10th International Conference on Composite Science and Technology
ICCST/10
A.L. Araújo, J.R. Correia, C.M. Mota Soares, et al. (Editors)

INFLUENCE OF THE STACKING SEQUENCE ON THE NONLINEAR MATERIAL BEHAVIOR OF COMPOSITE LAMINATES RELATED TO LARGE DEFORMATIONS

Robin Taubert*, Ulrich Mandel†, Roland Hinterhölzl†

*† Institute for Carbon Composites, Technische Universität München,
Boltzmannstraße 15, 85748 Garching b. München, Germany
taubert@lcc.mw.tum.de

Key words: Polymer-matrix composites, Angle-ply laminates, Damage progression, Nonlinear material behavior.

Summary: *Within the present study, the influence of the stacking sequence of a laminate on the nonlinear stress-strain response is experimentally evaluated. Therefore, uniaxial tension tests for several angle-ply laminates from IM7-8552 material with single and double ply clustering for* θ*=±30°, ±40°, ±45° are conducted. To evaluate the response at large deformations angle-ply laminates are well suitable, but, only provided that fiber rotation is taken into account. These laminates are driven from the matrix constitutive behavior, thus, several features provoke nonlinear response under transverse and in-plane shear loading. Special emphasis is placed on the damage progression in dependence on the layup. Therefore, a procedure is proposed that avoids interacting response with viscous material behavior. The results indicate, that only nonlinearity caused by damage is effected by the layup, while other sources are independent.*

1 INTRODUCTION

The precise simulation of the stress-strain response is essential for a reliable prediction of the structural integrity of components made of fiber-reinforced polymer-matrix composites (PMCs). The mechanical response of unidirectional continuous fiber-reinforced composites loaded in fiber direction is linear until failure at comparatively low achievable strains. Laminated plies subjected to transverse or shear loads exhibit a non-linear material behavior influenced from the polymeric properties. Several design demands require the structural ability for large deformations. This motivates in particular the application of laminates loaded off-axis to the fibers. These laminates are governed by a matrix dominated constitutive behavior and thus, offer the ability to employ their ductile mechanical characteristics. For this reason, angle-ply laminates offer the opportunity to investigate the influence of polymer features on the mechanical behavior of PMCs.

Various concurrently acting mechanisms are responsible for the degree of nonlinearity. The mechanical behavior of polymeric materials depends significantly on time. This results in viscoelastic and viscoplastic strain accumulation [1]. Another determining factor of the nonlinear behavior are damage processes during loading history [2-5]. Especially at large strains a growing crack development results in laminate stiffness reduction. Moreover, fiber rotation leads to an altering mechanical response of the material [6, 7]. The consideration of the sources of nonlinearity and their interaction in dependence on the laminate stacking sequence is essential for the accurate development of a constitutive modelling approach.

Within the presented study special emphasis is placed on the investigation of damage evolution in dependence on the stacking sequence of the laminate. An approach is presented, to quantify the damage state by measurement of the stiffness degradation. To allow for large deformations the contribution of influencing material features under large strains are considered in the determination of the damage. The tangent moduli from conducted loading cycles of several angle-ply tension tests are determined from the evaluation of the stress-strain envelopes. The polymer material inherent time dependence has a significant effect on the slope of the re-loading cycle due to viscous micromechanical processes in the polymer chains. The strain retardation process after fully unloading of a $[\pm 45°]_s$ laminate, loaded to 8.09% axial strain is shown in Fig. 1. After reaching the unloaded condition, the axial strain in the specimen decreases over time. The strain retardation rate is reduced with time and the response indicates, that a resulting amount of a residual deformation is reached. It has to be mentioned, that the retardation response is strongly influenced by the maximum strains prior to reloading. However, the time influence has to be carefully observed for the definition of loading and re-loading cycles, and to achieve a robust measurement method for variations in the slope of stress-strain response.

