# FAILURE AND DAMAGE BEHAVIOUR OF BIAXIAL REINFORCED WEFT KNITTED COMPOSITES

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**SUMMARY:** Unique biaxial reinforced weft knitted fabrics are a novel textile reinforcement composed of biaxial reinforcing layers that are held together by a 3D reinforcing knitting yarn system. The yarn systems provide a very high composite strength and stiffness and the knitting structures provide a high drapability of the preform as well as the good impact behaviour of the composite material. To design structural components made of these novel weft knitted fabrics, an improved understanding of the detailed material behaviour is essential.

For these composites, the phenomenological damage phenomena have been determined experimentally and have been evaluated by means of crack density studies and micromechanical models. Damage variables are introduced to describe the evolution of the damage state and as a subsequence the degradation of the material stiffness. Special emphasis is given to the interaction between fibre failure due to fibre stress and matrix failure due to transverse and shear stress. The predictive capability of the presented model is evaluated by carrying out a series of tensile tests using acoustic emission techniques to detect the damage and the failure behaviour of GF/RP biaxial flat bed weft knitted composites under static as well as under dynamic loading.

**KEYWORDS**: textile reinforced composites, anisotropic damage, micromechanics, crack density studies, acoustic emission tests

## INTRODUCTION

Because of the alignment of the reinforcing textiles according to the distribution of forces, the design process of textile reinforced composites opens up a great range in industrial applications (crash safety, structural damping etc.). Moreover, novel textile techniques allow a quick manufacturing of reproducible fabrics, e. g. in the form of preforms, for ultralight, reliable and efficient component structures [1]. Thereby, woven fabrics rank among the most important reinforcing textiles, because they are characterised by a simple manageability and a good handling in draping processes. Woven fabrics are fabricated in a prolific weaving process by means of intersecting of two filament systems, the warp yarn and the weft yarn. The different woven fabrics are characterised by the bond type that recurs in warp and weft direction. For the application for fibre reinforced composites, twill fabrics, satin fabrics and canvas fabrics are particularly important.

An elementary disadvantage of 2D composites reinforced by woven fabrics, that show an orthotropic arrangement of fibres with an adjustable ratio of warp yarns and weft yarns (“bi-directional reinforcement” when equal ratio), is the layerwise construction and the absence of a reinforcement in the thickness direction of the laminate. Thus, layered fibre reinforced or layered textile reinforced composites tend to delaminations, in particular if the composite structure is damaged by impact. To counteract such a failure behaviour, three-dimensional woven fabrics are under investigation since 30 years. Since that time various 3D weaving technologies have been developed, that differ in two fundamental groups, the 3D interlaced orthogonal fabrics and the 3D non interlaced orthogonal fabrics. As the interlaced fabrics show yarn ondulation like conventional woven fabrics, the reinforcing fibres of the non-interlaced fabrics are lying roughly craned in the textile. Non interlacing 3D-fibre alignment do not only appear in 3D woven fabrics, but similarly in 3D braided fabrics and knitted fabrics, too.

A further group of textile area-measured material are the knitted fabrics, whereas it will be differentiated between warp knitted fabrics and weft knitted fabrics. Knitted fabrics exhibit the best drape behaviour of all textile fabrics, but because of the twisting structure only very lox fibre-volume contents and clearly lower stiffnesses and strengths can be achieved in comparison to composites reinforced with woven fabrics, so that the conventional knitted fabrics are not suited as preforms for high-performance composites [2].

To increase the stiffness of knitted fabrics, warp knitted fabrics and weft knitted fabrics could be reinforced with weft threads. In contrast to woven fabrics, in knitted fabrics these reinforcing filaments are lying roughly craned in the textile preform, so that the stiffnesses and strengths characteristics in these textile composite are frequently exceeding the stiffnesses and strengths of composites reinforced by woven fabrics [2].

