DAMAGE EVALUATION OF GLARE®4B UNDER INTERLAMINAR SHEAR LOADING AT DIFFERENT TEMPERATURE CONDITIONS

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ABSTRACT

The fibre reinforced metal laminate GLARE®4B has been investigated under interlaminar shear loading conditions at temperatures between –50°C and 110°C. Short beam shear (ILSS) and double notched shear (DNS) tests were performed. The interlaminar shear strength decreases strongly with increasing temperature. The DNS test shows that the shear strain increases and the interlaminar shear stiffness decreases with increasing temperature. The observed damage occurs mainly in the 90°-fibre layer. For low temperatures delamination between the fibre-layers is the dominant failure mode. The higher the temperature, the more cracks develop in the 90°-layers. These multiple cracks grow with increasing shear load and form the final fracture surface. Light and electron microscopy showed that the cracks are mainly based on fibre-matrix interface failure. Beneath the strong decrease in stiffness of the reinforcement layer, the stiffness of 90°- and 0°-plies changes different with increasing temperature. This phenomenon can be traced back to different damage mechanisms of 0°- and 90° fibre layers at elevated temperatures.

1. INTRODUCTION

GLARE® is a glass fibre reinforced metal laminate (FML), advanced from the development of ARALL™ at the TU Delft in the early 80s. GLARE® is chosen for the fuselage of ultra high capacity aircrafts primarily because of its excellent fatigue properties [1]. Further reasons for its application as aviation material are primarily weight saving, as well as damage tolerance and safety aspects. The possibility to use common repair techniques, deployed for metallic structures, supports the application of GLARE® in the aircraft industry.

Static tension and compression strength, as well as damage tolerance characteristics of FMLs, such as fatigue or residual strength, as well as crack growth behaviour due to preceding loadings are already well investigated [2,3]. Also fracture mechanics tests on FMLs were made [4]. Hence, attention has been shifted towards stability aspects [5,6].

Due to the slightly reduced Young's modulus compared to monolithic aluminium, GLARE® panels tend to buckle earlier under compression or in-plane shear loading. Moreover, this becomes an important issue if the plies separate as a result of decreasing interlaminar shear stiffness or in the worst case, when interlaminar shear failure leads to delamination. If this occurs, the bending stiffness decreases rapidly and the separated plies cannot bear the applied bending or in-plain shear loadings. This leads to an increasing bending or shear deformation, followed by further delamination growth [7].

Therefore, the bending and in-plain shear behaviour depends strongly on the interlaminar shear properties of the laminate. These, are dominated by the properties of the matrix, which is in principle also the adhesive between the reinforcing and metallic layers. The matrix properties after all, are strongly affected by elevated temperatures.

Regarding the spatial stress states in the material when loaded in compression or in-plain shear, high stresses in thickness direction (mode I) occur only when delamination buckling has already initiated. Hence, interlaminar shear loadings (mode II) are considered first.

Due to these facts the investigation of interlaminar shear properties of GLARE® at different temperatures is evident. Beside that, the experimental results give basic data for model the material behaviour.

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2. EXPERIMENTAL, RESULTS & DISCUSSION

Material

GLARE® is a laminate, consisting of thin aluminium sheets bonded with interspersed composite plies made out of prepregs of epoxy and high-strength S2-glass fibres, cured at 120°C. The material has been developed in various grades with different numbers and orientations of the reinforcing fibre layers. Each glass fibre reinforced polymer (GFRP) layer of the investigated GLARE® 4B (Fig.1) consists of 3 single unidirectional (UD) prepreg layers with a thickness of nominal 0.127*mm* each, oriented in [90,0,90] direction with respect to the main orientation of the laminate (rolling direction of the aluminium). The investigated GLARE®4B-6/5-0.3 consists of 5 reinforcement layers and 6 alternate aluminium layers. The thickness of the 2024-T3 aluminium sheets is about 0.3*mm*.