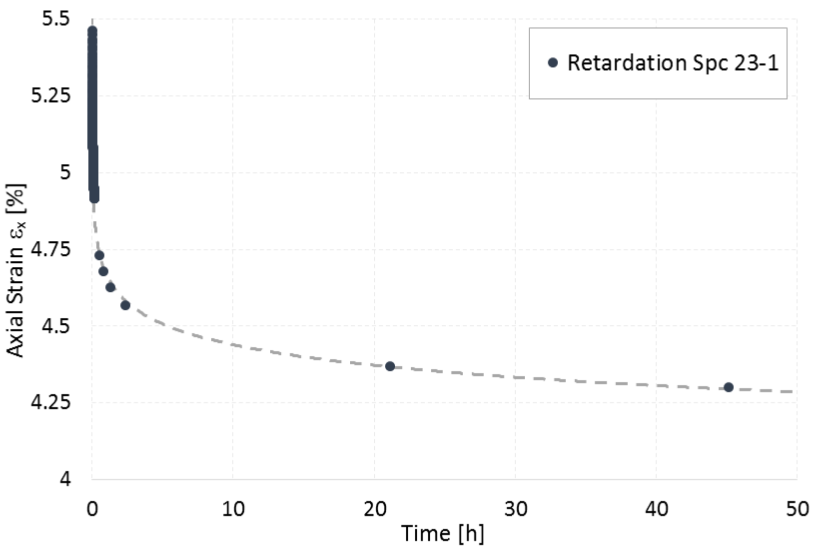

Figure 1: Strain retardation of a [±45°] angle-ply laminate from IM7-8552.

Composite laminates undergoing fiber longitudinal and transverse tension loading are in some studies used to investigate damage evolution [8, 9]. Stiffness reduction in relation to damage can be reduced to a problem of linear elastic material behavior combined with the development of matrix cracks. In laminates with off-axis plies, especially an angle-ply layup, notable shear deformation occurs. In this case, the stiffness not only change caused by matrix cracks. The stiffness measurement has to be critically examined, if a change in the elastic properties is due to damage or rather a result of the polymer features or fiber rotation in the specimen.

2 EXPERIMENTAL PROCEDURE

In consideration of the actual fiber re-orientation and inelastic strain accumulation a determination of the stiffness degradation due to damage mechanisms can be provided. The specimens were tested under tension in a load frame at a cross head strain-rate of $0.0001 s^{-1}$. All tests were conducted under displacement control. The strain was captured using a digital image correlation (DIC) system ensuring a full field strain measurement. This enables the determination of the global longitudinal strain ε_x and the global transverse strain ε_y.

Both, the constitutive behavior during loading and unloading cycles were investigated for a stiffness degradation measurement. The tested fiber reinforced PMCs exhibit a significant time dependence due to off-axis loading, and moreover a slow reconstitution of the mechanical equilibrium. Thus, a re-loading corresponds with the same prerequisites of an initially loaded specimen not until a certain time of relaxation. Based on this long-term retardation behavior, the test was interrupted for about 500h prior to re-loading. This relaxation is essential, to avoid a rate-dependent interaction on the re-loading response due to strain retardation in the material, and to ensure a reliable stiffness comparison.

2.1 Specimen Fabrication

Plates of angle-ply laminates were fabricated in a hot press machine with steel spacer to assure a constant thickness distribution of 2.0mm. The plates were produced according to the standard curing cycle. The material used for the experimental study is Hexcel IM7-8552 unidirectional carbon/epoxy prepreg with a single ply thickness of 0.125mm. Seven different angle-ply laminates were tested under uniaxial tensile load. Tests with un-clustered plies $[(\pm\theta)_4]_s$ and with double-clustered plies $[(+\theta)/(-\theta)_2/(+\theta)_2/(-\theta)_2/(+\theta)]_s$ were conducted for angles of $\theta = \pm 30°, \pm 40°, \pm 45°$. For the ±30° laminate additional samples with a triple-clustered layup in the form $[(+\theta)/(-\theta)_3/(+\theta)_3/(-\theta)]_s$ were fabricated. The laminated plates were cut into specimens with a length of 350 mm and a width of 50mm.