The design process of textile reinforced composite components requires adapted analytical and numerical simulation techniques as well as suitable realistic failure criteria which take into account the occurring damage mechanisms. Such composite failure conditions have to cover the full failure behaviour, fracture conditions and the non-linear analysis of the degradation behaviour. Though, in recent years first investigation has been undertaken to determine the damage mechanisms and the degradation behaviour of textile reinforced composites. The various models differ, however, in their formulation of the failure criteria and in their representation of damage in the form of appropriate damage variables. These models are either based on the principals of continuum damage mechanics, on micromechanics or on physically based failure criteria. LANGKAMP [3] developed a method that enables the use of physically based failure criteria of PUCK [4] and CUNTZE [5] for the description of the initial fracture of textile-reinforced composites. MATZENMILLER et al. [6] proposed a model, based on continuum damage mechanics, for the non-linear analysis of fibre composites. The phenomenological failure model [3] and the adapted degradation model [6] are combined by HUFENBACH et al. [7, 8] to describe the degradation behaviour of textile reinforced composites. Based on numerous experimental studies [9], the predictive capability of this method is shown for multi-layered carbon fibre reinforced PEEK [9]. Micromechanical studies allow the determination of the effective elastic properties of a cracked structure. But they are based on the assumption of a given distribution of cracks and a simple composite geometry. For $[0/90]_s$ fibre composites, KASHTALYAN et. al. [10] determine the effective elastic moduli depending on crack density parameters. The micro-mechanical approach requires that the microscopic mechanisms of degradation are all identified and the geometry and the distribution of cracks are simple and regular.

However, the performance of all these models strongly depends on the correct determination of the introduced damage parameters. On this account, special emphasis in this work is given to the experimental observation of stiffness loss and crack initiation as well as to their mechanical description.

## BIAXIAL FLAT BED WEFT KNITTED REINFORCEMENTS

Biaxial reinforced weft knitted fabrics are composed of weft and warp yarn layers which are held together by one or two stitching yarn systems, respectively. One simple structure of a biaxial reinforced weft knitted fabric is shown in Fig. 1.

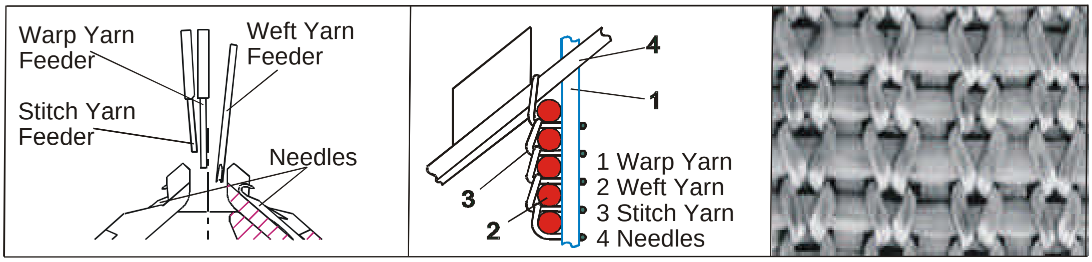


Fig. 1: Working area of a biaxial weft knitting machine, cross section and surface view of plain jersey stitch [2]

One main advantage of these new group of textiles is, that based on knitting principles complex shaped integral preforms with biaxial reinforcement can be produced. This can be either fully fashioned or three dimensional preforms. The flat weft knitting technology offers various shaping methods. These methods are distinguished in structural variation and variation of the number of stitches in course and wale direction.

Among multi-layer preforms, weft knitted fabrics feature outstanding drapability. The knitting structure of the weft knitted textiles represents a deformation mechanism that counteracts to the shear forces. Thus mass accumulation of the reinforcement yarns resulting from shearing first leads to decreasing yarn density before wrinkling occurs. Additionally the reset forces during the drape forming process are very low [2].

## FABRICATION OF THE TEXTILE REINFORCED GLASS EPOXY SPECIMEN

For the infiltration of the weft knitted textiles made from glass fibres the resin transfer moulding technology (RTM) was applied using the epoxy resing Bakelite L1000. Fig. 2 illustrates the RTM infiltration technique consisting of a pressure vessle and the heatable moulding tool. Alternatively a two-component infiltrations system of the company Wolfangl was applied. Using the infiltration set up different textile reinforcements with various fibre architecture and geometries can be infiltrated. The fabricated composite plates of the size 500 x 500 mm with 2 mm thickness were cut using water jet into 250 x 20 mm tension specimen.