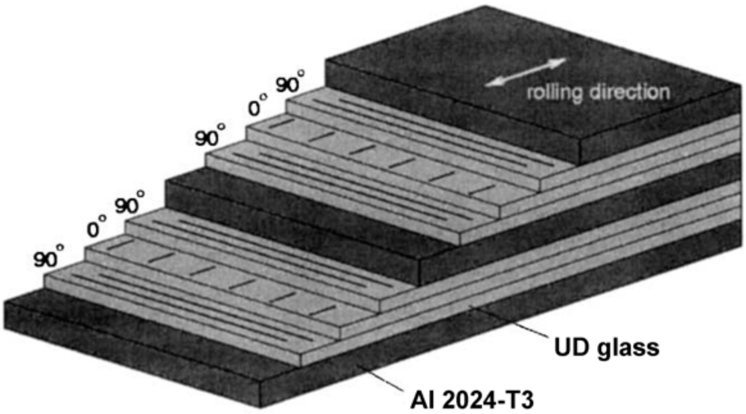


Fig.1 Schematic of GLARE®4B-3/2 lay-up [8]

With this material two types of tests had been performed: the interlaminar shear strength test (ILSS) according to ASTM D2344 and the double notch shear test (DNS) according to ASTM D3846.

Interlaminar shear strength

Interlaminar shear strength tests were carried out for temperatures between –55°C to 110°C in a climatic chamber. This short beam shear test is equivalent to a 3-point-bending test. With the geometrical dimensions of the specimen and the measured reaction force the shear stress can be calculated using the theory of bending straight beams according to ASTM D2234. The shear strength is calculated using the maximum occurring force.

To investigate the influence of the layer orientation, specimens in main orientation (L) as well as specimens transverse to their main orientation (LT) had been prepared. 3 specimens were tested per type at each temperature.

ILSS Results

Fig.2 shows typical force-displacement curves for different temperatures. The curves can be classified in three groups by the test temperature. This classification proves to be independent from the investigated material orientation and layer number.

The first group exhibits a steep regressive increase with a reduced displacement at maximum force for the lower temperatures from –55°C to 20°C. The curves show a rather elastic behaviour and failure mostly occurs spontaneously as delamination in one of the central GFRP-layers, aside from the load inducing region of the specimen.

The second group at temperatures between 50°C and 80°C shows a more elastic-plastic behaviour. After an initial increase, in the second section a pronounced reduction in slope, before reaching the maximum in the force-displacement curve, is obtained. This reduction starts the earlier the higher the temperature is. The curves develop with a relatively slow loss of force until failure. All test curves up to 80°C show an initial increase with approximately the same slope.

A more viscous behaviour can be observed for the third group at test temperatures above 90°C. The initial increase of the force-displacement curves is strongly reduced and shows a slope comparable to the second section of the curves of the second group. The slope decreases with increasing displacement. The maximum displacement increases as well. For elevated test temperatures over 90°C a value for the deflection at maximum force is hardly detectable.

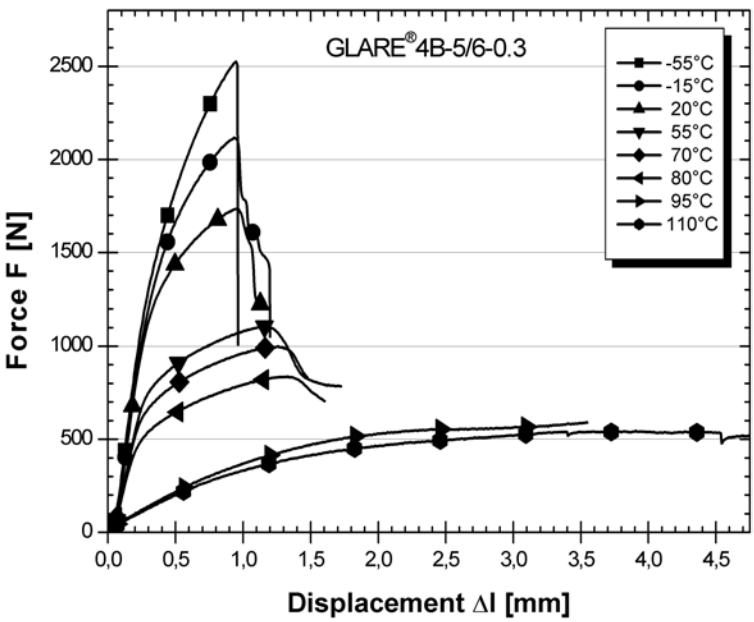
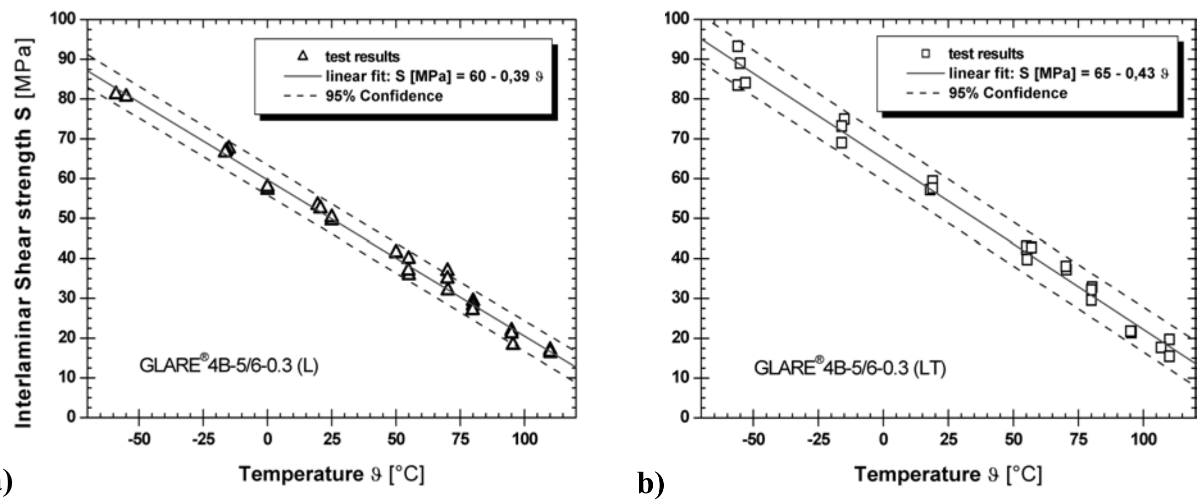


