ULTRASONIC DETERMINATION OF ANISOTROPIC DAMAGE IN FIBRE AND TEXTILE REINFORCED COMPOSITE MATERIALS

W. Hufenbach, T. Ritschel R. Böhm, A. Langkamp

TU Dresden, Institute of Lightweight Structures and Polymer Technology, 01062 Dresden, Germany

ABSTRACT

The description of the very complex damage and failure behaviour of fibre and textile reinforced composites in damage models is objective of various research efforts. Such models strongly depend on the nature of the reinforcement (fabric, uniaxial or multiaxial layup) and additionally on micro-cracking geometry. With respect to the practical applicability the number of input parameters of damage models should be in a reasonable way as low as possible. However, damage formulations have to be complex enough to cover the physic of the material and the anisotropic characteristic of damage in composites.

Within this theoretical and experimental investigation BASTE'S phenomenological model where damage is defined as the change of the elasticity tensor, will be proposed as a suitable description approach. In combination with this model, the determination of the anisotropic stiffnesses by ultrasonic phase velocity measurements will be shown to be the predestined experimental method. A specific ultrasonic device was developed to provide a system for an efficient recovery of the stiffness tensor coefficients from convenient sets of velocity measurements. Linked to a tensile machine, it is possible to measure the anisotropic damage of fibre and textile reinforced composites. The approach has a smeared and general characteristic and is consequently independent and unlimited in terms of the composite reinforcement nature, crack geometry and failure mechanisms.

KEYWORDS: textile-reinforced composites, anisotropic damage, tensile tests, ultrasonic non-destructive evaluation, phase velocity measurements

INTRODUCTION

The mechanical behaviour of fibre and of textile reinforced composites under static, dynamic and cyclic loading has been barely analysed so far. Thus, for designing with such textile-reinforced multi-layered materials, there is a lack of detailed knowledge about the stress-strain behaviour including the occurring fracture and damage mechanisms under practical loading conditions, in particular. Hence, a specification of safety factors for such textile-reinforced lightweight structures is not possible, yet. Only for quasi-static loading, the current development status for constitutive laws is estimated to 30 %, and for the failure criteria even only to 10% [1].

For numeric structural analysis macro-mechanical material characterisation and the formulation of textile-adapted material laws and failure criteria are of major importance. Especially for textile reinforced composite materials, occurring failure mechanisms depend on multiple parameters like textile geometry, manufacturing parameters and loading conditions. Modified physically based failure criteria are promising approaches to consider these influences, and for the development of suitable degradation and damage models [2-7]. Fundamental modifications of fracture-mode-related failure models to determine the onset of failure for elementary textile composites have been described and verified by CUNTZE [6] and LANGKAMP [7]. The coverage of the successive material degradation implicates unsolved problems though. First models that include damage effects on the stiffnesses have already been published [2, 5].

The experimental determination of the associated material parameters is of principal importance for the development of such textile-adapted material models. In particular, numerous arbitrary parameters for the description of the failure and degradation behaviour are needed. Prevalently, these parameters must be evaluated on the basis of phenomenological observations. To determine all required model parameters in a reliable way, material-adapted test methods need to be adopted in addition to the usual testing techniques [7, 8]. For the determination of interaction parameters, a central role is accorded to new testing methods like ultrasonic measurements.

PHENOMENOLOGICAL FRACTURE AND DAMAGE MODEL

There is a wide spectrum of damage types and phenomena that influence the mechanical behaviour of composite materials (Fig. 1). Damage can be discrete and measurable or diffuse and not measurable. Matrix cracking or delamination can be termed discrete as these damage types can be quantified by crack density or delamination area, whereas for microscopic phenomena like interface failure and whitening there is no sufficient experimental option of quantification. The architecture and the geometry of the material have a crucial influence on the damage nature. Most damage mechanic models use assumptions regarding damage crack geometry. Especially textile reinforced composites have a more complex internal geometry compared to composite made from a lay up of unidirectional plies and show a diffuse damage performance where considerations of micro-crack geometry are not possible.

