STRAIN RATE DEPENDENT DEFORMATION AND DAMAGE BEHAVIOUR OF TEXTILE-REINFORCED THERMOPLASTIC COMPOSITES

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Abstract
The present work focuses on the detailed characterisation and modelling of the strain rate dependent deformation and damage behaviour of a continuous fibre-reinforced thermoplastic composite (TPC) with multi-layered flat bed weft-knitted reinforcement. For this purpose, a novel experimental testing procedure is developed in the first part of this work. A so-called stepwise loading and reloading with stress relaxation and strain retardation phases enables the determination of the elastic, inelastic and viscoelastic portions with only one experimental test. Additionally, microscopic diagnostic is employed to investigate the complex deformation and damage behaviour and its provoking phenomenological damage mechanism like inter fibre failure and inelastic deformation. After the detailed experimental characterisation, an adapted viscoelastic-plastic damage model is developed in the second part of this work. This model on lamina level is based on a modified damage-plasticity model proposed by LADEVÈZE and uses an additional spring-dashpot system for describing the viscoelastic overstress. This model is implemented as a user-defined material (VUMAT) in the FE program ABAQUS for realising a model validation and structure application.

1. Introduction

Textile-reinforced thermoplastics made from hybrid yarns exhibit moderate up to very high specific mechanical properties (stiffnesses and strengths) [1, 2], high impact resistance as well as high fracture toughness [2-4] and are suitable for series production as well as recyclable due to their hot forming property [5-7]. The combination of both mechanical and technological advantages predestines this material group for the application in automotive lightweight structures [2-6]. Under mechanical loadings, textile-reinforced thermoplastics can show a distinct nonlinear behaviour caused by the development of inelastic deformation as well as of damage in conjunction with stiffness degradation [1, 2]. Furthermore, a highly strain rate dependent material behaviour occurs due to the thermoplastic matrix system [2]. This complex material behaviour has to be considered in a reliable design of lightweight structures.
The use of mesoscopic material models (lamina level) based on continuum damage mechanics (CDM) [8-13] within finite element (FE) programs represents the state-of-the-art in composite structure design. Thereby, mode specific failure criteria e.g. suggested by HASHIN [8] or CUNTZE, [9] are applied to calculate the initial failure under consideration of different failure modes like fibre failure (FF) and inter fibre failure (IFF). Additional anisotropic CDM approaches [10-13] often based on the work of MATZENMILLER ET AL. [10] are employed for describing the nonlinear post failure behaviour due to damage growth and stiffness degradation. The CDM based material models are developed

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originally for the brittle damage behavior of thermosetting fibre-reinforced composites. Hence, they are insufficient to represent the complete manner of thermoplastic composites. The distinct nonlinear mechanical behaviour of TPC is also caused significantly by the development of inelastic strains, which have to be considered in the reliable design of TPC structures. For years, some authors presented anisotropic material models based on pure plasticity approaches [14-15] and based on combined plasticity-damage approaches [16-18]. An important work with respect to combined plasticity-damage modelling was done by LADEVÈZE ET AL. [16], which was often picked up by other authors. Thereby, the equivalent stress-strain-curve is formulated with the effective quantities from the CDM. Furthermore, LADEVÈZE suggested a novel experimental procedure in using stepwise loading-unloading tests for characterising separately the damaged-induced stiffness degradation and the evolution of inelastic strains.

Another important effect is the strong time dependence of the TPC behaviour, which results in strain rate dependent properties as well as in distinct relaxation and creep processes. The consideration of time dependent mechanical behaviour in material models is partially done by engineering approaches often based on the work of JOHNSON and COOK [19]. Thereby, the different stiffness and strength values are scaled relating to a reference strain rate [12-13, 19-20]. Other authors suggest viscoplastic or viscoelastic approaches based on the serial or parallel connection of rheological elements [21-23]. The experimental characterisation of the time dependent mechanical behaviour is done by mechanical tests at different strain rates [12-13, 19-20] or by relaxation as well as by creep experiments [21-23].

In the scope of this work, an adapted experimental testing procedure is developed for the group of continuous fibre reinforced thermoplastics in order to characterize the evolution of stiffness degradation, inelastic strains and time dependence. Based on the experimental results, an adapted modelling approach is developed for the description of the complex deformation and damage behaviour as well as for the enabling of a reliable design of TPC structures for automotive applications.

