NON-LINEAR BEHAVIOUR OF PLAIN WEFT-KNITTED CARBON FIBRE REINFORCED COMPOSITES

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SUMMARY: Knitted fabrics offer a large deep-drawing potential. Characteristic for the textile structure is its interlooping yarns. A single loop consists of intermeshing regions and side limbs or legs. In this paper, the discussion of non-linear behaviour of knitted composites is focussed on the intermesh; in the intermesh the load is transferred between fibre bundles, due to the strong curvature, the stress state in the intermesh comprises a shear component. Due to the shear component the bending rigidity of the beam is decreased. The matrix dominates shear deformation, of which the influence is limited to the intermeshing area. Therefore, the deformation behaviour of knitted composites is defined as matrix directed for all in-plane directions.

KEYWORDS: Textiles, non-linearity, stress-strain behaviour, modulus prediction

INTRODUCTION

Investigations on knitted fabric reinforced composites have shown that the in-plane mechanical behaviour of this type of textile composite materials is dominated by the fibre bundle [1]. Since single layer specimens revealed similar properties compared to multilayer specimens, the bundle is regarded as the basic structural element which determines the mechanical properties of the composite.

In general, the absence of orientations with fully aligned fibres makes the mechanical behaviour of knitted fabric composites sensitive to the behaviour of the matrix. Since thermoset matrix systems behave in general more linear than thermoplastics, their knitted composites demonstrate similar mutual differences. Therefore, three material combinations were compared in this study: carbon/epoxy, carbon/polyetheretherketone (CF/PEEK) and carbon/polyamide 12 (CF/PA12).

MATERIALS AND METHODS

CF/epoxy panels were produced by handlamination of four double layers of knitted fabric and subsequent hot pressing of the impregnated textiles. Curing was performed at 100 °C for 2 hours with 5 bar consolidation pressure. CF/PEEK panels were formed by hot pressing (T = 420°C, 30 min., 30 bar) of four double layers co-knitted carbon and PEEK fibre yarns. CF/PA12 panels were formed by hot pressing (T = 225°C, 10 min., 10 bar) of four double layers co-knitted carbon and PEEK fibre yarns. Whereas the loop sizes were different: loop height and width were 7.1 and 4.3 mm for CF/PEEK and 5.7 and 5.5 mm for CF/epoxy.

Material	**Manufacturer, type**
carbon fibres	Tenax, HTA 5131
epoxy	Ciba, LY 556
PEEK - composite - injection moulded specimens	 Hoechst, PEEK M Victrex 450G
PA 12	Ems Chemie, L16

Table 1: Manufacturers of carbon fibres and matrix systems

Tensile test were performed on a universal testing device (Zwick 1456) according to EN 61, for composite specimens with a free testing length of 150 mm and a specimen width of 25 mm. Injection moulded tensile bars had dimensions deviating from the standards (72 x 4.95 x 2.75 mm^3) and therefore the free testing length was reduced to 50 mm. Strains were measured by means of an extensiometer over a length of 100 and 25 mm respectively. Tests were performed at a strain rate of 2 mm/min. For statistics at least 5 specimens were used.

EXPERIMENTAL RESULTS AND DISCUSSION

The behaviour of the matrix directs the mechanical properties of KFRCs in all in-plane and out-of-plane orientations. The fibres are arranged in bundles, which are the strain defining units for mechanical loads. Pure tensile loads are the only loads dominated only by the fibres, whereas the matrix influences all other loads. Due to the structural instability of the knitted network, e.g. the knitted fabric itself allows high deformations, the matrix plays a decisive role in the mechanical behaviour of knitted composites. The extent to which the matrix directs the macroscopic mechanical behaviour of the composite is dependent on yarn and fabric type.

Since the matrix directs the mechanical behaviour of KFRCs, the behaviour of the matrix systems PEEK and PA12 is investigated first. Both materials are thermoplastics and therefore, demonstrate time-dependent behaviour. Tensile test were performed with injection moulded specimens, under variation of the test speed and the temperature (Fig. 1).

