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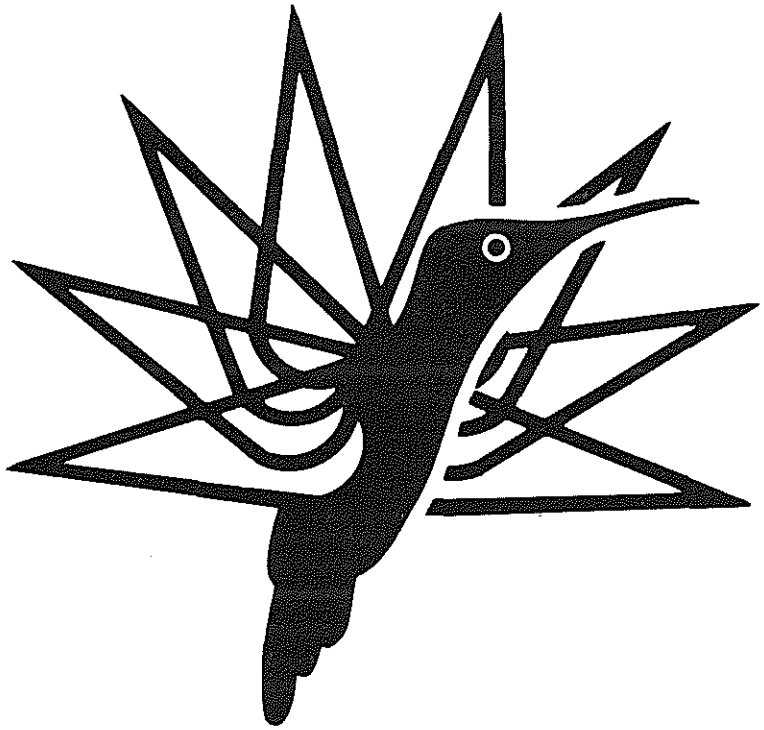

PROPERTIES OF GLASS AND CARBON FIBER FABRICS USED IN HELICOPTER ROTORS

by

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Abstract

A method to produce thick laminates out of fiber reinforced composites is described. Physical, mechanical and fatigue properties of quasi-isotropic glass and carbon fiber reinforced composites (GFC and CFC) are given.
The mechanical properties of CFC are better than the properties of GFC. The optimal curing cycle shows the best values regarding the ease of fabrication.
Samples manufactured with an optimized curing cycle have a higher fatigue strength than samples cut out of a rotor plate.

1. Introduction

For the design of rotor hubs (Fig. 1+2) out of fiber reinforced composites very thick laminates must be used to sustain the high dynamic and statistic loads. Because of the functional efficiency prepregs out of fabrics are used for the production.

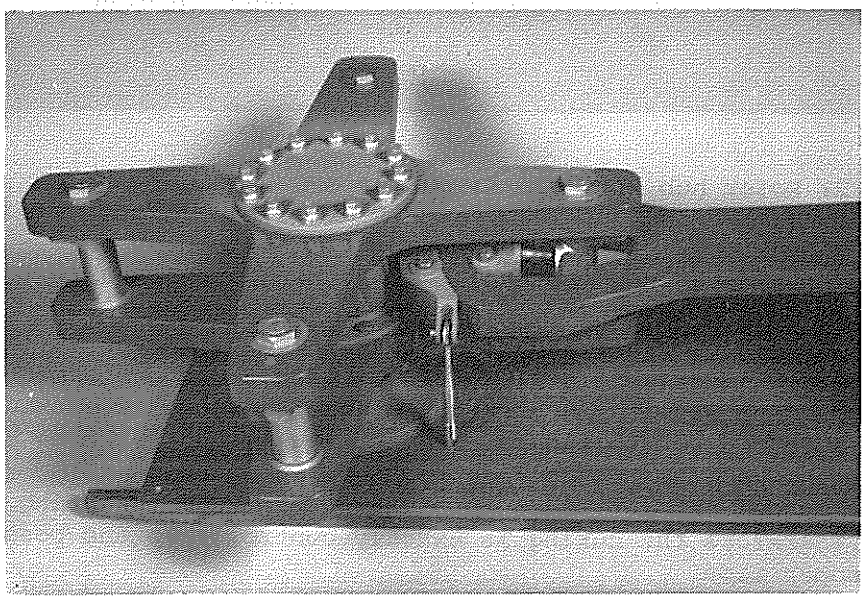

Figure 1: Model of a rotor with plates out of GFC

Prepreg resins are usually flow controlled and therefore have a high enthalpy content. As the thermal conductivity is relatively small, overheating during the curing may occur. Producing thick laminates in one shot also other disadvantages are possible: a nonuniform fiber distribution in the cross section and a high porosity. For these reasons a new technology for the production of thick laminates was developed. Samples with a different quality were manufactured and mechanically and physically tested. Samples cut out of rotor hub plates were also tested and compared with the samples from the (thinner) test plates.

Figure 2: Rotor hub with plates out of GFC

2. Description of the Method

A technology giving the desired results is the so called laminate-package-technology. This technology uses preformed prepreg packages. Onto these packages a high pressure is applied to get a very exact thickness. Simultaneously the packages are heated, so that the prepreg is precured. This causes a lower reactivity and a lower start temperature of the main curing cycle. Therefore the curing is exactly controllable and possible in a proper time.

The goals of these methods are:

- a constant fiber content over the cross section
- a small porosity
- a constant fiber orientation
- no exotherme reaction
- a constant degree of cross-linking (polymerization).

3. Technological Aspects

3.1 Fiber Volume Content

The epoxy F 913 is a resin with a high viscosity. Its flowing properties are controlled by a modifier. Therefore the thickness of the structural parts, the preformed packages and the prepreg have to harmonize.
The resin content of the prepreg should only be 1 to 4 volume percent higher than the desired resin content of the structural part.

The fiber content of prepregs differ in each batch as well as from batch to batch. The laminate-package-technology compensates this difference without any problem, if the resin content only varies about ± 4 weight percent.

The fiber content as a function of the laminate thickness is relatively constant using the laminate-package-technology. Only in the outer layers there are more fibers (Fig. 3). Producing the structural part out of single layers, the fiber content is much more inhomogenous.