As shown by Wisnom [10], free edge effects could increase the threat of delamination failure and thus significantly reduce the feasible deformations. The size of the specimens was selected to avoid a substantial dependence of edge delamination on the constitutive behavior. Wide specimens ensure that the width not affects the failure mode and a reliable comparison of specimens with varying stacking sequence is provided. Three samples for each layup were sliced from the fabricated plates. A glass fiber/epoxy material was used for the end-tabs. The dimensions of the end tabs are 50x50mm and the thickness is 1.0mm.

2.2 Damage Measurement

To determine a variation of the stiffness from the stress-strain response several procedures are presented in Pettersson et.al. [11]. Basically, this are the tangent modulus, as the slope of the beginning of the loading cycle, and the secant modulus, as the slope between the reversal point of un-loading and re-loading. As shown in Fig. 2 the secant modulus method causes a significant higher reduction in the stiffness. It results in a difference between the evaluation from the stress-strain response with $\{\tilde{E}_{xd}\}_{sec}$ and without retardation time $\{E_{xd}\}_{sec}$. An additional damage evolution during the retardation time is indicated. As shown in Chung et.al. [12] PMC`s accumulate additional plastic strains during un-loading. This material inherent behavior impedes an evolution of the damage state concerning a specific load using the secant modulus measurement. A physical reasonable damage growth of angle-ply laminates at high deformations cannot be achieved, as it is not able to account for the transient material behavior and correctly for the Bauschinger effect. A tangent moduli of the envelope without retardation is not possible to evaluate, as no distinct linear response is exhibited. Within the present study the tangent moduli after strain retardation $\{\tilde{E}_{xd}\}_{tan}$ is used for the correlation between stiffness variation and damage progression.

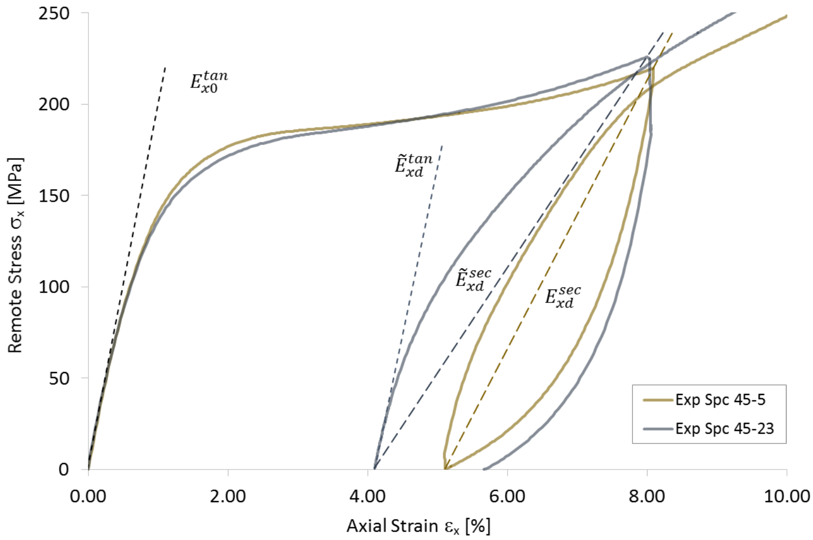

Figure 2: Evaluation approach for stiffness measurement.

Based on experimental findings, assumptions are made for the determination of the damage state from measured tangent stiffness moduli as follows.

(i) The laminates feature an initial linear elastic stress-strain response.
(ii) In fiber direction no damage is accumulated, the fiber modulus remains constant.
(iii) Transverse compression stress provoke no crack formation or damage growth.
(iv) No influence on transverse stiffness degradation of cracks formed under shear or transverse tension loading for plies subjected to transverse compression loads.
(v) Homogeneous crack evolution in all plies. The laminate remains balanced and orthotropic throughout the loading history.

As the stress-strain response exhibit no distinct tendency for an initial linear elastic behavior and changes in dependence on the previous loading step, the tangent stiffness is determined in a small strain interval immediately after load application. For the laminates of ±40° and ±45° the cycle is evaluated from 0 to 0.1% axial strain and for ±30° and ±50° specimens the stiffness is measured between 0 and 0.2%. This procedure is performed throughout the whole range of specimens. In the range of the evaluated strain a high framerate was used for picture recording of the DIC system. Thus, possible deviations in the strain field measurement are compensated.