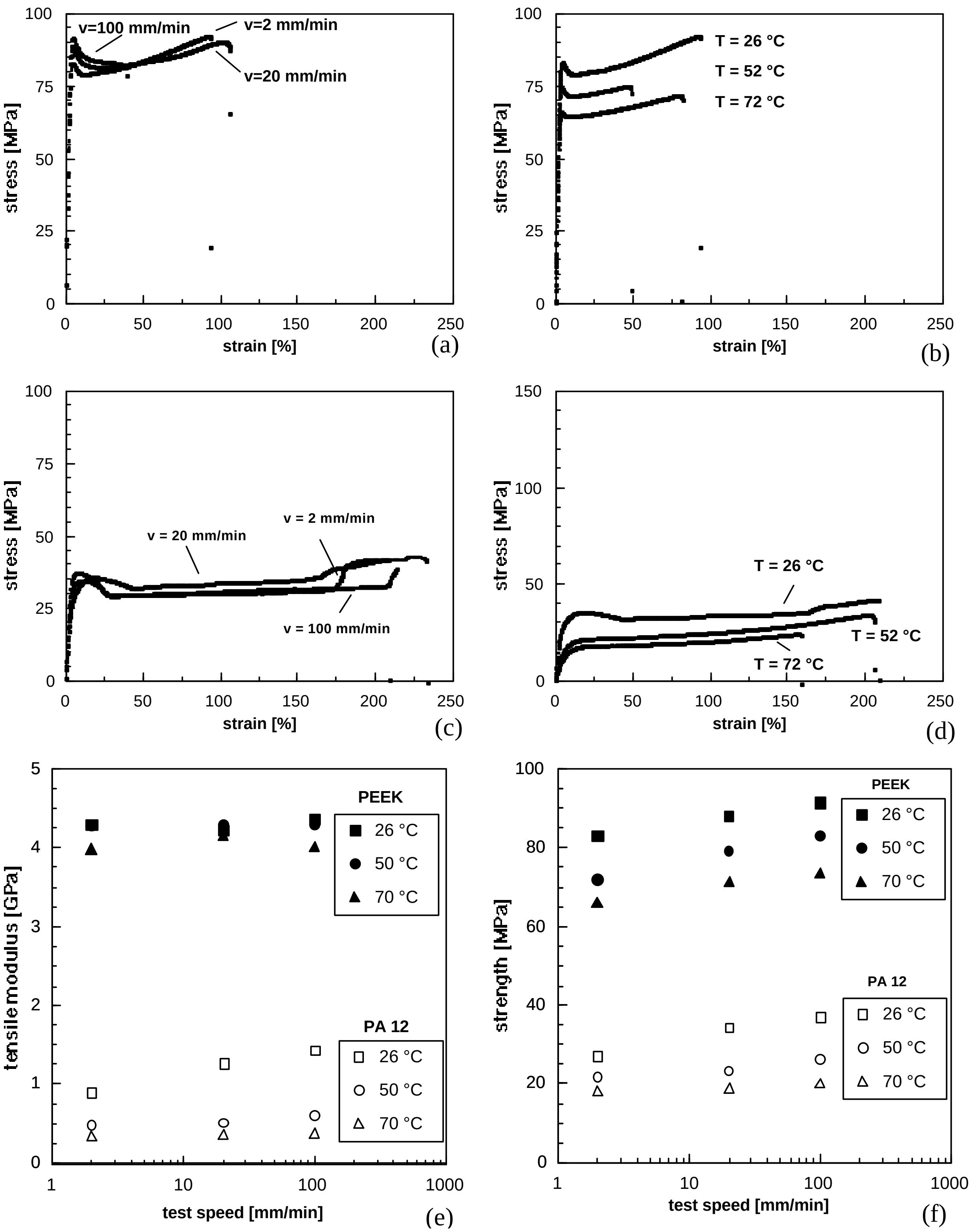


Fig. 1: Stress-strain behaviour of PEEK (a&b) and PA12 (c&d) injection moulded specimens. Due to temperature increase, lower modulus and ultimate stress level are observed. Increasing the test speed leads to higher modulus and strength values. Remarkable is, however, the stability of the PEEK specimens for modulus changes: The modulus changes are irregular and on an equal level indicating the temperature and speed independence of the material.