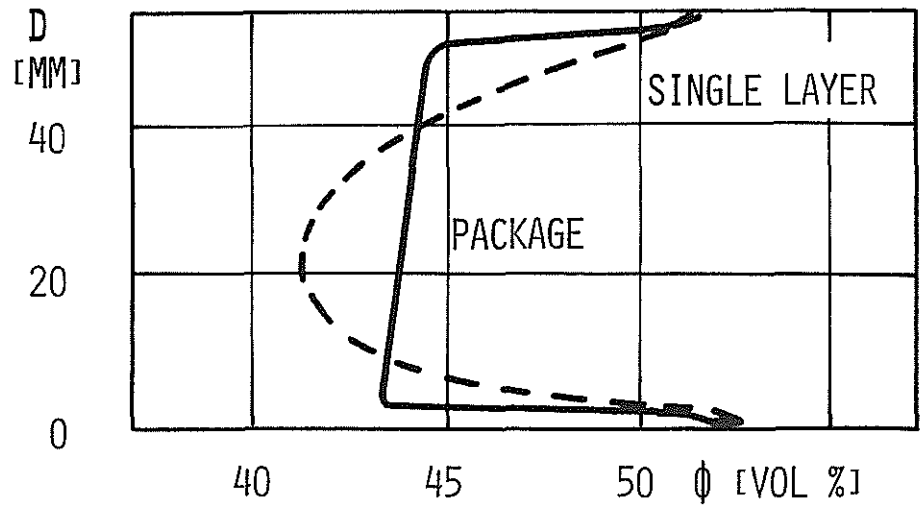

Figure 3: Fiber volume content as a function of the laminate thickness

3.2 Precuring and Pre-cross-linking

The precuring of the packages induces a pre-cross-linking of the resin. Then the advantages are a controllable polymerization in a resonable time and no temperature peaks caused by exotherme reactions. Also the starting temperature for the curing is lowered by the precuring. Therefore the structural part can polymerize at a considerably lower temperature of about 70° C instead of 135° c.

The optimal degree of cross-linking is 1o % to 2o %. The rest enthalpy of 8o % to 90 % and the low starting temperature cause a curing time of less than 6 hours for laminates up to 70 mm thick.

The pre-cross-linking also yields a higher viscosity of the resin. This is also the reason for the fact, that the packages keep their thickness after the prepressing.
If it is necessary to store the packages for a longer time, this should be done under external pressure or at temperatures lower than 0° C.

3.3 Prepressing

The prepressing of the packages has the following advantages:

- a defined thickness
- an exact overthickness
- the form can be almost completely closed at the beginning of the curing
- differences of the fiber content can be easily compensated
- packages can be easily cut with punching tools of steel strip

A package thickness of 4 to 5 mm is advantageous depending on the fiber structure for the use of punching tools of steel strip.
The overthickness of the packages depends on the form: a value of 0.15 to 0.35 mm has approved. With this overthickness the form can be closed without any problem.

3.4 Boundary layer

It was assumed that precuring and pre-cross-linking might cause boundary layers between the packages. Therefore two types of T-peel samples were tested: samples with two layers of prepreg and samples with four layers. The four-layer-sample shows about 3o % of the strength of the two-layer-sample because of the smaller curvature during testing (Tab. 1).

Table 1: Degree of pre-cross-links and T-peel strength depending on the precuring

T-peel sample	precuring temperature [° C]	degree of polymerization [%]	peel strength [N/cm]
4 layers	---	o	6.4
	85	10-15	7.5
2 layers	---	0	20.2
	85	2.3	20.6
	95	9.2	21.5
	100	22	20.0

Precuring times of 25 minutes at 85° C, 95° C and 100° C give a degree of pre-cross-links of 2.3 %, 9.2 % and 22.0 %, respectively. There is a maximum peel strength at about 10 % pre-cross-links (Fig. 4). The reason may be the different way of cross-linking: at low temperatures more elastic, long and chain-like molecules are linked together. At higher temperatures we get more compact, spacious, cross-linked and brittle molecules. If the packages are precured to more than 20 % polymerization a sharp decrease in the peel-strength occurs; in this case there are less links by resin flow from one package to the other and less chemical links between the packages.
Electron microscope pictures from the fracture surface of the T-peel samples have a different appearance depending on the degree of pre-cross-linking: a flake shaped relatively smooth surface of the fresh material, deep huckles on the surface of pre-polymerized material (Fig. 5).

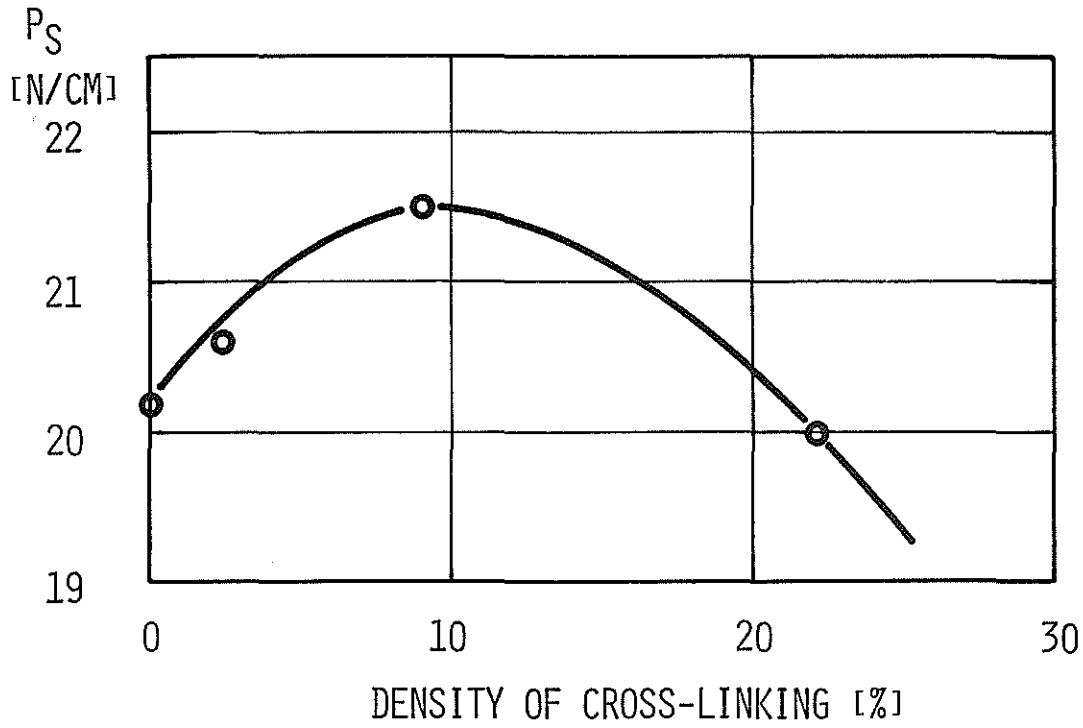

Figure 4: T-peel strength as a function of the pre-cross-linking caused by precuring

