{21}^{t} = (1 - D_2)\upsilon_{21}\,,\; \tilde{\upsilon}_{21}^{c} = (1 - h_2 D_2)\upsilon_{21} \tag{3}$$

the effective compliance matrix can be written for plane tension (t) and compression (c) states of stresses according to

$$\tilde{S}_{ij}^{t} = \begin{bmatrix} \frac{1}{E_1(1-D_1)} & -\frac{\upsilon_{21}}{E_2} & 0 \\ -\frac{\upsilon_{12}}{E_1} & \frac{1}{E_2(1-D_2)} & 0 \\ 0 & 0 & \frac{1}{G_{12}(1-D_{12})} \end{bmatrix},\; \tilde{S}_{ij}^{c} = \begin{bmatrix} \frac{1}{E_1(1-h_1D_1)} & -\frac{\upsilon_{21}}{E_2} & 0 \\ -\frac{\upsilon_{12}}{E_1} & \frac{1}{E_2(1-h_2D_2)} & 0 \\ 0 & 0 & \frac{1}{G_{12}(1-D_{12})} \end{bmatrix} \tag{4}$$

The damage parameter $D_{ij}$ has been introduced as a state variable and is therefore independent of the loading direction, however the stiffness degradation effect differs with the parameter $h_i$ (i = 1, 2) .

A subsequent failure analysis using the fracture mode related failure conditions, which are based on the FMC for fibre-reinforced materials under static loading by CUNTZE, provides the material effort $Eff^{\,*}\left({}^{*} = \|\sigma, \|\tau, \perp\sigma, \perp\tau, \perp\|\right)$ for every single fracture mode of the i-UD-layer (Fig. 2).

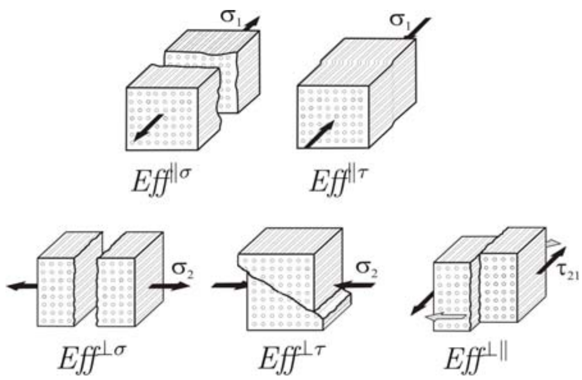


Figure 2: Fracture modes of the i-UD-Layer according to FMC by Cuntze [9]

In the case of fatigue loading the fracture mode specific effective material effort $Eff^{\,*}$ can be written in terms of the effective equivalent stress and the corresponding strength:

$$Eff^{\,\|\sigma} = \left(\frac{\sigma_1}{(1-D_1)R^{\|\sigma}}\right),\; Eff^{\,\|\tau} = \left(\frac{|\sigma_1|}{(1-h_1D_1)R^{\|\tau}}\right),\; Eff^{\,\perp\sigma} = \left(\frac{\sigma_2}{(1-D_2)R^{\perp\sigma}}\right),$$
$$Eff^{\,\perp\tau} = \left(\frac{|\sigma_2|}{(1-h_2D_2)R^{\perp\tau}}\right),\; Eff^{\,\perp\|} = \left(\frac{|\sigma_{12}|}{(1-D_{12})\left(R^{\perp\|} - \mu\tilde{\sigma}_2\right)}\right) \tag{5}$$

In combination with damage evolution functions $f_{ij}^{*}$ formulated in the fracture mode specific material efforts and the damage parameters $D_{ij}$ itself, the evolution of the anisotropic damage parameter is calculated according to

$$\frac{dD_{ij}}{dN} = f_{ij}^{\parallel\sigma}\left(Eff^{\parallel\sigma}, D_{ij}\right) + f_{ij}^{\parallel\tau}\left(Eff^{\parallel\tau}, D_{ij}\right) + f_{ij}^{\perp\sigma}\left(Eff^{\perp\sigma}, D_{ij}\right) + f_{ij}^{\perp\tau}\left(Eff^{\perp\tau}, D_{ij}\right) + f_{ij}^{\perp\parallel}\left(Eff^{\perp\parallel}, D_{ij}\right). \tag{6}$$