It is found, that the behaviour of PA12 is more sensitive to temperature and strain rate changes than PEEK, which can be related to the glass transition temperature (Tg) which are 143 and 41 °C respectively. The consequences for the modulus and the nonlinearity of their composites with carbon fibre as reinforcing material are investigated in the following sections.

For comparison of the moduli, initial values are compared since the non-linearity of the stress-strain behaviour is already present at the calculation ranges applied in the standards. Upon loading, the tangent modulus of a non-linear matrix is changed. Validation of the models for modulus prediction of non-linear knitted fabric reinforced composites is therefore restricted to the initial moduli, which were calculated from the tensile curves (Fig. 2) on the basis of a simple quadratic non-linear stress-strain model $\sigma = E_0 \cdot \varepsilon \cdot (1-D_1\varepsilon)$ [2].

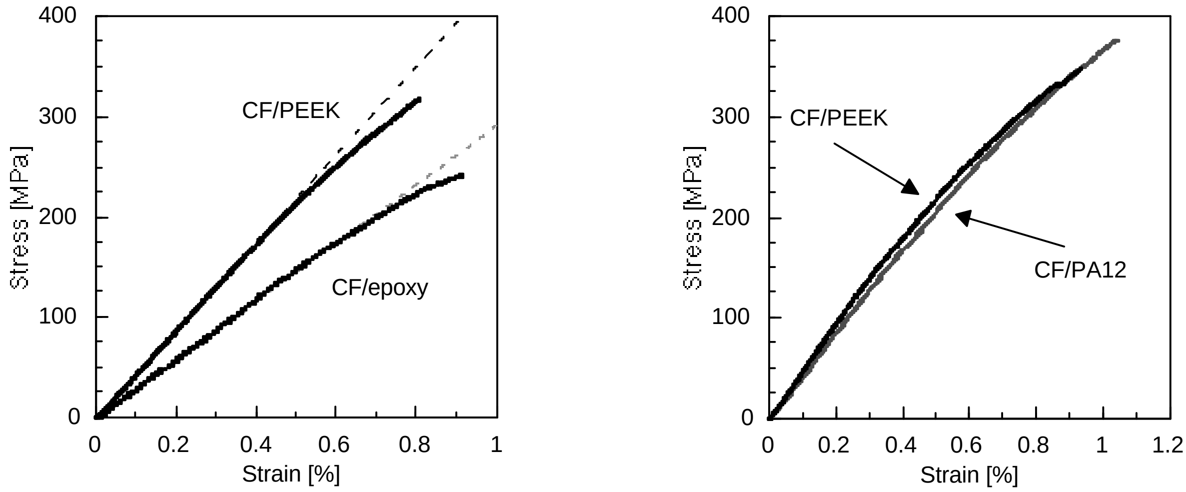
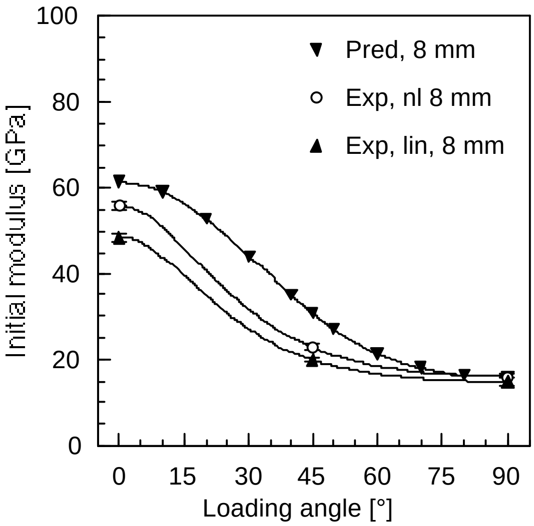


Fig. 2: Stress-strain curves for CF/PEEK and CF/epoxy (V_f=30-35%) (left) and CF/PEEK and CF/PA12 (V_f =50%) all tested in wale direction. It was shown that the linearity decreases from CF/epoxy to CF/PEEK to CF/PA12.