Fig.2 Force–displacement curves – ILSS tests on GLARE®4B-6/5-0.3 for various temperatures

From the above results the interlaminar shear strength can be calculated. It decreases strongly with increasing temperature. Fig.3 shows the test results for GLARE®4B-6/5-0.3 (L) and for GLARE®4B-6/5-0.3 (LT) as well as their linear approximations and the 95% confidence bands, respectively. The shear strength decreases from about 80*MPa* at -55°C to about 20*MPa* at 110°C for the L-specimens (Fig.3a). Although deformation and failure behaviour show pronounced differences with increasing temperature, the shear strength can be well approximated linearly.



a) b)

Fig.3 Influence of the temperature on the interlaminar shear strength of
a) GLARE®4B-6/5-0.3 (L) b) GLARE®4B-6/5-0.3 (LT)

The 95% confidence band for the L-results calculates smaller as for the LT-results. By comparing the approximation curves (see approximation functions in Fig.3a and Fig.3b), higher shear strength values are achieved for the transverse orientated specimen (LT) at lower temperatures. This points on an influence of the fibre lay-up besides the fibre dominated shear properties. The higher amount of 0°-fibres in the LT specimens leads to an increasing shear strength.

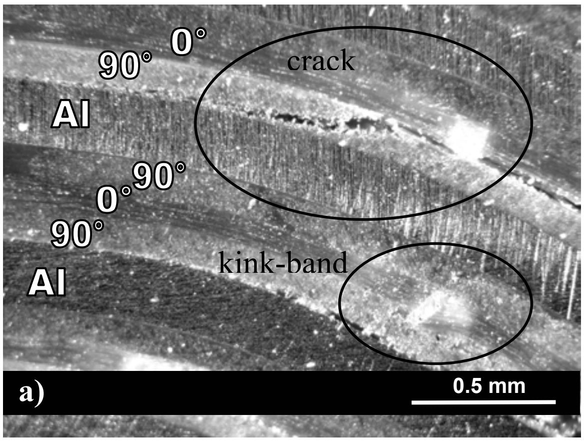
Damage behaviour in the ILSS-test

Due to a brittle damage behaviour for lower temperatures, shear stress induced delamination typically grow towards one edge of the specimen.

At higher temperatures above 50°C, although increasing deformation, the failure zones remain restricted to the region of high plastic deformation between the supports of the test assembly. Delamination could not be observed. This implies a more ductile damage behaviour for higher temperatures. At increasing temperatures an increasing damage develops in the 90°-plies.

The microscopic investigation of the damaged areas shows no pronounced differences between the test temperatures. It could be observed that damage occurs mainly in the 90° layer. There, starting from fibre-matrix debondings, matrix cracks form at the transition between the 90°-layer and their neighbouring (aluminium or 0°-) layer and grow, due to the applied shear stress, diagonal to the other layer interface of the 90°-plies (Fig.4a - crack).