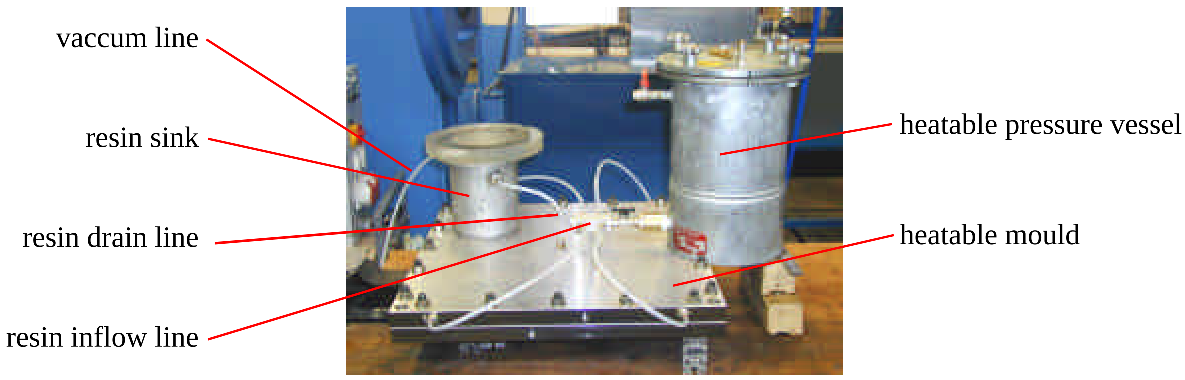


Fig. 2: RTM infiltration set up for textile reinforced composite plates

## STRUCTURAL BEHAVIOUR OF BIAXIAL REINFORCED WEFT KNITTED COMPOSITES – PHILOSOPHY OF THE DAMAGE ANALYSIS

The structural behaviour of biaxial reinforced weft knitted composites is of a very complex and diversified nature. The spatial curved fibre alignment complicates the description and modelling of representative volume elements in the design process for the engineer, like they can be found in the design of metal composites (unit cell) or fibre reinforced composites (UD-unit cell). Presently, for the definition of “textile” unit cells drastic and trivialising simplifications are taken up, that frequently foil a possible adaptation of the yarn architecture according to the acting loads under consideration of restrictions of the manufacturing process. The high variability of textile preforms predominantly complicates the modelling of “unit

Each type of “textile RVE” divides in numerous sub-types, whereas miscellaneous intersections, loops and joints in variable arrangement occur [11-13]. Thus, it seems to be very beneficial to describe the relative characteristics of the composite material properties by means of an more general approach: by means of suitable *equivalent single layers* [3].

Due to the complex yarn intersections and yarn enlacements, normally a non-linear stress-strain-behaviour occurs on the structural level (macroscale). Simultaneously, different microscopic failure modes interact, which causes unusual linking effects on the macroscale. This structural complexity result in a complex damage behaviour and subsequently to complex constitutive equations under static load as well as under dynamic loads. This is a considerable reason, why barely fused regulations for calculation and dimensioning of textile reinforced composites exist to this date. Nevertheless, practically applicable damage models have to offer a simple and manageable foundation. Hence, in the following we will embarke on a strategy that describes the non-linear behaviour of the novel biaxial reinforced weft knitted composites in a practically efficient way on the level of the equivalent single layer. To ensure the physical significance of these model, extensive verifications will be undertaken [14]: experimental crack density studies with the aid of video analysis and non-destructive testing methods, micromechanical studies, and additionally numerical studies.

## PHENOMENOLOGICAL ASPECTS OF DAMAGE IN BIAXIAL REINFORCED WEFT KNITTED COMPOSITES

Due to the complexity of the geometry and the fracture mechanisms of these heterogeneous textile reinforced composites, a convenient structural failure analysis causes extensive difficulties, since the micro-structural configuration is of vital importance for the description of the degradation behaviour. It becomes apparent that a successful damage analysis initially requires a phenomenological determination of all occurring damage mechanisms.

Matrix cracking has been recognised as the first observed damage mode. Its presence mainly causes the stiffness reduction of the textile composite. Because it does not necessarily result in an catastrophic failure, matrix cracking is normally not the most important failure mode. But it can trigger fibre failure or delamination, which is far more important in practical cases.