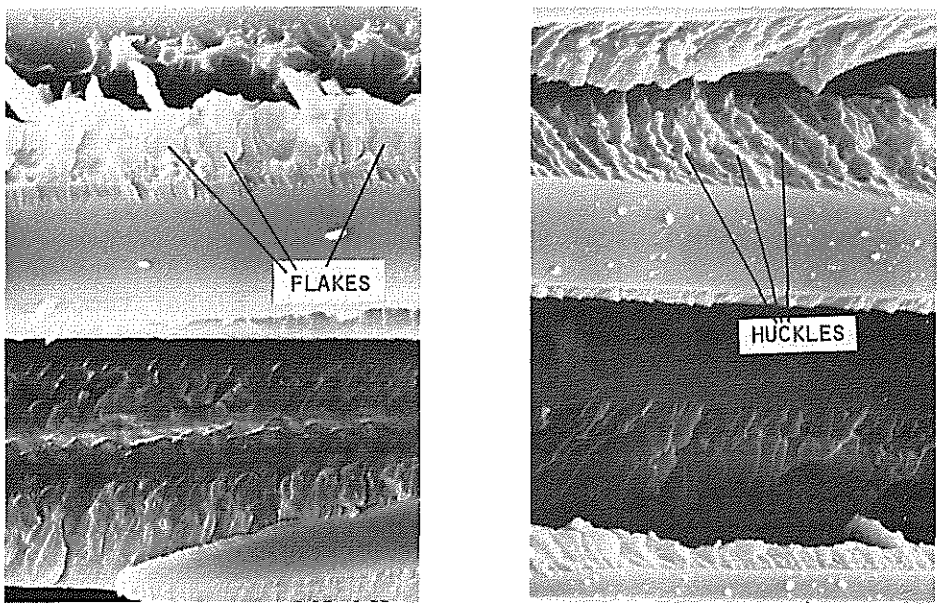

Figure 5: Fracture surface of T-peel-samples with 0 % and 9.2 % pre-polymerization

3.5 Porosity

Using the laminate-package-technology results in a much less porosity (Fig. 6). It is much smaller (1-2%) than in laminates produced with single layers (5-10 %). The distribution and the diameter of the pores also are quite different (Fig. 7): the pores of the single layer samples are huge compared with those of the packages.

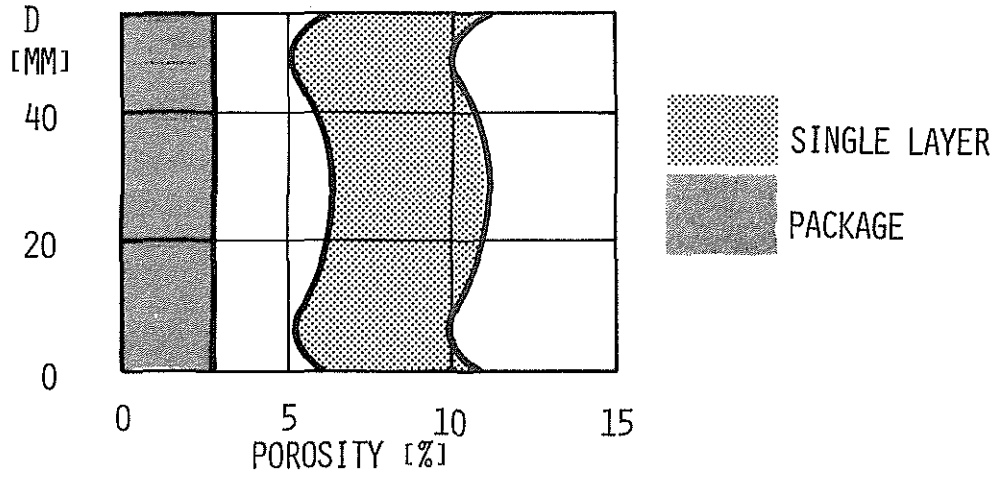

Figure 6: Porosity as a function of the laminate thickness of samples constructed with single layers or packages

