Adhesive and Cohesive Failure Criteria of Unidirectional Fibre / Matrix Composites

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Introduction

In unidirectional (UD) fibre/matrix composites three modes of failure occur:

1.) cohesive failure of the fibre,
2.) cohesive failure of the matrix,
3.) adhesive failure of the fibre/matrix interface.

Tensile stress parallel to the fibres $\sigma_{\parallel}$ (fig. 1) mostly leads to fibre failure, tensile stress perpendicular to the fibres $\sigma_{\perp}$ and shear-stress in the Laminaplane $\tau_{\#}$ leads to cohesive failure of the matrix or adhesive failure of the interface respectively. If the stress-strain response of the fibre and the matrix and the failure criteria of the fibre, the matrix and the interface are known as well as the correlation between the stresses of the UD-Lamina and the microstresses of the fibre, the matrix and the interface, we can calculate the stress-strain response and the different failure curves of the UD-Lamina. By comparison of the calculated and experimentally determined values one can conclude to the really occuring mode of failure.

Microstresses

We regard the UD-Lamina as a regular array of fibres in the matrix (in this paper we use a mixture of square and hexagonal array). When the UD-Lamina is loaded by a plane state of stress,

the matrix and the interface respectively are mainly under a plane state of stress too. Therefore we apply as an approximation in determining the microstresses the so called "sliced model" [1] to the UD-Lamina. I. e. we assume that the UD-Lamina is split up into slices of an infinitely small thickness by cuts parallel to the Lamina plane so that no forces can be transmitted in z-direction (fig. 1, b). Thus the threedimensional state of stress in the matrix and the interface respectively it reduced to a plane state of stress. Since the stiffness of the matrix is much lower than the stiffness of the fibre, the matrix must nearly endure the whole deformation of the UD-Lamina (strain magnification). The point of the highest equivalent total stress is the slice across the centres of two neighbouring fibres. Under loading by $\sigma_{\perp}$ and $\tau_{\#}$ crazing will start here in the matrix or in the interface. When the load of the UD-Lamina will be increased, the cracks will propagate through the neighbouring slices and lead to total failure of the UD-Lamina.

Materials

We tested UD-Lamina of glass reinforced plastics (GRP). The matrix material was a standard epoxy resin, CY 232 with hardener HY 951 (CIBA-GEIGY AG, Basel). As reinforcement we used rovings with silane size (ES 9-360x21-K43) in order to get good adhesion and spunfibres with oil size (ES 10-400-GT07) to get bad adhesion to the resin (GEVETEX GmbH, Düsseldorf). To determinate the strengthes of the interface we bonded resin specimens with E-glass balls, which were cut and grinded (fig. 2). The resin tubes were made by centrifugal casting, the UD-tubes by filament winding process. Loading by axial tension or compression and torsion was performed with a special hydraulic equipment[2] , loading by internal pressure was performed with hydrostatic pump.

Results

The tested epoxy resin shows tough behaviour in the range of tensions-torsion and brittle behaviour in the range of biaxial tension (int. press.). The strengthes for adhesive failure are remarkably low. Characteristical for adhesive failure is the shear strength which is about 2 to 3 times higher than the tensile strength. (fig. 2). Under the assumption of cohesive matrix failure we calculated the stress-strain curves of the UD-Lamina (fig. 3). We remark that by $\sigma_{\perp}$-loading the first crack in the matrix leads to total failure of the UD-Lamina, while $\tau_{\#}$ -loading can be increased after the first matrix crack, until crack propagation reaches a critical value and total failure occurs. In comparison with the experimentally found curves on UD-tubes (roving) we see that not only the shape of the stress-strain response but also the strenthes and strains at break can be predicted by means of the "sliced model". Strengthes and deformations at break of UD-GRP with spun-fibre reinforcement (bad adhesion because of oil size) are essentially lower than those calculated for cohesive failure. Fig. 4 shows failure curves for UD-GRP, calculated with the experimentally determined data from Fig. 2. We find the curve for cohesive matrix failure (a in fig. 4), in accordance to the measured data of roving tubes, while the strengthes of the spunfibre tubes coincide with the calculated curve for adhesive failure (b). Since the surface and the surface treatment of the E-glass balls are not identical with the surface of the rovings and spunfibres, we now assume that the absolute values of the adhesive strengthes can vary with different surfaces but the shape of the adhesive failure curves (fig. 2) must be similar. Two hypothesis are discussed.