Also, micro-buckling of 0°-fibres occurs with increasing deformation (Fig.4b). This failure mode occurs due to the flexure of the specimen which induces high compressive stresses in the 0°-plies. This was only observed for temperatures above 70°C where the deformation is strongly increased.



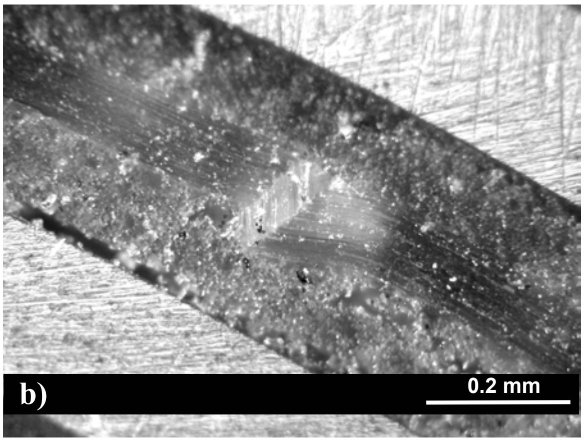


Fig.4 Damage pattern by ILSS-test of GLARE®4B-6/5-0.3 at 50°C
a) Cracks in 90°-ply and kink-bands in 0°-ply b) magnification of micro-buckling in 0°-ply

Double notched shear test

To validate the results from ILSS tests, the double notched shear (DNS) test according to ASTM D3846 had been performed. The improvement of the DNS test method, compared to the ILSS-test, lies in the fact that bending does not occur and does not influence the measurement of the resulting shear stress. The interlaminar shear stress state is rather uniform.

For the test asymmetrically notched specimens were used. The notches were machined from above and below on a vertical layered GLARE®4B (L) laminate with a depth of more then half the specimen thickness. Thus, all plies of the central fibre reinforcement layer [90,0,90] are longitudinally freestanding. Therefore, axial stresses can not be induced in the region between the notches (see also Fig.8). By applying compression loads on the ends of the specimen, in the region between the notches, the axial load could only be transmitted via shear stresses. To avoid bending, the specimens were supported by an anti-buckling guide. The DNS-tests were performed in the temperature range between -45°C and to 110°C with 5 specimens at each investigated temperature.

To obtain the shear deformation of the single plies, a digital video camera was connected to a microscope. This enables to look with a magnification factor of about 50 at the lateral surface of the specimen inside the heat chamber. Subsequently, digital video prints could be evaluated, measuring the longitudinal deflection of the layer interfaces, using the natural surface pattern. The shear deflection and consequently the shear angle could be correlated with the respective shear stresses calculated from the loads of the testing machine. Thus, the shear stiffness, dependent on the shear strain and temperature could be obtained.

Results of DNS-tests

Fig.5 shows the mean curves of shear stress-shear strain for 0°- and 90°-plies at all investigated temperatures. The curves show a regressive increase in shear stress with increasing shear strain. For lower temperatures they exhibit a higher pronounced shear stiffness. With increasing temperature the slope of the shear stress-strain curves reduces. At elevated temperatures for both layers a general trend of increasing shear strain to failure can be stated.

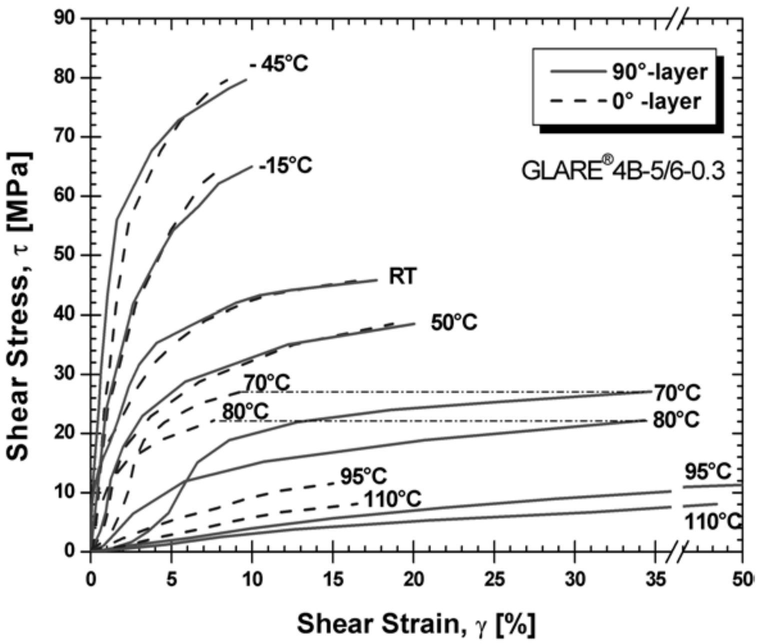


Fig.5 Local shear stress-shear strain curves for the 0°- and 90°-plies in GLARE®4B at various temperatures. (Shear strain values from video image evaluation)