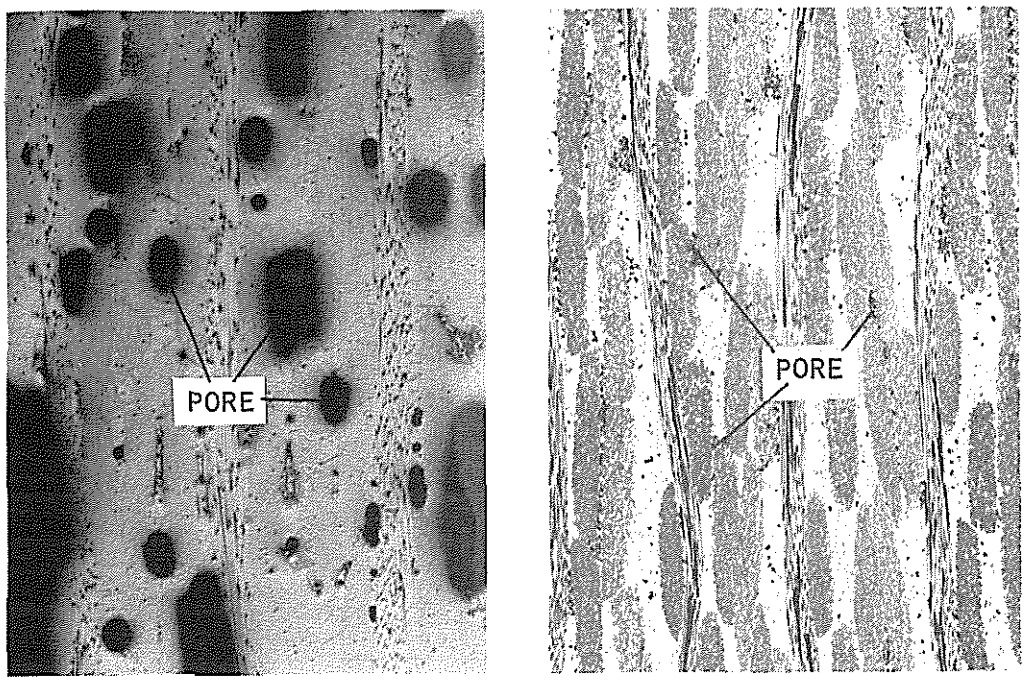

Figure 7: Micrographs of samples constructed with single layers or packages

3.6 Physical-chemical Investigation

To find the optimal curing cycle for the laminate-package-technology physical-chemical investigations were preformed. IR-spectroscopy and liquid-chromatoraphy showed, that there is no difference due to various curing cycles after tempering. The very same result was got by dissolving the laminate. Before tempering there was a larger part soluble and more non-reacted hardener was found in the solution. From caloric measurements the optimal temperature for precuring was found to be 85° C for this resin. At high heating-up-rates the chemical reaction is accelerated very much. Precuring and cooling down to room temperature reduce the activation energy necessary to start the reaction again and therefore reduce the reaction start temperature, too.

These investigations lead to the following curing cycle:

- precuring at 85° C to 15 % cross-link density
- cooling down to room temperature
- cutting the packages
- filling the form with the packages
- heating slowly (1-2° C/min) up to 70° C
- controlling the reaction by heating or self-heating to temperatures T < 100° C until about 60 % of the polymerization has happened
- curing completely at 135° C
- tempering at 190° C

The optimal curing cycle and the other investigated curing cycles are given in Fig. 8.

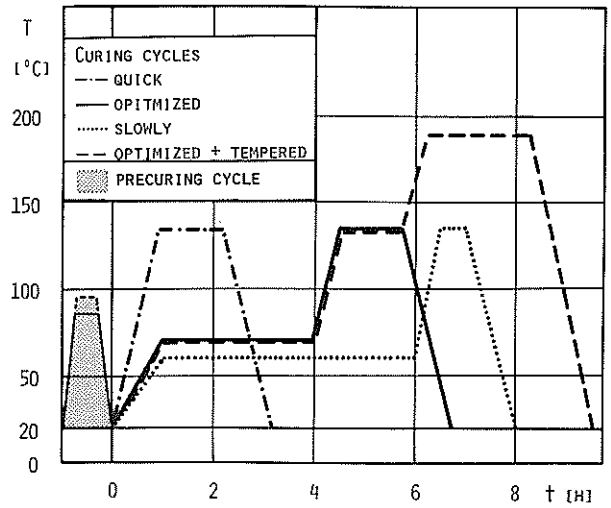

Figure 8: Curing and Precuring cycles

4. Mechanical Data

4.1 Test Sample

Having now found the optimal curing cycle regarding the T-peel test and the caloric data, there is now the question, how the mechanical data are influenced.
The most interesting mechanical value in this relation is the interlaminar shear strength. This value is determined with the short bending sample (Fig. 9). The sample is fixed at 3 points on the upper and lower surface (this allows alternating fatigue). There are no bearings in the holding. The deflection is possible by bending of the 4 GFC-springs.
Test frequencies of about 60 Hz are used.

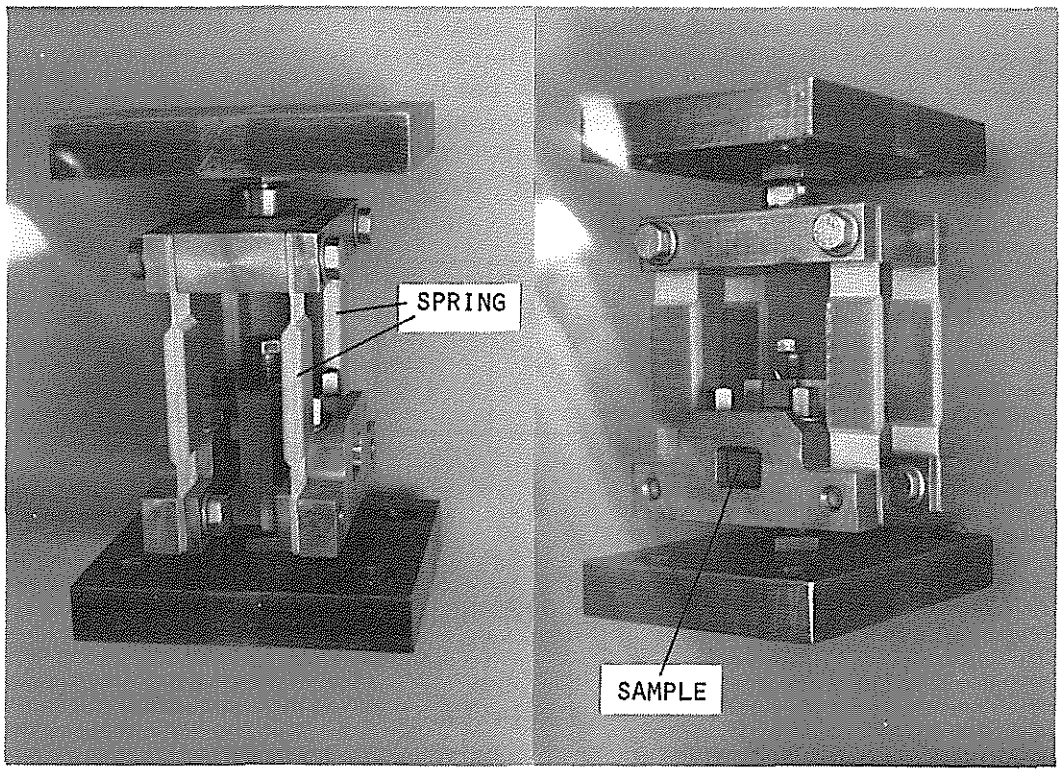

Figure 9: Short bending sample in the test device

4.2 Interlaminar Shear Strength

Four different curing cycles combined with two precuring cycles were tested (Fig. 8):

I	quick	: heating up to 135° C for 75 minutes
II	optimized	: heating up to 70° for 180 minutes and to 135° C for 75 minutes
III	slowly	: heating up to 60° C for 300 minutes and 135° C for 30 minutes
IV	optimized and tempered	: as cycle II plus tempering at 190° C for 120 minutes

The precuring cycles were:

A: no precuring
B: 85° C 25 minutes long (10 % polymerized)
C: 95° C 25 minutes long (20-30 % polymerized)

The interlaminar shear strength τ_{ILSS} is given in Fig. 10 and Tab. 2 as a function of the precuring temperature. There is a considerable decrease in shear strength if the degree of pre-cross-linking is higher than 10 % for all curing cycles. From 0 to 10 % cross-linking there is nearly no difference, only the samples with the quick curing cycle show a small decrease of the shear strength of about 6 %.
The highest strength was reached with the optimized curing cycle and a temper cycle of 190° C.