Subjected to tensile loading, three different modes of matrix cracking could be observed in $[0/90]_s$ composites, transverse cracking in the 90°-layer, splitting in the 0°-layer and debonding of the 3D stitching yarns (Fig. 3)

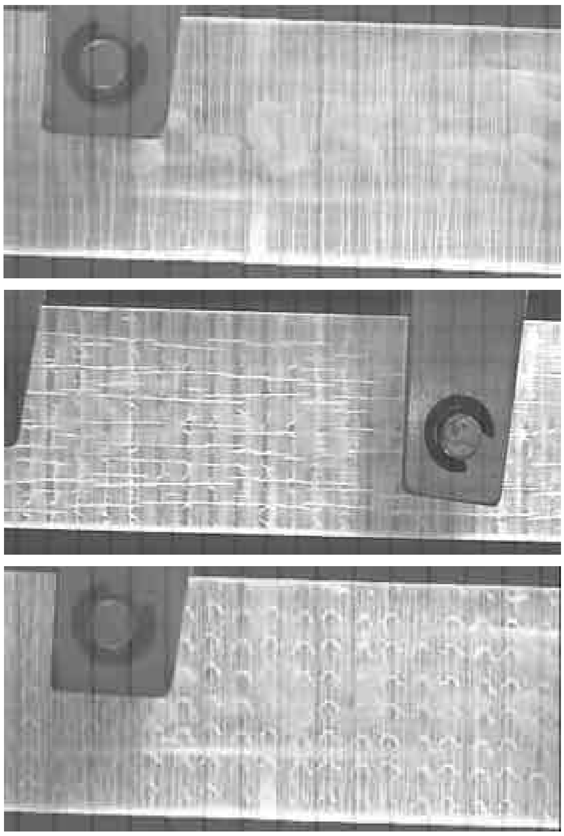

Fig. 3: Matrix cracking failure modes: transverse cracking, splitting and debonding of the stitching yarns [14]

## DAMAGE MECHANICS MODEL

### General aspects and constitutive assumptions

For a practical design of complicated structural components made from textile composites, the description of the material degradation behaviour using continuum damage mechanics (CDM) is very advisable. Hence, the damage behaviour will be described with a CDM based model and adapts the work of MATZENMILLER et al. [6] to textile composites. This model is feasible under the following assumptions:

- The textile composite can be recomposed by equivalent single layers.
- All damage modes are experimentally separable, well known and quantifiable.
- All nonlineaer effects of the constitutive behaviour are attributed to damage.
- The orthotropic nature of the mechanical response is maintained at all states of damage.

In this case, plane stress conditions (CLT) are assumed adequate to model the stress-strain behaviour of the textile composite. The analysis described below is conducted layer-wise having regard to the real textile structure by the use of correction factors. Action plane related failure criteria act as a set of boundary conditions (damage threshold) for the damage mechanics model [7, 8].

### Non-linear Stress-Strain-Relationship

To transform the nominal stress $\boldsymbol{\acute{o}}$ of the orthotropic i-UD-layer to the effective stress $\tilde{\boldsymbol{o}}$, MATZENMILLER et al. [6] introduze a rank-four damage operator $\boldsymbol{D}$:

$$\tilde{\boldsymbol{o}} = \boldsymbol{D}\boldsymbol{\acute{o}}$$

with

$$\boldsymbol{D} = \begin{bmatrix} \frac{1}{1-D_{11}} & 0 & 0 \\ 0 & \frac{1}{1-D_{22}} & 0 \\ 0 & 0 & \frac{1}{1-D_s} \end{bmatrix}.$$

The degradation variables $D_{11}$ and $D_{22}$ denote the damage in the two principal axis of the equivalent layer. An additional degradation variable, $D_s$, is introduced to characterize the modification of the shear behaviour. The introduced degradation parameters $D_{11}$ and $D_{22}$ needs to be verified separately for the tension and the compressive domain. All degradation parameters take the value $D_i = 0$ for the undamaged, initial state, and the value $D_i = 1$ for the completely damaged state, respectively. The compliance relationship for the damaged state then results in

$$\boldsymbol{e} = \boldsymbol{S^0}\tilde{\boldsymbol{o}} = \boldsymbol{S^0}\boldsymbol{D}\boldsymbol{\acute{o}} = \tilde{\boldsymbol{S}}\,\boldsymbol{\acute{o}}\ ,$$

where $\boldsymbol{S^0}$ denotes the compliance matrix at the initial state, with

$$\tilde{\boldsymbol{S}}(\boldsymbol{D}) = \begin{bmatrix} \tilde{S}_{11} & \tilde{S}_{12} & 0 \\ \tilde{S}_{21} & \tilde{S}_{22} & 0 \\ 0 & 0 & \tilde{S}_{66} \end{bmatrix} = \begin{bmatrix} \frac{1}{(1-D_{11})E_{\parallel}} & -\frac{n_{21}}{E_{\parallel}} & 0 \\ -\frac{n_{12}}{E_{\perp}} & \frac{1}{(1-D_{22})E_{\perp}} & 0 \\ 0 & 0 & \frac{1}{(1-D_s)G} \end{bmatrix}$$