In plain weft-knitted fabrics two principal directions are distinguished: the wale and the course direction. Both directions have different deformation mechanisms due to the structure of the fabric. The wale direction is the preferred fibre direction and therefore stiffer, whereas in course direction the flexibility is higher. In Fig. 3 the angle dependence of the modulus is shown. The linear data, as calculated by the standards are compared with non-linear data and the predictions for the investigated structure on the basis of the theory which was presented by Rudd, Middleton and Owen [3].

Material combination	Nonlinearity factor D_1 0°	90°
CF/PEEK V_f = 30 %	31.2	46.7
CF/epoxy V_f = 35 %	0	20.2
CF/PEEK V_f = 53 %	15.2	46.1
CF/PA12 V_f = 50 %	37.8	50.8

(a)



(b)

Fig. 3: Non-linearity values increase from CF/epoxy to CF/PEEK and CF/PA12 (a). Comparison of the predicted (pred) and experimental (exp) angle dependent values for the modulus of CF/PEEK (b). The 0° direction coincides with the on-axis direction of the knitted fabric, the wale direction, whereas the 90° direction denotes the course direction. For the experimentally obtained values both the linear (lin) and the non-linear (nl) approaches are given.

For glass fibre reinforced composites (Gommers [4]), the discrepancy between model and experimental results was found to be smaller than for the carbon fibre fabric reinforced composites investigated in this study. The increase was attributed to the higher stiffness ratio of reinforcement and matrix, which results in larger deviations.

CONCLUSIONS

Knitted carbon fibre reinforced epoxy demonstrated linear stress-strain behaviour up to stresses where fracture occurs, whereas the combination of carbon fibres with highly non-linear matrix systems (PA12) resulted in non-linear stress-strain behaviour. By means of a mathematical model for the nonlinearity, the stress-strain behaviour was described. Subsequently, the initial modulus was compared with predicted values for the modulus. The values obtained with the mathematical model where more realistic for comparison with the predicted values. The discrepancy between experimental and predicted results was reason for further development of the mechanical models for KFRCs [1] and a detailed investigation of the bundle geometry [5].

Nonlinearity values for epoxy based composites where lower than for PEEK and PA12 based composites. The nonlinearity, attributed to the matrix, is expected to predominantly affect the intermeshing area. The high curvature gives rise to additional shear stresses. The deformation behaviour under shear loading is dominated by the matrix, thus resulting in non-linear behaviour of the intermeshing area. For loads in wale direction, the intermeshing area and legs are placed in series connection. Thus, the mechanical behaviour of the composite is influenced by the behaviour of the intermesh. For loads in course direction the intermeshing area and the legs are placed in parallel. However, since the legs of the loop are loaded in transverse direction, the mechanical behaviour is dominated by the matrix. Therefore, the stress-strain behaviour for loads in course direction demonstrates higher nonlinearity than for loads in wale direction.

REFERENCES

[1] de Haan, J., Structure-property relations in plain weft-knitted fabric reinforced composites (KFRCs) preparing for load bearing implants: experimental study and beam model approach, Ph.D. thesis ETH Zürich (No 13042), 1999, p. 66-85.

[2] Schmachtenberg, E., Die mechanischen Eigenschaften nichtlinearer viskoelastischer Werkstoffe, Ph.D. Thesis RWTH Aachen, Aachen, 1985

[3] Rudd, C.D., Middleton, M.J., Owen, M.J., Mechanical properties of weftknitted glass fibre/polyester laminates, Composites Science and Technology, 39, 1990, p. 261-277

[4] Gommers, B., The elastic properties of knitted fabric composites, Ph. D. Thesis, KU Leuven, Leuven, 1997, p. 110-118.

[5] Reber, R., Micro- and macromechanical properties of knitted fabric reinforced composites (KFRCs) with regard to environmental exposure, Ph.D. thesis ETH Zürich (No 13080), Zürich, 1999, p. 17-28.