1. UD-GRP (roving) will fail adhesively by shear-loading $\tau_{\#}$

Unter this assumptions we calculate a failure curve (c in fig. 4) which predicts failure below the experimentally found values. Adhesive shear-failure can be therefore excluded.

2. UD-GRP (roving) will fail adhesively by tensile loading $\sigma_{\perp}$

Under this assumption we calculate a failure curve (d in fig. 4), which coincides approximately with the measured data in the range of preponderant tensile loading. In the range of prepcnderant shear loading this curve is not realistic because the calculated curve for cohesive failure is in good agreement with experiment.

Conclusions

Under shear loading $\tau_{\#}$ UD-GRP has a higher fracture toughness than under tensile loading $\sigma_{\perp}$. The ratio tensile strength to shear strength of cohesively failed GRP is higher than the ratio of adhesively failed GRP (see experimental data, fig. 4). If the glassfibres have a good treatment with coupling agent (size), adhesive failure under shear loading can be excluded, adhesive failure under preponderant tensile failure is possible but not probable. If the glassfibres were treated with oil size, the UD-GRP will fail adhesively under plane loading by $\sigma_{\perp}$ and $\tau_{\#}$. This results are only valid for short time loading under normal dry climate.

References

[1] A. Puck, W. Schneider: Plastics & Polymers, Febr. 1969, 33

[2] W. Knappe, W. Schneider: Kunststoffe 62 (1972) No.12

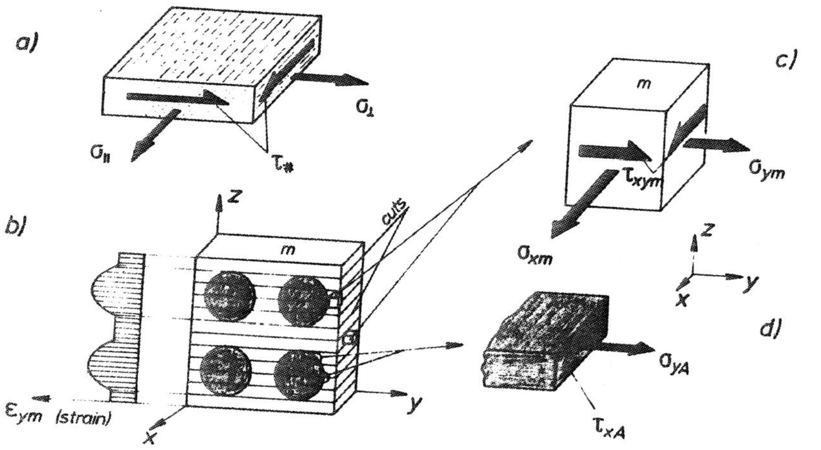

fig. 1 a) Unidirectional lamina under plane state of stress b) "sliced model" (m = matrix, f = fibre) c) microstresses of the matrix d) microstresses of the interface (A)