Damage evolution in unidirectional continuous fiber reinforced PMC’s is determined by the crack development in the single plies of a laminate. Depending on the off-axis direction of the ±θ° layers an axial load causes a normal stress longitudinal and perpendicular to the fibers and an in-plane shear stress. If the stress state consists of tensile transverse or shear stresses new inter-fiber cracks are formed. According to the change of the lamina compliance and with the laminated plate theory the local response of the ply and the global constitutive behavior of the laminate are coupled. For the applied uniaxial laminate tension load, a stress state results in the three angle-ply laminates with θ = ±30°, ±40° and ±45° that consists only of transverse compression and in-plane shear stresses. Thus, the global stiffness variation is exclusively driven by an additional in-plane shear compliance of the plies:

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_{12} \end{pmatrix} = \begin{bmatrix} S_{11}^0 & S_{12}^0 & 0 \\ S_{12}^0 & S_{22}^0 & 0 \\ 0 & 0 & S_{66}^0 + \dfrac{\mathrm{d}_S}{(1-\mathrm{d}_S)G_{12}} \end{bmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{pmatrix} \tag{1}$$

The shear damage is introduced as a scalar variable $\mathrm{d_s}$, representing

$$\mathrm{d}_S = 1 - \frac{G_{12}^d}{G_{12}^0} \tag{2}$$

The growth of the damage variable $\mathrm{d_S}$ depends on the direction of the $+\theta$ and $-\theta$ ply, as different stress components and directions follow. Due to the combined stress state a determination of the local stresses from the applied axial load is precluded. A direct proportional factor between local and global stiffness does not exist, and it is imperative to evaluate the relation in consideration of fiber rotation and local damage effect, here represented by the compliance variation in Eq. (1). The evaluation of the damage variable can be achieved by the recorded global longitudinal strain ε_x and the transverse strain ε_y and the therewith determinable actual axial laminate stiffness E_x^d and the Poisson ratio ν_{xy}^d. From laminated plate theory follows for the relation of the axial laminate stiffness and the laminate Poisson`s ratio and the damage variable $\mathrm{d_S}$, that is given by Eq. (3) and (4).

$$E_x^d(d_S,\theta') = \frac{-2{E_1}^2E_2 + \{E_1[-E_1E_2 + (1-d_S)E_1G_{12}] + [-(d_S-1)E_2G_{12}(1-2\nu_{12})]\}(8c^4-8c^2)}{-2E_1E_2c^4 - 4E_1E_2\nu_{12}c^2s^2 - 2{E_1}^2s^4 + 8(d_S-1)G_{12}[E_1 - E_2{\nu_{12}}^2]c^2s^2} \tag{3}$$

$$\nu_{xy}^d(d_S,\theta') = \frac{-E_1E_2\nu_{12}c^4 - E_1(E_1 + (1-d_S)E_2)c^2s^2 - E_1E_2\nu_{12}s^4 - 4(d_S-1)G_{12}[E_1 - E_2{\nu_{12}}^2]c^2s^2}{-E_1E_2c^4 - 2E_1E_2\nu_{12}c^2s^2 - {E_1}^2s^4 + 4(d_S-1)G_{12}[E_1 - E_2{\nu_{12}}^2]c^2s^2} \tag{4}$$

with $c = \cos\theta'$ and $\mathrm{s} = \sin\theta'$.