The effective compliance $\tilde{S}_{11}$ is only affected by the damage parameter $D_{11}$, and will only be reduced if a fibre failure criterion is fulfilled. Consequently, $D_{11}$ could be interpreted as the damage variable for fibre damage. The transverse elastic compliance $\tilde{S}_{22}$ is only governed by the damage parameter $D_{22}$, which should be accordingly interpreted as a crack density parameter [8]. For an orthotropic layer, the shear compliance $\tilde{S}_{66}$ is independent of the residual compliances. Thus, the determination of shear damage by the damage parameter $D_s$ is a direct consequence of the definition of the constitutive equation [8]. The inversion of the damaged compliance matrix $\tilde{\boldsymbol{S}} = \boldsymbol{S}^0 \boldsymbol{D}$ leads with $\tilde{\boldsymbol{C}}(\boldsymbol{D}) = \tilde{\boldsymbol{S}}(\boldsymbol{D})^{-1}$ to the effective material stiffness matrix for the damaged state

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

with $d = 1-(1-D_{11})(1-D_{22})\nu_{12}\nu_{21}$. It becomes apparent that the elastic stiffnesses $\tilde{C}_{12}$ and $\tilde{C}_{21}$ are also affected by damage, which could be attributed to the change of the Poisson´s ratio due to matrix cracking or fibre failure.

**Damage Threshold**

Within the framework of a continuum damage mechanics, physically based failure criteria [3-5] act as threshold functions; similar to the yield surface in plasticity theory. The elastic region is bounded by the fracture surfaces associated with the different composite failure modes. The threshold functions $r$, defining the elastic region during the damage process, become a function of the effective stress $\tilde{\boldsymbol{\sigma}}$ (and consequently of the damage operator $\boldsymbol{D}$) in the fracture plane. In detail, the surface $f_{ff}$ represent the fibre failure mode, and on the other hand $f_{iff,t}$ and $f_{iff,c}$ typify the IFF modes in the tension and the compressive domain, respectively:

$$f_{ff} = \left( \frac{\tilde{\sigma}_1}{g_{\parallel}^{(\pm)} R_{\parallel}^{(\pm)}} \right)^2 - r_{ff1} = 0\,,$$

$$f_{iff,t} = \left( \frac{\tilde{\sigma}_n}{g_{\perp}^{(+)} R_{\perp}^{(+)}} \right)^2 + \left( \frac{\tilde{\tau}_{nt}}{g_{\perp\perp}^{(A)} R_{\perp\perp}^{(A)} - p_{\perp\perp}^{(+)} \tilde{\sigma}_n} \right)^2 + \left( \frac{\tilde{\tau}_{n1}}{g_{\perp\parallel} R_{\perp\parallel} - p_{\perp\parallel} \tilde{\sigma}_n} \right)^2 - r_{iff1,t} = 0\,,$$

$$f_{iff,c} = \left( \frac{\tilde{\tau}_{nt}}{g_{\perp\perp}^{(A)} R_{\perp\perp}^{(A)} - p_{\perp\perp}^{(-)} \tilde{\sigma}_n} \right)^2 + \left( \frac{\tilde{\tau}_{n1}}{g_{\perp\parallel} R_{\perp\parallel} - p_{\perp\parallel}^{(-)} \tilde{\sigma}_n} \right)^2 - r_{iff1,c} = 0\,.$$