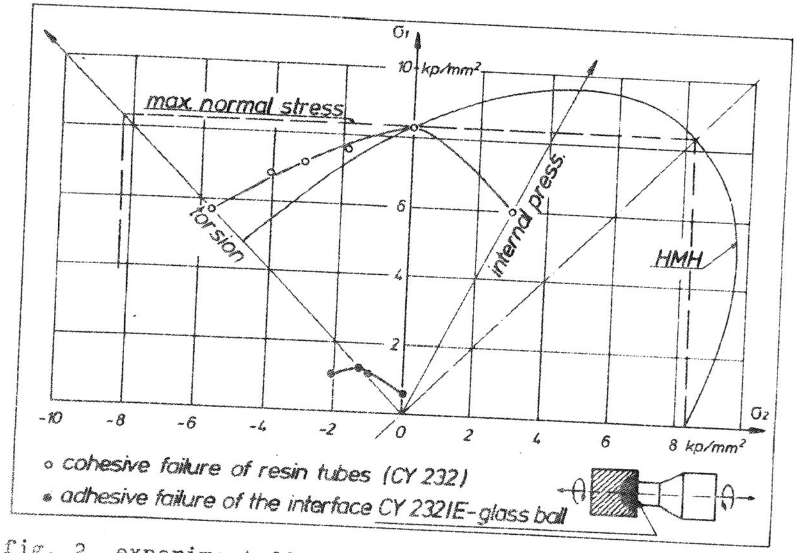

fig. 2 experimentally determined failure curves plotted in the principal-stress diagramm (HMH = failure criterion of HUBER, von MISES, HENCKY)

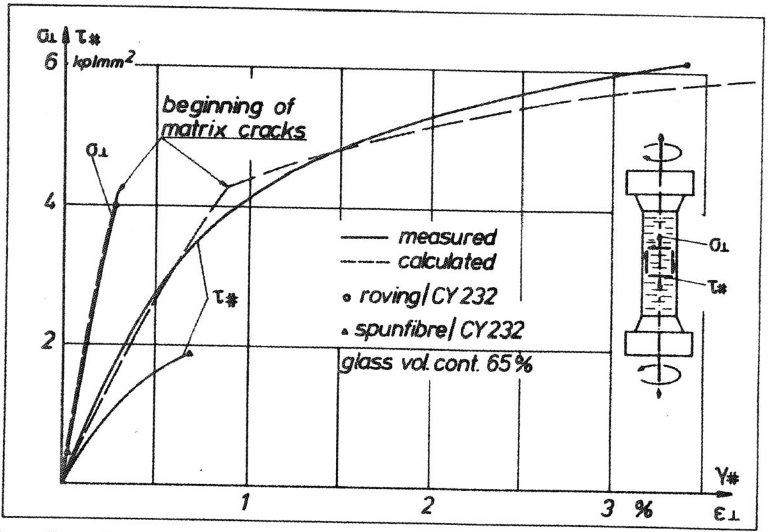

fig. 3 stress-strain curves for unidirectional GRP under tensile ($\sigma_\perp$ - $\varepsilon_\perp$) and shear ($\tau_\#$ - $\gamma_\#$) loading respectively (calculated with the "sliced model)

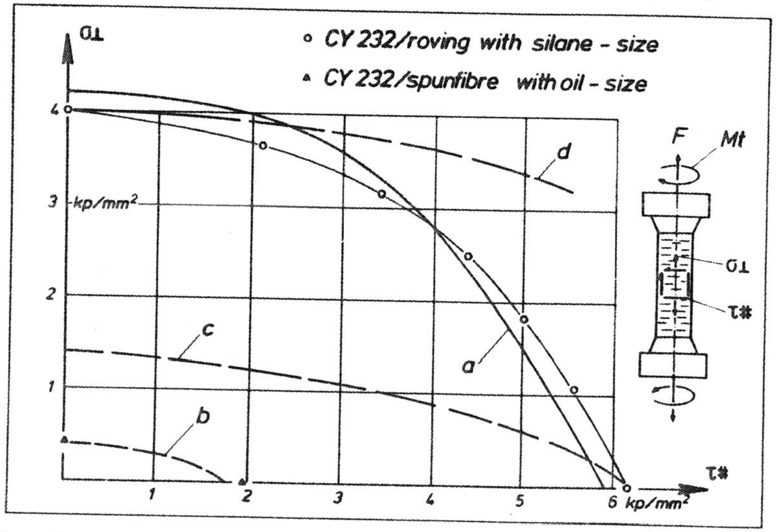

fig. 4 calculated failure curves for UD-GRP (glass vol. cont. = 65 %, ○ ,▲ experimental data)
a. on the assumption of cohesive failure, b. on the assumption of adhesive failure, c. on the assumption of adhesive failure under $\tau_\#$-load, d. on the assumption of adhesive failure under $\sigma_\perp$-load