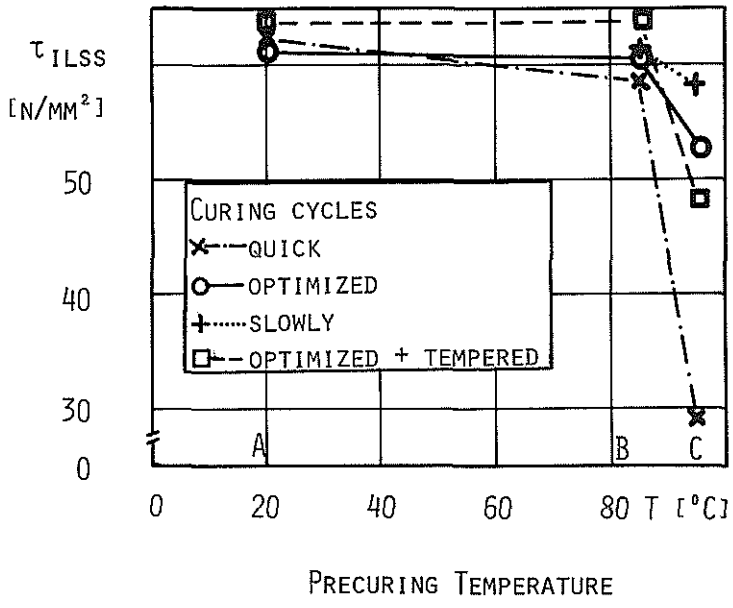

Figure 10: Interlaminar shear strength as a function of the precuring temperature

Table 2: Shear strength of quasi-isotropic laminates manufactured with various curing cycles

curing cycle No.	temper cycle	pre-cross-linking [%]	shear strength [N/mm^2]
I quick	-	0	62.3
II optimized	-	0	61.3
IV optimized + tempered	-	0	63.7
I quick	B	10	58.4
II optimized	B	10	60.5
III slowly	B	10	61.4
IV optimized+ tempered	B	10	63.8
I quick	C	20-30	29.2
II optimized	C	20-30	52.6
III slowly	C	20-30	58.2
IV optimized + tempered	C	20-30	48.1

4.3 Shear Modulus and Glass Transition Points

The dynamic shear modulus was measured with a torsion pendulum. At high temperatures the modulus decreases as shown in Fig. 11.

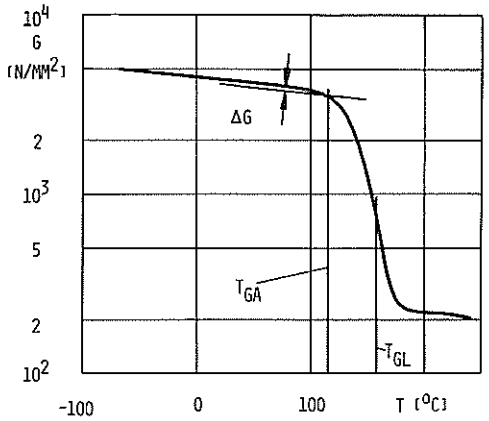

Figure 11: Shear modulus depending on the temperature

T_{GL} is the point of inflection of this curve. At T_{GA} a decrease of 5 % of the modulus compared to a linearised curve has occurred. Fig. 12 shows these two temperatures as a function of the precuring temperature.

The temperature T_{GA} is not much influenced by precuring, only at 95° C precuring temperature there is a small fall. Contrary to this is the behaviour of the point of inflection: precuring to 10 % gives slightly higher values, and precuring to 20-30 % shows a visible increase.