2. Procedure

2.1. Experimental testing procedure

The focus of the experimental investigations lies on a novel textile-reinforced glass fibre polypropylene (GF/PP) composite, a so-called multi-layered weft-knitted fabric (MKF) with a glass fibre volume fraction of 54.5 %. The advantage of the MKF is the non-crimped alignment of reinforcement fibres and a high delamination resistance due to a fibre reinforced knit thread system (Fig. 1). A unidirectional (UD) as well as a bidirectional (BD) configuration of the MKF are characterised by experiments in detail. The UD type allows the determination of the mechanical properties of the single layer including the influence of the knit thread system. However, the BD type enables the investigation of the behaviour of the multiaxial laminate and the embedded single layer.

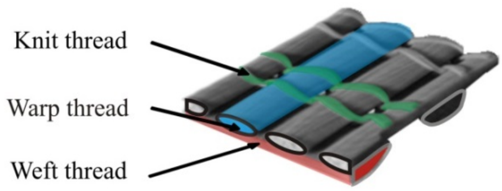

Figure 1. Textile architecture of the multi-layered weft-knitted fabric in bidirectional configuration.

Two experimental testing methods, which are suggested from LADEVÈZE [16] and KÄSTNER [21], are combined together in this work. This novel adapted testing procedure includes on the one hand a continuous stepwise loading and reloading (Fig. 1a), and on the other hand the imposing of stress relaxation and strain retardation phases (Fig. 1b). Every experimental cycle (Fig. 1c) starts with a

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displacement-controlled loading, followed by a stress relaxation phase of 5 h at a defined strain level as well as afterwards a force-controlled unloading and ends with a strain retardation phase of 5 h at an external force of zero. The reloading in the next cycle is performed up to a higher strain level. The relaxation and retardation time of 5 h was determined in preliminary tests. This value corresponds to a decay of the viscoelastic overstress as well to a decay of the creep strain of 90 percent. After the decay of the viscoelastic overstress, the stress-strain-curve represents the time-independent material behaviour (equilibrium curve).

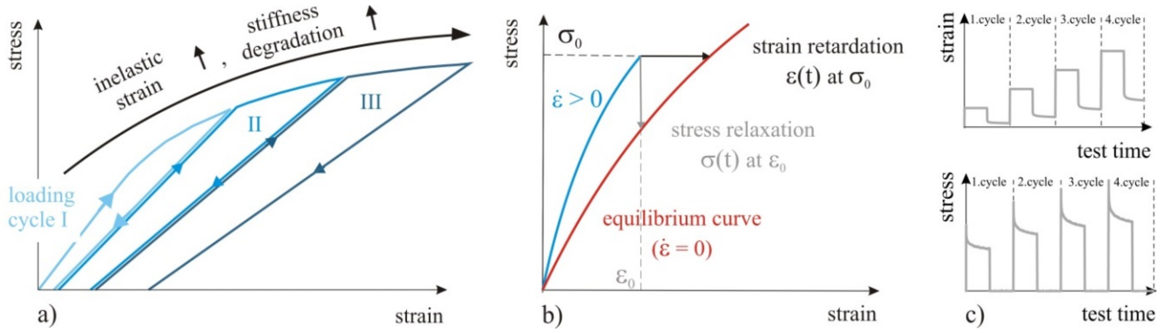

Figure 2. a) Continuous stepwise loading and reloading test [16], b) stress relaxation and strain retardation [21], c) stress-time and strain-time regime of the adapted experimental testing procedure.

This so-called stepwise loading and reloading test with stress relaxation and strain retardation phases enables the determination of the elastic, inelastic and viscoelastic quantities with only one test (Fig. 3a). This experimental testing procedure is performed with specimens of GF/PP MKF in fibre direction, perpendicular to fibre direction as well as under tension, compression and in-plane shear loading on off-axis specimens with a balanced lay-up of ± 45°. To obtain a better overview in this paper, the procedure is explained exemplarily with the results of the in-plane shear loading. More detailed results, especially for the other material directions, can be found in Ref. [24].