The damage evolution functions $f_{ij}^{*}$ can be rewritten as a sum of the product of the fracture mode specific evolution functions $\phi_i$ and a coupling vector $q_i$. For plane states of stresses the damage evolution equation can then be expanded in general form:

$$\frac{dD}{dN} = \frac{d}{dN}\begin{bmatrix} D_{\parallel} \\ D_{\perp} \\ D_{\parallel\perp} \end{bmatrix} = \phi_{\parallel}^{t}\begin{bmatrix} q_{\parallel}^{\parallel,t} \\ q_{\perp}^{\parallel,t} \\ q_{\parallel\perp}^{\parallel,t} \end{bmatrix} + \phi_{\parallel}^{c}\begin{bmatrix} q_{\parallel}^{\parallel,c} \\ q_{\perp}^{\parallel,c} \\ q_{\parallel\perp}^{\parallel,c} \end{bmatrix} + \phi_{\perp}^{t}\begin{bmatrix} q_{\parallel}^{\perp,t} \\ q_{\perp}^{\perp,t} \\ q_{\parallel\perp}^{\perp,t} \end{bmatrix} + \phi_{\perp}^{c}\begin{bmatrix} q_{\parallel}^{\perp,c} \\ q_{\perp}^{\perp,c} \\ q_{\parallel\perp}^{\perp,c} \end{bmatrix} + \phi_{\parallel\perp}\begin{bmatrix} q_{\parallel}^{\parallel\perp} \\ q_{\perp}^{\parallel\perp} \\ q_{\parallel\perp}^{\parallel\perp} \end{bmatrix} \tag{7}$$

Following the concept of the effective stress, the anisotropic damage parameter influences the corresponding stiffness and strength of the constitutive layers. This procedure is continued until the fatal failure is observed or the maximum number of cycles is reached. As a result the order of stress redistribution between the constitutive single layers, the driving failure or damage mechanism and the lifetime are calculated and a purposeful optimization of fibre-reinforced composites for cyclic loading conditions is enabled. The model parameters have to be determined experimentally as it is demonstrated in the following, on the example of tensile-torsion loadings.

## TEXTILE REINFORCEMENT AND SPECIMEN MANUFACTURE

The focus of experimental studies is directed towards novel 3D textile-reinforcements, which are developed at the Institute of Textile and Clothing Technology of the TU Dresden [7]. These glass fibre multi-layered weft knits (GF-MLG) exhibit high levels of stiffness and strength, because the load-bearing warp and weft threads are in a non-crimp straight orientation. In addition, the glass fibre knitting loop threads that secure the fibre interlock prevent the delamination between the individual layers. The here used textile type (MLG 1b) consists of a 2-layer flat knit with E-glass fibres (GF) for warp, weft and loop fibres (Figure 3). A roving with a fibre fineness of 2400 tex is used as warp (0° direction) and a roving with a fibre fineness of 1200 tex is used as weft (90° direction). The setting of a warp density of 20 1/dm and weft density of 38,9 1/dm results in a nearly equal mass share in the 0° and 90° direction, of 43.6 % and 42.5 % respectively. A glass fibre yarn with a fibre fineness of 136 tex (loop density in warp direction 38.9 1/dm, loop density in weft direction 5 1/inch) is used as a loop fibre for z-reinforcement, resulting in a loop fibre share of 13.9 %. The matrix system MGS RIMR135/RIMH137 is used for the infiltration of the multi-layer knit. The resin system has a low viscosity and is cold curing within 24 hours. The infiltration and curing is carried out at 40 °C mold and resin temperature. A curing time of 10 hours is followed by a tempering cycle of 5 hours at 70 °C.