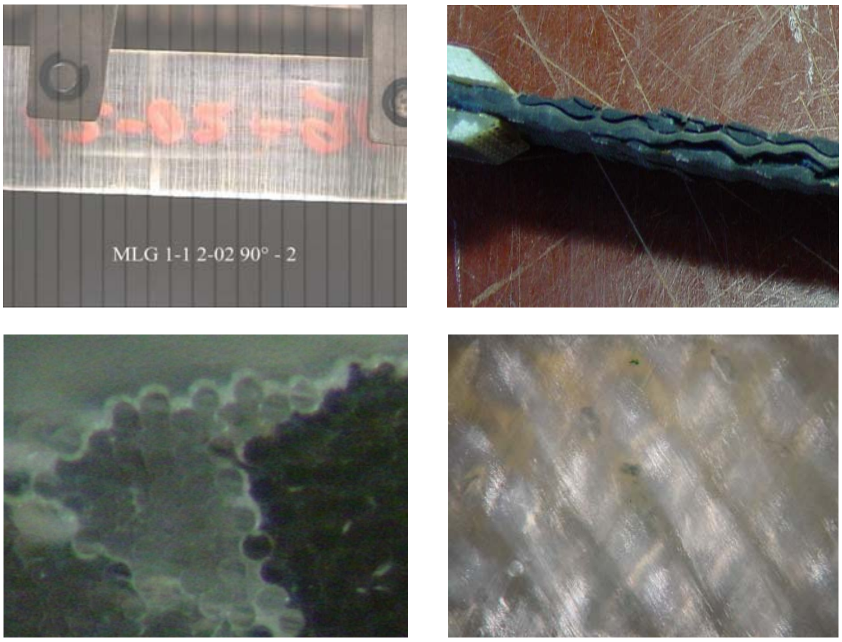

Fig. 1 Damage phenomena: matrix cracking, delamination, interface failure, whitening

The crucial advantage of the damage model suggested by BASTE and AUDION [9] is the general validity and its purely phenomenological character. This model is considered to be a suitable damage model especially for textile composites because no generalising assumptions about micro-crack initiation and geometry as well as resulting failure criteria are made. The model assumes that the sum of all occurring damage phenomena causes a corresponding loss of stiffness. The reduction of the stiffness is directly used to describe material damage. The stiffness tensor is split in a constant part C_0, describing the undamaged material situation, and a variable part C_d which describes the loss of stiffness due to damage.

$$\tilde{C} = C_0 - C_d \tag{1}$$

The change of the stiffness will be used as internal damage variable that characterises the particular damage state in the material.

$$\omega = C_d = C_0 - \tilde{C} \tag{2}$$

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 value $\omega_{ij}^{\lim}$. The normalised components of the damage tensor finally result to

$$\omega_{ii} = 1 - \frac{\tilde{C}_{ii}}{C_{ii}^{0}} \qquad i = 1,2,\ldots,6 \tag{3}$$

$$\omega_{ij} = \frac{C_{ij}^{0} - \tilde{C}_{ij}}{C_{ij}^{0} + \mathrm{sign}\left(C_{ij}^{0} - \tilde{C}_{ij}\right)\sqrt{C_{ii}^{0}\left(1-\omega_{ii}\right)C_{jj}^{0}\left(1-\omega_{jj}\right)}} \qquad i, j = 1,2,\ldots,6;\ i \neq j\,. \tag{4}$$

In contrast to the low theoretical complexity, the experimental effort is highly increasing. The model requires the experimentally determination of the stiffness tensor components. Here the use of classical testing methods is limited to the in-plane constants. Thus for experimental verification ultrasonic phase velocity measurements are used.

ULTRASONIC MATERIAL CHARACTERISATION

Basic principles

In 1970 MARKHAM [11] did early research work on determination of elastic constants of composite materials from wave speed measurements. In anisotropic media, such as composite materials, the propagation velocity of elastic waves travelling through the material depends on the direction of propagation and the corresponding stiffness. Based on this dependency, the stiffness constants can be obtained by time-of-flight measurements [9-15]. Ignoring any body forces, damping an dispersion effects, the equation of motion can be written as

$$C_{ijkl} \cdot u_{k,lj} = \rho \cdot \ddot{u}_i \qquad i, j, k, l = 1,2,3\,, \tag{5}$$

with C_{ijkl} being the stiffness tensor and ρ the material density**.** Assuming linear elastic wave propagation, the displacement u is given by

$$u_i = A_0 \cdot p_i \cdot \exp\left[i\,\omega(m_r\,x_r - t)\right]. \tag{6}$$

Equation (6) leads to the eigenvalue problem

$$(C_{ijkl}\,n_j\,n_l - \rho V^2\,\delta_{ik})\,p_i = 0\,. \tag{7}$$

Here, V is the phase velocity of the wave, n_j and n_l are two components of the unit vector describing the propagation direction of the wave, p_i is the wave polarisation and δ_{ik} the Kronecker symbol. With $\Gamma_{ik} \equiv C_{ijkl} n_j n_l$, eq. (7) can be written in the form:

$$\det(\Gamma_{ik} - \rho V^2\,\delta_{ik}) = 0\,. \tag{8}$$

Solving the inverse problem of eq. (8) leads to the unknown stiffness tensor components C_{ijkl} [10]. Therefore, a set of experimentally determined velocity data in distinct directions *n* is needed. To recover the complete set of nine elastic constants of an orthotropic material, a minimum of nine wave speed measurements is required. In order to reduce the experimental error, the number of measurements should be reasonably larger than the required minimum. The resulting over determined set of nonlinear equations is solved by using numerical methods. Here, the LEVENBERG-MARQUARD algorithm is used to minimise the square deviation between the analytical solution of eq. (8) and the experimentally determined phase velocities. This algorithm was found to converge in a reliable way, even when the initial guess is outside the range of convergence of other methods like NEWTONS method [15].