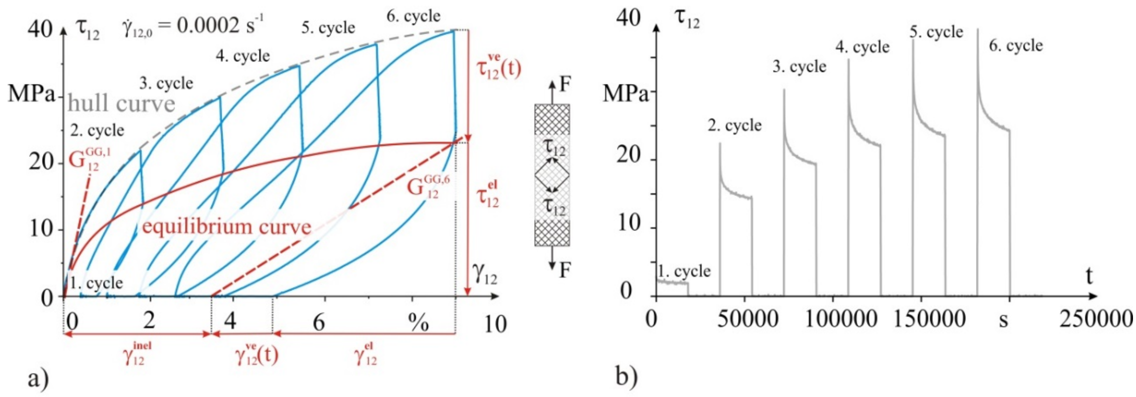

Figure 3. Experimental results of GF/PP MKF under in-plane shear loading: a) stepwise loading and reloading with stress relaxation and strain retardation and b) analysing of the viscoelastic overstress.

The time dependent behaviour is determined by analysing the viscoelastic overstress for each cycle (Fig. 3b). After the decay of the viscoelastic parts, this experimental procedure enables the identification of the time independent behaviour at the equilibrium (eq) curve. Therefore, it is possible to get discrete values of the current degraded stiffness due to damage growth (Fig. 4a) and current inelastic strain (Fig. 4b) for each cycle.

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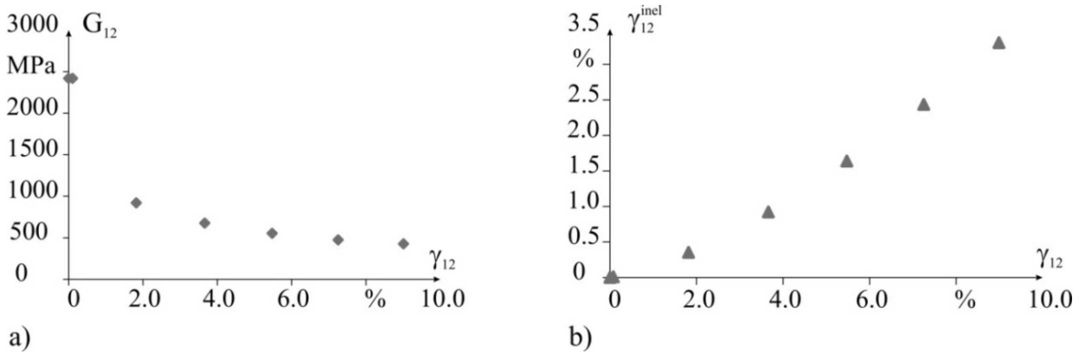

Figure 4. Experimental results of GF/PP MKF under in-plane shear loading: a) evolution of stiffness degradation due to damage growth and b) evolution of the inelastic strain.

Additional to the adapted loading and reloading test, microscopic diagnostic at different loading levels (Fig. 5) is employed to investigate the complex deformation and damage behaviour and its provoking phenomenological damage mechanism. Thereby, inter fibre failures in matrix regions and in fibre-matrix-interfaces as well void growth are identified as the main damage mechanisms. Especially under in-plane shear loading, a large increase of inelastic deformation occurs. The reason lies in the interaction of plastic deformation in the thermoplastic matrix regions and the IFF formation.