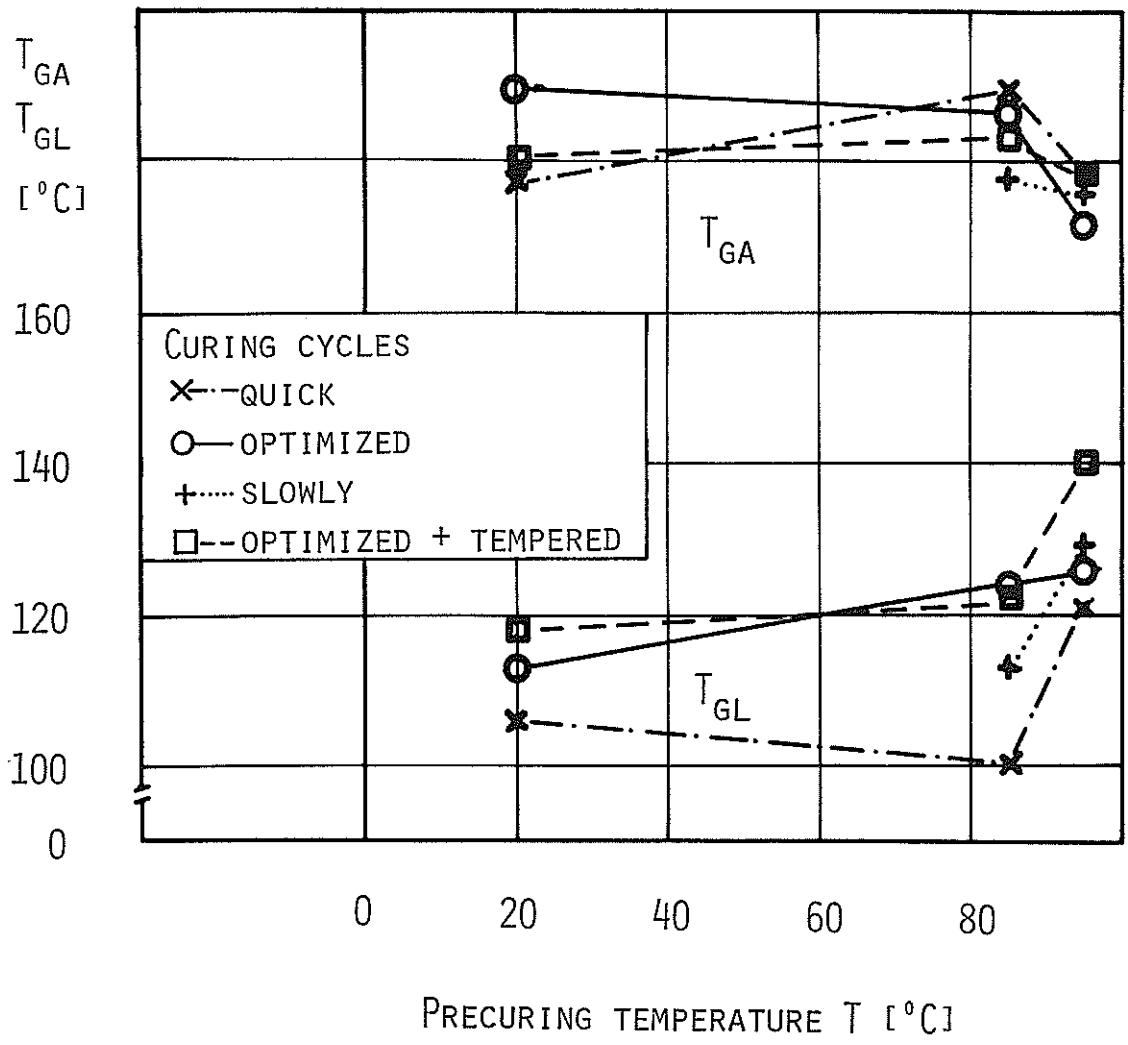

Figure 12: Glas transition points as a function of the precuring temperature

4.4 Interlaminar Shear Fatigue

As rotors are loaded dynamically, the shear strength also has to be tested with alternating forces. The resulting S-N curve of all investigated curing cycles is given in Fig. 13. The scattering of the strength is higher at low cycles than at high cycles.

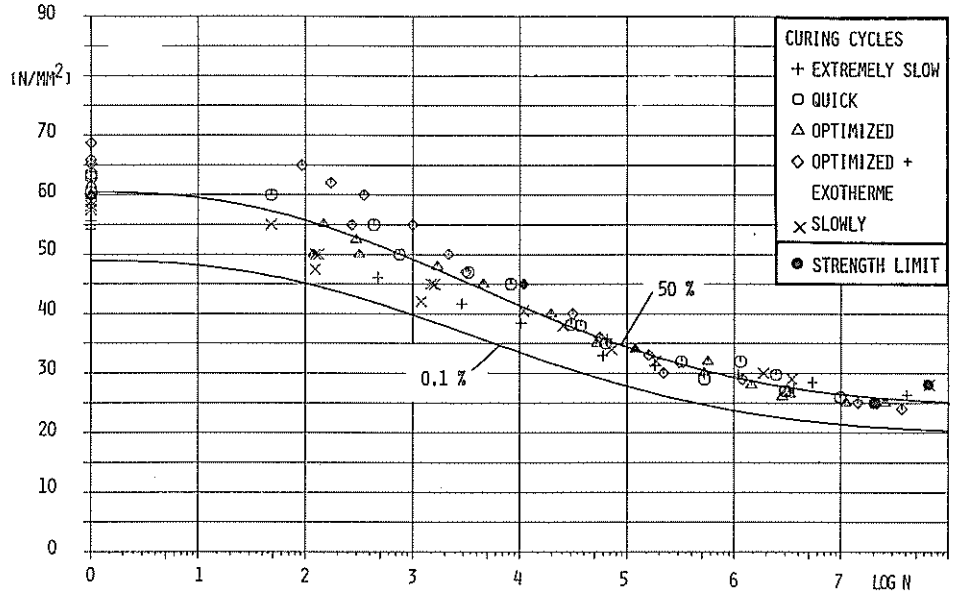

Figure 13: SN-curve measured with samples with various curing cycles

The samples with the optimized curing cycle and the undesired exotherme give he highest results. The next best results are obtained by the samples with the quick curing cycle without tempering. The lowest values yield the extremly slow curing. This can also be seen in Fig. 14, where the fatigue strength is shown as a function of the static strength. But there is a small trend that a high static strength corresponds to a small fatigue strength. Taking the 0.1 % fracture probability values, the same results can be found. This means, that the standard deviation has no great influence.

Quite different is the behaviour of the endurance strength for 10^4 cycles (Fig. 15): a high static strength corresponds to a high dynamic strength. The 99.9 % values give the same result.

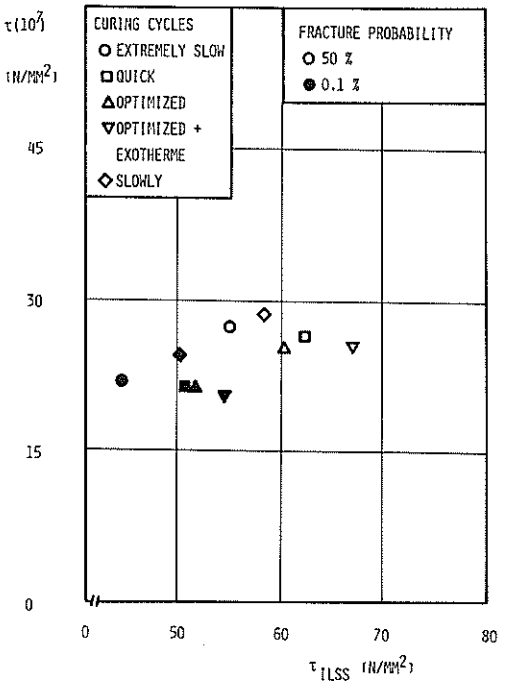

Figure 14: Shear fatigue (10^7 load cycles) as a function of the static shear strength