The effective stresses acting in the fracture plane are calculated using the general state of stress and the common transformation

$$\begin{Bmatrix} \tilde{\sigma}_1 \\ \tilde{\sigma}_n \\ \tilde{\sigma}_t \\ \tilde{\tau}_{nt} \\ \tilde{\tau}_{t1} \\ \tilde{\tau}_{n1} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c^2 & s^2 & 2sc & 0 & 0 \\ 0 & s^2 & c^2 & -2sc & 0 & 0 \\ 0 & -sc & sc & c^2 - s^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & c & -s \\ 0 & 0 & 0 & 0 & s & c \end{bmatrix} \begin{Bmatrix} \tilde{\sigma}_1 \\ \tilde{\sigma}_2 \\ \tilde{\sigma}_3 \\ \tilde{\tau}_{23} \\ \tilde{\tau}_{31} \\ \tilde{\tau}_{21} \end{Bmatrix}$$

with $s = \sin\theta$ and $c = \cos\theta$ .

**Damage Evolution Laws**

Numerous models with various damage evolution laws for fibre composites are proposed in the literature, e.g. [6, 8, 15]. The main problems to consider for the practical user is the formulation of physically based damage evolution laws and degradation parameters, subsequently. Additionally, the possibility of an accurate and efficient determination of these parameters has to be considered. It is an appropriate approach to determine the damage evolution laws experimentally, instead of deducing them from thermodynamic potentials. Within this study, the following principal damage growth law proved to be a reasonable choice [14] (Fig. 4):

$$D_i = \begin{cases} 0 & if \quad e_{ij} < e_0 \\ D_m(e_{ij}) & if \quad e_0 < e_{ij} < e_1 \\ D_m(e_{ij}) + D_c(e_{ij}) & f \quad e_1 < e_{ij} < e_2 \\ 1 & if \quad e_{ij} > e_2 \end{cases}$$

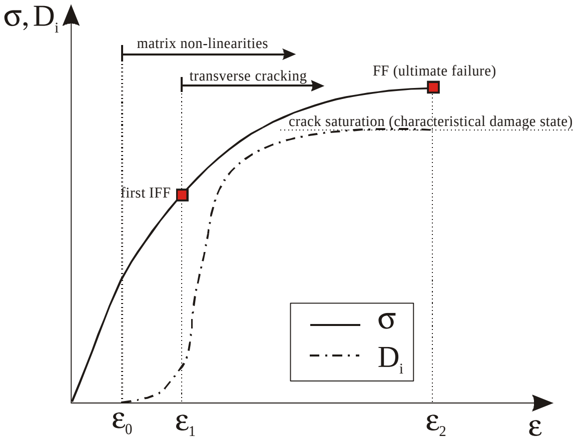


Fig. 4: Principal damage evolution law

The stress-strain curve, and as a consequence the damage evolution law, too, is subdivided into four parts. Within the first part, the stress-strain curve is linear and no damage occurs ($D_i=0$). If $e_{ij} > e_0$ matrix non-linearities (*diffuse damage*) are assumed to occur. Therefore, the damage function controlling matrix non- linearities $D_m(e_{ij})$ is introduced. After the first IFF, effects due to transverse matrix cracking (*discrete damage*) have to be superimposed to the effects due to matrix non-linearities and the damage function becomes $D_m(e_{ij}) + D_c(e_{ij})$. Depending on the textile structure (e.g. fibre distance or distance between stitching yarns), the characteristical damage state (CDS) is reached: no further cracks are assumed to occur in the damaged layer. Accompanied by further IFF, the structure is damaged until the ultimate failure (FF) occurs ($D_i=1$). The parameters in the damage evolution law describe the gradient of the damage function and should be correlated with experimental data.

## Material behaviour under high strain rates

The material behaviour of composites is known to be strain rate dependent in the high strain rate domain. To adapt the proposed damage model also for highly dynamic loading cases, some model-specific enhancements need to be taken. The most common approach is to refer the strain rate dependent stiffness values $\boldsymbol{C}_{\dot{e}}$ as well as the strain rate dependent strength values $\{\boldsymbol{R}_{\dot{e}}\}$ to their particular static values $\boldsymbol{C}_{\boldsymbol{ref}}$ and $\{\boldsymbol{R}_{\boldsymbol{ref}}\}$ by introducing a simple set of equations [16, 17].

$$\boldsymbol{C}_{\dot{e}} = \boldsymbol{C}_{\boldsymbol{ref}}\left(1 + \boldsymbol{C}_{\boldsymbol{rate}} \ln \frac{\dot{e}}{\dot{e}_0}\right)$$

$$\{\boldsymbol{R}_{\dot{e}}\} = \{\boldsymbol{R}_{\boldsymbol{ref}}\}\left(1 + \boldsymbol{R}_{\boldsymbol{rate}} \ln \frac{\dot{e}}{\dot{e}_0}\right)$$

Two additional material constants ($\boldsymbol{C}_{\boldsymbol{rate}}$ and $\boldsymbol{R}_{\boldsymbol{rate}}$) need to be determined experimentally in order to describe the stiffness change and the strength change, respectively, in terms of the particular strain rate $\dot{e}$ .