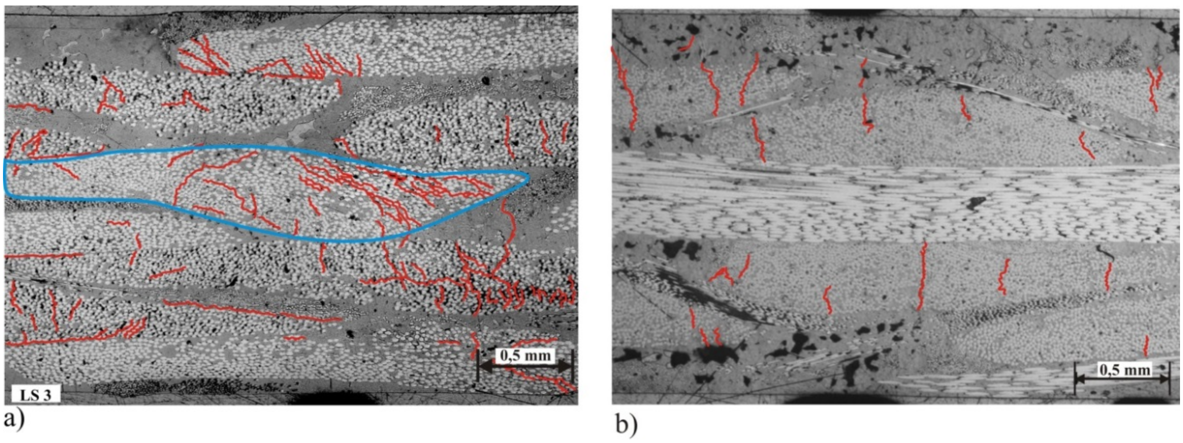

Figure 5. Microscopic analysis of the damage and deformation mechanisms within in the BD GF/PP MKF a) after in-plane shear strain loading of 10 % and b) after tension strain loading of 2 %.

2.2. Modelling approach

After the detailed investigation of the deformation and damage behaviour as well the corresponding mechanisms, an adapted viscoelastic-plastic damage model is developed in the second part of this work. This model on lamina level is based on the combined damage-plasticity model proposed by LADEVÈZE [16] and uses additional nonlinear spring-dashpot systems for the description of the viscoelastic overstresses. Therefore, the general constitutive relations result in

$$\boldsymbol{\sigma} = \widetilde{\boldsymbol{C}}^{eq}\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{inel}\right) + \boldsymbol{\sigma}^{ve}, \tag{1}$$

with the effective stiffness of the damaged material $\widetilde{\boldsymbol{C}}^{eq}$, the inelastic strains $\boldsymbol{\varepsilon}^{inel}$ and the viscoelastic overstresses $\boldsymbol{\sigma}^{ve}$. In Fig. 6a, the connection scheme of the rheological model is presented. Thereby, on the one hand a nonlinear spring element and a sliding frictional element are connected in series for the modelling of the time independent behaviour. On the other hand, a nonlinear dashpot and spring element are connected in series for the modelling of the time dependent behaviour.

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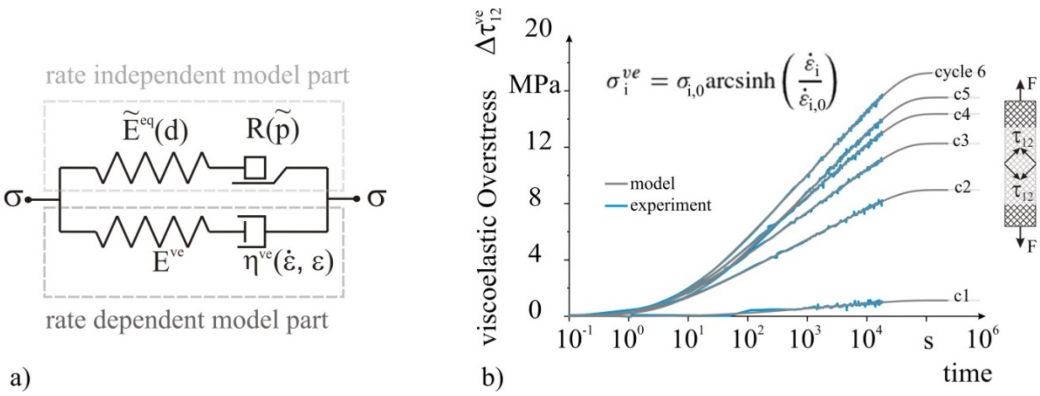

Figure 6. a) Connection scheme of the rheological model and b) mathematical description of the stress relaxation behaviour of GF/PP MKF under in-plane shear loading.