A deformation induced fiber rotation has a substantial influence on the nonlinear material behavior and on the true stress state. An in-plane shear deformation causes an additional rotation of the fibers. Due to the inherent orthotropy of carbon fiber composites, this fiber reorientation has a strong influence on the constitutive response of the laminate. As the axial strains becomes large for some of the considered laminates, neglecting the fiber rotation can alter the predicted damage state. The additional stiffening of the laminate can cause a misinterpretation of the stiffness degradation. The actual fiber angle θ' can be related to the global strains ε_x and ε_y and the initial fiber orientation θ^0 by

$$\theta' = \tan^{-1}\left[\frac{(1+\varepsilon_y)}{(1+\varepsilon_x)}\tan\theta^0\right]. \tag{5}$$

Due to large deformations the specimens undergo a substantial reduction in the cross-sectional area. To take into account this effect, the specimen dimensions are determined previously to the re-loading cycle. The actual cross-sectional area is considered for the stress calculation from the recorded axial force, and therefore included in the stiffness evaluation.

3 RESULTS

An evaluation of the damage growth was conducted for several angle-ply laminates, measuring actual values for E_{xd} and ν_{xyd} at the beginning of the loading cycle. For the determination of the damage variable d_S, calculated from balancing Eq. (3) and (4), the material properties given in Table 1 for the carbon/epoxy prepreg IM7/8552 are used.

Longitudinal Stiffness	E_1	171 420	[MPa]	*[13]*
Transverse Stiffness	E_2	9080	[MPa]	*[13]*
In-plane Poisson`s Ratio	ν_{12}	0.32	[-]	*[13]*
In-plane Shear Stiffness	G_{12}	5290	[MPa]	*[13]*

Table 1: Material properties for IM7-8552 used for the present study.

[±30°] Angle-ply Tension Laminates

The evaluation of the tangent stiffness according to the presented approach indicates for both types of laminates, single and double clustered, no damage accumulation, see Fig. 3. This was verified by subsequently prepared micrographs of the specimens, which show no crack development.

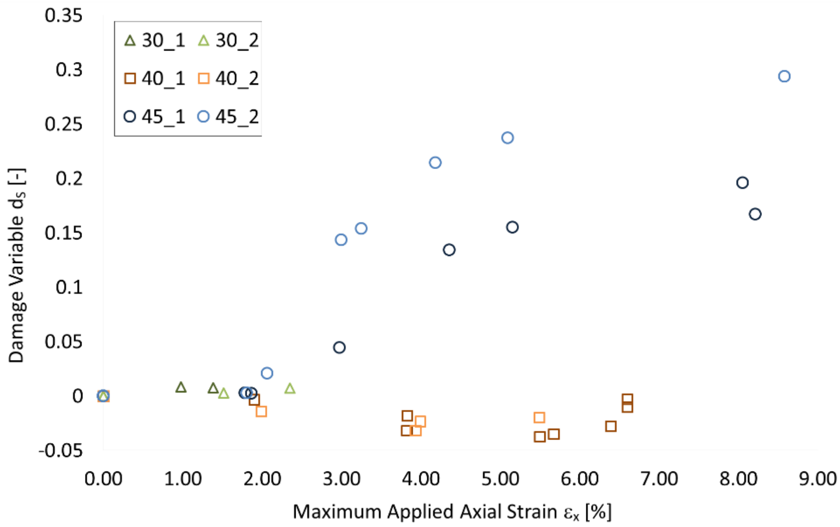

Figure 3: Measured damage variable d_s for different IM7-8552 angle-ply laminates and types of lay-up cluster.

[±40°] Angle-ply Tension Laminates

The evaluation of the ±40° angle-ply laminates indicate as well no damage accumulation (see Fig. 3). Caused by the matrix dominated constitutive behavior, ±40° angle-ply laminates exhibit large axial deformations prior to laminate failure. Due to fiber rotation the stress-strain response exhibits a stiffening, which cause a substantial increase of the stiffness ratio E_x/E_{x0}, see Fig. 4. A direct measurement of the damage variable, without deduction of the fiber rotation influence, would result in a serious misinterpretation of the damage state. With consideration of the fiber rotation induced stiffening, we obtained a damage variable d_S of almost zero at all stages of axial loading. The results refer to the un-clustered laminates, but the same outcome was evaluated for the double-clustered layup.