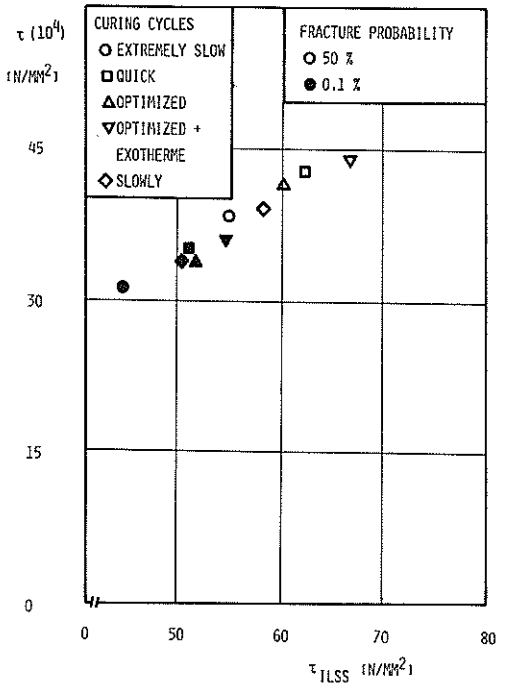

Figure 15: Endurance strength (10^4 load cycles) as a function of the static shear strength

The different fatigue behaviour of the shear specimens is used by a different fracture mode: at small loads the fibers fracture. If the applied stress is higher than a limit strength, interlaminar shear fracture occurs, if it is lower, the fibers on the tensile side of the sample crack (Fig. 16). This crack sometimes grows up to the middle of the sample. Sometimes the shear fracture can hardly be seen: the delamination causes white parts at the side of the sample. The strength limit depends on the curing cycle: the higher the static shear strength, the higher is this limit.

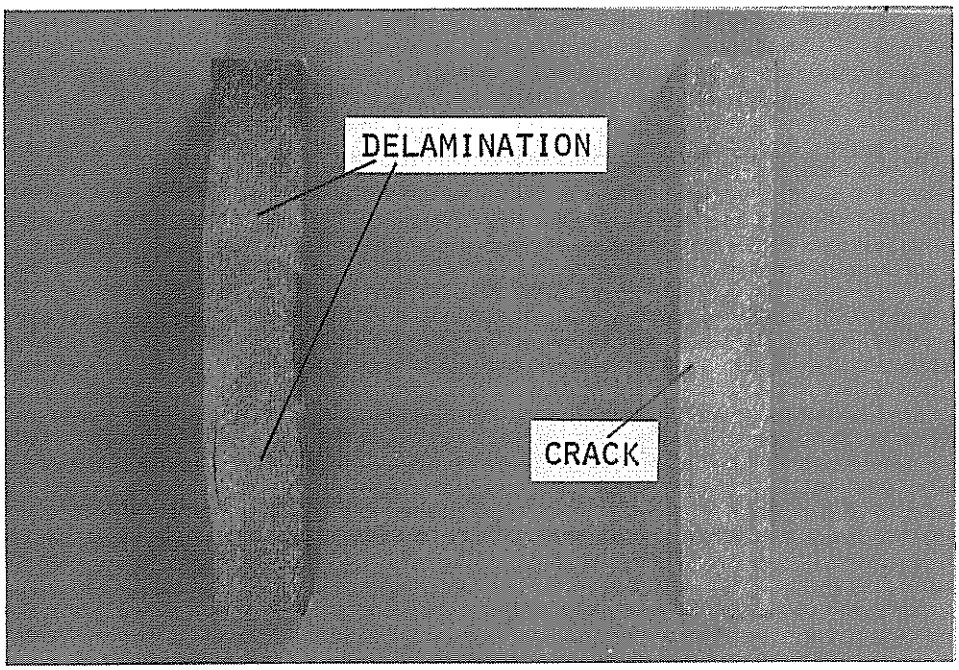

Figure 16: Shear fracture (left) and fiber fracture (right) of GFC

The reason for the fiber fracture is the fact, that due to a good curing cycle the shear strength is larger than the bending strength compared with the bending stress in the sample:

$$\frac{\tau_{ILSS}}{\tau} > \frac{\sigma_{ULT}}{\sigma}$$

To avoid this fracture, either the height of the sample has to be enlarged or the support distance has to become smaller.

In Fig. 17 4 SN-curves are given: two with glass fiber laminates and two with carbon fiber laminates. One of each type is cut out of a sample plate with the optimized curing cycle and the other one is out of a plate built for a rotor hub.

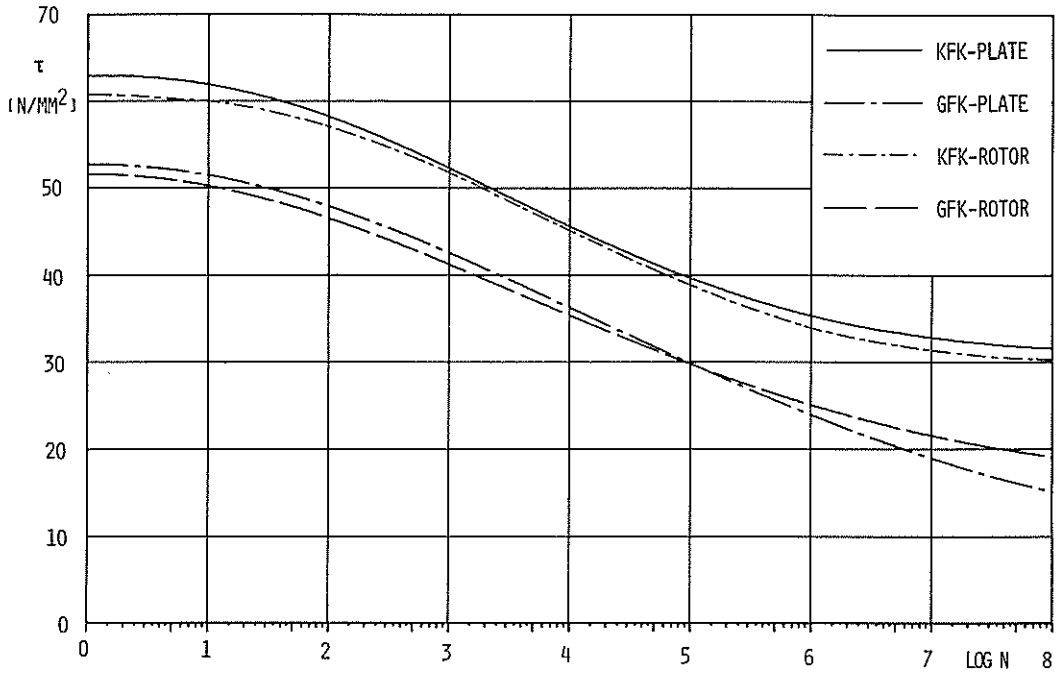

Figure 17: SN-curves of GFC and CFC samples with the optimized curing and out of rotor hub plates