The analysis of the experimental results for the different material directions of the UD GF/PP MKF shows, that the influence of the damage, inelastic strain as well as the viscoelastic overstress in fibre direction is negligible. The rheological model, presented in Fig. 6a, is needed for each matrix-dominated direction (perpendicular to fibre orientation and in-plane shear), whereas a simple spring element is sufficient for represent the fibre direction. Hence, the constitutive relations with assumption of plane stress conditions for thin-walled laminas is defined as follows

$$\begin{bmatrix} \sigma_1 \\ \sigma_2(t) \\ \tau_{12}(t) \end{bmatrix} = \begin{bmatrix} \tilde{Q}_{11}^{eq} & \tilde{Q}_{12}^{eq} & 0 \\ \tilde{Q}_{12}^{eq} & \tilde{Q}_{22}^{eq} & 0 \\ 0 & 0 & \tilde{Q}_{66}^{eq} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 - \varepsilon_2^{inel} \\ \gamma_{12} - \gamma_{12}^{inel} \end{bmatrix} + \begin{bmatrix} 0 \\ \sigma_2^{ve}(t) \\ \tau_{12}^{ve}(t) \end{bmatrix}, \tag{2}$$

with the effective layer stiffnesses $\tilde{Q}_{ij}^{eq}$ of the equilibrium behaviour

$$\tilde{Q}_{11}^{eq} = \frac{E_1}{1-(1-d_2)\nu_{12}\nu_{21}}, \tilde{Q}_{22}^{eq} = \frac{E_2(1-d_2)}{1-(1-d_2)\nu_{12}\nu_{21}},$$

$$\tilde{Q}_{12}^{eq} = \frac{\nu_{12}E_2(1-d_2)}{1-(1-d_2)\nu_{12}\nu_{21}} \text{ and } \tilde{Q}_{66}^{eq} = G_{12}(1-d_{12}). \tag{3}$$

The next step is to estimate the different mathematical approaches of the single rheological model components. The analysis of relaxation behaviour (Fig. 6b) turns out, that the nonlinear EYRING approach [22]

$$\sigma_2^{ve} = \sigma_{2,0} \operatorname{arcsinh}\left(\frac{\dot{\varepsilon}_2}{\dot{\varepsilon}_{2,0}}\right) \text{ and } \tau_{12}^{ve} = \tau_{12,0} \operatorname{arcsinh}\left(\frac{\dot{\gamma}_{12}}{\dot{\gamma}_{12,0}}\right) \tag{4}$$

is suitable for the description of the viscoelastic overstress, whereat $\sigma_{i,0}$ and $\dot{\varepsilon}_{i,0}$ represent model parameters. The characterisation of the stiffness degradation and the corresponding damage growth (Fig. 7a) show, that the hyperbolic law suggested by BÖHM [11] with the model parameters β^j and κ^j

$$\phi^{12} = \tanh\left[\beta^{12}(r^{12}-1)^{\kappa^{12}}\right] \text{ and } \phi^{2(+)} = \tanh\left[\beta^{2(+)}(r^{2(+)}-1)^{\kappa^{2(+)}}\right], \text{with } r^j > 1 \tag{5}$$

is very proper for the calculation of the damage evolution ϕ^j depending on the damage thresholds r^j

$$r^{2(+)} = \frac{\tilde{\sigma}_2^{eq}}{R_0^{2(+)}} \text{ and } r^{12} = \frac{\tilde{\tau}_{12}^{eq}}{R_0^{12}}, \tag{6}$$