Immersion technique

For time of flight measurements usually non-continuous ultrasonic signals are used. If for testing non-continuous signals are used, considerations regarding phase and group velocity have to be made. Therefore in many cases for experimental examinations only wave propagation along principle directions is considered, because along these directions of high symmetry phase and group velocity coincide just as for isotropic materials [14]. In general ultrasonic coupling technique in combination with block-shaped cut specimen geometry is used for such testing. However damage investigations require a specimen geometry that allows a well defined, controlled and successive induction of damage due to loading. Thus tensile specimens have to be considered. In combination with such specimen geometry immersion technique is used as a sufficient ultrasonic testing method to realize wave velocity measurements.

Limiting the immersion technique examination to principal planes considerably reduces the effort of recovering stiffnesses from velocity data compared to non-principal plane considerations. For wave propagation in arbitrary directions phase-group-velocity-deviation must not be ignored. However phase velocity can directly be calculated from time-of-flight measurements in principal planes, using through transmission specimens of orthotropic material symmetry [14]. For such material symmetry, relevant for most laminates, there are four elastic constants in every principal plane corresponding to the phase velocity distribution within the plane (Fig. 2 left). Due to the use of plane specimens with limited thickness of 2 - 5 mm, measurements in the 1-2 plane are not possible and measurements in non-principal planes and have to be considered (Fig. 2 right) for fully recovery of elastic properties.

Velocity measurements in non-principal planes and arbitrary directions cause problems in practical experimental work because of the severe deviation of phase and group velocities. These deviations complicate the interpretation of the ultrasonic signal and the finding of the time-of-flight data. Hence, measurements in these planes are disputed and not often applied. However, from measurements in the two easily accessible planes (1-3 and 2-3) seven of nine stiffness constants can be obtained.

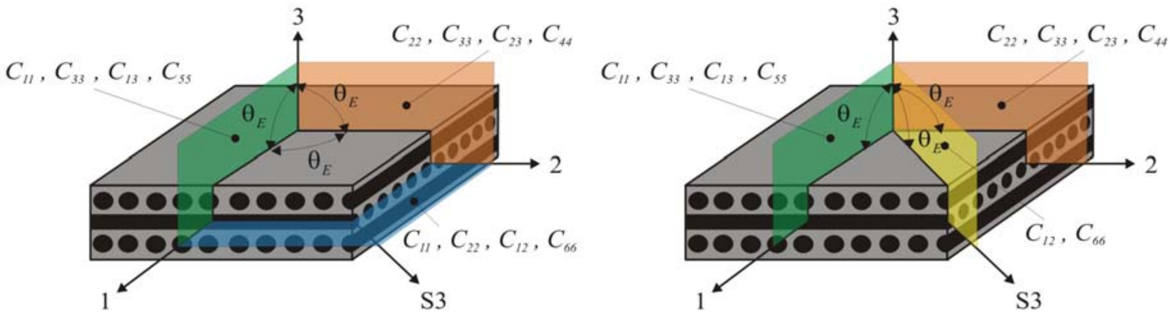

Fig. 2 Stiffness recovery by means of measurements in the planes of symmetry (left), stiffness recovery if in-plane measurements are not possible (right) [12]

Phase velocity distribution

In each of the examined planes, multiple time-of-flight measurements are made within a spectrum of oblique angles. The phase velocities are calculated from the time delay using the direct water path travel time as a reference. Consequently a set of velocity data for quasi-longitudinal (QL) and quasi-transversal (QT) wave modes is obtained (Fig. 3). From this data, representing an overdetermined set of equation, the associated stiffnesses can be calculated using the least square optimisation routine (LEVENBERG-MARQUARD). Experimental determined data points and the optimised velocity distribution can be visualised in polar diagrams (Fig. 3). The velocity level of an undamaged sample is higher than the velocity level of a damaged sample. Thus, the reduction of stiffness can be deduced directly.

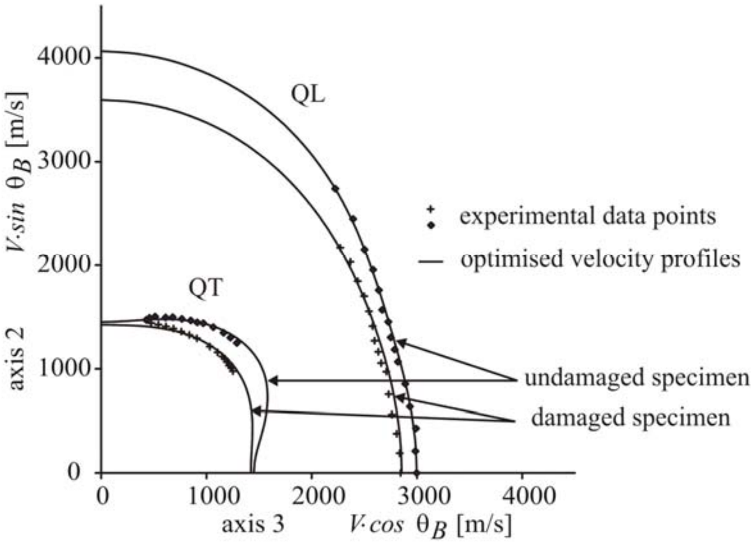

Fig. 3 Experimentally determined velocity data and optimised velocity distributions for damaged and undamaged material situation [15]