The 0°- and 90°-layers show a similar behaviour at lower temperatures. This changes for temperatures above 50°C. Exceeding this temperature region, the 0°-layer (dashed lines in Fig.5) behaves relatively stiffer as the 90°-layer.

In this test, failure was observed to occur typically by debonding and successive matrix cracking in the 90°-layer, partly supported by inter-layer failure. For the 90°-layers, an increase of maximum shear strain for increasing temperatures is found.

The test finishes when failure occurs in one of the shear loaded layers or between them. Thus, the failure shear strength could only be determined for the failed 90°-ply or the complete lay-up (see doted and dashed lines in Fig.5). Consequently, the shear strain to failure could not be observed separately for the 0°-layer. This explains the apparent decrease of the maximum shear strain of the 0°-layer at elevated temperatures.

For temperatures between 50°C and 80°C an anomalous shear deformation behaviour for 0°- and 90°-plies was found (e.g. 70°-curves in Fig.5). In this temperature region the initial slope of the shear stress-shear strain curve is strongly reduced, compared to lower and higher temperatures. At proceeding deformation, the deformation resistance increases strong (e.g. curve of 90°-ply at 70°C for 5% shear strain). For higher deformations (for 90°-ply at shear strains of about 10%) the slope of the curve diminishes again and for higher shear strains its shape is transferred to an behaviour expectable, looking at the shape of the curves at lower and higher temperatures.

Fig.6 shows the interlaminar shear strength for the investigated temperature range, obtained by performing the DNS-test. The shear strength decreases strongly with increasing temperature from about 80*MPa* at -50°C to 10*MPa* at 110°C. As obtained by the ILSS-test, the shear strength can be linearly approximated.

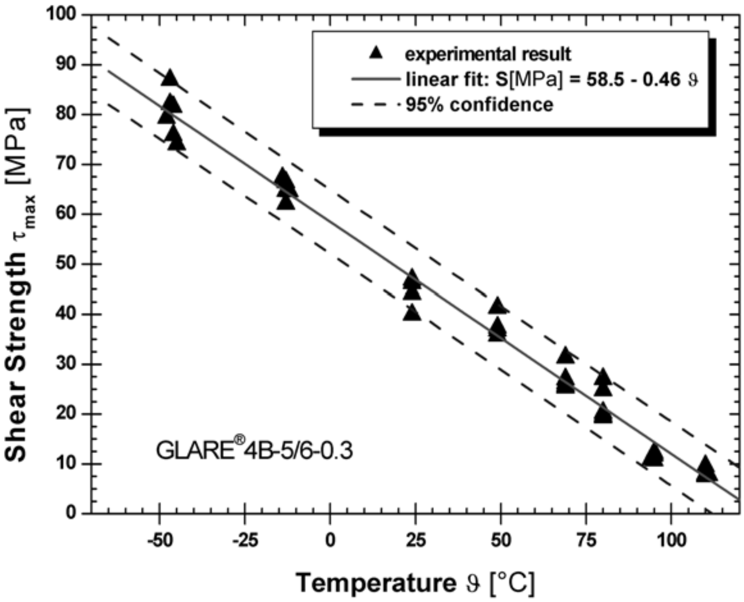


Fig.6 Shear strength of GLARE®4B determined by DNS-test for one reinforcement fibre layer [90,0,90]

The introduced method of optical analysis allowed a resolution of the shear deflection of approximately 0.5% shear strain. To determine the initial slope of the shear deformation curves the increase up to 1% shear deformation was chosen to calculate the shear modulus "$G_{1\%}$". The development of this shear modulus for 0°- and 90°-layers is shown in Fig. 7.

The initial shear stiffness shows pronounced differences for the different fibre-layer orientations at the lowest investigated temperature of -50°C. They disappear for a medium temperature range up to 50°C. By considering the anomalous shear behaviour between 50°C and 80°C, the shear modulus is underestimated in this temperature region. This explains the increase in shear modulus $G_{1\%}$ for both fibre orientations at 80°C, where the anomalous shear behaviour cannot be observed anymore.