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after exceeding the initial damage strength R_0^j for the different damage modes j (tension loading perpendicular to fibre direction 2(+) and in-plane shear loading 12). The computation of the damage parameter d_i is done in consideration of damage interaction by the coupling parameters q_i^j and the interaction coefficient n:

$$(d_i)^n = \sum_j (\phi^j q_i^j)^n \,. \tag{7}$$

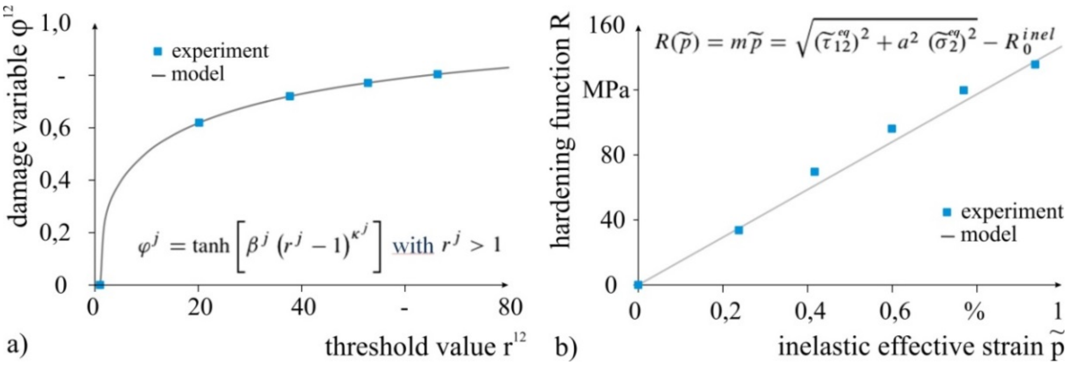

Figure 7. Modelling of the a) damage progress and b) inelastic strain evolution for GF/PP MKF.

Based on the combined damage-plasticity model proposed by LADEVÈZE [16], equivalent stress-strain-curve in conjunction with the effective stresses $\tilde\sigma_i^{eq}$ and effective strains $\tilde\varepsilon_i^{inel}$ from the CDM are used to describe the evolution of the inelastic strains (Fig. 7b). Thereby, the hardening function $R(\tilde p)$ with the anisotropic model parameter a and the initial yield strength R_0^{inel}

$$R(\tilde p) = m\tilde p = \sqrt{\left(\tilde\tau_{12}^{eq}\right)^2 + a^2\left(\tilde\sigma_2^{eq}\right)^2} - R_0^{inel} \text{ with } \tilde\sigma_2^{eq} = \frac{\sigma_2^{eq}}{(1-d_2)} \text{ and } \tilde\tau_{12}^{eq} = \frac{\tau_{12}^{eq}}{(1-d_{12})} \tag{8}$$

shows a linear characteristic with the slop m and is controlled by the equivalent inelastic strains $\mathrm{d}\tilde p$

$$\mathrm{d}\tilde p = \sqrt{(\mathrm{d}\tilde\gamma_{12}^{inel})^2 + \frac{1}{a^2}(\mathrm{d}\tilde\varepsilon_2^{inel})^2} \text{ with } \tilde\varepsilon_2^{inel} = \varepsilon_2^{inel}(1-d_2) \text{ and } \tilde\gamma_{12}^{inel} = \gamma_{12}^{inel}(1-d_{12}). \tag{9}$$

2.3. Validation and structure application

This model is implemented as a user-defined material (VUMAT) with an explicit algorithm in the FE program ABAQUS. The validation is done by analysing different strain rates and other lay-ups (Fig. 8).

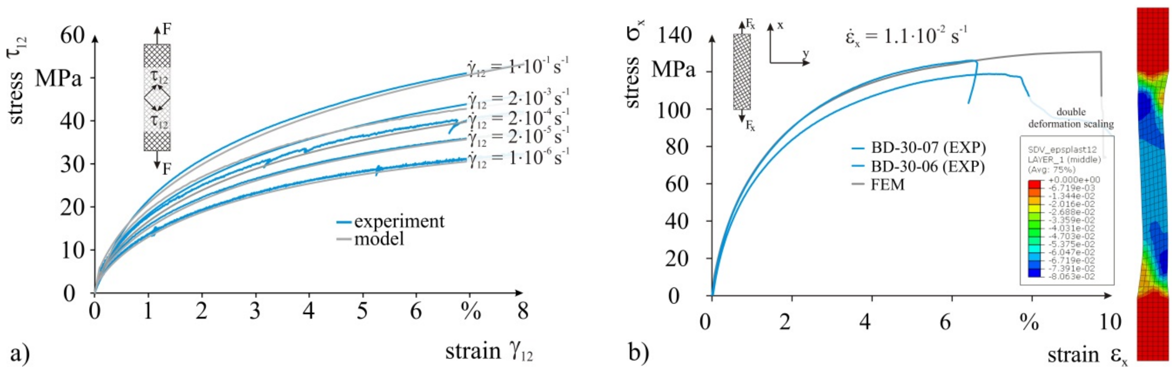

Figure 8. Validation of developed model by comparing measured and calculated stress-strain-results of GF/PP MKF under continuous loading with different a) strain rates and b) another off-axis lay-up.