EXPERIMENTAL SET UP

The immersion testing device

For the purpose of phase velocity measurements in an angle range of 90° in two planes an immersion testing device has been developed (Fig. 4). The device is implemented in a water tank. The PANAMETRICS ultrasonic sensors used, from work with a centre frequency of 2,25 MHz. The imaging of the measured signals was realised with the ultrasonic inspection system HFUS 2400 Air Tech. The evaluation and interpretation of the experimental data has been carried out by means of the A-picture.

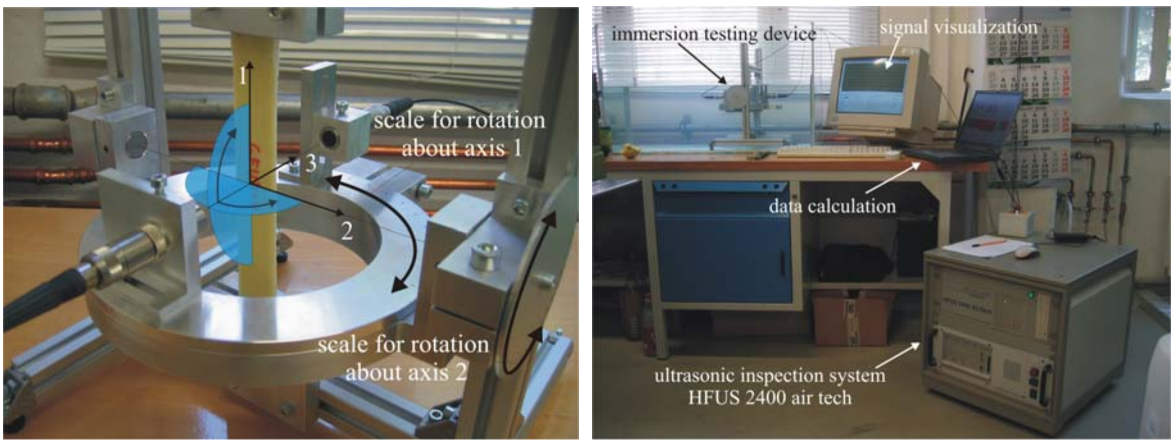

Fig. 4 ILK immersion testing device

Measurement of damage in tensile tests

For the damage evaluation, a gradual damaging of the sample is required. Therefore, axial tensile load was applied to tensile specimen with different textile reinforcement and different specimen geometry. Dog-bone shaped specimens were found to be more suitable to restrict the area of damage in the zone examined by the ultrasonic sensors. The load was applied stepwise and ultrasonic examinations in planes 1-3 and 2-3 were performed after every load step. Additionally, classical mechanical stress-strain measurements have been carried out.

Special interest was placed on the correlation between the microscopic damage phenomena and the subsequent stiffness degradation. For this purpose, microscopic pictures were taken at different loading stages (Fig. 5). It could be shown that the propagation of voids that partially exist already at the virgin state due to manufacturing restrictions is the main matrix damage mode in woven GF/PP specimens. This void growth could also influence the very heterogeneous structure of the hybrid fibre bundle. Resulting observable phenomena are the formation of larger cracks and pull-outs of parts of the fibre bundle. From these observations it becomes clear that complex crack geometry in textile reinforced materials can not be reduced to simple models.