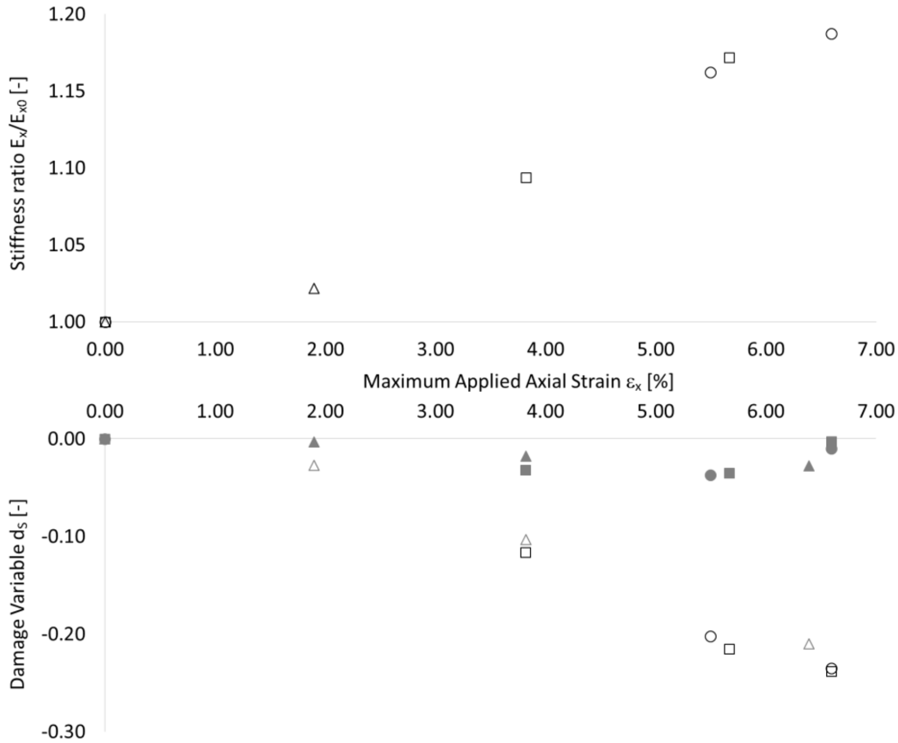

Figure 4: Development of the laminate axial stiffness ratio and damage variable in dependence on consideration of fiber reorientation for un-clustered ±40° angle-ply laminates.

[±45°] Angle-ply Tension Laminates

Conducted micrographs and the XCT study of Sket et.al. [14] indicate, that ±45° angle-ply laminates undergo an extensive intraply crack accumulation with increased load. Fig. 5 shows the tangent stiffness moduli evaluation after strain retardation of the un-clustered laminate. In Fig. 3 the damage variable d_S is given in relation to the maximum axial strain, applied in the previous load steps. A comparison of both figures shows a mismatch of the stiffness ratio and the evolution of the damage variable. While the stiffness ratio decreases for large applied axial strains, the damage variable increases continuously. This is due to a significant fiber rotation. The off-axis angle is reduced that causes a global stiffening of the laminate. For both, the un-clusters and the double-clustered ±45° laminates, a damage variable of zero is determined up to an axial strain of 2%. For higher strains, damage evolve with increasing axial strain. No difference in damage initiation is detected. Moreover, the results show that the damage variable of the double-clustered laminates increases faster in comparison to the un-clustered plies.

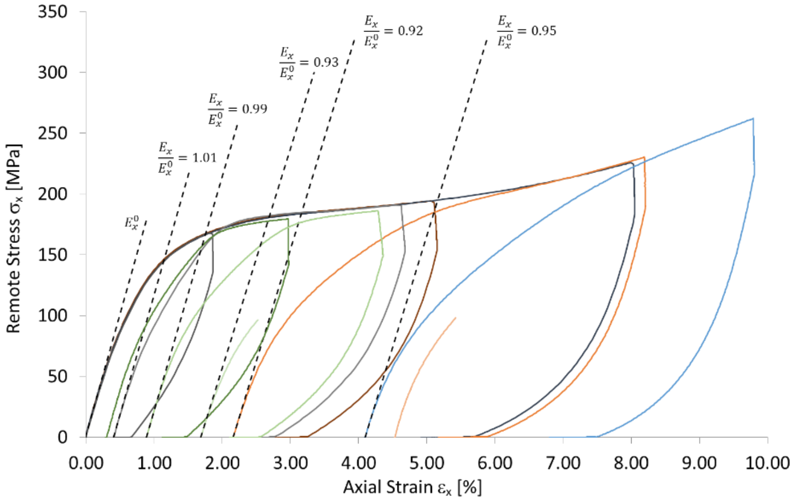

Figure 5: Global stiffness evaluation scheme for un-clustered ±45° angle-ply laminates.