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As shown in Fig. 8, the developed material model has the ability to represent the measured stress-strain-curves under continuous loading with both different strain rates and another off-axis lay-up in an excellent manner. Finally, the developed model is used for structure application. Thereby, the measured and calculated structure behaviour of a beam structure under 3-point bending and different loading rates are compared. The beam structure, which is manufactured in a hot forming process, consists of GF/PP MKF with a balanced ± 45° lay-up in the top layer and short fibre reinforced GF/PP in the rib regions. As shown in Fig. 9, the developed material model has also the ability to represent the measured structure behaviour under different loading rates. This includes structure stiffness, the loading capacity and the post-failure behaviour.

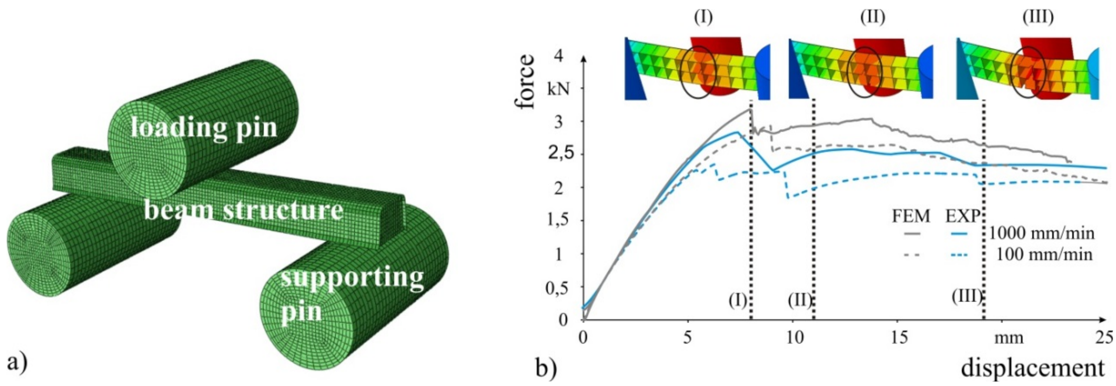

Figure 9. Structure application of the developed model: a) setup of the beam structure bending test and b) comparison of measured and calculated behaviour of the GF/PP MKF beam structure under different loading rates.

3. Conclusions

The presented work focuses on the detailed characterisation and modelling of the strain rate dependent deformation and damage behaviour of continuous fibre-reinforced thermoplastic composites. For this purpose, a novel experimental testing procedure with stepwise loading and reloading as well as stress relaxation and strain retardation phases was developed. This method enables the determination of the elastic, inelastic and viscoelastic quantities with only one experimental test for the first time. Based on the experimental results, an adapted viscoelastic-plastic damage model was developed on lamina level and was implemented as a user-defined material in the FE program ABAQUS. It was demonstrated, that the model is also valid for different loading rates and is applicable for reliable structure design.

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References

[1] W. Hufenbach, M. Gude, R. Böhm, M. Zscheyge. The effect of temperature on mechanical properties and failure behaviour of hybrid yarn textile-reinforced thermoplastics. *Materials and Design*, 32: 4278-4288, 2011.

Excerpt from ISBN 978-3-00-053387-7

[2] K.A. Brown, R. Brooks, N.A. Warrior. The static and high strain rate behaviour of a commingled E-glass/polypropylene woven fabric composite. *Compos Sci Technol*, 70: 272–283, 2010.

[3] W. Hufenbach, R. Böhm, M. Thieme, A. Winkler, E. Mäder, J. Rausch, et al. Polypropylene/glass fibre 3D-textile reinforced composites for automotive applications. *Materials and Design*, 32(3): 1468–1476, 2011.