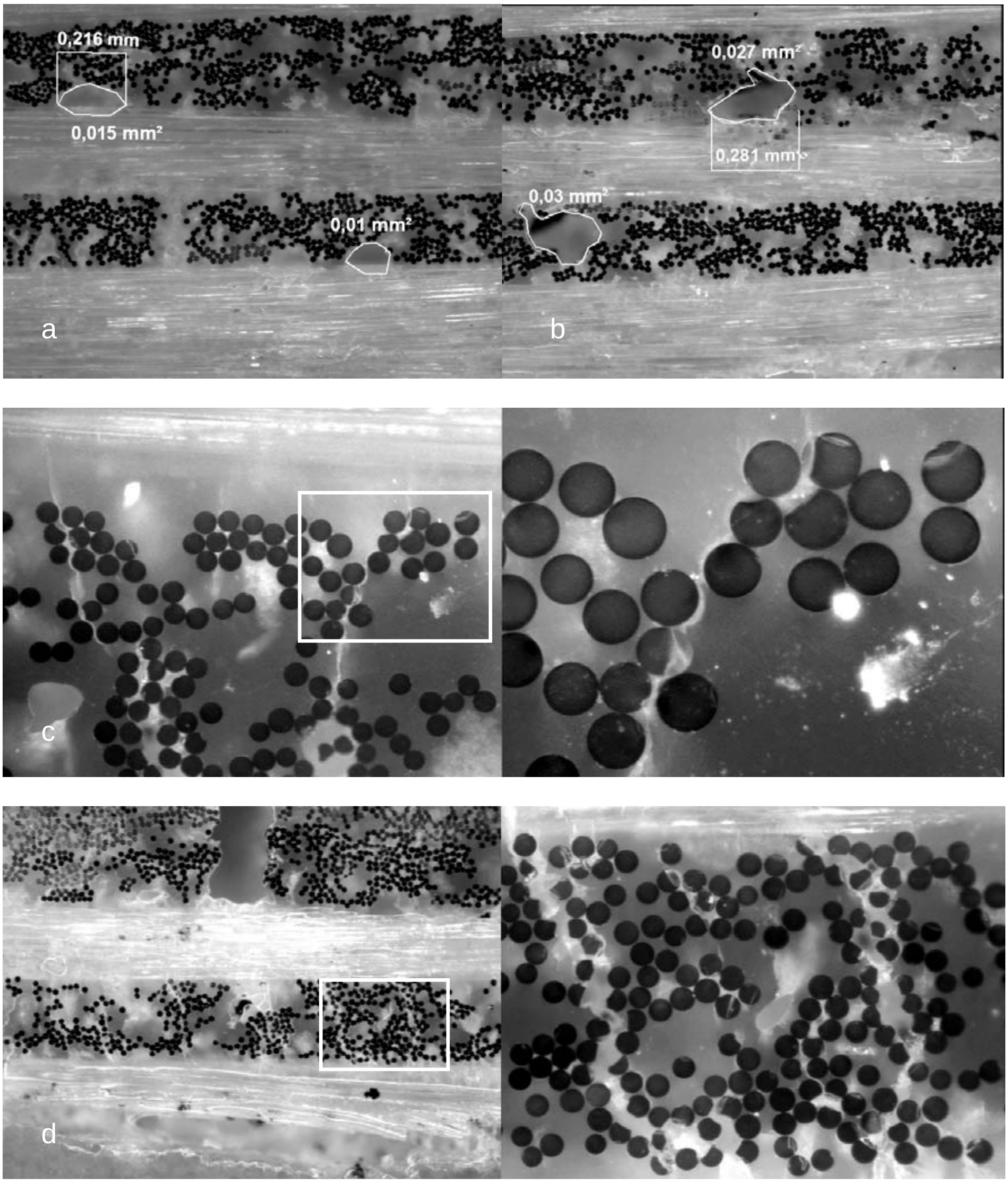

Fig. 5 Microscopic pictures of a woven GF/PP-specimen a) at virgin state, b) 150 MPa, c) 230 MPa and d) at final failure state 260 MPa

RESULTS AND DISCUSSION

Stiffness tensor variation during tensile tests

For each configuration, a number of specimens have been tested until fracture occurred. Selected results of the stiffness tensor identification of the woven TWINTEX® specimens and their statistical scattering intervals are plotted in Fig. 6.