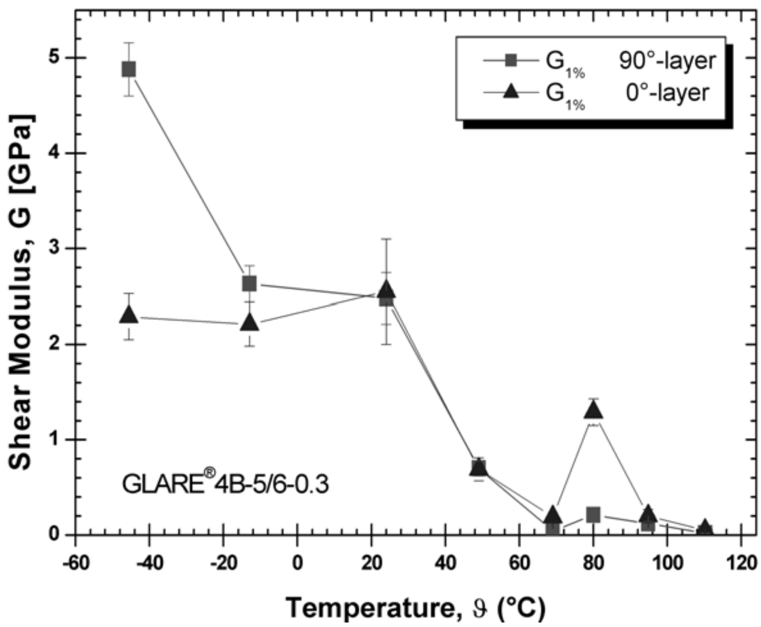


Fig. 7 Shear modulus (secant shear modulus between 0% and 1% shear strain).

In general a declining shear stiffness with increasing temperature can be found as it is expectable for a matrix dominated shear behaviour. Thus, the differences in development of the shear stiffness for 0°- and 90°-plies as well as the anomalous shear behaviour have to be ascribed to the effect of the fibre orientation.

Damage behaviour in DNS-test

A typical damage pattern is shown in Fig.8. It consists of a delamination between 90°- and 0°-layer, followed by successive inter-fibre failure in the 90°-ply. The 90°-layer is the most damage affected layer type for all temperatures. For low temperatures the ratio of inter-layer failure to inter-fibre failure and debonding in the 90° plies is elevated. Failure, involving the 0°-fibres could not be observed although in some SEM micrographs locally distributed 0°-cracks seem to be existent.

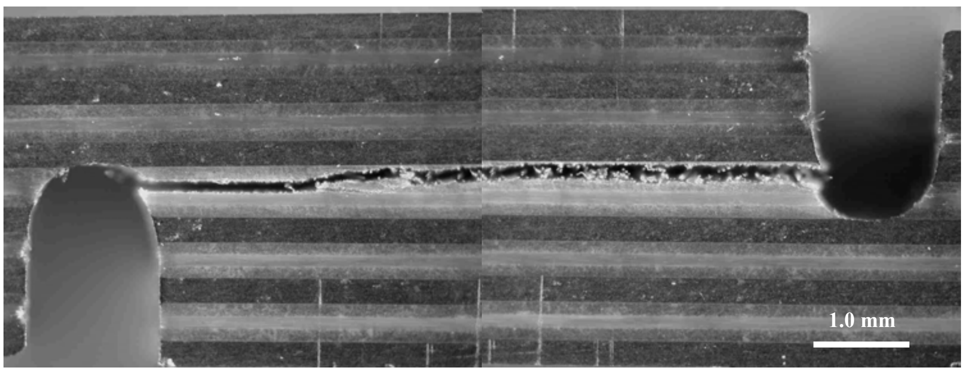


Fig.8 Crack path in double notched shear (DNS) specimen at 20°C

The examination of matrix crack initiation could not be carried out because the magnification of the microscope used for the observations was to low to determine single matrix cracks or debondings.

Although, when specimens are investigated by light microscopy, matrix cracks and debondings lead to light refraction at the respective crack surfaces. This again leads to white scattered light at the edges of the damaged 90°-plies. A similar whitening effect of single plies is also observed in the DNS-test. It is assumed that it also corresponds to the formation of matrix cracks. This crack formation should increase continuously with the applied shear deflection and initiates at about 30% of the ultimate shear deflection at the respective temperature.