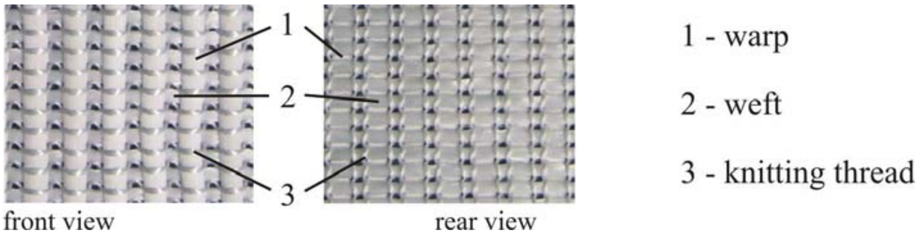


Figure 3: Front view (left) and rear view (right) of the glass fibre multi-layered weft knitted fabric (GF-MLG)

Tension/compression-torsion tests on standardised tubular test specimens with an outer diameter of 43 mm and a wall thickness of 1,5 - 2 mm (depending on the number of layers used) are performed for the induction of uni- and multi-axial (σ-τ) states of stress along defined load paths. The specimen geometry has been selectively chosen to reduce stress concentrations during fatigue loading (see Figure 4). The warp fibres are oriented in the longitudinal direction of the test specimens. Due to the resin rich areas between the warp fibres a fibre volume fraction of about 30 % has been reached. Despite the unsymmetrical layup of the specimen the layerwise stress distribution in the undisturbed testing length can very well be calculated by the classical laminate.

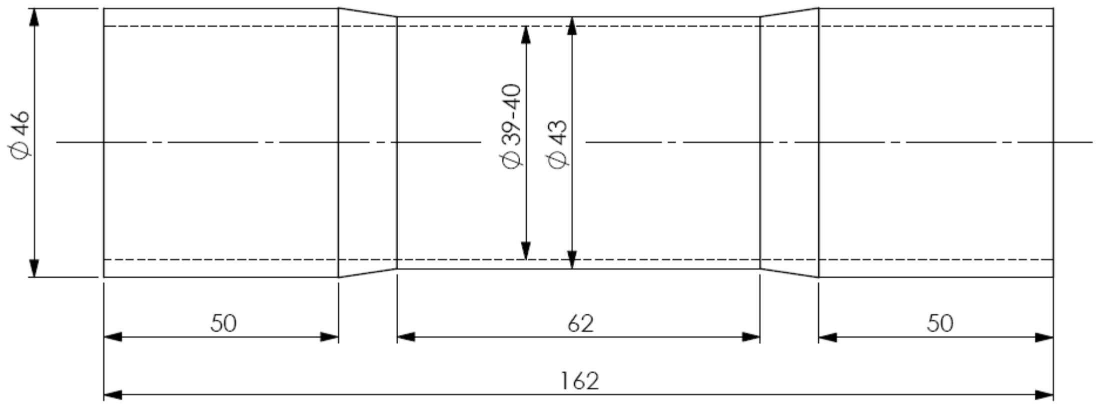


Figure 4: Sketch of fibre-reinforced tube specimen for tension/compression-torsion-fatigue loading

## EXPERIMENTAL DAMAGE EVALUATION

Extensive constant amplitude tests with uni-axial and in-phase multi-axial load conditions were carried out for the fracture-type related damage analysis of GF-MLG reinforced polymers. On the basis of the characteristic stiffness drop during cyclic loads, as well as the visually verifiable growth of cracks, the evolution of damage and its effect on the degradation of material properties is analysed. According to the test methods for quasi-static loads, cyclic loads without zero crossing were applied in order to prevent any change in the fracture mode. Furthermore, the test specimens were held under constant prestress ($R = 0.1; R = 10$), to avoid peak stresses. By means of a load specific adaptation of the test frequency in the range of 2-5 Hz the test specimen temperature of below 30 °C was maintained, since, in particular with matrix-dominated deformation conditions, significant warming of the test specimen is observed otherwise.