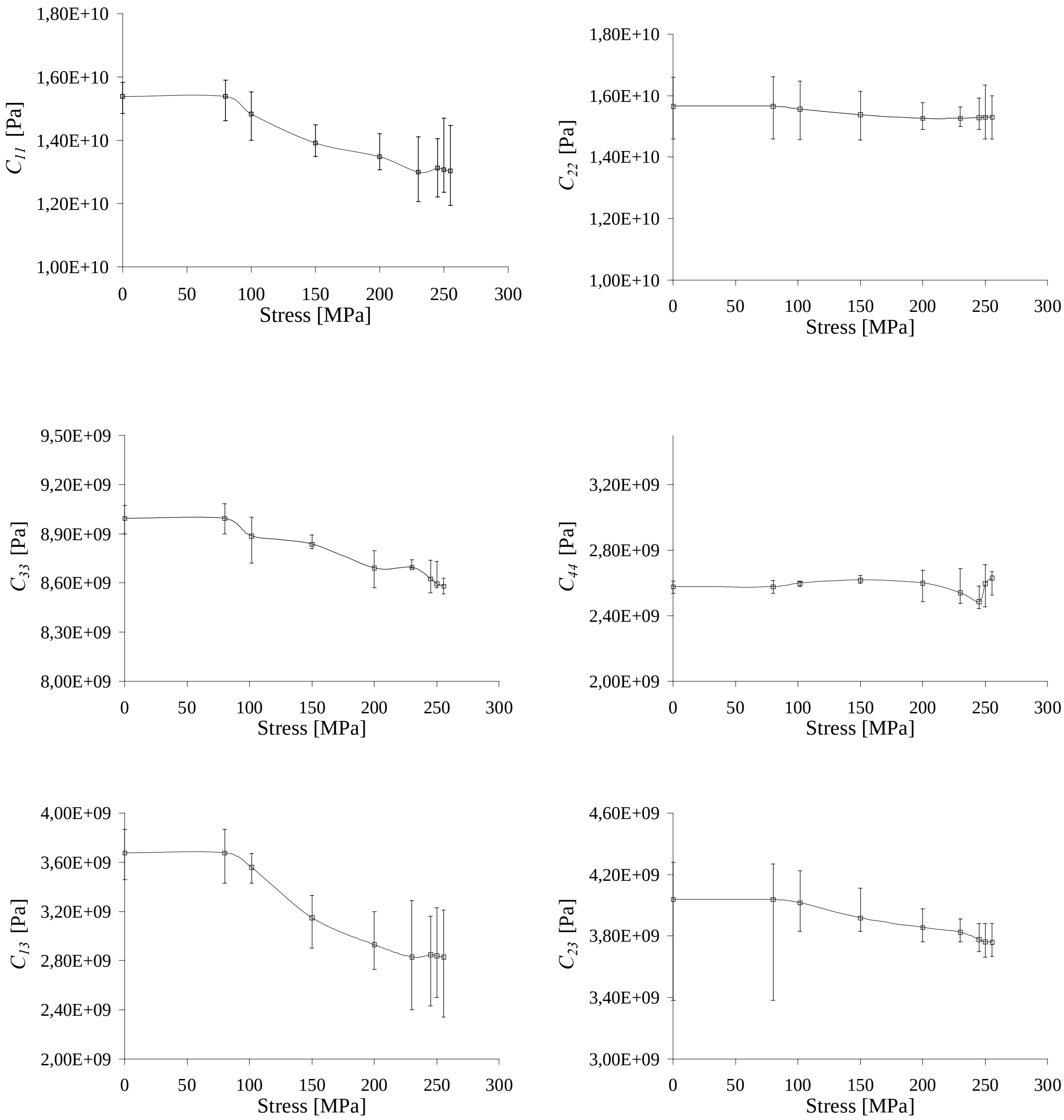

Fig. 6 Variation of the stiffness tensor coefficients of TWINTEX® specimens in tensile tests

All plots show that up to 80 MPa no stiffness variation could be identified. Up to that value, the material behaviour is elastic and this value marks the damage threshold. Stresses that go beyond this threshold cause stiffness reduction. This phenomenon could be attributed to a combination of matrix plasticity, void growth and micro-cracking (Fig. 5). Only the stiffness components C_{11} , C_{13}, C_{23} and C_{33} show a significant decrease under tensile loading. These observations corroborate the theory of decomposition of textile composites into i-UD-layers like proposed by LANGKAMP [7]. It is worth noting that the damage in the loading direction 1 has a considerable effect on the out-of-plane properties, and particularly on those relative to the planes which contain the loading direction (C_{13}). In contrast, the effect on the shear stiffnesses (see: C_{44}) is very low.

Damage coefficients (for tensile loading)

The damage coefficients plotted in Fig. 7 are calculated from the stiffness changes (Fig. 6) using Eq. (3) and (4). For these calculations, the coefficients of the undamaged material are supposed to be those of the specimens at the initial loading stage.

The values of the damage parameters D_{22} and D_{44} are negligible small, so that no coupling between these parameters and D_{11} has to be considered. The typical saturation level of micro-cracking and void growth is reached very late in the loading path (at approximately 230 MPa). It must be concluded that the woven GF/PP composite shows more diffuse damage behaviour than brittle composites [3-7, 13]. Thus, phenomenological material parameters like crack density distributions are not suitable to characterise the damage behaviour of this class of composites.