SEM micrographs of the GFRP-plies, shear loaded to failure, show differences between lower and higher temperatures. For temperatures below 20°C (Fig. 9) crack initiation far from the fracture surface does barely occur. Micro-cracks did appear only in or close to the layer interface in longitudinal direction and could hardly be observed within the 90° plies.

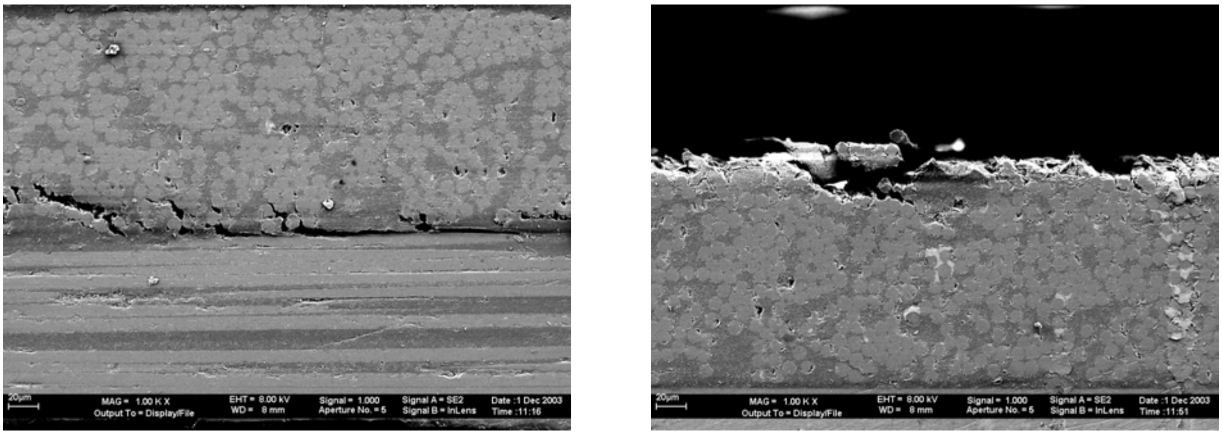


Fig. 9 SEM micrograph: lateral view on shear loaded layers at –50°C (crack formation similar to Fig.8).
a) 90° and 0°-ply above the fracture surface (not visible) b) view on 90°-ply below the fracture surface

For high temperatures above 50°C (Fig.10) the formation of matrix crack in the 90°-layers is strongly pronounced. Micro-cracks form evenly distributed over the layer thickness as fibre-matrix interface failure. Regarding the damage pattern, besides debonding, a local distortion of groups of fibres occurs as a result of the shear movement of the layer (Fig.10a), followed by intense deformation of participating matrix bridges (e.g. Fig.10b, close to layer boundary).

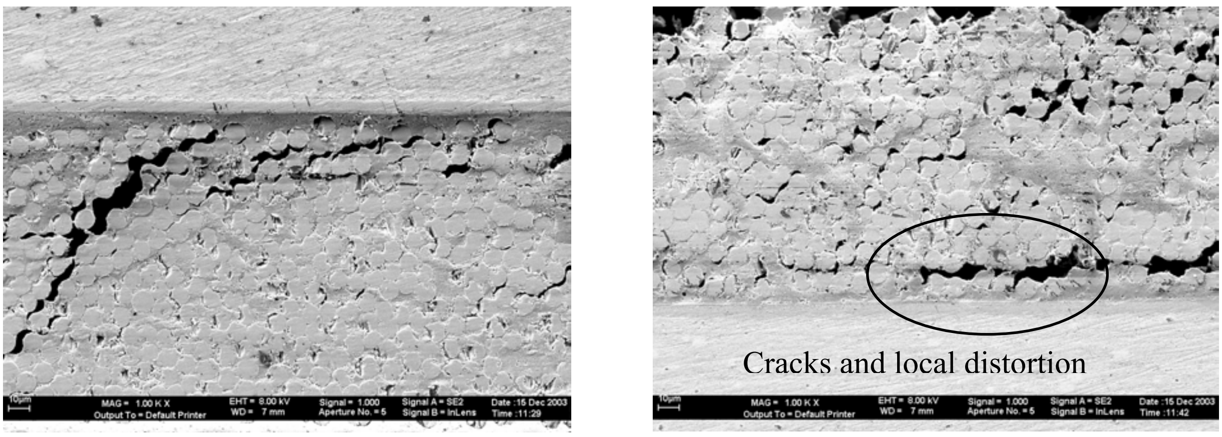


Fig.10 SEM micrograph: lateral view on shear loaded layers at 110°C (crack formation similar to Fig.8).
a) view on upper 90°-ply (fracture surface below – not visible) b) view on 90°-ply below the fracture surface – locally distorted region

The final fracture surface develops for all temperatures mainly in the 90°-layer near the layer interfaces, sometimes crossing the 90°-layer (see Fig.8). Cracks in the 0°-plies could hardly be detected.