## VERIFICATION OF THE DAMAGE MECHANICS MODEL

### Crack density studies and micromechanical verification

To describe the degradation of the elastic properties depending on the crack initiation and the crack propagation, respectively, experimental crack density studies have been performed [14]. Therefore, $[0/90]_s$ and $[\pm45]_s$ textile composites are loaded in tensile direction and the tensile test is observed by a high-speed camera (Fig. 5). Subsequently, the reduced elastic properties of the $[0/90]_s$ composites could be compared with the reduced moduli predicted by the analytical micromechanical degradation model of KASHTALYAN et. al. [10]. Based on the experimental and analytical crack density studies on such composites, conclusions regarding the determination of damage parameters could be drawn [14].

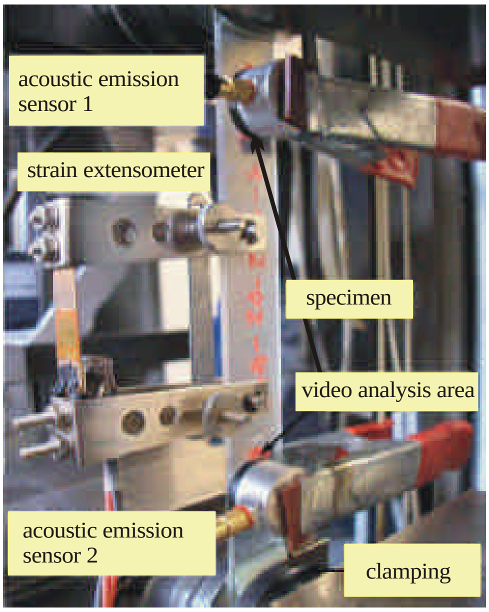

Fig. 5: experimental setup for the performed crack density studies

### Tensile tests and acoustic emission analysis

To verify textile-compatible damage models, the experimental determination of the associated material parameters is of prior importance. In particular to describe the damage evolution of textile composites, numerous parameters are required which are often only estimated based on simple phenomenological assumptions. In order to be able to determine all the required model parameters experimentally, adapted testing methods that enable a reliable multi-axial application of loads have been developed [7, 9]. Furthermore, the combination of strain measurement and acoustic emission techniques (AE) provides fundamental information about the crack initiation and the subsequent damage behaviour [14, 18].
The AE technique, which uses elastic waves resulting from crack initiation and propagation in a material, is a very useful method to evaluate hidden fracture mechanisms and the microscopic damage degree in composite materials [19]. Hence, the tensile tests on the GF/RP specimen were carried out using a VALLEN AMSY-5 AE monitoring system (Fig. 5). The complete waveforms of the detected acoustic emissions have been recorded. In the quantitative evaluation, amplitude values, the hit accumulation and the released energy were considered. Using the VALLEN AMSY-5 AE evaluation unit, the acoustic values were implicated with the measured stress-strain-curve and the crack densities of the tensile specimen.

## RESULTS AND DISCUSSION

Uniaxial tensile tests have been performed with [0/90/90/0], [90/0/0/90] and [45/-45/-45/45] biaxial weft knitted composites to record the non-linear stress-strain-curve, the crack densities of the several layers and the acoustic emission data. Thus, conclusions could be drawn between the accurate experimental measured damage phenomenology and the acoustic emission data, on the one hand, and the experimentally measurable elastic moduli reduction, respectively (Fig. 6). Subsequently, these crack density curves act as input data for the damage evolution laws of the proposed damage model. A comparison between the experimental measured and the theoretically predicted degradation of the elastic moduli shows good agreements (Fig. 7).