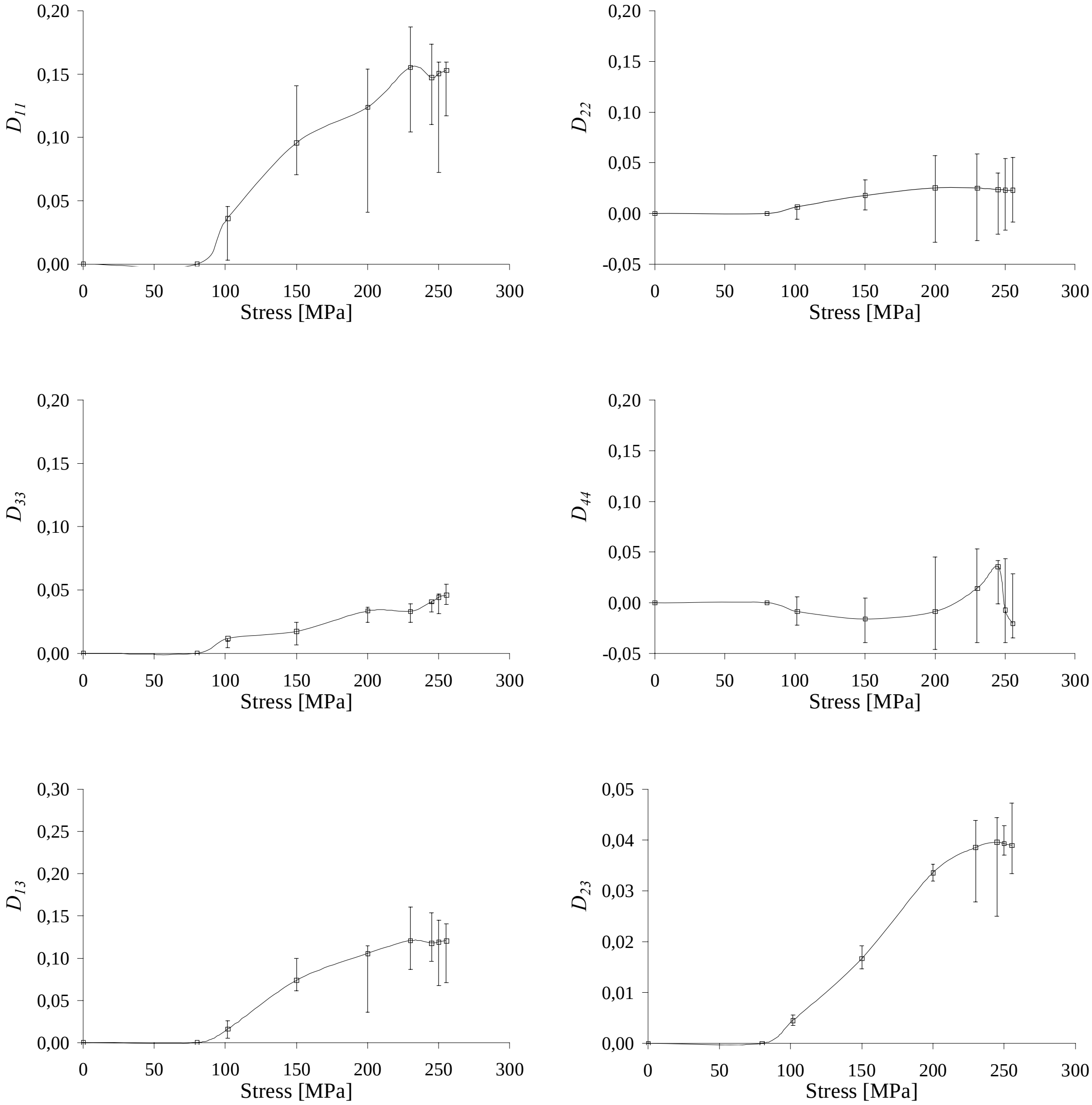

Fig. 7 Damage coefficients of TWINTEX® specimens in tensile tests

Finally, it must be remarked that the stiffness decrease values and the dispersion of the data are in a comparable order of magnitude. This conclusion is also valid for the damage parameters. Thus, for future damage calculations, statistical approaches for gathering the material data should be considered.

Comparison to classical measurements

The results calculated from the performed ultrasonic measurements have been compared to the ones from classical stress-strain measurements. Due to the limited possibilities of conventional methods, only the stiffness reduction in loading direction C_{11} could be drawn on as a comparable value. From Fig. 8, it becomes apparent that the stiffness reduction measured by ultrasonics and the stiffness reduction measured conventionally largely coincide. Only the real onset of damage occurs noticeably earlier than forecasted by the ultrasonic measurements.

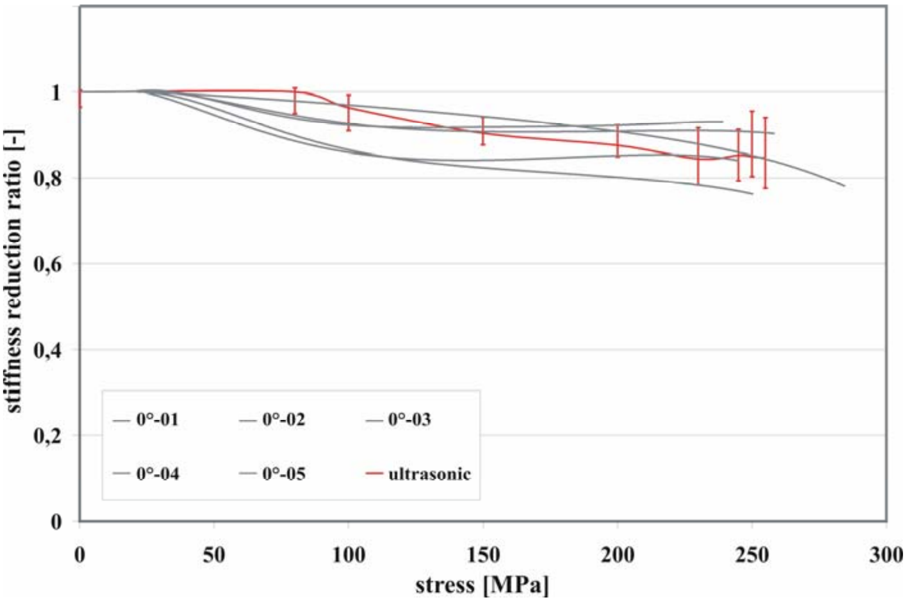

Fig. 8 Comparison of the stiffness reduction ratio (C_{11}) determined by classical stress-strain measurements (grey) and ultrasonic measurements (red)

Nevertheless, the results underline the overall comparability of the two characterisation methods, the mechanical and the ultrasonic one, in describing the damage related to non-linear mechanical behaviour of fibre an textile reinforced composites.