The influence of the stacking sequence on the nonlinear material behavior of the considered angle-ply laminates is summarized in Fig. 6. At least damage has a substantial influence on the nonlinearity. This can be concluded, as only the ±45° laminates differ in the response of the un-clustered and double-clustered layup. The onset in variation of the degree of nonlinearity is coincident with the evolution of the damage variable. This indicates, that damage of the investigated ±45° laminates is not initiation driven, but rather only damage propagation is responsible for the difference in non-linear response of the considered layup cluster types.

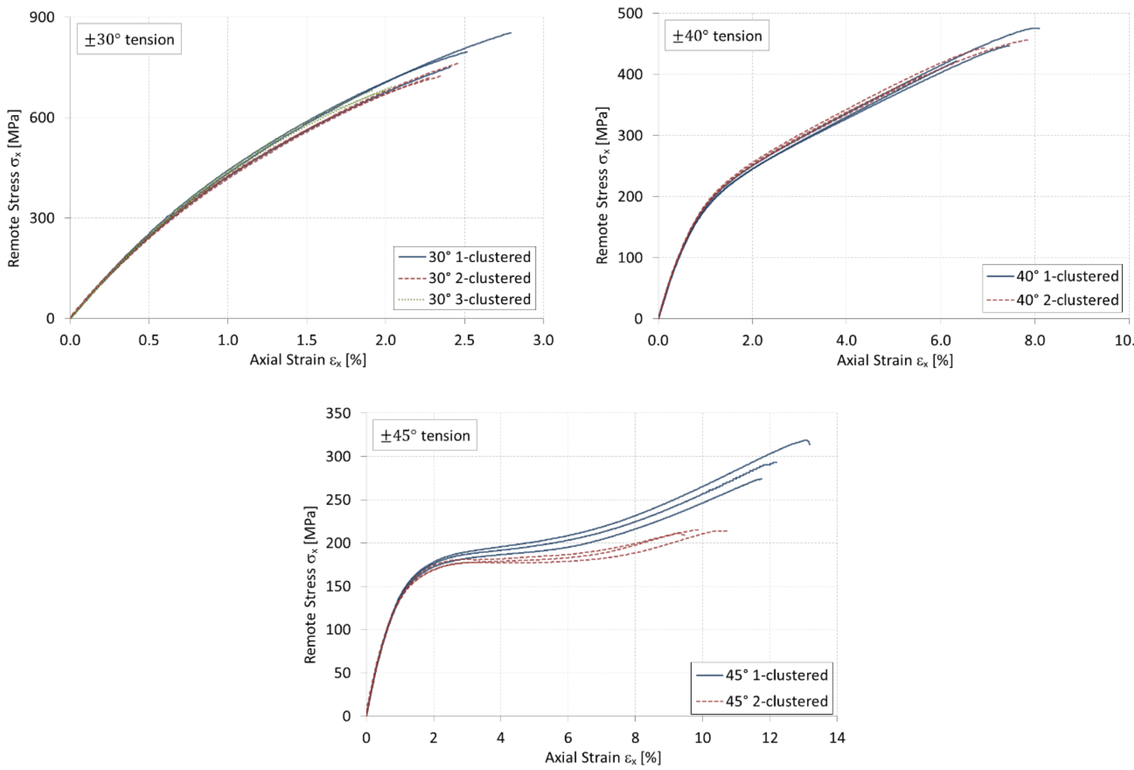

Figure 6: Remote axial stress-strain response of angle-ply tension specimens for IM7-8552 for different types of lay-up cluster.