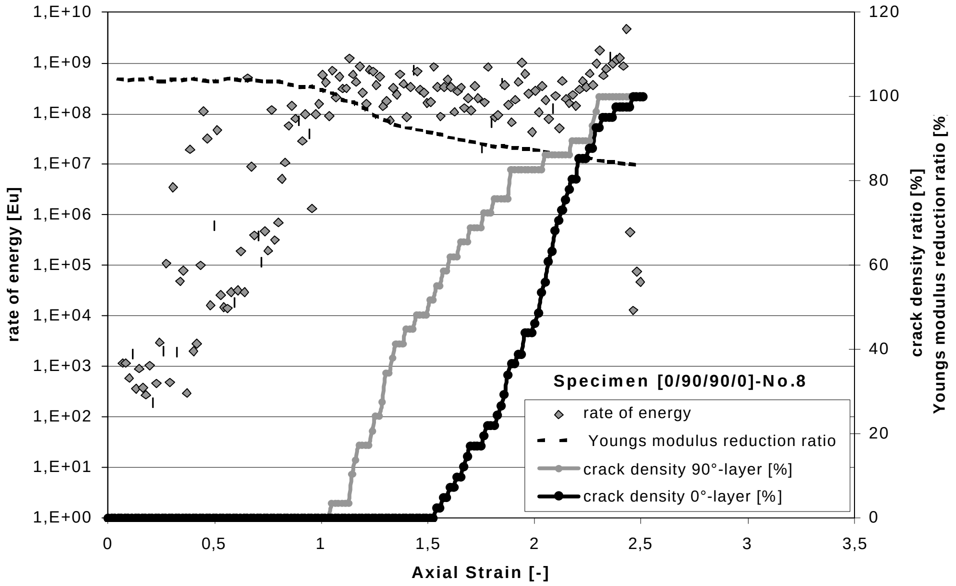


Fig. 6: Experimental data: Youngs modulus reduction, crack densities and acoustic emission data as a function of axial strain [14]

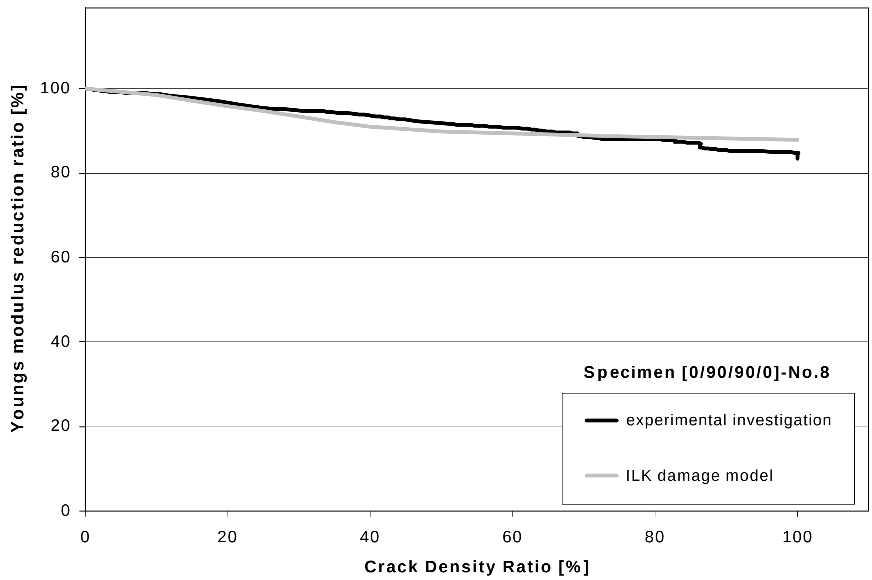


Fig. 7: Crack density studies: experimental and theoretical elastic moduli reduction [14]

## CONCLUSIONS

This investigation considers the attributes of textile GF/RP composite damage analysis necessary for use in the design of complex lightweight applications where the need for reliable prediction of performance must be balanced by simplicity and ease of use. Damage evolution laws have been determined based on numerous experimental and micromechanical data. It was found that the correct determination of the degradation parameters denoting the significant effects of the damage state plays an important role in the damage concept. The predictions of the damage model have been compared with experimentally observed stress-strain-curves and acoustic emission measurements. They provide an independent identification of the damage modes associated with the microstructural changes: transverse matrix microcracking, longitudinal microcracking (splitting) and fibre rupture.

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