CONCLUSION

The demand for a high degree of lightweight design is increasingly becoming the focus of design efforts in the development of a new generation of textile-reinforced structural components. For the purpose of developing practical composite damage models, current endeavours have not only focused on a realistic description of the initial and final failure but also on the non-linear failure analysis of novel textile-reinforced composites.

This investigation considers the principal procedure of textile reinforced composite damage analysis necessary for use in the design of complex lightweight applications where the need for reliable prediction of performance must be balanced with simplicity and ease of use. The damage evolution of GF/PP specimens under tensile loading has been determined based on ultrasonic analysis and on an inverse identification scheme. 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 are in good agreement with stress-strain curves from classical measurements. The proposed results are of great practical significance for innovative developments in high-performance lightweight applications.

REFERENCES

[1] HUFENBACH, W.; LANGKAMP, A.: *Entwicklung von Leichtbaustrukturen in neuartiger Textilverbundbauweise für Anwendungen im Fahrzeug- und Maschinenbau.* 5. Dresdner Textiltagung, Dresden, 28.-29. 6. 2000

[2] MATZENMILLER, A.; LUBLINER, J.; TAYLOR, R.L.: *A constitutive model for anisotropic damage in fiber-composites*. Mech. Mater., Vol. 20, 1995, No. 2, p. 125-152.

[3] PUCK, A.; SCHÜRMANN, H.: *Failure Analysis of FRP Laminates by means of physically based phenomenological models*. Composites Sci. and Tech., Vol. 58, 1998, pp. 1045-1067.

[4] KASHTALYAN, M; SOUTIS, C.: *Stiffness degradation in cross-ply laminates damaged by transverse cracking and splitting*. Composites: Part A, 31, 2000, pp. 335-351.

[5] HUFENBACH, W.; BÖHM, R.; KROLL, L.; LANGKAMP, A.: *Theoretical and experimental investigation of anisotropic damage in textile reinforced composite structures.* Mechanics of Composites Vol. 40 (6), 2004, pp. 519-532

[6] CUNTZE, R.G.; FREUND, A.: *The predictive capability of failure mode concept-based strength criteria for multidirectional laminates*. Composite Science and Technology, Vol. 64 (3-4), 2004, pp. 343-377

[7] LANGKAMP, A.: *Bruchmodebezogene Versagensmodelle von faser- und textilverstärten Verbundwerkstoffen mit polymeren, keramischen sowie metallischen Matrices.* Dissertation, TU Dresden, 2002

[8] HUFENBACH, W.; LANGKAMP, A.; KROLL, L.; BÖHM, R.: *Experimental investigation and modeling of failure and damage behaviour of multi-layered carbon fibre reinforced PEEK* 14th. International Conference on Composite Materials (ICCM 14), San Diego, July 14th–18th 2003, published on CD-ROM

[9] BASTE, S.; AUDOIN, B.: *On internal variables in anisotropic damage*. European Journal of Mechanics, A/Solids, Vol. 10 (6), 1991, pp. 587-606

[10] CASTAGNÈDE B., JENKINS, J. T., SACHSE W., BASTE S.: *Optimal determination of the elastic constants of composite materials from ultrasonic wave-speed measurements* Journal of Applied Physics, Vol.67, 1990

[11] MARKHAM M.F.: *Measurement of the elastic constants of fibre composites by ulrtrasonics* Composites, 1970

[12] MOUCHTACHI A., GUERJOUMA R. EL, BABOUX J.C., ROUBY D., BOUAMI D.: *Optimal determination of the elastic constants of woven 2D SiC/SiC composite materials* Journal of Physics D: Applied Physics, 2004

[13] AUDOIN B., BASTE S.: *Ultrasonic evaluation of stiffness tensor changes and associated anisotropic damage in a ceramic matrix composite* Journal of Applied Mechanics, Vol.61, 1994

[14] SAHAY, S, KLINE R., MIGNOGNA, R.: *Phase and group velocity considerations for dynamic modulus measurements in anisotropic media.* Ultrasonics Vol 30 No 6, 1992, pp. 373-382

[15] HUFENBACH W., KROLL L., BÖHM R.: *Mechanical behaviour of novel textile multi-axial reinforced thermoplastic composites made from hybrid yarns*. International Conference on Advanced Fibers and Polymer Materials (ICAFPM 2005), Shanghai, 19.10.-21.10. 2005, pp. 397-401