Temperature dependent behaviour of 0° and 90°-layers

The differences in shear behaviour of 0°- and 90°-plies are strongly pronounced for elevated temperatures. Crack initiation in the 90°-plies is reduced at low temperatures. Thus, damage accounts for the shear deformation of the 90°-plies, whereas 0°-plies show a rather temperature independent damage behaviour. The absent of crack initiation explains the lower loss of stiffness for the 0°-plies at increasing temperature.

The increasing crack initiation in the 90°-plies at elevated temperatures can be related to decreasing thermal stresses, which imply easier debonding because of diminishing radial compression around the fibres. For the 0°-plies the loss of thermal stresses might be nullified by friction and the disposition for shear torsion in the 90°-plies which constitutes compression perpendicular on the surface of the 0°-ply.

Differences between ILSS- and DNS-test

By comparing the two test methods, a lower interlaminar shear strength is obtained by the DNS-test at elevated temperatures (Fig.11). Whereas interlaminar shear strength shows a value of about 80*MPa* at -50°C for both tests, the shear strength is halved from 20*MPa* to 10*MPa* at 110°C.

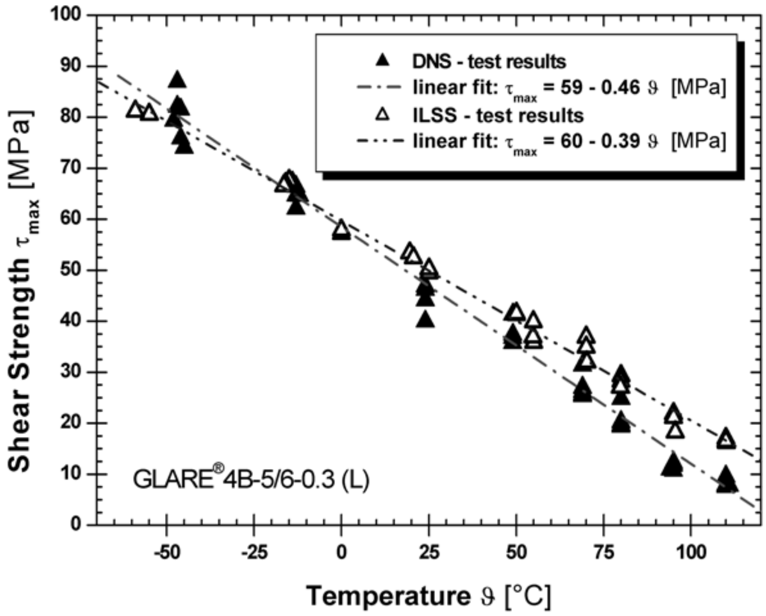


Fig.11 Shear strength determined by ILSS- and DNS-tests

The interlaminar shear properties of GLARE®4B are dominated by the glass fibre reinforcement layers and the respective matrix properties and more pronounced at elevated temperatures. While the shear properties of the GFRP plies strongly reduces, the aluminium plies are hardly affected by temperature. The shear strength is calculated by the ILSS-test instruction over all layers. Thus, shear properties of the aluminium plies are included and the interlaminar shear strength is overestimated by the ILSS-test at higher temperatures. Further, the ILSS-test shows limitations because of its inhomogeneous shear stress state, strongly pronounced for high shear deflections at elevated temperatures.

3. CONCLUSION

The interlaminar shear strength of GLARE®4B decreases strongly with increasing temperatures. Differences of the test methodology leads to different values of interlaminar shear strength at elevated temperatures. For the evaluation of the test method the double notched shear test is to be preferred because of its more homogenous interlaminar shear stress state.

The interlaminar shear stiffness also decreases with increasing temperature. In general shear softening for increasing temperatures can be traced back to the matrix dominated shear properties. Differences between the layer orientations can be ascribed to the different behaviour for 0°- and 90°-plies at elevated temperatures. Whereas damage increases in the 90°-plies by matrix crack initiation and debonding at elevated temperature, damage could not be observed in the 0°-plies.

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