As damage changes the degree of nonlinearity in dependence of the stacking sequence, it can be classified as a laminate specific property. In contrast, other sources for nonlinear stress-strain response are not subjected to a stacking sequence influence, and thus, they are material inherent.

4 CONCLUSIONS

The axial stress-strain response of single and double clustered angle-ply laminates from IM7-8552 are investigated in order to evaluate the influence of different sources for nonlinear material behavior. A damage measurement procedure is presented, able to evaluate the damage state for large deformations. Therefore, fiber rotation is considered in the calculation. The damage evaluation is based on cyclic loading and strain retardation to avoid an interaction with viscous material behavior. The evaluation of the results indicates that the nonlinear response of laminates influenced by damage mechanisms is independent of clustered plies in the stacking sequence. In contrast, especially for the [±45°] laminate, that exhibits significant intra-ply damage, the constitutive response is dependent on the clustering. The correct evaluation of damage is essential for the development of a numerical damage propagation model. The laminate dependence has to take into account these effects, for a reliable prediction of damage evolution.

REFERENCES

[1] K. Giannadakis,J. Varna, Analysis of nonlinear shear stress–strain response of unidirectional GF/EP composite. *Composites Part A: Applied Science and Manufacturing,* **62,** 67–76, 2014.

[2] C. Herakovich, Damage evolution in [±45]s laminates with fiber rotation. *Composites Science and Technology,* **60,** 2781–2789, 2000.

[3] J. Varna, Damage in composite laminates with off-axis plies. *Composites Science and Technology,* **59,** 2139–2147, 1999.

[4] C.V. Singh,R. Talreja, Analysis of multiple off-axis ply cracks in composite laminates. *International Journal of Solids and Structures,* **45,** 4574–4589, 2008.

[5] R.M. O'Higgins,C. T. McCarthy,M.A. McCarthy, Identification of Damage and Plasticity Parameters for Continuum Damage Mechanics Modelling of Carbon and Glass Fibre-Reinforced Composite Materials. *Strain,* **47,** 105–115, 2011.

[6] J.D. Fuller,M. R. Wisnom, Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. *Composites Part A: Applied Science and Manufacturing,* **69,** 64–71, 2015.

[7] C. Sun, The effect of deformation-induced change of fiber orientation on the non-linear behavior of polymeric composite laminates. *Composites Science and Technology,* **60,** 2337–2345, 2000.

[8] R. Talreja, Transverse Cracking and Stiffness Reduction in Composite Laminates. *Journal of Composite Materials,* **19,** 355–375, 1985.

[9] L. Boniface,P. A. Smith,M. G. Bader,A. H. Rezaifard, Transverse Ply Cracking in Cross-Ply CFRP Laminates--Initiation or Propagation Controlled? *Journal of Composite Materials,* **31,** 1080–1112, 1997.

[10] M.R. Wisnom, Size effects in the testing of fibre-composite materials. *Composites Science and Technology,* **59,** 1937–1957, 1999.
[11] K.B. Pettersson,Jonas M. Neumeister,E.K. Gamstedt,H. Öberg, Stiffness reduction, creep, and irreversible strains in fiber composites tested in repeated interlaminar shear. *Composite Structures*, **76,** 151–161, 2006.
[12] K. Chung,H. Ryou, Development of viscoelastic/rate-sensitive-plastic constitutive law for fiber-reinforced composites and its applications. Part I: Theory and material characterization. *Composites Science and Technology,* **69,** 284–291, 2009.
[13] P.P. Camanho, P. Maimi, C.G. Davila, Prediction of size effects in notched laminates using continuum damage mechanics. *Composite Science and Technology*, **67**, 2715-2727, 2007.
[14] F. Sket,A. Enfedaque,C. Alton,C. González,J.M. Molina-Aldareguia,J. Llorca, Automatic quantification of matrix cracking and fiber rotation by X-ray computed tomography in shear-deformed carbon fiber-reinforced laminates. *Composites Science and Technology,* **90,** 129–138, 2014.