Aside from the reduction in strength, cyclic loads have a significant influence on the stiffness of textile-reinforced polymers. The dynamic modulus $E_{dyn}$ has been chosen as an indicator for the stiffness of the test specimen in cyclical tests according to

$$E_{dyn} = \frac{\sigma_o - \sigma_u}{\varepsilon_o - \varepsilon_u}, \tag{8}$$

with the maximum (o) and minimum (u) stress and strain values of the hysteresis. The diagram of Figure 5 shows typical curves of the normalised dynamic modulus over the relative lifetime of the specimen of representative uni-axial pulsating tensile, compressive and torsion tests. While in case of pulsating tensile and torsion loads the drop in stiffness can be divided in three typical areas, as also known from [2, 8], a steep drop in stiffness at the beginning and end of the live span as well as a shallow, linear drop in stiffness in the middle of the life span, no significant drop in stiffness is observed under pulsating compressive loads up to the point of total failure. In comparison to tubular test specimens under pulsating tensile loads, the drop in stiffness of test specimens under torsion loads is more significant due to the matrix-dominated deformation.

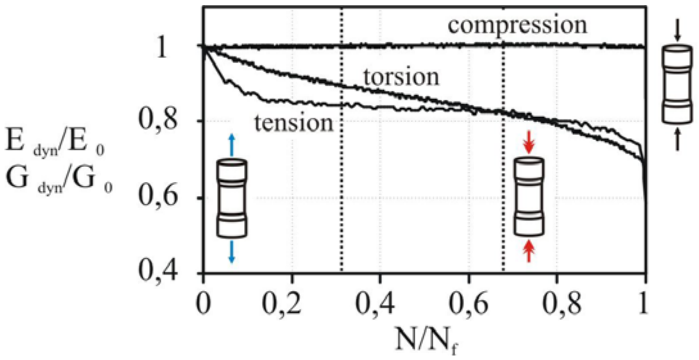


Figure 5: Stiffness degradation of GF-MLG/EP under uniaxial cyclic load

The findings from the stiffness degradation correlate with the results of the analysis of the crack patterns using micrograph and photographic methods. Test specimens subjected to tensile and shear stresses exhibited significant cracks, while test specimens subjected to compressive stresses remain nearly free of visible cracks until just prior to total failure. The damage phenomenology at pulsating tensile stresses is mainly characterised by transverse cracks in the tangentially oriented warp threads and by damage to the loop threads (Fig. 6 a). In the case of tubular test specimens subjected to torsional loads, debonding of the loop thread occurs first. In addition, longitudinal and transverse cracks begin to form towards the end of the life span in the area of both systems of reinforcement rovings and the knit thread (Figure 6 c). Under cyclic compressive stress failure occurs without prior damage evolution with a characteristic wedge like fracture surface according to Figure 6 b.