The SN-curves for carbon fiber show about 30 % higher values than the ones out of glass fibers. The standard deviation of the glass curves however, is smaller. All carbon fiber samples showed shear fractures. There is also a difference in the behaviour of the deflection of the samples as a function of the load cycles: the CFC samples show an increase of the deflection by steps, wheras the deflection of the GFC grows continuously (Fig. 18).
There is no relation of the deflection to the fracture mode (interlaminar shear fracture or fiber fracture).

The sample plate out of CFC was manufactured with unidirectional taples. A carbon fabric was used for the CFC rotor hub. The dynamic strength of the fabric is negligible smaller than the laminate constructed with tapes (Fig. 17).

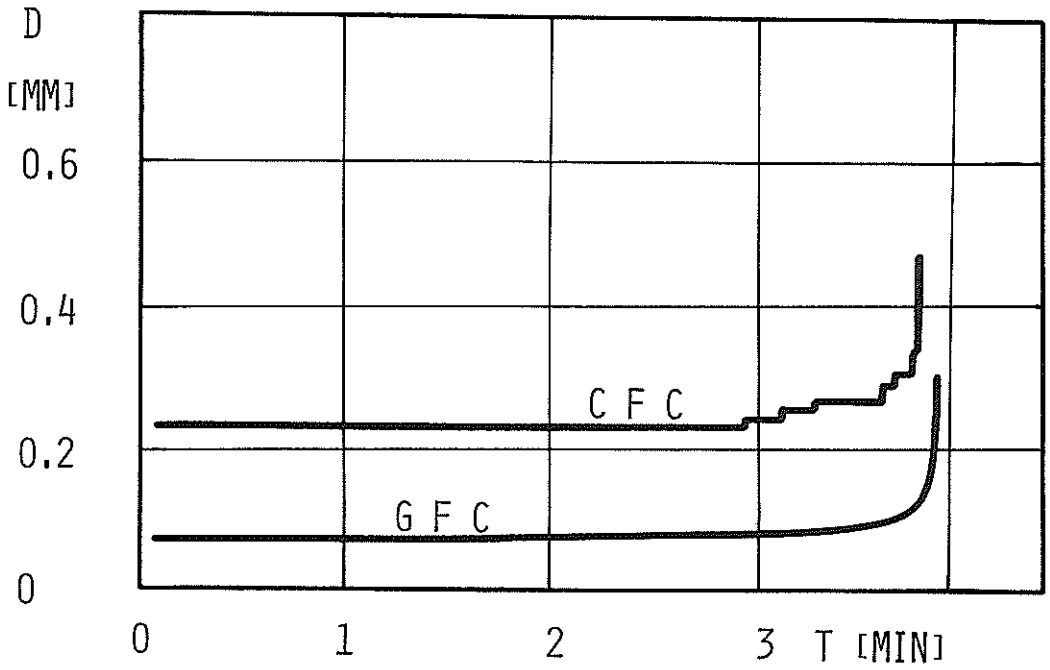

Figure 18: Deflection as a function of the time (corresponds load cycles) for GFC and CFC

A fatigue curve was also measured with samples cut out of a GFC rotor hub. The static shear strength of these samples is higher than the one with the optimized curing cycle. Contrary to that the optimized samples show the better fatigue strength, however.

This means, that optimizing the curing cycle yields a not negligible advantage, especially if one keeps in mind, that there was fiber fracture and that the shear fatigue strength is even higher.

4.5 Bending Fatigue

Another important property for the rotors is the bending strength. Fig. 19 shows the SN-curves out of plates used for rotor hubs. The carbon samples show a much higher strength especially in the high cycle region. The glass fiber samples decrease very much from 10^3 to 10^5 cycles and then remain constant.

The carbon fiber samples show a steady decrease of the bending strength from 10^2 to 10^8 cycles. The standard deviation of the glass fiber is smaller than that of the carbon fiber samples.

The superiority of the carbon fiber is still larger, when the specific weight is considered (Fig. 20). This is true for both, the bending strength and the interlaminar shear strength.

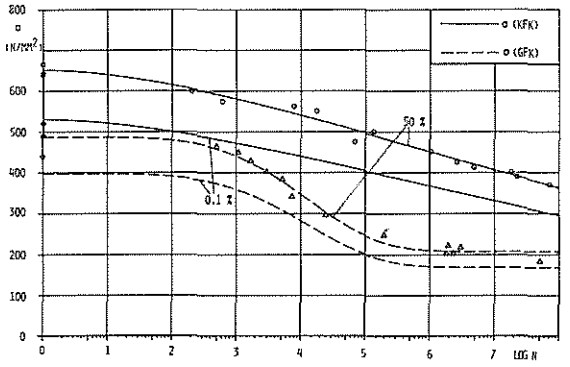

Figure 19: Bending fatigue for GFC and CFC

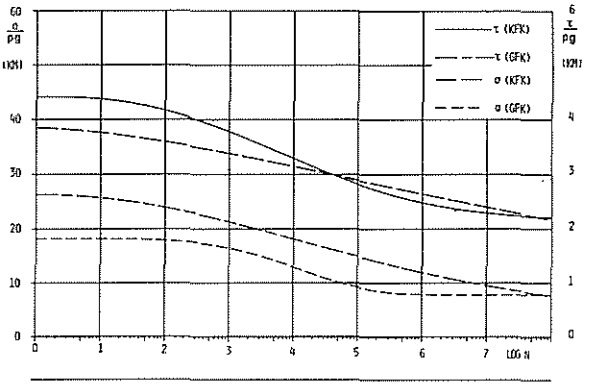

Figure 20: Specific fatigue strength for bending and interlaminar shear