[4] O. Diestel, P. Offermann. Thermoplastische GF/PP-Verbunde aus biaxialverstaerkten Mehrlagengestricken? Werkstoff zur Verbesserung der passiven Fahrzeugsicherheit? *Technische Textilien*, 43(4): 274–277, 2000.

[5] C. Cherif, H. Rödel, G. Hoffmann, O. Diestel, C. Herzberg, C. Paul, et al. Textile manufacturing technologies for hybrid based complex preform structures. *J Plast Technol*, 6: 103-129, 2009.

[6] W. Hufenbach, F. Adam, J. Beyer, M. Zichner, M. Krahl, S. Lin, et al. Development of an adapted process technology for complex thermoplastic lightweight structures based on hybrid yarns. *17th internat. conference on composite materials ICCM 17,* Edinburgh, July 27–31 2009.

[7] A.C. Long, C.E. Wilks, C.D. Rudd. Experimental characterisation of the consolidation of a commingled glass/polypropylene composite. *Compos Sci Technol*, 61: 1591–1603, 2001.

[8] Z. Hashin. Failure criteria for unidirectional fibre composites. *J Appl Mech*, 47: 329–334, 1980.

[9] R.G. Cuntze, A. Freund. The predictive capability of failure mode concept based strength criteria for multidirectional laminates. *Composites Science and Technology*, 64: 343-377, 2004.

[10] A. Matzenmiller, J. Lubliner, R.L. Taylor. A constitutive model for anisotropic damage in fibre composites. *Mechanics of Materials*, 20 (2): 125–152, 1995.

[11] R. Böhm, M. Gude, W. Hufenbach. A phenomenologically based damage model for textile composites with crimped reinforcement. *Composites Science and Technology*, 70: 81–87, 2010.

[12] J.R. Xiao, B.A. Gama, J.R. Gillespie. Progressive damage and delamination in plain weave S-2 glass/SC-15 composites under quasi-static punch-shear loading. *Comp Struct*, 78: 182-196, 2007.

[13] K.A. Brown, R. Brooks, N.A. Warrior. Numerical simulation of damage in thermoplastic composite materials. *5th European Ls-Dyna Users Conference*, Birmingham, 2005.

[14] A.C. Hansen, D.M. Blackketter, D.E. Walrath. An invariant-based flow rule for anisotropic plasticity applied to composite materials. *Journal of Applied Mechanics*, 58: 881-888, 1991.

[15] G.M. Vyas, S.T. Pinho, P. Robinson. Constitutive modelling of fibre-reinforced composites with unidirectional plies using a plasticity-based approach. *Compos Sci Technol*, 71: 1068-1074, 2011.

[16] P. Ladevèze, E. Le Dantec. Damage modelling of the elementary ply for laminated composites. C*omposites Science and Technology*, 43: 257-267, 1992.

[17] C. Herakovich. *Mechanics of fibrous composites*. John Wiley & Sons, 1998.

[18] T. Flatscher, H.E. Pettermann. A constitutive model for fibre-reinforced polymer plies accounting for plasticity and brittle damage including softening. *Comp Struct 93*: 2241-2249, 2011.

[19] G.R. Johnson, W.H. Cook, A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. *Proceedings of the 7th international symposium on ballistics*: 541-547, 1983.

[20] M. Gude, W. Hufenbach, C. Ebert. The strain-rate-dependent material and failure behaviour of 2D and 3D non-crimp glass-fibre-reinforced composites. *Mech Comp Mat,* 45 (5): 467-476, 2009.

[21] M. Kästner. *Skalenübergreifende Modellierung und Simulation des mechanischen Verhaltens von textilverstärktem Polypropylen unter Nutzung der XFEM.* Dissertation, TU Dresden, 2009.

[22] J. Fritsch, S. Hiermaier, G. Strobl. Characterizing and modelling the nonlinear viscoelastic tensile deformation of a glass fibre reinforced polypropylene. *Compos Sci Technol*, 69: 2460-2466, 2009.

[23] J. Tsai, C.T. Sun. Constitutive model for high strain rate response of polymeric composites. *Composites Science and Technology* 62: 1289-1297, 2002.

[24] M. Zscheyge. *Zum temperatur- und dehnratenabhängigen Deformations- und Schädigungsverhalten von Textil-Thermoplast-Verbunden*. Dissertation, TU Dresden, 2015.

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