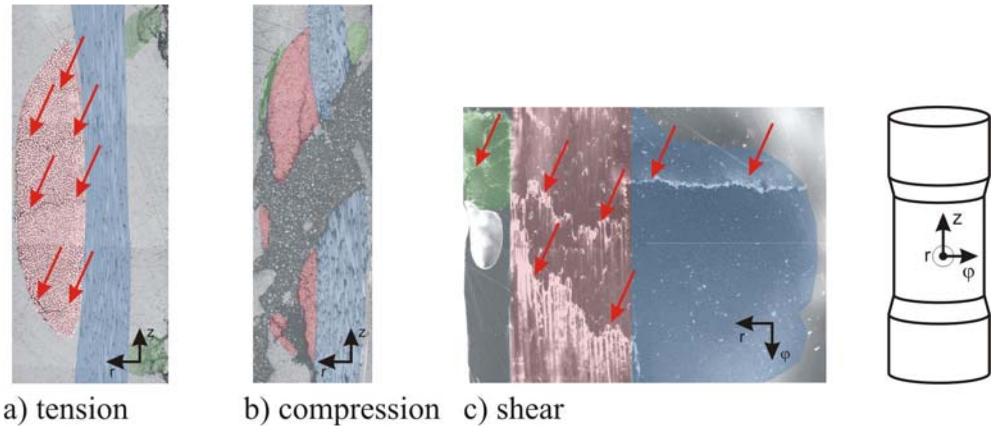


Figure 6: Micrographs of damaged GF-MLG/EP after uniaxial cyclic loading a.) transverse crack development under tension loading, b.) catastrophic wedge like failure under compression loading, c.) distributed crack development and growth under shear loading

In a comparison of the degradation of stiffness under uni-axial loads to that of multi-axial load conditions, the influence of in-phase superposed loads can be clearly seen (Fig. 7). Superposed tensile/torsional loads lead to a more significant degradation of shear stiffness at a largely identical drop in tensile stiffness. The damage phenomena due to tensile and torsional loads occur combined.

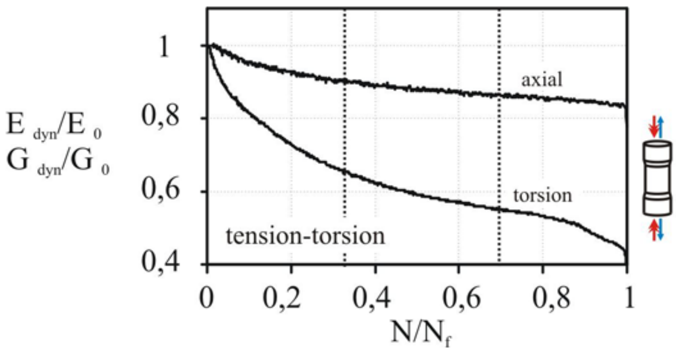


Figure 7: Stiffness degradation of GF-MLG/EP under superposed cyclic tension/torsion load

## EXPERIMENTAL PARAMETER IDENTIFICATION

For the determination of the parameters and the first model adoption the uni-axial and multi-axial constant amplitude tests of 3D textile-reinforced tube specimens made of weft knitted glass fibre reinforced epoxy (GF-MLG/EP) with a balanced fibre volume fraction in warp (tangential) and weft (axial) direction and a non-crimp fibre arrangement have been carried out under tension/compression-torsion loading. The in-plane deformation behaviour of the specimen has been modelled with the help of the CLT as a [0/90]-laminate.

In the experimental damage evaluation it has been observed, that the stiffness drop at the beginning of the uni-axial cyclic tension tests is caused mainly by transverse crack development in the 90°-layer. In case of in-plane shear loading both layers are damaged identically. The damage evolution equation of the textile reinforced material under tension loading can therefore be reduced to the damage evolution function $f^{\perp\sigma}$ of the 90°-layer (see (9)) and in the case of in-plane shear loading to the damage evolution function $f^{\perp\parallel}$ of the 0°- and the 90°-layer (see (10)). The parameters can therefore be identified separately.

$$\frac{dD}{dN}=\frac{d}{dN}\begin{bmatrix}D_{\parallel}\\ D_{\perp}\\ D_{\parallel\perp}\end{bmatrix}=\phi_{\perp}^{t}\left.\begin{bmatrix}q_{\parallel}^{\perp,t}\\ q_{\perp}^{\perp,t}\\ q_{\parallel\perp}^{\perp,t}\end{bmatrix}\right|_{90°}\neq 0,\quad \frac{dD}{dN}=\frac{d}{dN}\begin{bmatrix}D_{\parallel}\\ D_{\perp}\\ D_{\parallel\perp}\end{bmatrix}=\phi_{\parallel}^{t}\left.\begin{bmatrix}q_{\parallel}^{\parallel,t}\\ q_{\perp}^{\parallel,t}\\ q_{\parallel\perp}^{\parallel,t}\end{bmatrix}\right|_{0°}=0 \qquad (9)$$

$$\frac{dD}{dN}=\frac{d}{dN}\begin{bmatrix}D_{\parallel}\\ D_{\perp}\\ D_{\parallel\perp}\end{bmatrix}=\phi_{\parallel\perp}^{t}\left.\begin{bmatrix}q_{\parallel}^{\parallel\perp}\\ q_{\perp}^{\parallel\perp}\\ q_{\parallel\perp}^{\parallel\perp}\end{bmatrix}\right|_{0°,90°}\neq 0 \qquad (10)$$

In accordance with Figure 8 the stiffness degradation under cyclic tension loading of different stress levels can be modelled with one set of parameters.

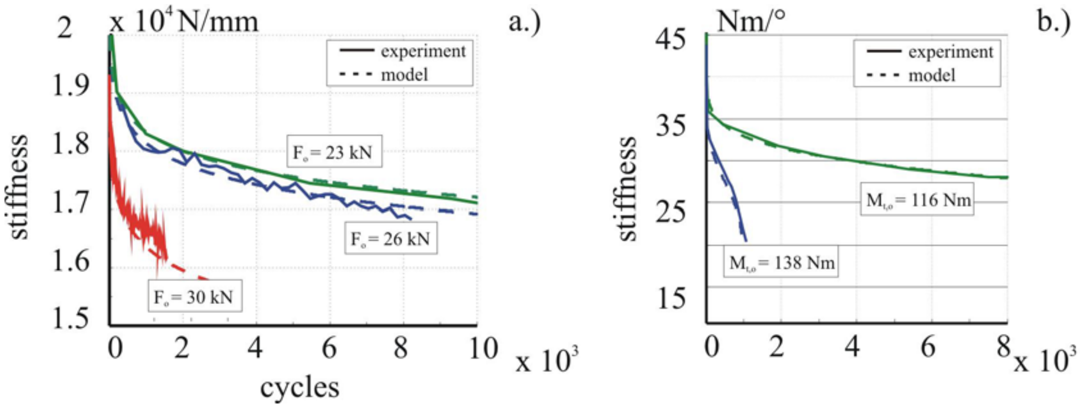


Figure 8: Modelling results for a.) uniaxial tension and b.) shear loading of 3D textile-reinforced tube specimen

The parameter identification for the remaining failure mode dependent damage evolution functions as well as for the coupling vector is currently performed.

## SUMMARY

The fatigue strength behaviour and the damage phenomenology of glass fibre 3D textile-reinforced composites under cyclical loads was investigated in uni- and multi-axial stress tests on tubular test specimens. The visual inspection of the material condition and the evaluation of photographic and light microscopic make it possible to quantify the material damages developing under cyclical loads and to gain approaches for the formulation of the damage evolution. According to these tests, the measurable drop in composite stiffness under cyclical tensile and shear stresses is directly attributable to the creation and propagation of visible mesoscopic cracks. In contrast to that, cyclical compressive stresses do not cause the development of visible cracks and thus no reduction in stiffness during the fatigue life. With the aid of the failure criterion according to CUNTZE modified for fatigue stresses, the mode related material effort is provided for the failure analysis and the determination of the damage growth in order to formulate the damage evolution separately for each fracture mode and thus for the occurring damage phenomena. The damage evolution finally given by the sum of the damage evolution functions of all fracture modes multiplied with a coupling factor to take multi-axial states of stresses into account. The proposed model was adopted to first experimental results and will furthermore be verified in fatigue tests under superposed ($\sigma$, $\tau$)-loading conditions.

## ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the German Research Foundation (DFG) within the project HU 403/24.

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